Study of Deemed HVAC Measures Uncertainty Year 2 Report (HVAC4)

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1 EXECUTIVE SUMMARY

The CPUC engaged DNV GL in early 2014 to conduct a two-year study (though recently extended to three years) to examine the energy savings for selected HVAC energy efficiency measures promoted through California's 2013-14 rebate programs. The goal of this study (HVAC4) is to assess the uncertainty of predetermined expected (deemed) savings for selected HVAC measures. This report discusses the Year 2 results and recommendations for additional research during Year 3.

While the CPUC has long required impact evaluations to report the uncertainty of the final evaluated savings, an identified challenge has been quantifying and reducing the degree of uncertainty inherent in deemed savings. The CPUC established an overarching effort to estimate the uncertainty of major measure groups at the portfolio level for planning purposes.[1] The HVAC4 study was established to quantify the uncertainty of deemed savings of some key HVAC measures and identify influential underlying parameters and assumptions. Quantifying the uncertainties of both the deemed and evaluated savings allows for a more informed comparison of them by the energy efficiency community in California. Furthermore, determining which underlying parameters and assumptions have the greatest influence on the uncertainty of the deemed savings—for a given measure—highlights research opportunities most likely to reduce uncertainty.

The objectives of this study include:

- Developing the methods for assessing the uncertainty of deemed savings
- Quantifying uncertainty for some selected measures
- Identifying the input parameters that contribute the most uncertainty to the deemed savings in order to help guide future data collection efforts.

During Year 1 of this study, DNV GL developed a method for determining the uncertainty for measures that use deterministic equations to calculate deemed savings. The results of these analysis results were reported in the Year 1 report. During Year 2 of this study, we developed a method—using parametric simulations—for those measures that require complex analysis to calculate deemed savings; these intermediate results were then used to determine the uncertainty. Given that the majority of deemed HVAC measures are based upon building simulations that draw from California's existing Database of Energy Efficiency Measures (DEER)[2] and technical workpapers prepared by the investor-owned utilities (IOUs) in California, this method has far broader applications.

1.1 Measures studied in Year 2

Under the guidance of the CPUC, the DNV GL research team selected four HVAC measures to study in Year 2 based upon review of the 2013-15 IOU tracking data. Measures considered for this study were outside of those currently being evaluated that either yielded high savings or demonstrated an upward savings trend. The four measures studied include:

- High efficiency residential furnaces

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[1] The CPUC established a portfolio parameter uncertainty analysis and annually develops an uncertain measures list. See: http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6339

[2] The Database for Energy Efficient Resources (DEER) is a database sponsored by the California Energy Commission and the CPUC to provide well-documented estimates of annual energy and peak demand savings, costs, effective useful life (EUL), and costs of energy efficiency measures.

- Optional variable-speed motor (VSMs) on residential furnaces
- High efficiency nonresidential boilers
- Variable frequency drives (VFDs) installed at nonresidential HVAC fan motors.

1.2 Uncertainty analysis methodology

For each of the HVAC measures studied thus far, DNV GL performed an in-depth review of the sources of the deemed savings—either IOU workpapers, secondary sources cited in workpapers, or DEER—to assess the savings methodology and sources of the input parameters. Based on this review, DNV GL decided for the Year 1 study that propagation of error analyses using Monte Carlo simulations[3] would be conducted to assess uncertainty by creating a model of the measure's energy consumption or savings using some of the same input parameters used by the IOUs. Monte Carlo was selected as the forecasting tool for this study because it is a versatile forecasting tool that is used by many industries. In Year 2, building simulations were run to develop regression models that could be used in Monte Carlo simulations. The Monte Carlo simulations were performed by varying the input parameter values for each of the selected measures to determine the average (point) estimate of the deemed savings forecast, its associated uncertainty as well as the relative sensitivity of the variance of the deemed savings to changes to input parameter values.

1.3 Key findings and recommendations

1.3.1 Deemed savings forecasts

For three of the four measures studied, it was possible to directly compare the deemed savings per DEER to the average savings forecasts produced by the Monte Carlo simulations, as provided in Table 1. Each of the savings forecasts has an associated standard deviation, a common measure of uncertainty. Note that the average savings differ somewhat from the DEER estimates in each case. This is partly the result of using previously-published probability distributions—both normal and non-normal—rather than point estimates for the input parameters. When input parameters have non-normal distributions around the DEER point estimate, the mean of the savings outputs may differ from the DEER point estimates. In all cases, though, the DEER estimates are within the uncertainty bands of their respective savings analyses. It would be premature, however, to recommend that the average deemed savings values determined by this study should be considered to replace those presently in use—further discussion within California's energy efficiency community is warranted. Given that there is an existing formal process for updates to deemed savings, these results can be referenced during that process. More importantly, these results can be used to identify parameters to be considered for rebate applications and/or to help design future impact evaluations.

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[3] Monte Carlo simulation was named for Monte Carlo, Monaco, where the primary attractions are casinos offering games of chance. Games of chance, such as roulette wheels, dice, and slot machines, exhibit random behavior. The random behavior in games of chance resembles how Monte Carlo simulation randomly selects variable values to simulate a model. When rolling a die, the roller knows that a 1, 2, 3, 4, 5, or 6 will come up, but cannot know the outcome for any given roll. Each time a Monte Carlo simulation is run, it randomly selects the values of the input variables, within their predetermined ranges, and determines the outcome for that run (e.g., interest rates, staffing needs, stock prices, inventory, phone calls per minute).

Table 1. Uncertainty analysis savings results for measures studied in Year 2

Deemed Savings Results	Uncertainty Analysis	DEER
High Efficiency Residential Furnaces (AFUE 95) in Climate Zone 12		
Average Normalized Annual Natural Gas Savings, therm/kBtuh	0.66	0.64
Standard Deviation, percent	± 81%	N/A
Optional VSM at High Efficiency Residential Furnaces—without cooling–in Climate Zone 12		
Average Normalized Annual Electric Savings, kWh/kBtuh[4]	5.3	N/A
Standard Deviation, percent	± 74%	N/A
Optional VSM at High Efficiency Residential Furnaces—with cooling—in Climate Zone 12		
Average Normalized Annual Electric Savings, kWh/kBtuh[4]	7.6	N/A
Standard Deviation, percent	± 63%	N/A
High Efficiency Boiler at Large Office Buildings in Climate Zone 04		
Average Normalized Annual Natural Gas Savings, therm/kBtuh[4]	1.3	0.75
Standard Deviation, percent	± 69%	N/A
VFD for HVAC Fan w/Discharge Dampers at Large Office Buildings in Climate Zone 03		
Average Annual Electric Savings, kWh	1,512	1,030
Standard Deviation, percent	± 30%	N/A

As can be seen from Table 2**.**, the standard deviations range from 30 percent of the forecasted savings for VFDs at HVAC fans (across all large office buildings in California's Climate Zone 03) to 81 percent of the forecasted savings for high efficiency residential furnaces (across all large office buildings in Climate Zone 12). Knowing that their uncertainties are so broad may give readers a new regard for the much narrower uncertainties generally associated with impact evaluation results, and the role of ex-post evaluation in reducing the uncertainty in ex-ante savings estimates.

1.3.2 Sensitivity analyses

From the sensitivity analyses performed for each measure, DNV GL learned which of the studied factors had the greatest influence on the uncertainty of the savings forecasts as shown in Figure 1. Knowing which parameters contribute the most to the uncertainty of deemed savings can be used to guide future deemed savings values, future rebate applications, and/or evaluation activity.

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[4] Savings are normalized to heating capacity of equipment.

Table 2. Leading contributors to deemed savings uncertainty for Year 2 measures

Input Parameters	Relative Contribution[5] to Variance
High Efficiency Residential Furnaces (AFUE 95) in Climate Zone 12	
Heating Setpoint	93.9%
Building Vintage Bin Weights	4.0%
Optional VSM at AFUE 95 Residential Furnaces—without cooling—in Climate Zone 12	
Minimum Airflow Ratio	35.2%
Baseline/Post-retrofit Fan Control Strategy	34.8%
Optional VSM at AFUE 95 Residential Furnaces—with cooling—in Climate Zone 12	
Minimum Airflow Ratio	31.9%
Baseline/Post-retrofit Fan Control Strategy	28.9%
High Efficiency Boiler at Large Office Buildings in Climate Zone 04	
Minimum Airflow Ratio	82.5%
Δ Thermal Efficiency	16.7%
VFD for HVAC Fan at Large Office Buildings in Climate Zone 03	
Fan Power Index (W/cfm)	42.4%
Minimum Airflow Ratio	28.5%

1.3.3 Recommendations

As previously described, the goal of the HVAC4 study is to quantify the uncertainty of deemed savings of some key HVAC measures and identify influential underlying parameters and assumptions. As shown in Figure 1, the results of this study can be used in several ways. First, the Year 2 findings of this study have already been informally incorporated into the database for the Portfolio Parameter Prioritization Project (P4) Uncertainty Analysis Tool. A formal method for ongoing incorporation will be developed during Year 3 of this study.

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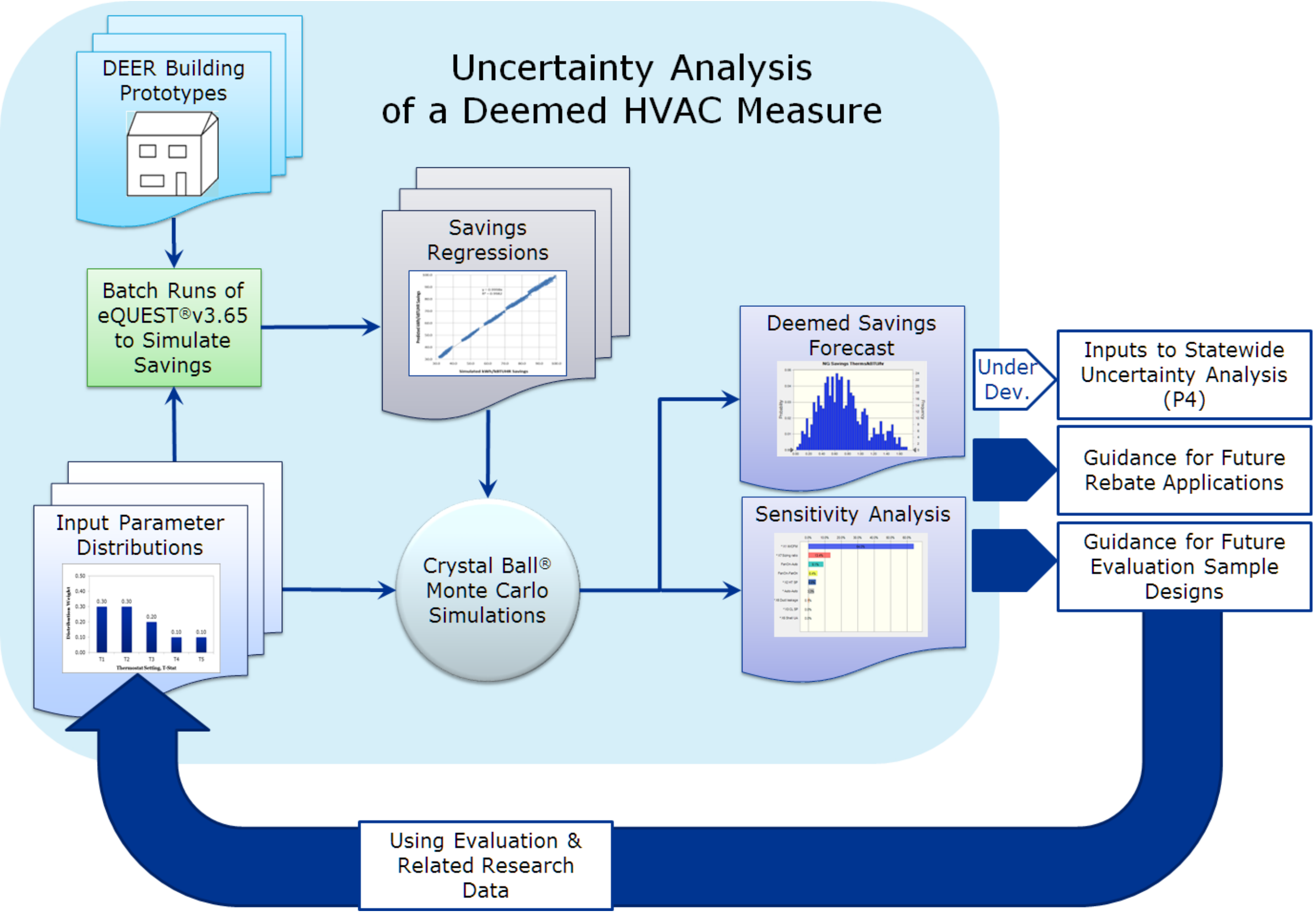
[5] Absolute values of relative proportions provided herein.

Figure 1. HVAC4 Uncertainty Analysis Results Useful to the HVAC Roadmap



To further leverage the Year 2 findings, the deemed savings forecasts and sensitivity analyses can be used to determine which additional data should be gathered to reduce future savings uncertainty. Such new data can be gathered—at very little additional cost—by either modifying future HVAC rebate applications, for basic data, or during the course of upcoming evaluations. To this end, the following strategies are suggested:

1. The heating setpoint for residential furnaces should become a question on rebate applications (or conducted as a survey by evaluators) and used to true up savings for a specific program population.
2. Through the ongoing 2013-14 HVAC Market Assessment of Permitting and Compliance (HVAC6) study—another study in the HVAC Roadmap—gather data to determine the distribution of sizing ratios of residential furnaces by way of the ongoing effort to perform load calculations. (Conversely, data gathered through HVAC6 were already used to inform the fan power index[6] distribution used for this study. While HVAC6 was not specifically designed to target these parameters, it is an example of leveraging data from existing studies to reduce the uncertainty of deemed savings.)

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[6] The fan power index—the inverse of fan efficiency—was used extensively for the uncertainty analysis of the high efficiency residential furnace and optional variable-speed motor measure.

3. The minimum airflow ratio is a simulation input used to describe fan system operation and zonal re-heat for variable air volume systems. The results show that future evaluations of boiler measures should not focus exclusively on verifying installed efficiency, but also on the zonal controls in use since these dictate the boiler load.
4. For VFD measures, it is important to study both the performance and baseline conditions leading to the change in fan power index as well as those zonal controls of air distribution that influence the fan flow profile.

2 INTRODUCTION

The California Public Utilities Commission (CPUC) asked DNV GL to conduct a study (HVAC4) to advance the understanding of uncertainty of HVAC energy efficiency measure savings that are claimed by California investor-owned utilities (IOUs). The first goal was to develop methods to quantify the uncertainty that could be applied to many different HVAC measures. An emphasis was placed on those measures not already being evaluated by the separate (but related) impact evaluations of the Upstream (HVAC1), Quality Installation (HVAC2), and Quality Maintenance (HVAC3) programs.

For many energy efficiency measures, the utilities claim a predetermined amount of savings per installed measure or measure-unit—these are called deemed savings. Subsequent to implementing such measures, many energy efficiency programs are evaluated to determine the extent to which the claimed energy savings were achieved. Ideally, the results of these impact evaluations—that report ex post savings and associated error bounds—would be used to update the deemed savings to improve the match between deemed savings and ex post savings for future program cycles. Instead, a perception persists that impact evaluation results have too much uncertainty to be used in this way.

What has been missing from the industry's body of knowledge, though, is the extent of the uncertainty already inherent in the deemed savings. This study was established to quantify the uncertainty of deemed savings of some key HVAC measures. It is hoped that, upon quantifying the uncertainty of deemed savings, future research and data collection planning will consider studying those parameters that have the greatest influence on the savings uncertainty.

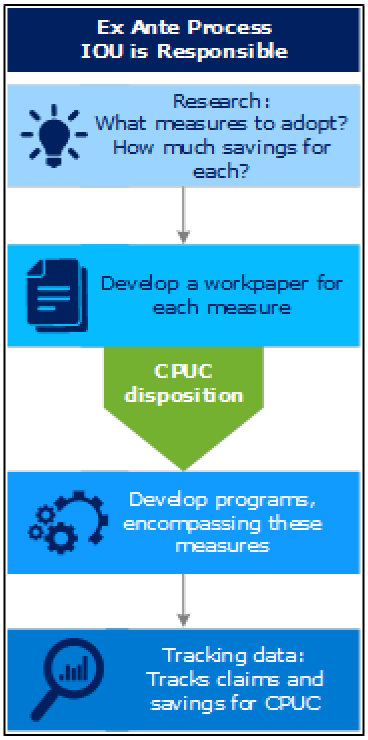
2.1 Background information

Prior to the beginning of every energy efficiency rebate program, the IOUs in California—Pacific Gas & Electric (PG&E), Southern California Edison (SCE), Southern California Gas (SCG), and San Diego Gas & Electric (SDG&E)—describe how the energy savings will be determined for each measure to be rebated and implemented, as shown in Figure 1.

For many types of energy efficiency measures, the per-unit energy savings are fixed prior to the program's start based on factors such as the building type climate zone and operation of the systems affected the measure installation. These measures are called deemed measures, and are intended to represent, on average, the savings for the measure across the population of program participants. For other energy efficiency measures, predetermining the savings is not practical due to the wide variability of project factors that greatly influence savings. These measures require savings calculations on a case-by-case basis, and are called custom measures. Some HVAC measures involve a wide variability of influencing factors, but since it would not be cost-effective to implement them as custom measures, they are also deemed.

IOUs present the savings for every deemed measure using one of the following two vehicles:

Figure 2. Ex ante process



1. DEER: This is an online database documenting the energy savings associated with deemed measures in California. DEER savings are determined by combining the following information:
    a. Building prototypes generated using CPUC's Measure Analysis Software Control (MASControl),
    b. Baseline unit energy consumption levels (UECs) used by MASControl,
    c. For residential measures, weights for climate zones, building types, building vintage bins, etc., from the California Residential Appliance Saturation Study (RASS), and
    d. For non-residential measures, building characteristics data are drawn from a variety of sources including CMST, CSS, CEUS, and past evaluation studies.
    e. Measure-specific performance characteristics that correspond to input parameters available in eQUEST® v. 3.65, which is based on DOE-2.2.
2. Non-DEER workpaper: This is a technical document that provides the equations, input parameters, and baseline assumptions used to estimate the energy savings that will result from the implementation of a given measure. Workpapers typically use the same types of methods as those currently used for DEER.

Once an energy efficiency program has begun, every measure implemented under that program is logged in the IOU's program tracking database along with the associated energy savings (whether deemed or custom) and other identifying information. The savings recorded in the tracking database are referred to as the ex ante savings,[7] or the claimed savings.

Throughout the program cycle, these tracking databases are used by the IOUs to track and report the ex ante energy savings produced (or claimed) by the program. They are also provided to the CPUC as one component of the required IOU reporting. Subsequently, the tracking databases are provided to independent program study team contractors selected by the CPUC. For energy efficiency measures that yield directly measurable energy savings installed through resource programs (rather than non-resource programs such as educational or marketing programs), direct impact studies are often performed for a sample of the projects listed in the tracking database. This process, as described in Figure 3, is intended to determine the actual energy savings realized at each of the sites in the sample. The savings values produced by this review are referred to as ex post savings,[8] or impacts.

To determine the project-specific ex post savings, a measurement and verification (M&V) process is established by DNV GL using an agreed-upon level of rigor that is appropriate for the evaluation budget. The project-level M&V process often includes a site visit or telephone interview to achieve some or all of the following goals: confirm the baseline equipment for early-replacement applications, verify the installation of the measure, and gather data to estimate the ex post measure savings. In most instances, the evaluation will estimate savings from a random sample of individual projects. In some instances, the evaluation might focus on gathering data to refine some of the specific inputs used for the ex ante savings calculations. For example, a study may measure lighting time of use and average fixture wattages across a sample to inform the average ex post-retrofit savings for lighting measures. In both cases, the ex post retrofit savings within the sample are used to estimate the ex post retrofit savings across all measures in the program(s) covered by evaluation activity.

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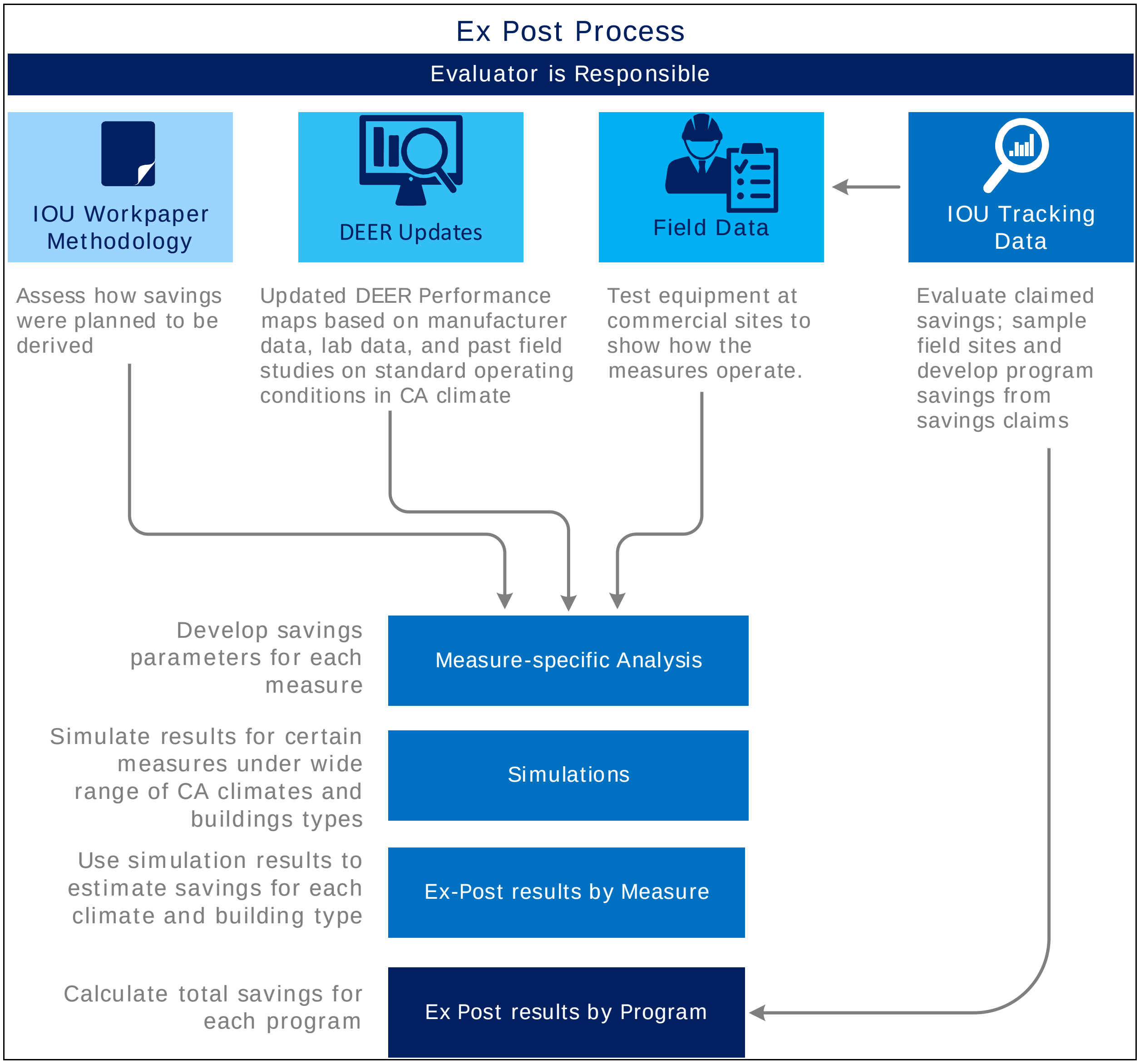
[7] Ex ante savings are estimated by the IOU or the program implementer before the installation of the energy efficiency measure.

[8] Ex post retrofit savings, or impacts, are determined by the evaluation team for a sample of measures or project sites selected.

Figure 3. Ex post retrofit savings-estimation process



Since the ex post savings determined by the evaluation team often differ from the ex ante savings claimed by the IOUs, program study team results are very closely scrutinized by all stakeholders, including the CPUC and its advisors, the IOUs, the program implementation contractors, and the IOU ratepayers. Hence, Evaluators' Protocols[9] were established to prescribe how the impacts are to be determined and reported in California. For each ex post-retrofit savings value reported by an impact study team—typically annual electric savings, peak demand savings, and annual natural gas savings—evaluators are required to report some or all of the following precision ex post metrics:

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[9] California Public Utilities Commission. April 2006. *California Energy Efficiency Study team Protocols: Technical, Methodological, and Reporting Requirements for Study team Professionals* (a.k.a. Evaluators' Protocols).

- Mean savings
- Standard error
- Standard deviation
- Absolute precision
- Relative precision

Once the gross ex post-retrofit impacts have been estimated by the evaluators at the program level, they are then compared with the ex ante savings that were recorded in the tracking database, or claimed, by the IOUs. Thereafter, much discussion ensues among the many stakeholders. One limitation to the discussion, however, is that the ex ante savings claimed by the IOUs do not report—and often do not have available—precision or uncertainty metrics of any sort. Hence, the standard measure for comparing the ex post retrofit impacts to the ex ante claimed savings is a simple ratio, known as the realization rate.[10] While realization rates are typically published with associated precision statistics, these are presently determined without consideration for the uncertainty of the ex ante savings. If the statistical precision associated with ex ante savings can be determined, the statistical precision of the realization rates can be better understood. Prior to this study, however, the uncertainties associated with ex ante savings had not been quantified.

2.2 Study objectives

This study sets out to determine the uncertainty of the ex ante savings for a few key HVAC measures by using the same information source used by the IOUs—either a workpaper or DEER, depending on the measure. This is intended to achieve the following:

- Produce distributions and uncertainty values, including standard deviation, for ex ante savings associated with some key HVAC measures using a Monte Carlo simulation method.
- Determine the relative influence of input parameters—each with their own distributions—on the ex ante savings for each installation of a given measure. These results could help to guide future data collection efforts aimed at reducing uncertainty by gathering information related to the input parameters with the greatest influence on ex ante savings.

2.3 Study tasks

DNV GL performed the following tasks to complete the uncertainty analysis study:

1. Review the HVAC Roadmap tracking data to identify relevant deemed HVAC measures and rank their contribution to the portfolio savings.
2. Select the measures to study.
3. Perform an in-depth review of the sources of the ex ante savings to assess the savings methodology and sources of the input parameters.
4. Create a model of the energy consumption or savings that used the same input parameters used by the IOUs. Run the Monte Carlo simulations by varying the input parameter values for each of the selected measures to determine:
    a. The mean of the distribution of ex ante savings outcomes and the associated uncertainty, and
    b. The relative sensitivities of the ex ante savings forecasts to changes to the input parameter values.

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[10] The realization rate is the ratio of the ex post retrofit savings to the ex ante savings; it is often reported as a percentage.

5. Prepare report to present uncertainty analysis results, recommendations for future research efforts that would facilitate reducing the ex ante savings uncertainty or updating the sources for the input parameters.

2.4 Report organization

The report consists of the following sections and appendices:

- Section 3, “UNCERTAINTY ANALYSIS METHOD,” describes the steps involved in the method used for Year 2 of this study.
- Section 4, “RESIDENTIAL FURNACES,” describes the methods and references used to determine the ex ante savings for two residential furnace measures within one climate zone, the input parameters used for the regression analyses and the Monte Carlo simulations, the simulated savings distributions and input parameter sensitivities, and resulting recommendations for future study.
- Section 5, “NONRESIDENTIAL BOILERS,” describes the methods and references used to determine the ex ante savings distributions for boilers at large office buildings within one climate zone.
- Section 6, “VARIABLE FREQUENCY DRIVES FOR HVAC FANS,” describes the methods and references used to determine the ex ante savings distributions for fan VFDs at large office buildings in one climate zone.
- Section 7, “OVERALL FINDINGS AND RECOMMENDATIONS,” provides a summary of the findings regarding each of the studied measures along with some recommendations for future research.
- APPENDIX A, “Residential furnace input parameters,” provides more detailed tables and figures than was appropriate for the body of the report, but which may be of interest to some readers.
- APPENDIX B, “Boiler input parameters,” provides more detailed tables and figures than was appropriate for the body of the report, but which may be of interest to some readers.
- APPENDIX C, “VFD input parameters,” provides more detailed tables and figures than was appropriate for the body of the report, but which may be of interest to some readers.
- APPENDIX D, “Public-review period comments and responses,” lists the comments received about this report during the public review period and DNV GL’s responses.

3 UNCERTAINTY ANALYSIS METHOD

For our analyses during Year 1 of this study, the input parameters and mathematical formulae used by the IOUs to determine the deemed savings were directly entered into Oracle Crystal Ball®, a Microsoft Excel®-based application designed to determine the probabilities of each forecasted outcome possible. For this year's effort, however, we studied measures for which the savings had been determined using an elaborate set of established building simulations. This necessitated the development of a more elaborate process of employing the building simulation outputs to generate mathematical regressions with respect to select input parameters. These regression models could then be used to perform Monte Carlo simulations. The method developed and used by DNV GL is shown in a graphical format in Figure 4 and is described in greater detail below:

1. Building Prototypes. We used MASControl,[11] the CPUC's tool for storing and reproducing DEER's eQUEST-ready prototype building models. Each version of MASControl contains different prototype building models for the various DEER measures. For each measure, we located the version of MASControl that contained the relevant prototypes and ran MASControl to generate the necessary eQUEST-ready prototypes.

2. Input Parameter Selections & Distributions. Using available data, the team selected a range of values for each selected input parameter and an associated probability of occurrence within the California building population or, in some instances, the program population. Of the many variables used by eQUEST, DNV GL engineers selected a handful for each measure to study based on the following criteria:

   - They would have a large influence over the measure energy savings
   - They were largely (though not always entirely) independent of one another
   - They have some degree of uncertainty

3. Building Simulations. In preparation for using eQUEST v3.65,[12] a DOE-2.2 based simulation software package used to produce estimates of energy use of prototype building models, we used an Excel-based batch-processing workbook to define the simulation cases by varying the values of the input parameters. This approach allowed the team to perform many hundreds of simulations using all possible combinations of the selected input parameters in a fraction of the time it would take to perform each simulation individually. Upon completion of the batch run, eQUEST produced an Excel-based output workbook that reported the resulting end-use energy usage for each individual simulation.

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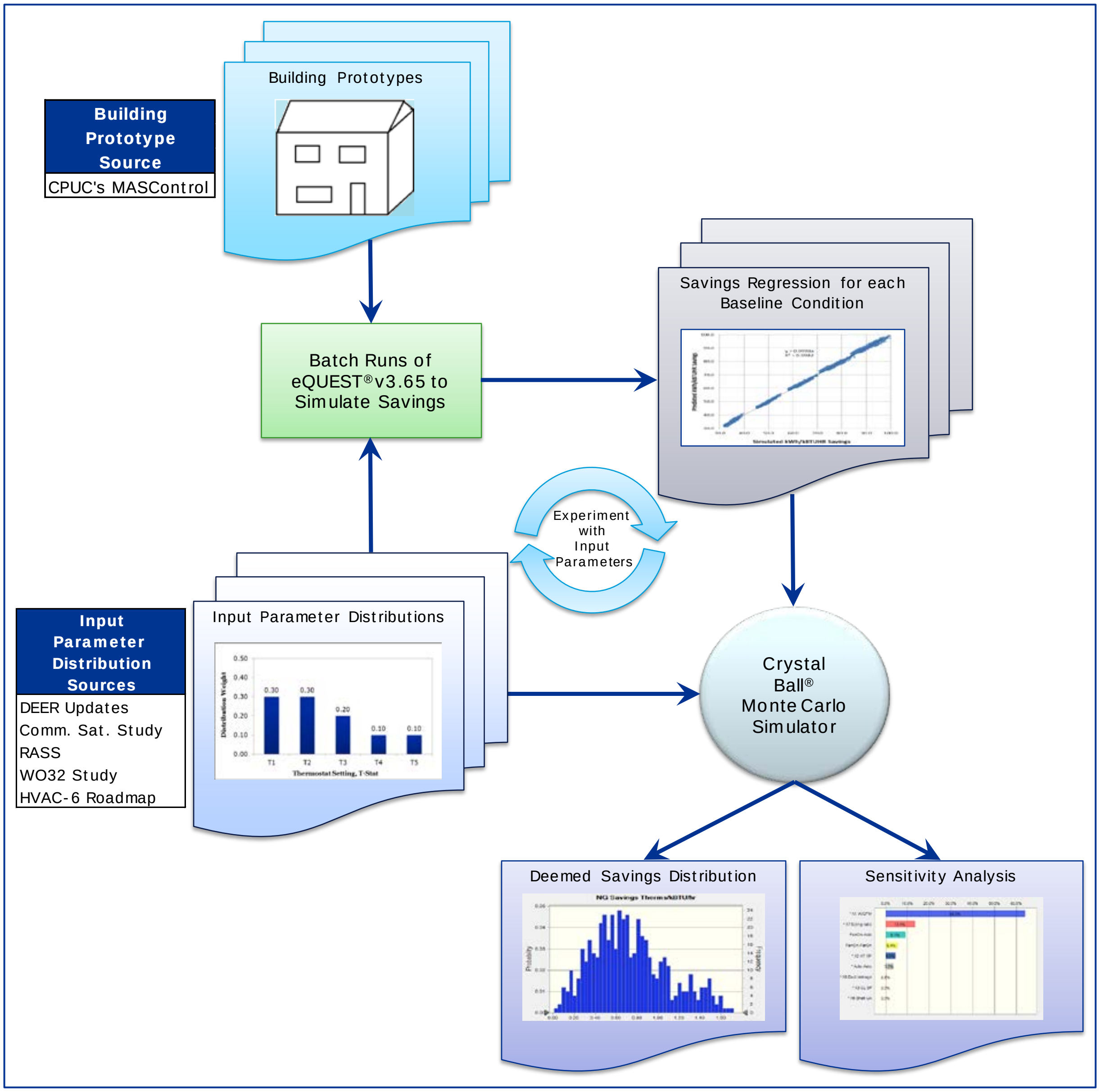
[11] http://www.doe2.com/download/DEER/MAStool/

[12] eQUEST – Building Energy Use and Cost Analysis Software, developed by James J. Hirsch & Associates (JJH), version 3.65 was the latest release. http://www.doe2.com/

Figure 4. Graphical representation of uncertainty analysis method



4. <u>Multivariate Bi-quadratic Regression Analysis.</u> A post-modelling Excel workbook was then developed by DNV GL to be filled with the simulation results provided within the batch run output workbook. This workbook compared the eQUEST simulation results from the different input parameter combinations to develop savings based on those differences. Using the LINEST function in Excel, we created linear, multivariate bi-quadratic regression models of the eQUEST-simulated savings. Each regression model of the saving—represented by Y—was unique to a specific measure, building type, and climate zone where the selected input parameters—represented by x_1 through x_n—were used to generate regression models and their coefficients—represented by a_0 through a_n and $a_{1,1}$ through $a_{n,n}$ as shown in the following equation:

$$Y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1, j=1, i \leq j}^{i=n, j=n} a_{i,j} x_i x_j$$

Although efforts were made to select input parameters that were independent of one another, some of the input parameters may vary similarly. In statistics, such dependencies are described as multicollinear.[13,14] In this study, however, all savings simulations were determined by interpolating within the defined region of the regression models (rather than by extrapolations) and reliable savings predictions were produced. That said, regression models inherently introduce some error that, for this study, is quantified using an R-squared metric.[15]

5. Uncertainty Analysis. To assess the uncertainty of ex ante savings, DNV GL used the regression analysis equation within Oracle Crystal Ball, a Microsoft Excel add-in used for predictive modelling, forecasting, simulation, and optimization. The user must select input parameters (called “Assumptions”) and provide a distribution of values for each input parameter. Based on the provided input parameter distributions, the Crystal Ball tool will perform Monte Carlo simulations to generate hundreds or thousands of scenarios and produce a distribution profile of the forecast. Analysis of the forecast reveals the range of possible outcomes, their probability of occurring, which input has the most effect on the forecast uncertainty, and where to place efforts to reduce the forecast uncertainty. Descriptions of the outputs of Crystal Ball are below:
    - Deemed Savings Distribution. After running thousands of Monte Carlo simulations, Crystal Ball produces a savings distribution chart—as shown in Figure 4–to show the frequency of each savings result. The histogram shows the minimum and maximum measure savings as well as the mean savings. The results also include a variety of statistical descriptors about the savings distribution.
    - Sensitivity Analysis. Alongside the simulation savings distribution, Crystal Ball also produces a sensitivity chart (sometimes called a tornado chart) to rank input parameter(s) by their contribution to the variance of the savings about the mean, as shown in Figure 4. These results show which input parameters are most worthy of additional study to reduce the uncertainty of the deemed savings distributions.

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[13] Multicollinearity can have serious effects on the estimates of the regression coefficients and on the general applicability of the estimated model when predicting or extrapolating beyond the original region of the inputs for which data exist; in such cases, poor results are often encountered

[14] Douglas C. Montgomery, George C. Runger. 2003. Applied Statistics and Probability for Engineers, 3rd version. John Wiley & Sons, Inc.

[15] Future uncertainty analyses should consider accounting for the uncertainty introduced by the regression model in the overall sensitivity assessment.

4 RESIDENTIAL FURNACES

The first uncertainty analysis undertaken in Year 2 of this study pertained to residential furnaces. Residential furnaces were selected based upon their prevalence in the 2013 tracking data provided by the CPUC data management team. In this section, we describe the components of the furnace measure that is incented, the methodology and input parameters used to determine the deemed savings, and the uncertainty analysis results. At the end, we summarize our findings and present recommendations based upon those findings.

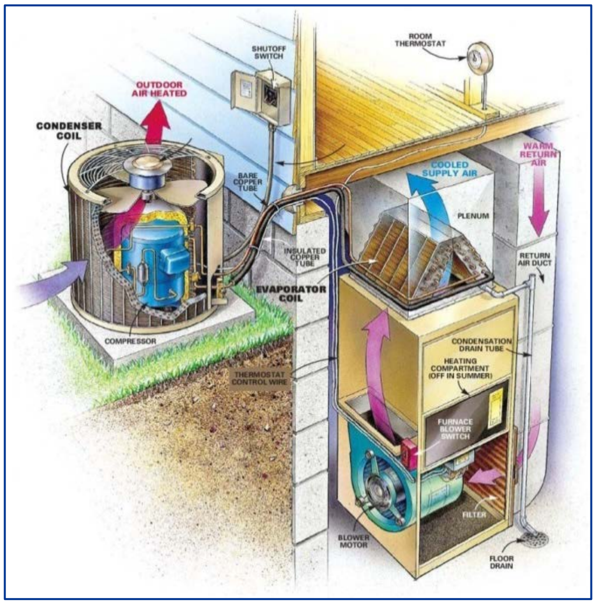
4.1 Measure description

The measure involves retrofitting a baseline furnace with a high efficiency furnace measure. In doing so, energy savings primarily result from the higher annual fuel utilization efficiency (AFUE) rating of the replacement equipment relative the baseline furnace. The post-retrofit furnace has an AFUE of 95 whereas the baseline furnace is assumed to have an AFUE of 80. The high efficiency furnace may also include the following:

- An optional variable-speed fan motor (VSM)—typically an electronically commutated motor (ECM)—that delivers heating, ventilation, and, sometimes, cooling. The baseline is a permanent split capacitance (PSC) fan motor that operates at a constant speed.

Figure 5 shows a typical configuration of a residential cooling and heating system. In this instance, the AC condenser and compressor are located outdoors and the evaporator is located at the top of the furnace in line with the supply duct. Furthermore, the fan is located at the bottom of the furnace and the return air duct connects to the lower part of the furnace. Fan power savings occur whenever the fan is running at partial speed.

Figure 5. Residential furnace component diagram



Source: www.atlanticphac.com/heat-and-air-install.html

During Year 1 of this study, we reviewed the workpapers published by the IOUs in which the ex ante savings for residential furnaces are established, and reviewed secondary sources that were referenced by the workpapers that offered different but credible methodologies. Because the workpaper used the natural gas savings from 2011 DEER database, we could not conduct Crystal Ball analysis for the high efficiency furnace measure and just reviewed the information used to populate DEER, such as weights for climate zone and building vintage, thermostat usage bin, and number of building stories. For the ECM motor replacement measure, we used the simulated electric energy usage provided in the workpaper to conduct CB analysis. However, we could only explore limited factors, such as number of stories, climate zone, and vintage. We studied the results for single family (SFM), mobile home (DMO) and multi-family (MFM) dwellings.

For this year of the study, we simulated energy savings directly from prototype models using a batch processing spreadsheet. This new method gave us flexibility to explore simulation model inputs such as fan power index, fan mode (continuous v. intermittent fan operation), sizing factor, and duct leakage. We focused on SFM in Climate Zone 12. We defined the distributions of these variables based on empirical data resources where available, such as WO032, HVAC 6, and 2009 Residential Appliance Saturation Study (RASS) projects. Using eQUEST simulation results, we were able to dive into the energy consumption breakdown and identify some of the sources of energy savings uncertainty.

To overcome the influence of any interactive effects, we performed separate simulations and analyses for the 95 AFUE measure and the ECM measure for the furnace fan:

- For the high-efficiency furnace 95 AFUE measure, the baseline furnace is assumed to be 80 AFUE. The post-retrofit furnace is between 95 AFUE and 97 AFUE in accordance with the workpaper. This measure is described as a “Replace on Burnout” (ROB) measure. The baseline and post-retrofit cases have the same motor type, PSC motors or ECMs, and the same fan control mode, intermittent (Auto) or continuously operating (On).
- For an optional variable-speed fan motor (VSM), the baseline case is a constant-speed PSC motor while the post-retrofit case is a variable-speed ECM. Both cases have the same furnace efficiency of 95 AFUE and the same supply-fan power index at the design airflow rate, measured in watts per cubic feet per minute of air (W/cfm). Energy savings result from the reduced fan power draw of an VSM operating at partial speed. Furthermore, this study accounted for the fan power savings due to varying the fan control type. There are four baseline/post-retrofit fan control scenarios considered: automatically-controlled/automatically-controlled, automatically-controlled/fan-always-on, fan-always-on/fan-always-on, and fan-always-on/automatically-controlled. Since each scenario has different baseline and post-retrofit fan operating hours, different fan power savings result.

4.2 Workpaper review

To learn how the ex ante savings are determined for residential furnace measures, DNV GL: 1) reviewed the workpapers published by the IOUs in which the ex ante savings for residential furnaces are established, and 2) reviewed secondary sources that were referenced by the workpapers that offered different but credible methodologies. This section summarizes the findings from the furnace workpaper review.

DNV GL identified and reviewed two workpapers pertaining to high efficiency furnace measures.[16] The first pertains to installing furnaces with a minimum efficiency rating of 95 AFUE,[17] and the second addressed 97

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[16] Workpapers were located via: http://www.deeresources.com/index.php/non-deer-work-paper-values-13-14.

AFUE[18] furnaces. The 95 AFUE workpaper applies to furnaces with ratings from 95 AFUE to 96.9 AFUE; the 97 AFUE workpaper applies to furnaces with an AFUE or 97 of greater. Though they pertain to furnaces of differing AFUE ratings, both workpapers utilize identical methodologies.

This study focuses on the residential high efficiency furnace 95 AFUE measure. The application type for this measure is replaced on burnout (ROB). The baseline case for ROB is a central natural gas furnace that meets minimum federal standards of 80 AFUE and has a maximum capacity of 225,000 Btuh. The workpaper extracted gas energy savings from the 2011 Database for Energy Efficient Resources (DEER 2011) v4.01, under measure ID Res-GasFurnace-AFUE95. This measure is only available to homes located in climate zones (CZ) 11, 12, or 13. The eligible building types include single family homes, mobile homes, and multifamily buildings.

For furnace retrofits that include optional variable-speed fan motors, the resulting power savings are also eligible for incentives. The workpaper made use of an eQUEST simulation tool to estimate the power and peak demand savings. The wattage for the baseline furnace with a PSC motor is assumed to be 0.650 W/cfm and, for a post-retrofit furnace with a VSM, is assumed to be 0.365 W/cfm. The workpaper used Typical Meteorological Year Three (TMY3)[19] weather files for the eQUEST simulation. Although modifications were made to the eQUEST input files to mimic a baseline furnace with a PSC motor, no changes were made for the post-retrofit case as it already assumes a variable speed motor. It should be noted that both natural gas and fan power savings are reported per household in the workpaper.

To study the VSM measure, we also reviewed two additional residential Quality Maintenance (QM) workpapers pertaining to blower motor replacement from SCE[20] and SDGE.[21] These two workpapers used very similar methods to estimate energy savings from residential quality maintenance. To estimate savings from the optional variable-speed fan motor, these two workpapers used the same baseline and post-retrofit fan power indices as the high efficiency furnace workpapers did. The methodology used in the QM workpapers, such as Expected Values Analysis and Design of Experiment Process, provided some insight into the workpaper assumptions that were useful for this uncertainty study.

4.3 Uncertainty analysis steps

This section describes the uncertainty analysis process specifically for the residential furnace 95 AFUE measure and the related ECM measure. Here are some simple differences between the furnace workpapers and this study:

- In this study, we normalized the natural gas and fan power savings by the furnace input capacity, in kBtuh, instead of per household. This is consistent with DEER database.
- For illustrative purposes, we analysed the single family building type (SFM) in Climate Zone 12, although the same method can also be applied to other building types and climate zones.
- Consistent with the DEER prototypes, we conducted analyses for two one-story houses and two two-story houses in each prototype model and the results represent the average of these four houses.

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[17] "High Efficiency Furnace 95 AFUE (1.04 HIR) – Residential," Pacific Gas & Electric Company, 8/28/2012, PGECOHVC145.

[18] "High Efficiency Furnace 97 AFUE (1.02 HIR) – Residential," Pacific Gas & Electric Company, 8/28/2012, PGECOHVC147.

[19] National Solar Radiation Database, Typical Meteorological Year three (TMY3). http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html#C

[20] Residential HVAC Quality Maintenance and Evaporator Motor Retrofit, Southern California Edison Company, 05/29/2012, SCE13HC029 Revision 0.

[21] Residential HVAC Quality Maintenance and Motor Retrofit, San Diego Gas & Electric, 26/06/2012, workpaperSDGEREHC1065 Revision 0.

4.3.1 Furnace tracking data

To manage the number of simulation cases, it was necessary to select a single climate zone to analyze. We extracted all furnace tracking records during the 2013 to 2014 program years from the database. All of the annual electric savings due to furnace motor retrofits are reported by Plug Load and Appliances program. The annual electric savings claimed for that program are split between two measures: “AFUE >= 94% < 96% GAS FURNACE WITH BUILT-IN VSM” (26 percent) and “AFUE >= 96% GAS FURNACE WITH BUILT-IN VSM” (74 percent). Furthermore, almost all annual electric savings claims are concentrated in climate zones 11, 12, and 13. As shown in Table 3, approximately 80 percent of the annual electric savings occurred in CZ12.

Table 3. 2013-14 annual claimed savings for furnace motor/control retrofits

Program Name	Annual Electric Savings, kWh		
	CZ 11	CZ 12	CZ 13
PLUG LOAD AND APPLIANCES (PGE21002)	19,104	83,790	1,996
Program Name	**Annual Natural Gas Savings, therm**		
	CZ 11	**CZ 12**	**CZ 13**
PLUG LOAD AND APPLIANCES (PGE21002)	7,669	46,973	1,081
RESIDENTIAL HVAC (PGE21006)	733	39	
SW-CALS-PLUG LOAD AND APPLIANCES (SCG3702)			1,748

Natural gas savings are reported across eight programs: EAST BAY PGE211009, LOCAL GOVERNMENT ENERGY ACTION RESOURCES (LGEAR) PGE2110051, MULTIFAMILY ENERGY EFFICIENCY REBATES PROGRAM (PGE21003), PLUG LOAD AND APPLIANCES (PGE21002), RESIDENTIAL HVAC (PGE21006), SW-CALS - RESIDENTIAL HVAC UPSTREAM (SDGE3302), SW-CALS-PLUG LOAD AND APPLIANCES (SCG3702), and SW-CALS-PLUG LOAD AND APPLIANCES-HEER (SDGE3203). The Plug Load and Appliances program (PGE21002) covering 75% of the total natural gas savings claimed. Program SW-CALS-PLUG LOAD AND APPLIANCES (SCG3702) covers another 21%. Natural gas savings claims are spread to all climate zones except for Climate Zone 5. Since Climate Zone 12 has the highest proportion of (27% statewide) of the natural gas savings and 80% of the electricity savings, this study analyzed the uncertainty for furnaces in CZ12. The same methodology can be directly applied to other climate zones.

4.3.2 Prototype models for eQUEST

eQUEST v3.65[22] is a DOE-2 based simulation software package used to produce estimates of energy use of prototype residential building models. MASControl[23] is the CPUC’s tool used to generate eQUEST-ready prototype models. There are different versions of MASControl and each version contains different DEER measures.

This study used MASControl v3.00.20 to generate single family house prototype models for each combination of seven building vintage bins, sixteen climate zones, and five thermostat schedules. Each

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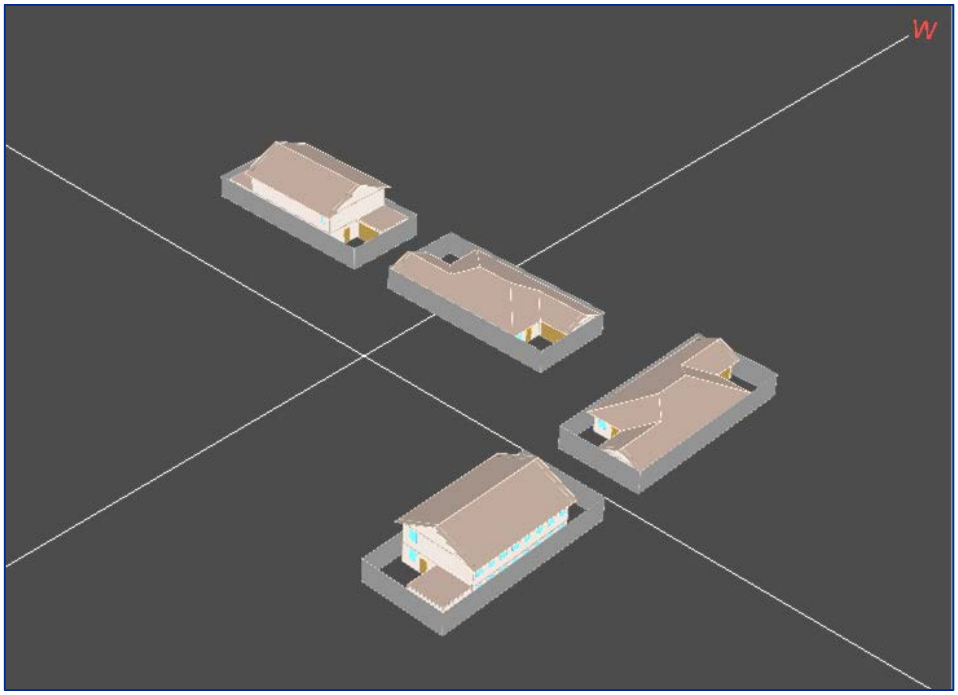
[22] eQUEST – Building Energy Use and Cost Analysis Software, developed by James J. Hirsch & Associates (JJH), version 3.65 was the latest release. http://www.doe2.com/

[23] http://www.doe2.com/download/DEER/MAStool/

single family prototype consists of two one-story houses and two two-story houses as shown in Figure 6. One house in each pair is rotated 90 degrees to capture the influence of orientation. Each model has two electric meters and two natural gas meters to quantify the energy consumption of one-story and two-story houses, separately. Each building vintage bin consists of different values for building and system component properties based either on the current code or typical building characteristics. These prototypes were developed to approximate the range of housing stock in California. We used CZ2010 weather files for all simulations. We only simulated CZ12 due to constraint of time and budget. However, the method could be easily applied to other climate zone.

Figure 6. eQUEST single-family home prototype



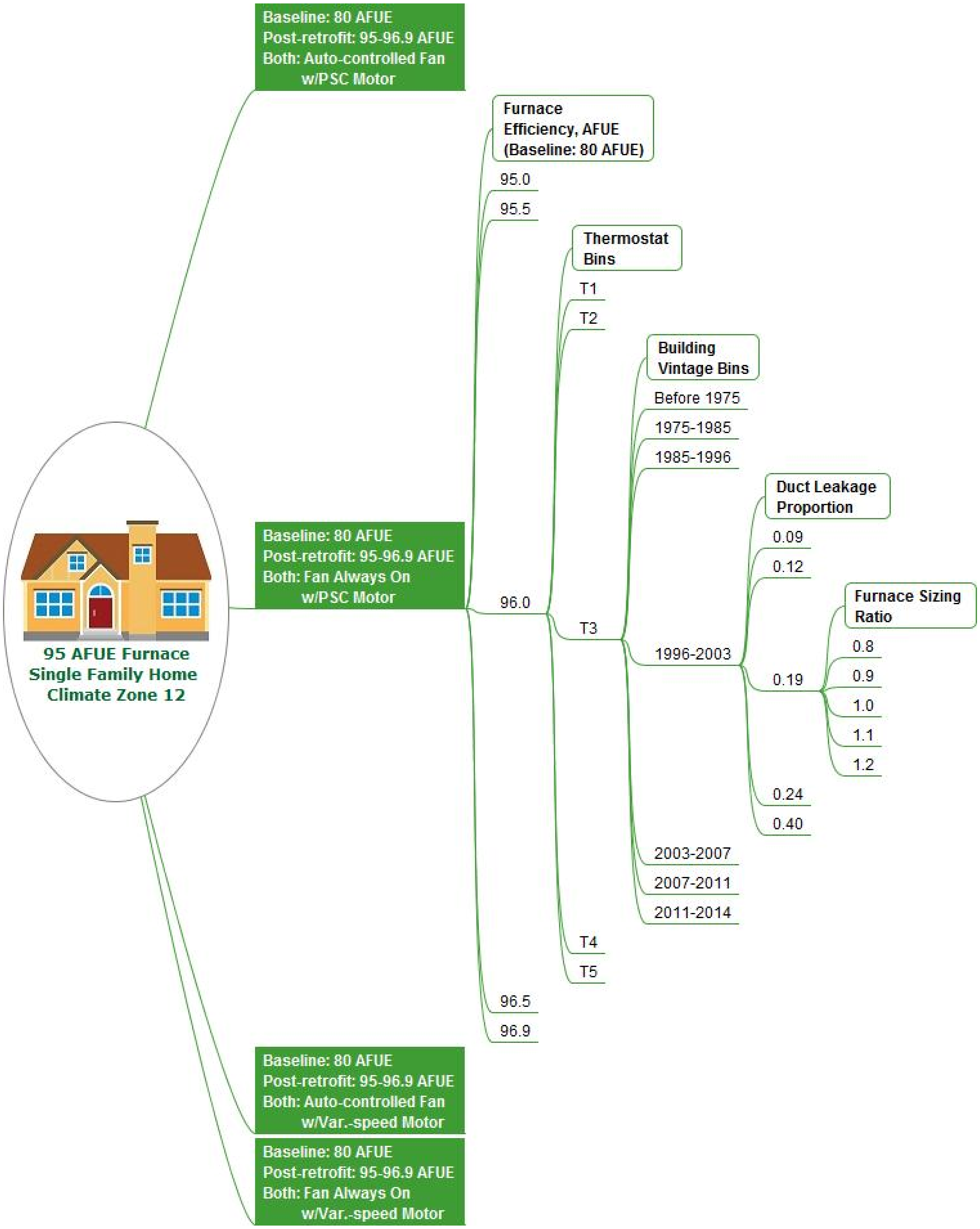
4.3.3 eQUEST batch processing

We prepared a batch processing spreadsheet to run through all variants of prototype models with CZ2010 weather files. We used this spreadsheet to vary the selected inputs of the prototype models and ran the models in eQUEST v3.65 in the batch mode. In order to represent the full range of possibilities, we designed combinations of the highest and lowest values for each input that are likely to be encountered in the population of homes, including likely values at the high and low end. In this way, the effect of each input parameter is represented in the resulting eQUEST savings result. The following savings metrics are generated within an Excel output file during the batch run: annual electric energy savings, annual natural gas savings, and peak demand electric energy.

4.3.3.1 95 AFUE furnace retrofits

For the 95 AFUE furnace measure, there are four baseline/post-retrofit fan control and motor scenarios, six AFUE levels (one baseline level and five post-retrofit levels), five duct leakage levels, five sizing ratios, seven vintage bins, and five thermostat bins (see APPENDIX A for more detail). The batch run design tree is shown in Figure 7. For example, the first scenario has both baseline and post-retrofit fan control as AUTO and PSC motors. The second one has baseline and post-retrofit control as FAN-ON and motor type as PSC motors. For each scenario, there is one baseline AFUE level (80) and five post-retrofit AFUE level (95 to 97). The total number of simulation cases is 17,500.

Figure 7. Batch-run tree design for 95 AFUE furnace measure

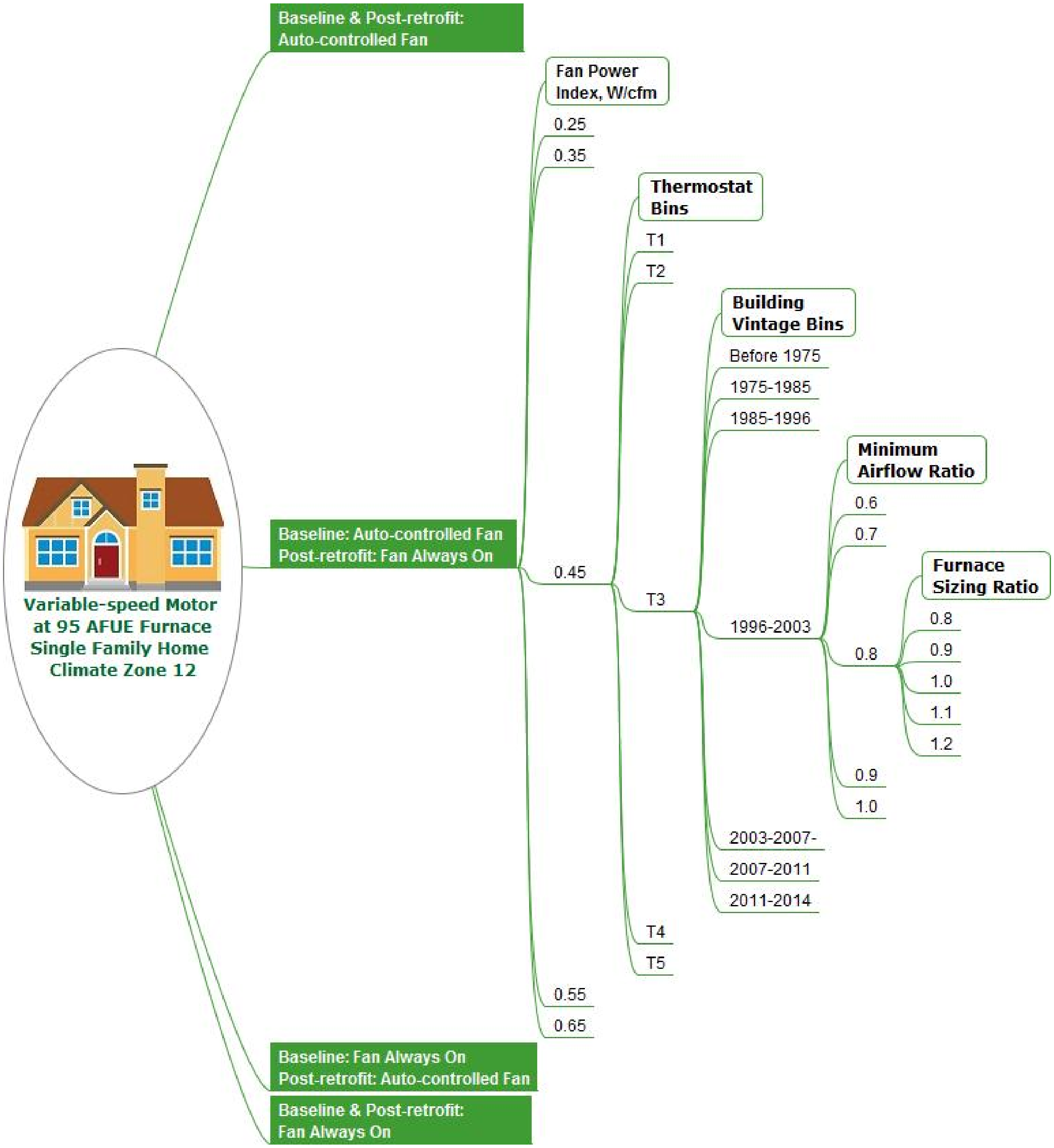


See APPENDIX A for more details about each input parameter used to run the eQUEST models EC motor retrofits and for 95 AFUE furnace retrofits at single family homes in Climate Zone 12.

4.3.3.2 Optional variable-speed motor

For the VSM option, we selected four baseline/post-retrofit fan control scenarios, five supply fan power indices (W/cfm), five furnace sizing ratios, seven building vintage bins, five minimum airflow ratios and five thermostat bins (see APPENDIX A for more detail). The batch run design tree is shown in Figure 8. The first scenario assumes that the fan motor is automatically controlled for both the baseline and post-retrofit cases. The second scenario assumes that the fan motor is automatically controlled for the baseline case and is always running for the post-retrofit case. For each scenario, there are five different fan power indices ranging from 0.25 to 0.65. For each fan power index, there are five standard thermostat settings based on DEER definitions. For each thermostat setting, there are 7 different building vintage bins to represent all existing single family houses. For each building vintage bin, we defined five minimum airflow rates ranging from 0.6 to 1.0. And for each minimum airflow rate, there are five furnace sizing ratios. All simulations were performed for climate zone CZ12. All combinations of these variables led to a total number of 17,500 simulation cases.

Figure 8. Batch-run tree design for optional VSM for furnace measure with varying controls



4.3.4 Multivariate bi-quadratic regression models

As described in Section 3, we used the savings results produced by the eQUEST batch runs to create bi-quadratic regression models for annual electric savings, for the EC motor retrofit, and gas savings, for the 95 AFUE furnace retrofit. These results are described in the two subsections that follow.

4.3.4.1 95 AFUE furnace retrofit

Figure 9 shows the eQUEST simulation results and the regression model—produced using the LINEST Excel function—for one of the four baseline/post-retrofit scenarios: 95 AFUE furnace, auto-controlled fan w/PSC motor. The savings for this measure were somewhat scattered with numerous savings arcs. These arcs correspond to different building vintage bins. On the graph, the coefficient of multiple determination i.e., the R-squared value (R^2), associated with each simulation is provided. This is used to assess the goodness of fit of the regression to the eQUEST simulation results where an R-squared value of one indicates a perfect fit between the regression and the results and a zero indicates "no" fit. The regression shown in Figure 9 yields an R^2 of 0.9371. For Year 2 of this study, we excluded the uncertainty introduced by the regression itself from the total uncertainty analysis. For the next phase of this study, the team may explore how to include the goodness of fit of the regression into the overall uncertainty analysis and/or assess whether it makes sense to perform the uncertainty analysis for each of the individual savings "trajectories" that appear in Figure 9.

Figure 9. Regression and eQUEST simulations for 95 AFUE furnace w/auto-controlled VSM

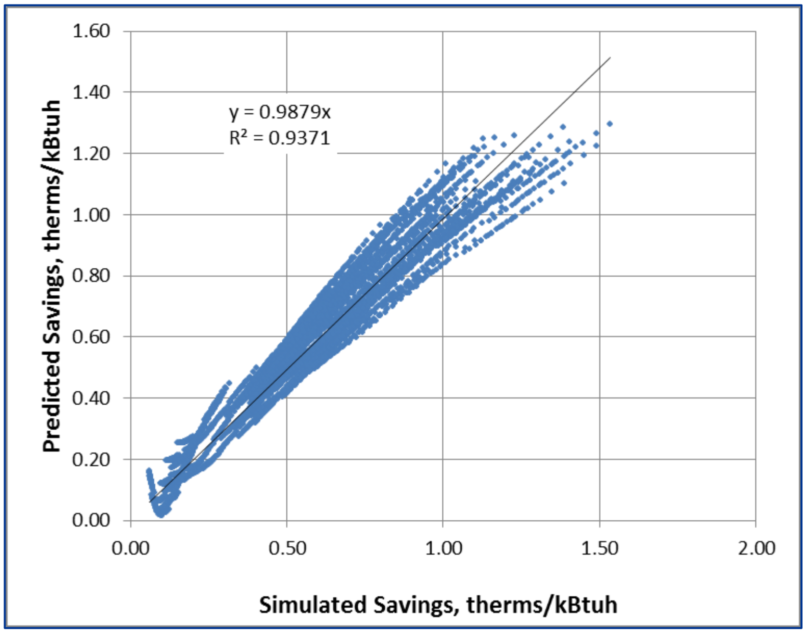
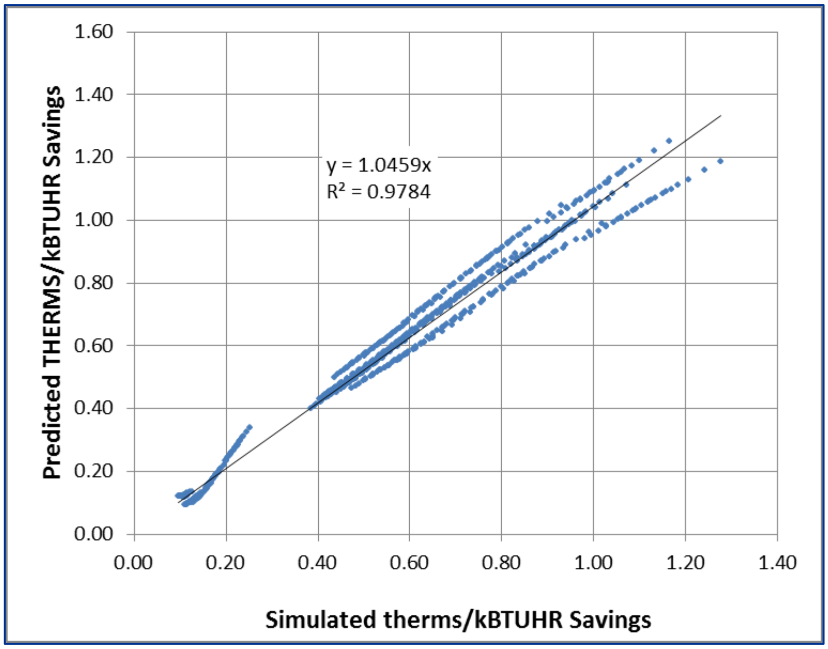


Figure 10 shows the simulation results and regression model for the same baseline, but for only the 2003-07 building vintages. The resulting savings arcs correspond to the four heating schedules in the prototype models.

Figure 10. Regression and eQUEST simulations for 95 AFUE furnace w / auto-controlled PSC motor



The regression model takes the form as follows for each of four baseline/post-retrofit cases for each of two measures:

$$Y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1,j=1,i\leq j}^{i=n,j=n} a_{i,j} x_i\, x_j$$

where

Y represents energy savings, therm

X_0 represents the fan mode ratio used to represent each baseline/post-retrofit fan control scenario

X_1 represents the change in furnace efficiency, ΔAFUE (Baseline: 80 AFUE)

X_2[24] represents the heating setpoint, °F

X_3 represents the cooling setpoint, °F

X_4[25] represents the building vintage bin, dimensionless

X_6 represents the duct leakage proportion, dimensionless

X_7 represents the furnace sizing ratio, dimensionless

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[24] Although the eQUEST simulations used the daily weighted average temperature associated with DEER's thermostat bins as shown in APPENDIX A, the heating and cooling setpoints were varied, instead, for the regression model and the uncertainty analysis.

[25] X_4 and X_5 were originally used to represent building shell UA, but were ultimately determined to be better represented by building vintage bins. Hence X_4 was ultimately used to represent building vintage bins and X_5 was not used

The corresponding coefficients for the annual natural gas savings due to the 95 AFUE furnace retrofit are provided in APPENDIX A.

Table 4 shows the resulting correlation table created for Climate Zone 12 for the 95 AFUE furnace measure. This table is used to determine the extent to which the input parameters influence the savings results similarly on a scale of -1 to 1. We used the CORREL function of Excel and the input values of all run cases to estimate correlation coefficients between two inputs. The correlation coefficient ranges from −1 to 1. A value of 1 implies that a linear equation describes the relationship between input X and input Y perfectly, with all data points lying on a line for which Y increases as X increases. A value of −1 implies that all data points lie on a line for which Y decreases as X increases. A value of 0 implies that there is no linear correlation between the variables. From Table 4, we can see that Building Vintage (X4) has a positive correlation (0.2063) with Heating Setpoint (X2) and a negative correlation coefficient (-0.4340) with Cooling Setpoint (X3). This indicates a new house tends to have a slightly higher average heating setpoint and a lower cooling setpoint. This could be because occupants can achieve higher thermal comfort without worrying about energy costs in newer houses.

Table 4. Correlation table for the regression model inputs of 95 AFUE furnace in CZ12

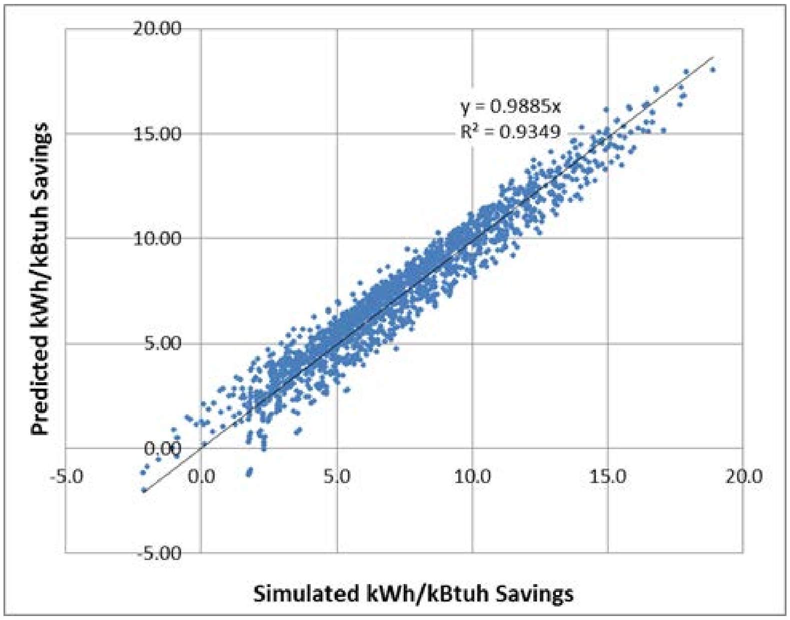
Correlation	Supply Fan, W/cfm	Heat Setpoint	Cooling Setpoint	Building Vintage	Duct Leakage	Furnace Sizing Ratio
by Variable	X_1	X_2	X_3	X_4	X_6	X_7
X_1	1					
X_2	0.0000	1				
X_3	0.0000	-0.1433	1			
X_4	0.0000	0.2063	-0.4340	1		
X_6	0.0000	0.0000	0.0000	0.0000	1	
X_7	0.0000	0.0000	0.0000	0.0000	0.0000	1

4.3.4.2 Optional variable-speed motor

Figure 11 shows the eQUEST simulation results and the regression model—produced using the LINEST Excel function—for one of the four baseline/post-retrofit scenarios: Fan-On /Fan-On. The simulated savings range from 31.4 to 100.4 kWh/kBtuh. The scatter plot is made up of five distinct clusters, each corresponding to one of the supply fan power indices. The higher the fan power index, the higher the resulting energy savings.

On the graph, the coefficient of multiple determination, i.e., the R-squared value (R^2), associated with each baseline/post-retrofit scenario is provided. Again, this is used to assess the goodness of fit of the regression to the eQUEST simulation results where an R-squared value of one indicates a perfect fit between the regression and the results and a zero indicates “no” fit. The regression yields an R^2 of 0.9982.

Figure 11. Regression and eQUEST simulations for optional VSM with fan-auto mode at T1 thermostat usage bin



The regression model takes the form as follows for each of four baseline/post-retrofit cases for each of two measures:

$$Y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1,j=1,i\leq j}^{i=n,j=n} a_{i,j} x_i \, x_j$$

where

Y represents energy savings, kWh for optional VSM and therm for 95 AFUE furnace retrofit

X_1 represents the baseline fan power index, W/cfm

X_2[26] represents the heating setpoint, °F

X_3 represents the cooling setpoint, °F

X_4[27] represents the building vintage bin, dimensionless

X_5 represents the post-retrofit fan power index, W/cfm

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[26] Although the eQUEST simulations used the daily weighted average temperature associated with DEER's thermostat bins as shown in APPENDIX A, the heating and cooling setpoints were varied, instead, for the regression model and the uncertainty analysis.

[27] X_4 and X_5 were originally used to represent building shell UA, but were ultimately determined to be better represented by building vintage bins. Hence X_4 was ultimately used to represent building vintage bins and X_5 was not used

X_6 represents the minimum flow ratio, dimensionless

X_7 represents the furnace sizing ratio, dimensionless

4.3.5 Monte Carlo Analysis in Crystal Ball

As described in Section 3, Crystal Ball (Crystal Ball) is a spreadsheet-based risk analysis add-in for predictive modeling, forecasting, simulation, and optimization. The user needs to provide the distribution of each selected input parameter. Based on the provided input parameter distributions, the Crystal Ball tool performs Monte Carlo simulations to generate hundreds or thousands of scenarios and produce the distribution profile of the forecast. Crystal Ball tool offers a variety of distribution types (e.g., normal, uniform, log, binomial, and gamma). It is also possible to define a custom continuous or discrete distribution based on a data set. Analysis of these scenarios reveals the range of possible outcomes, their probability of occurring, which input has the most effect on the forecast and where to focus efforts to reduce the forecasting uncertainty.

The regressions presented in the preceding subsections were entered into the Crystal Ball add-in to determine the range of savings outcomes that could be expected from each post-retrofit/baseline scenario by simulating many combinations of the selected input parameter. These simulations were used to create savings distribution profiles and sensitivity analysis portfolios.

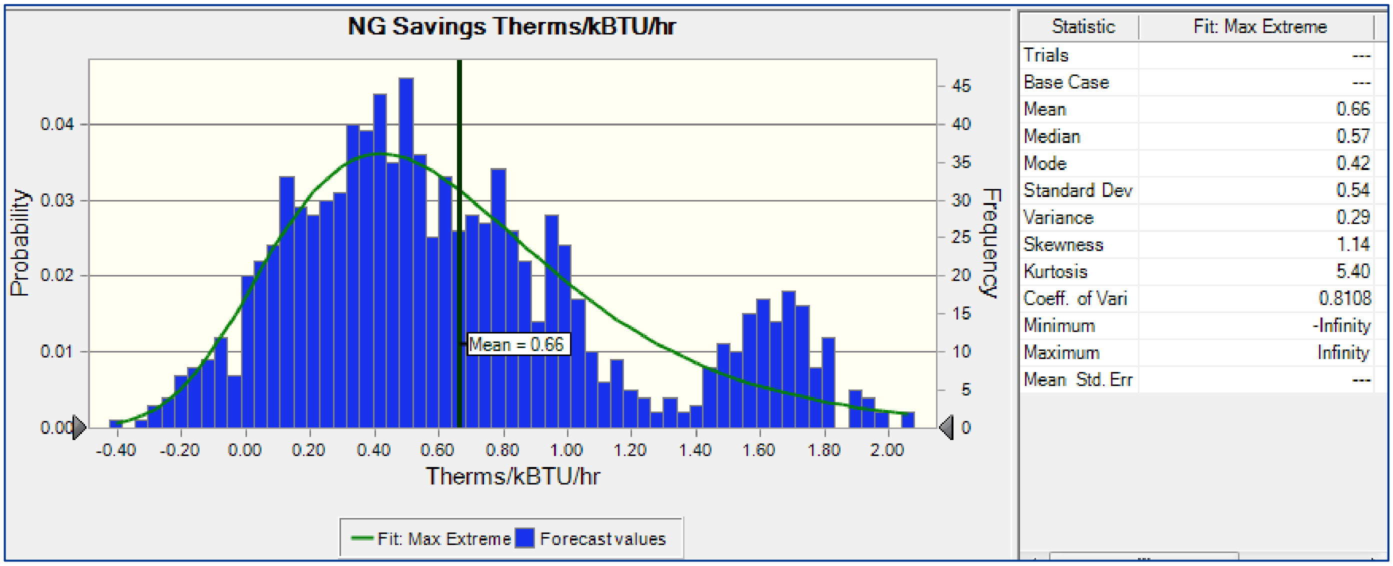
4.4 Uncertainty analysis results

This section presents the annual natural gas and annual electric savings identified by the Monte Carlo simulations and the proportions of savings uncertainty that can be attributed to each of the selected assumptions.

4.4.1 95 AFUE furnace retrofits

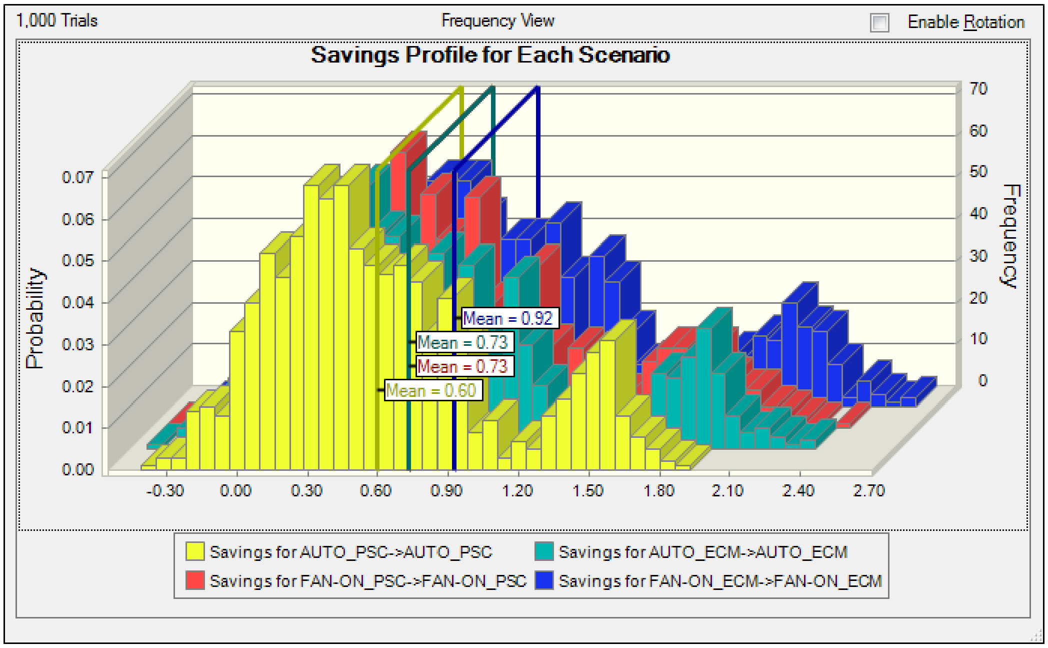
Figure 12 shows the distribution of the natural gas savings as well as the corresponding statistics based on 1,000 trials. This plot also indicates that the predicted natural gas savings ranges from 0.0 to 1.6 therm/kBtuh and the closest fit is labeled “Max Extreme.” To understand the source of uncertainty, we plotted the natural gas savings profile for each of four scenarios in Figure 13. The NG savings distribution profiles are very similar to one another. The scenario of FAN-ON_VSM to FAN-ON_VSM has the highest mean savings of 0.99 therm/kBtuh, while the scenario of AUTO_PSC to AUTO_PSC has the lowest of 0.66 therm/kBtuh. The other two scenarios yield very similar savings. Hence, the likelihood of each scenario does not appear be a major contributor to the average savings.

Figure 12. Distribution of 95 AFUE furnace natural gas savings



Statistic	Fit: Max Extreme
Trials	---
Base Case	---
Mean	0.66
Median	0.57
Mode	0.42
Standard Dev	0.54
Variance	0.29
Skewness	1.14
Kurtosis	5.40
Coeff. of Vari	0.8108
Minimum	-Infinity
Maximum	Infinity
Mean Std. Err	---

Figure 13. Distribution of natural gas savings for each scenario



The natural gas savings from the uncertainty analysis are also provided in Table 5 to allow for a comparison to the DEER savings (based on READI v.2.1.0 DEER 2011 FOR 13-14, residential gas furnace AFUE 95, Single Family House). The average natural gas savings is 0.66 therm/kBtuh and the standard deviation is 0.54 therm/kBtuh. If the average furnace input size is 75 kBtuh, the resulting annual natural gas savings is 49.5 therm. According to DEER, the deemed savings ratio is 0.64 therm/kBtuh; hence, the deemed annual savings is 47.9 therm for the same furnace size.

Table 5. Uncertainty analysis of natural gas savings for high efficiency furnaces

Annual Savings Ratio	Uncertainty Analysis	DEER
Average Savings, therm/kBtuh	0.66	0.64
Standard Deviation of Average Savings, therm/kBtuh	0.54	N/A
Annual Savings for 75 kBtuh Furnace	**Uncertainty Analysis**	**DEER**
Annual Savings, therm	49.5	47.9
Standard Deviation of Annual Savings, therm	40.5	N/A

Figure 14 shows the relative contributions of each input parameter to the variance around the mean savings. The sum of absolute values of all proportions equals one. A positive proportion means there is a positive correlation between the input and prediction whereas a negative proportion means there is a negative correlation.

As can be seen in Figure 14, the space heating setpoint contributes 93.9% of the total variance. Higher average heating setpoints lead to higher natural gas savings. This is reasonable considering that space heating schedules have a major influence on both the space heating load and on the natural gas consumption of furnaces. The average heating setpoints range from 55°F to 73°F based on the 2009 RASS. The next most influential parameter—the building vintage bin weights—contribute -4% and is followed by -1.3% from the furnace sizing ratio. The negative sign indicates that the higher the sizing ratio is, the lower the savings. This sensitivity study indicates that space heating schedule is critical to reducing the uncertainty around the natural gas savings of high efficiency furnace upgrades.

Figure 14. Sensitivity analysis of furnace measure savings to input parameters

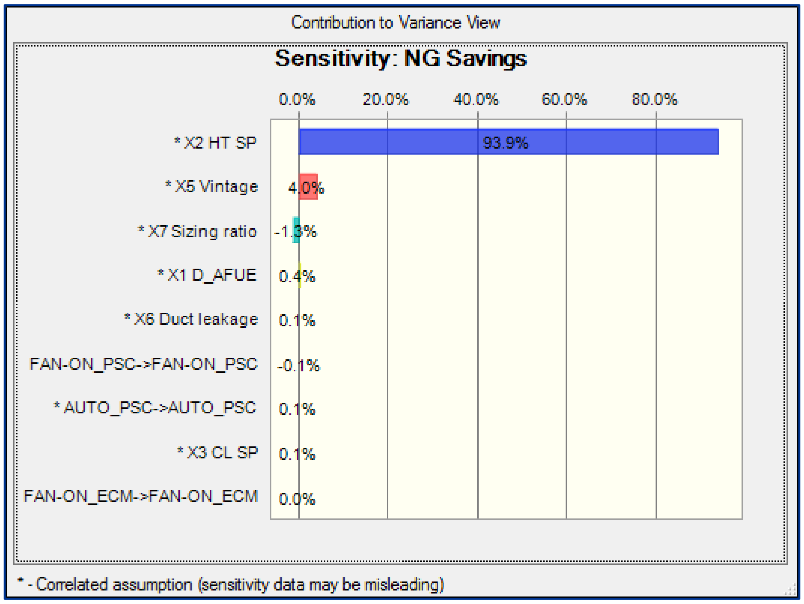


Table 6. Ranked contributors to deemed savings uncertainty for 95 AFUE furnaces

Input Parameters	Relative Contribution[28] to Variance
Heating Setpoint	93.9%
Building Vintage Bin weights	4.0%
Furnace Sizing Ratio	1.3%
Δ Furnace Efficiency	0.4%
Fan Motor/Control Strategy	0.2%
Duct Leakage Proportion	0.1%
Cooling Setpoint	0.1%

4.4.2 Optional variable-speed motor

We have categorized the optional VSM for the furnace measure into four fan control baseline-post-retrofit scenarios as described in Table 7.

Table 7. Fan control strategies for VSM option

Scenario	Baseline Control	Post-retrofit Control
Auto-Auto	Auto-controlled by thermostat (for heating or cooling*)	Auto-controlled by thermostat (for heating or cooling)
Auto-FanOn	Auto-controlled by thermostat (for heating or cooling)	Fan operates all the time (for heating, ventilation, or cooling*)
FanOn-Auto	Fan operates all the time (for heating, ventilation, or cooling)	Auto-controlled by thermostat (for heating or cooling)
FanOn-FanOn	Fan operates all the time (for heating, ventilation, or cooling)	Fan operates all the time (for heating, ventilation, or cooling)

*only applies for furnace systems that have integrated central cooling equipment

The resulting forecast is defined as the weighted average of the savings of the four scenarios. These weights are provided in APPENDIX A.

We performed a similar analysis for the optional VSM to determine the annual electric savings distribution as well as the associated statistics based on 1,000 Monte Carlo trials. For furnace systems without integrated cooling, the average annual electric savings in climate zone 12 is 5.29 kWh/kBtuh with a standard deviation of 3.92 kWh/kBtuh. The combined savings for all fan control scenarios are shown in Figure 15; the individual savings for each scenario are shown in Figure 16. For an average furnace size of 75 kBtuh, the average annual electric savings comes to 397 kWh with a standard deviation of 294 kWh.

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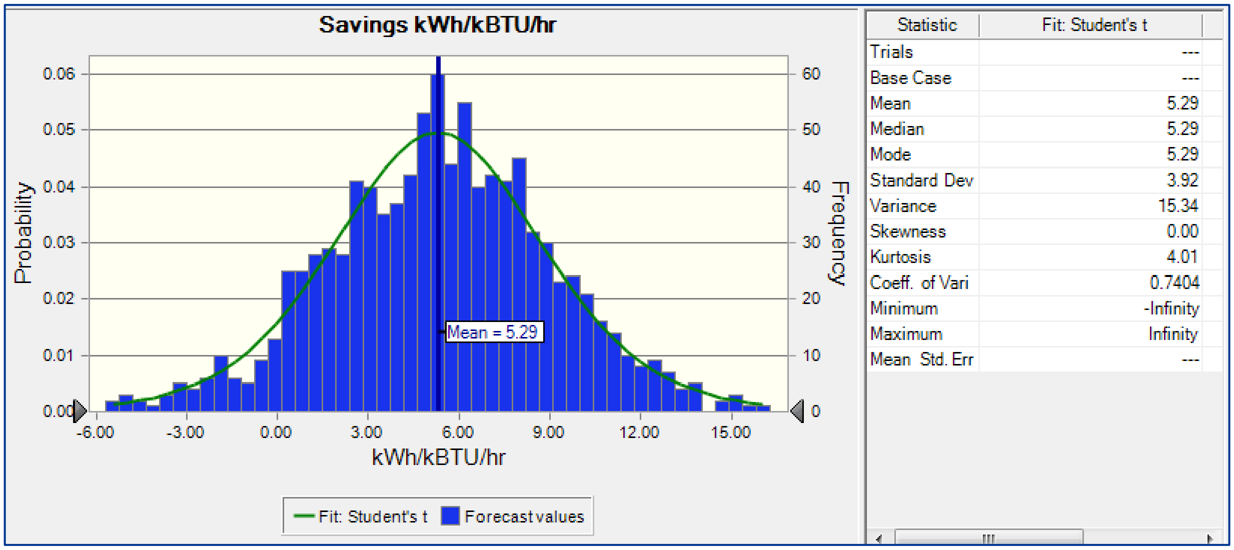
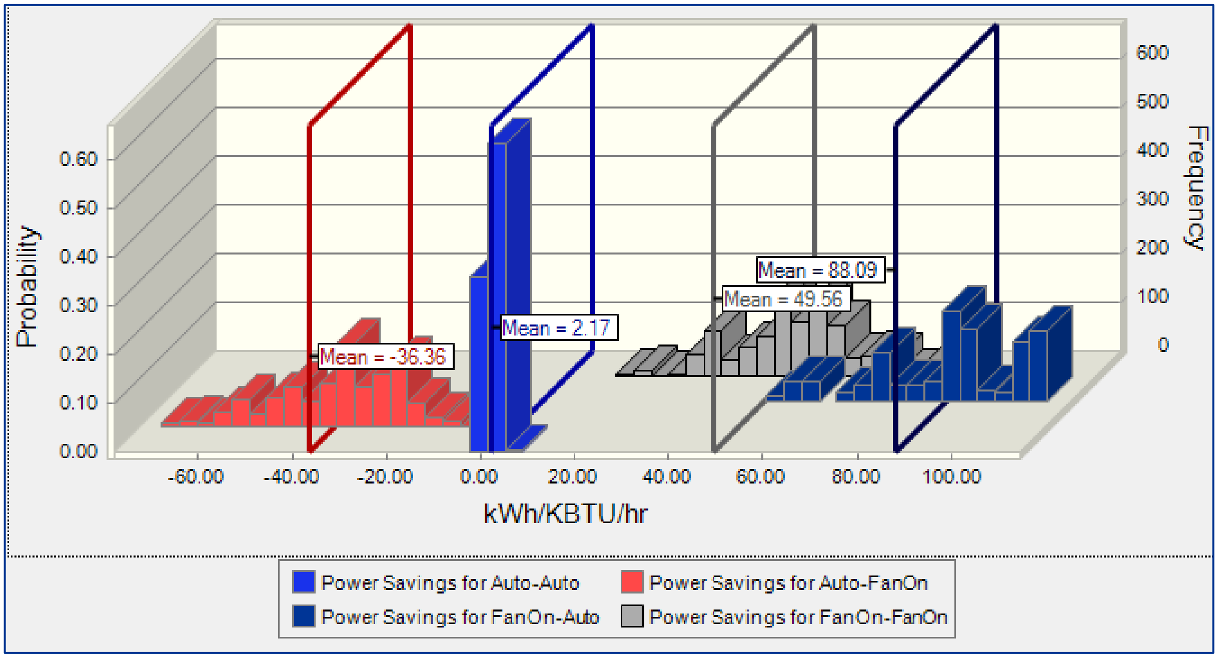
[28] Absolute values of relative proportions provided herein.

Figure 15. Distribution of annual electric savings for 95 AFUE furnace w/o cooling and with optional VSM



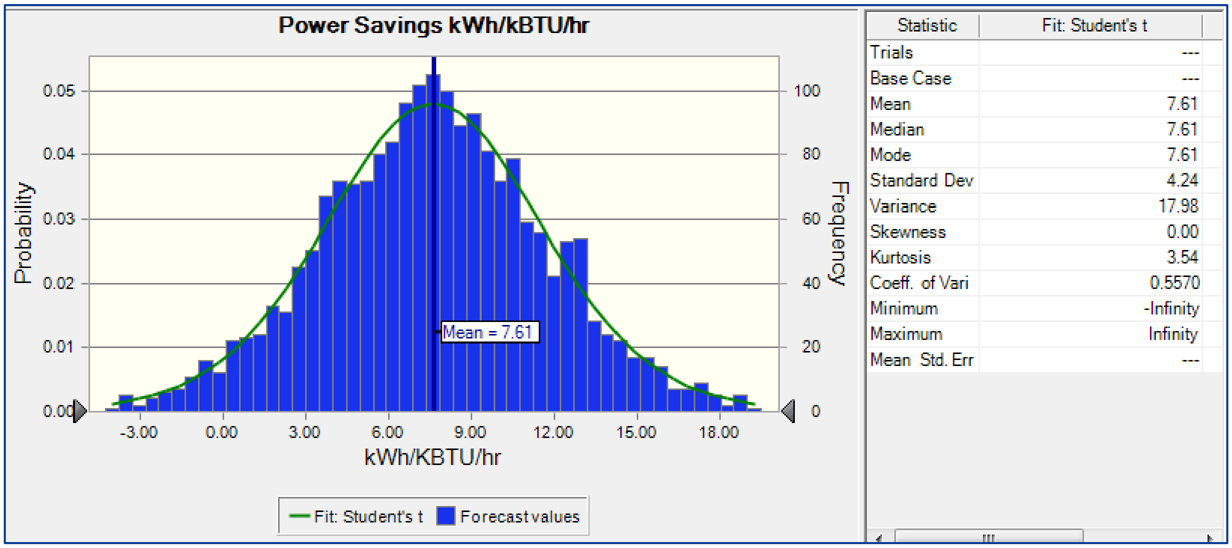
Statistic	Fit: Student's t
Trials	---
Base Case	---
Mean	5.29
Median	5.29
Mode	5.29
Standard Dev	3.92
Variance	15.34
Skewness	0.00
Kurtosis	4.01
Coeff. of Vari	0.7404
Minimum	-Infinity
Maximum	Infinity
Mean Std. Err	---

Figure 16. Annual electric savings distribution for each scenario of 95 AFUE furnace w/o cooling and with optional VSM



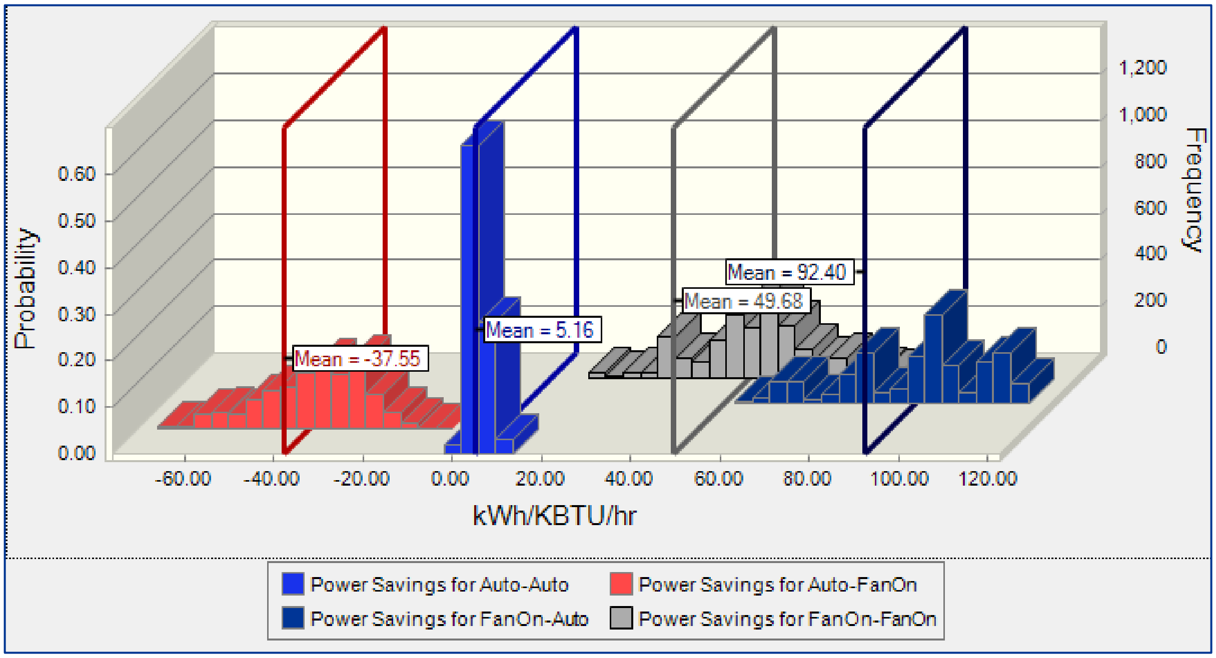
For systems with integrated central cooling, the average annual electric savings in climate zone 12 is 7.61 kWh/kBtuh with a standard deviation of 4.24 kWh/kBtuh. The combined savings for all fan control scenarios are shown in Figure 17; the individual savings for each scenario are shown in Figure 18. For an average furnace size of 75 kBtuh, the average annual electric savings is 571 kWh with a standard deviation of 318 kWh.

Figure 17. Distribution of savings for 95 AFUE furnace with cooling and optional VSM



Statistic	Fit: Student's t
Trials	---
Base Case	---
Mean	7.61
Median	7.61
Mode	7.61
Standard Dev	4.24
Variance	17.98
Skewness	0.00
Kurtosis	3.54
Coeff. of Vari	0.5570
Minimum	-Infinity
Maximum	Infinity
Mean Std. Err	---

Figure 18. Savings distribution for each 95 AFUE furnace scenario with cooling and optional VSM



The electricity savings results labeled as kWh/kBtuh from the uncertainty analysis are also provided in Table 8. This measure is not included in the DEER database; the energy savings for the blower motor replacement is presented in the SCE workpaper.[29] This workpaper provides total weighted average power savings ranging from 157 kWh to 1,347 kWh per year. The simple average of the nine climate zone in SCE territories is 488.6 kWh per year.

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[29] Residential HVAC Quality Maintenance and Evaporator Motor Retrofit, Southern California Edison Company, 05/29/2012, SCE13HC029 Revision 0.

Table 8. Uncertainty analysis results for 95 AFUE furnace with optional VSM in CZ12

Results	Uncertainty Analysis	DEER
95 AFUE / VSM furnaces without cooling		
Normalized Savings per kBtuh		
Average Savings, kWh/kBtuh	5.29	N/A
Standard Deviation, kWh/kBtuh	3.92	
Annual Savings for 75 kBtuh unit		
Average Annual Savings, kWh	397	NA
Standard Deviation, kWh	294	
95 AFUE / VSM furnaces with cooling		
Normalized Savings per kBtuh		
Average Savings, kWh/kBtuh	7.61	N/A
Standard Deviation, kWh/kBtuh	4.24	
Annual Savings for 75 kBtuh unit		
Average Annual Savings, kWh	571	N/A
Standard Deviation, kWh	318	

Figure 19 and Table 9 show the breakdown of the uncertainty contributions from each input parameter for 95 AFUE/VSM furnaces without integrated cooling. The top two contributors include the minimum airflow ratio and the proportion of retrofits that occur with the FanOn-Auto fan control scenario. Figure 20 and Table 10 show the breakdown of the uncertainty contributions from each input parameter for 95 AFUE/VSM furnaces with integrated cooling. Again, the top two contributors include the minimum airflow ratio and the proportion of retrofits that occur with the FanOn-Auto fan control scenario. Given the importance of the fan control strategies to the uncertainty of the annual electric savings, we recommend confirming the proportions currently assumed through future studies.

Figure 19. Sensitivity chart for electric savings at 95 AFUE/VSM furnace without cooling

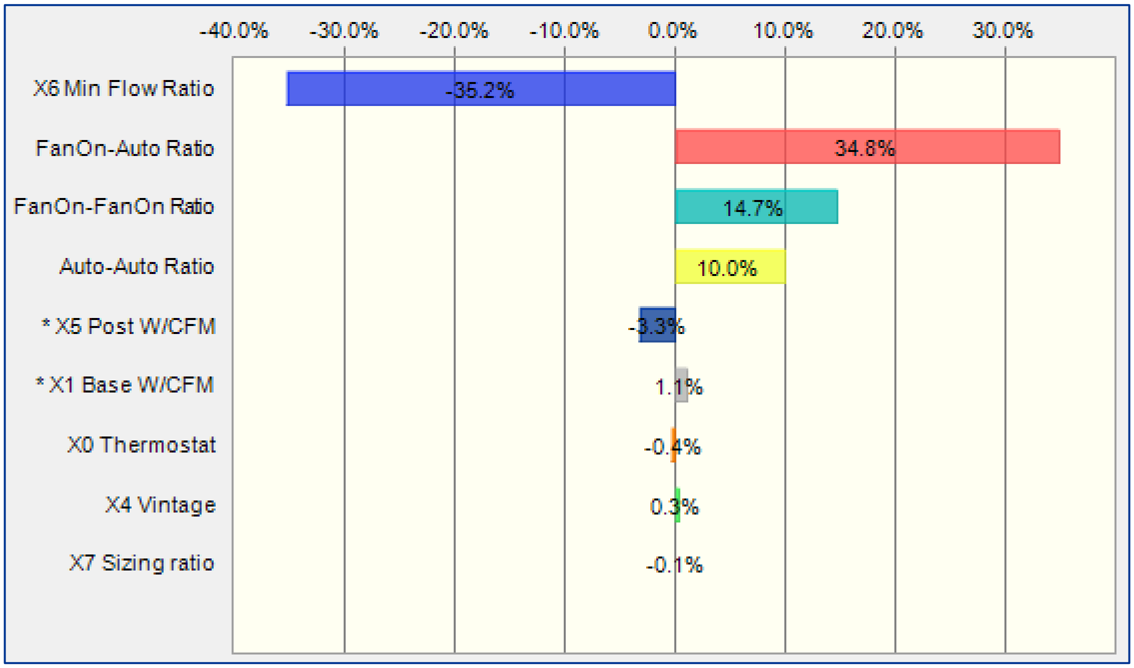

Table 9. Ranked contributors to deemed savings uncertainty for 95 AFUE/VSM furnace without cooling

Input Parameters	Relative Contribution[30] to Variance
Minimum Airflow Ratio	35.2%
Fan Control Strategy (FanOn-Auto)	34.8%
Fan Control Strategy (FanOn-FanOn)	14.7%
Fan Control Strategy (Auto-Auto)	10.0%
Post-retrofit Fan Power Index (W/cfm)	3.3%
Baseline Fan Power Index (W/cfm)	1.1%
Thermostat Bin	0.4%
Building Vintage Bin	0.3%
Furnace Sizing Ratio	0.1%

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[30] Absolute values of relative proportions provided herein.

Figure 20. Sensitivity chart for electric savings at 95 AFUE/VSM furnace with cooling

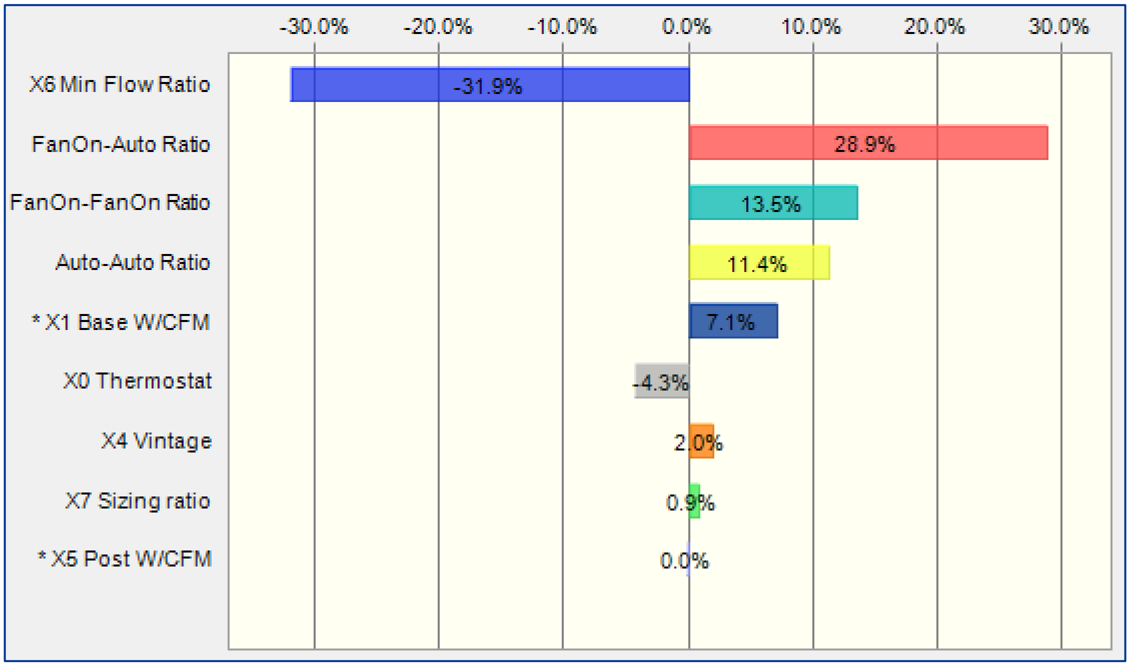

Table 10. Ranked contributors to deemed savings uncertainty for 95 AFUE/VSM furnace with cooling

Input Parameters	Relative Contribution[31] to Variance
Minimum Airflow Ratio	31.9%
Fan Control Strategy (FanOn-Auto)	28.9%
Fan Control Strategy (FanOn-FanOn)	13.5%
Fan Control Strategy (Auto-Auto)	11.4%
Baseline Fan Power Index (W/cfm)	7.1%
Thermostat Usage Bin	4.3%
Building Vintage Bin	2.0%
Furnace Sizing Ratio	0.9%

---

[31] Absolute values of relative proportions provided herein.

5 NONRESIDENTIAL BOILERS

This chapter discusses the types of deemed nonresidential space heating boilers that were incented in the 2013, 2014, and 2015 program years. It also provides a summary of the measure's savings methodology, the input parameters used to determine the deemed savings, the uncertainty analysis methodology, and the uncertainty analysis results. At the end of the chapter, the findings are summarized and recommendations are presented based on those findings.

5.1 Measure description

The ex ante savings for commercial space heating boiler measures are derived from DEER. Boiler measure savings are derived solely from the higher annual fuel utilization efficiency (AFUE), thermal efficiency (TE), or combustion efficiency (CE) of the replacement equipment relative to the baseline equipment. DEER uses eQUEST commercial building models that are informed by various sources, including the Commercial Saturation Survey (CSS), the Commercial Market Share Tracking Study (CMST), the Commercial End-Use Study (CEUS) and ex post evaluation studies[32]. DNV GL determined the derivation of ex ante savings by: 1) reviewing the workpapers published by the IOUs, and 2) analyzing the DEER prototypes and the database software (e.g., READi and MASControl) that DEER uses to publish the DEER deemed measure savings.

5.2 Workpaper review

Three workpapers pertaining to commercial space heating boilers were identified and reviewed by the DNV GL. Space heating boiler types are categorized by hot water or steam generation, whether the boiler technology utilizes latent heat reclamation (i.e., condensing boilers), and the boiler rated input heating capacity. All workpapers are based on a replace-on-burnout (ROB) and new construction (NC) baseline. This year's study incorporated DEER model prototype batch processing which allows Monte Carlo simulations for measures utilizing DEER model results as their sole methodology basis.

The workpaper measures—and the DEER measures referenced by the workpapers—use a change in the boiler heating efficiency to drive fuel savings.[33] No other parameters (e.g., controls, schedules, part-load performance curves) are adjusted in the DEER measures that the workpapers utilize for their deemed savings estimates.

The PG&E workpaper, PGECOHVC101 (Space Heating Boiler), uses DEER as its sole source of measure savings derivation.[34] The baseline and measure case descriptions for each of the boiler types are listed in Table 11 below. Note that the table values and descriptions (e.g., efficiency units and capacity ranges) are extracted directly from the PG&E workpaper. In the case where two defining efficiency metric are given, either metric may be the qualifier.

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[32] CSS: http://calmac.org/publications/California_Commercial_Saturation_Study_Report_Finalv2.pdf; CMST: http://calmac.org/publications/California_Commercial_Market_Share_Tracking_Study_Reportv2.pdf; CEUS : http://calmac.org/publications/CEC_CEUS_Executive_Summary_03012006.pdf

[33] The DEER measures use DOE-2 building prototypes to calculate weather-sensitive savings. DOE-2 uses a heating efficiency keyword called "heat input ratio" or HIR. There are various formulas for converting typical heating efficiency metrics (AFUE, thermal efficiency, combustion efficiency) to HIR.

[34] D11v4.00-060 for H111 – Small Water Space Heating Boiler; D11v4.00-067 for H112 – Small Steam Space Heating Boiler; D11v4.00-055 for H113 – Large Space Heating Boiler; and D11v4.00-056 for H746 – Condensing Space Heating Boiler

Table 11. PG&E workpaper (PGECOHVC101) measure descriptions

Equipment / Efficiency Descriptions	Small Water Space Heating Boiler	Small Steam Space Heating Boiler	Large Space Heating Boiler	Condensing Space Heating Boiler
Qualifying Description	AFUE ≥ 82% and input rating < 300 MBtuh[35]	AFUE ≥ 77% and input rating < 300 MBtuh	Thermal efficiency ≥ 84% and input rating ≥ 300 to < 5,000 MBtuh	Thermal efficiency ≥ 92% and input rating < 5,000 MBtuh
Baseline Case Description	Space heating water boiler with AFUE efficiency of 80%	Space heating steam boiler with AFUE efficiency of 75%	Space heating hot water or steam boiler with thermal efficiency of 75%	Space heating hot water or steam boiler with thermal efficiency of 75%
DEER Measure Case Description	The energy consumption for a commercial boiler per MBtuh with an AFUE efficiency of 84.5%	The energy consumption for a commercial boiler per MBtuh with an AFUE efficiency of 82%	The energy consumption for a commercial boiler per MBtuh with a thermal efficiency of 85%	The energy consumption for a commercial boiler per MBtuh with a thermal efficiency or AFUE of 94%

Source: PG&E

The SCG (workpaperSCGNRHC120206A) and SDG&E (workpaperSDGENRHC1061 Rev0) workpapers use the same modified DEER measure savings for the deemed commercial space heating boiler measure savings.[36] While DEER measures use AFUE and TE as efficiency metrics for the boiler measures, the SCG/SDG&E workpapers convert TE to CE using an assumed conversion formula.[37] The other notable difference between the workpapers and the DEER measures are the baseline efficiencies for the medium and large hot water boilers and the baseline efficiencies for the medium and large steam boilers. The workpapers use combustion efficiency values that match Title 20/24 values for gas-packaged boilers (while the DEER baseline values are lower than Title 20/24 values). Table 12 lists the equipment and efficiency descriptions for qualifying equipment and the corresponding baseline- and measure-case efficiency assumptions.

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[35] MBtuh is a unit of heat energy and is equal to 1,000 Btuh

[36] DEER Version 2011 4.00, For Use in the California IOU 2013-14 Energy Efficiency Planning

[37] "Thermal efficiency is generally 1-3% lower than combustion efficiency. The conversion from TE to CE is made by assuming 2% drop in efficiency due to jacket loss." (i.e., CE = TE + 2%)

Table 12. SCG/SDG&E workpaper (SCGNRHC120206A and SDGENRHC1061) measure descriptions

Equipment/ Efficiency Description	Small HW Boilers (non-condensing)[38]	Small HW Boilers (condensing)[39]	Small Steam Boilers	Medium/ Large HW Boilers (non-condensing)	Medium/ Large HW Boilers (condensing)	Medium/ Large Steam Boilers
Qualifying Description	AFUE ≥ 84% and input rating < 300 MBtuh	AFUE ≥ 90% and input rating < 300 MBtuh	AFUE ≥ 82% and input rating < 300 MBtuh	CE ≥ 85% and input rating ≥ 300 MBtuh	CE ≥ 90% and input rating ≥ 300 MBtuh	CE ≥ 83% and input rating ≥ 300 MBtuh
Baseline Case Description	AFUE = 80%	AFUE = 80%	AFUE = 75%	CE = 80%	CE = 80%	CE = 80%
Measure Case Description	AFUE = 84%	AFUE = 90%	AFUE = 82%	CE = 87% (TE = 85%)	CE = 92% (TE = 90%)	CE = 83% (TE = 85%)

Sources: SCG and SDG&E

The SCG/SDG&E workpapers calculate the energy saved by program-claimed boilers by the following formula:

$$\Delta Q_{3-4} = \Delta Q_{1-2} \times \left(\frac{1}{E_3} - \frac{1}{E_4}\right) \Big/ \left(\frac{1}{E_1} - \frac{1}{E_2}\right)$$

where

ΔQ – Energy Saved (therm/yr). Savings which results from installing the high-efficiency measure equipment.

E – Efficiency (%), in appropriate efficiency units (annual fuel utilization efficiency, combustion efficiency, or thermal efficiency) where:

Subscript 1 = DEER 2011 baseline (reference) equipment (averaged across building types, building vintage bins, and burner types)

Subscript 2 = DEER 2011 measure (new high-efficiency) equipment (averaged across building types, building vintage bins, and burner types)

Subscript 3 = Adjusted baseline equipment value[40]

Subscript 4 = Adjusted measure equipment value[41]

While the workpaper methodology includes a step external to the DEER methodology, DNV GL chose to assess uncertainty based on parameters informed by the DEER methodology.

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[38] Non-condensing also known as Tier 1

[39] Condensing also known as Tier 2

[40] Minimum baseline efficiency

[41] Minimum qualifying measure efficiency

5.3 Uncertainty analysis steps

This study's analysis focused on the natural draft (non-condensing) hot water boiler. Research for the other boiler types (steam boilers and condensing hot water boilers) are expected to yield similar results, although the chosen uncertainty inputs would likely be modified to take in to account different energy relationships, like the hot water supply temperature and hot water return temperature (an important metric for condensing boilers), for example. To simulate the annual energy savings for the nonresidential space heating boilers, DNV GL created a model within Crystal Ball to conduct Monte Carlo simulations. The model was created to represent implementation of the "Large Hot Water Natural Draft Boiler".[42] This boiler type was chosen for analysis based on the measure's high frequency in the 2013-14 tracking data for the PG&E measure "HIGH EFFICIENCY LARGE BOILER (>300 MBTUH)". The condensing and steam-generating boiler types were not analyzed for this study, although the methodology would be very similar to that for a natural draft boiler measure.

DNV GL selected building model inputs to research the direct and indirect effect those inputs had on the natural gas savings produced by the efficiency change modeled by the boiler measure.

Section 3 describes the use of multivariate linear regression models to predict savings from eQUEST simulation results as well as how these regression models and Oracle Crystal Ball were utilized for performing sensitivity analysis on the four selected inputs—the change in efficiency (referred to as delta efficiency), building vintage bin, minimum airflow ratio, and boiler sizing ratio. These inputs are discussed in greater detail in subsequent subsections.

5.3.1 Boiler tracking data

Table 13 provides the list of the nonresidential deemed measures included in the HVAC Boilers measure group, including the frequency of claims, in the 2013, 2014, and 2015 tracking data.

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[42] The prototypes that were used to analyze the measure used a natural draft boiler. That boiler type selected the "Atmospheric-Blr-HIR-fPLR" performance curve from the DOE-2 bdl library

Table 13. 2013-15 tracking claim frequency by measure name[43]

2013-14 Tracking Data (Nonresidential, deemed)	IOU	Count of Claims	Natural Gas Savings, therm
HEATING - SPACE HEATING BOILERS - LARGE	SDG&E	1	728
HIGH EFFICIENCY LARGE BOILER (>300 MBTUH)	PG&E	49	319,873
HIGH-EFFICIENCY CONDENSING BOILER	PG&E	34	358,408
SPACE HEATING BOILERS - GAS - LARGE	PG&E	25	110,304
SPACEHEATINGBOILERS-STEAM-LARGE-(>=83%CE)	SCG	2	33,331
SPACEHEATINGBOILERS-STEAM-LARGE-0.83CE	SCG	1	1,473
SPACEHEATINGBOILERS-STEAM-MEDIUM-(>=83%CE)	SCG	2	1,764
SPACEHEATINGBOILERS-WATER-LARGE-TIER1(>=85%CE)	SCG	1	13,193
SPACEHEATINGBOILERS-WATER-LARGE-TIER1-0.85CE	SCG	2	1,380
SPACEHEATINGBOILERS-WATER-MEDIUMLARGE-TIER2(>=90%CE)	SCG	8	31,520
SPACEHEATINGBOILERS-WATER-MEDIUM-TIER1(>=85%CE)	SCG	17	46,218
SPACEHEATINGBOILERS-WATER-SMALL-TIER1(>=84%AFUE)	SCG	2	2,697
SPACEHEATINGBOILERS-WATER-SMALL-TIER2(>=90%AFUE)	SCG	2	1,822
2013-2014 Total		**146**	**922,711**
2015 Tracking Data (Nonresidential, deemed)	**IOU**	**Count of Claims**	**Natural Gas Savings, therm**
COMMERCIALBLR-DWH-SMALL(<=200MBTUH)-TIER2 (>=90%EF)	SCG	1	1330
HEATING - SPACE HEATING BOILERS - LARGE	SDG&E	5	9,675
SPACEHEATINGBOILERS-WATER-LARGE-TIER1 (>=85%CE)	SCG	19	54,732
SPACEHEATINGBOILERS-WATER-LARGE-TIER1-0.85CE	SCG	3	2,231
SPACEHEATINGBOILERS-WATER-MEDIUMLARGE-TIER2(>=90%CE)	SCG	13	32,359
SPACEHEATINGBOILERS-WATER-MEDIUM-TIER1 (>=85%CE)	SCG	1	653
2015 Total		**42**	**100,980**

Notice that there are several forms of efficiency metrics used in the measure descriptions including combustion efficiency (CE) and AFUE. Thermal efficiency (TE) is not explicitly described in the measure names; however, the PG&E measures use AFUE and TE, while SDG&E and SCG use AFUE and CE.

5.3.2 Prototypes models for eQUEST

While the Residential Furnace measure used single family house prototype models, the nonresidential boiler measure utilized the same version of MASControl to generate nonresidential prototype models for each

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[43] Natural gas savings are expressed as first year gross savings without realization rate applied.

combination of seven building vintage bins and sixteen climate zones. The nonresidential prototypes use a single thermostat schedule for each building type rather than a series of simulations with different thermostat schedules whose results are weighted to produce a single "thermostat" result, as used in the residential prototypes. Each nonresidential prototype characterizes a different building type. Table 14 is a list of available nonresidential DEER building types within MASControl that have built-up systems and utilize boilers as their space heating source.

Table 14. DEER commercial building types

Building Code	Full Building Name
ESe	Education - Secondary School
ECC	Education - Community College
EUn	Education - University
Hsp	Health/Medical - Hospital
Nrs	Health/Medical - Nursing Home
Htl	Lodging - Hotel
MBT	Manufacturing - Bio/Tech
OfL	Office - Large
OfS	Office - Small
Rt3	Retail - 3-Story Large

Each vintage has different values for building and system component properties based either on the current code or typical values. The sources of these "typical" values are from various sources and are not always entirely clear in available DEER documentation; however, they are likely derived from available saturation and characteristic studies for California commercial buildings. The study utilized CZ2010 weather files for all simulations.

5.3.3 eQUEST batch processing

We prepared a batch processing spreadsheet to run through variants of prototype models with CZ2010 weather files. The methodology of the nonresidential prototype batch process closely resembles that of the residential prototype batch process and is explained in Section 4.3.3. The differences lie in the building type, climate zone, and input parameters selected for the uncertainty analysis.

For the nonresidential boiler measure, we selected the Large Office building type in climate zone 04, and selected seven building vintage bins, eight minimum airflow ratios, seven thermal efficiencies, and six system sizing ratios.[44,45] The boiler research case has a total of 2,016 unique simulations. As previously indicated, the building type and climate zone that was selected for simulation was chosen because of its high frequency in the 2013-2015 tracking data for the commercial boiler measure. Selecting other building types

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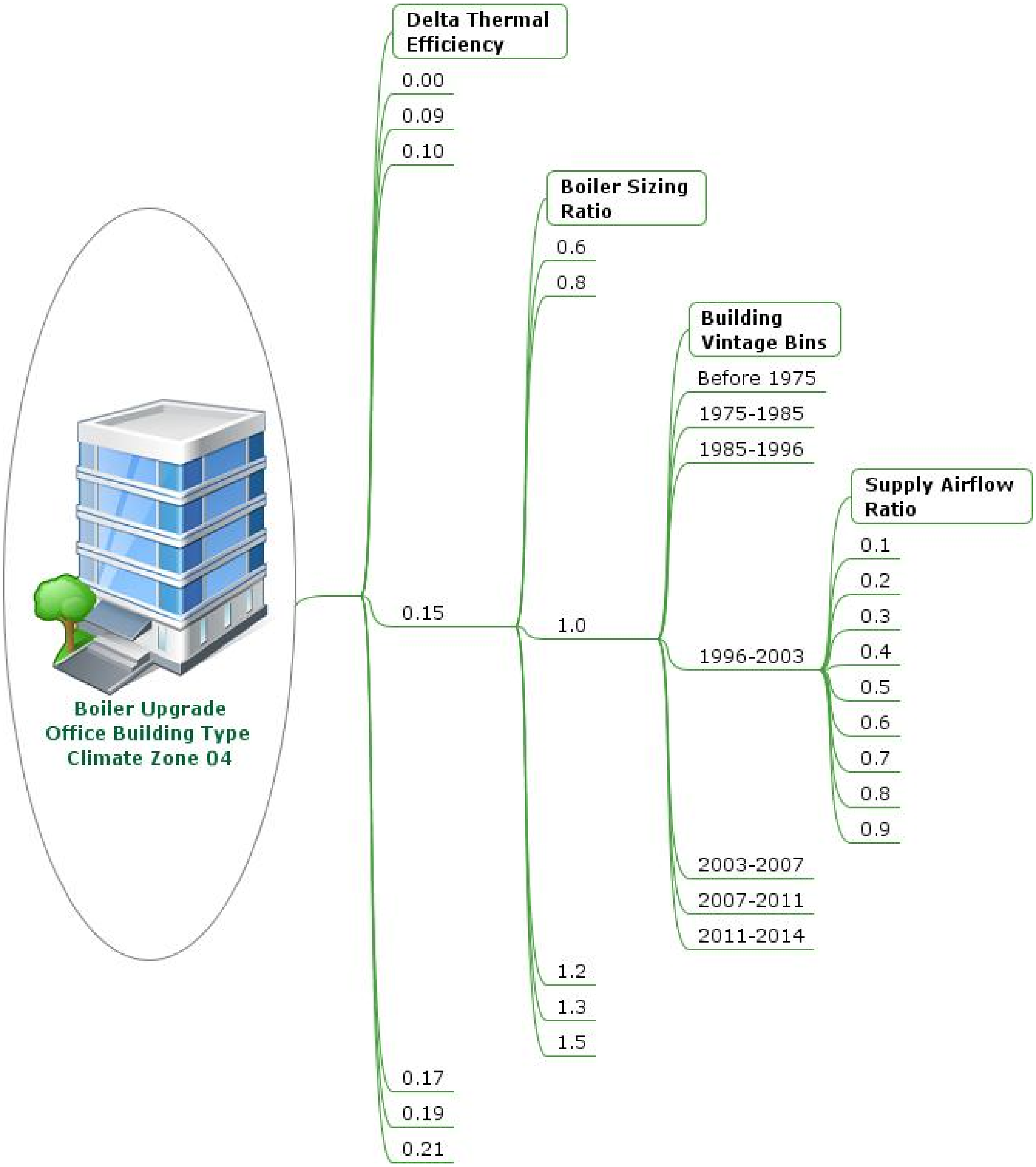
[44] The sizing ratio adjustments did not introduce a significant increase in unmet conditioning hours

[45] MASControl creates DEER prototype models that are inherently oversized by a factor of 1.3 in a "sizing" run. The ratio is then reset to 1 in the final prototype model. For our experiment, the sizing ratio was characterized by adjusting the prototype boiler's rated capacity (which is already oversized by a factor of 1.3) by additional sizing ratios.

and climate zones is a relatively straight-forward process and uses the same methodology but would require minor changes to the eQUEST batch run workbook.

Figure 21 shows a batch run tree that represents the combination of input parameter values selected for the batch processing spreadsheet. The origin of the parameter values and reasons behind selecting these input parameters can be found in APPENDIX B.

Figure 21. Batch-run tree design for nonresidential boilers

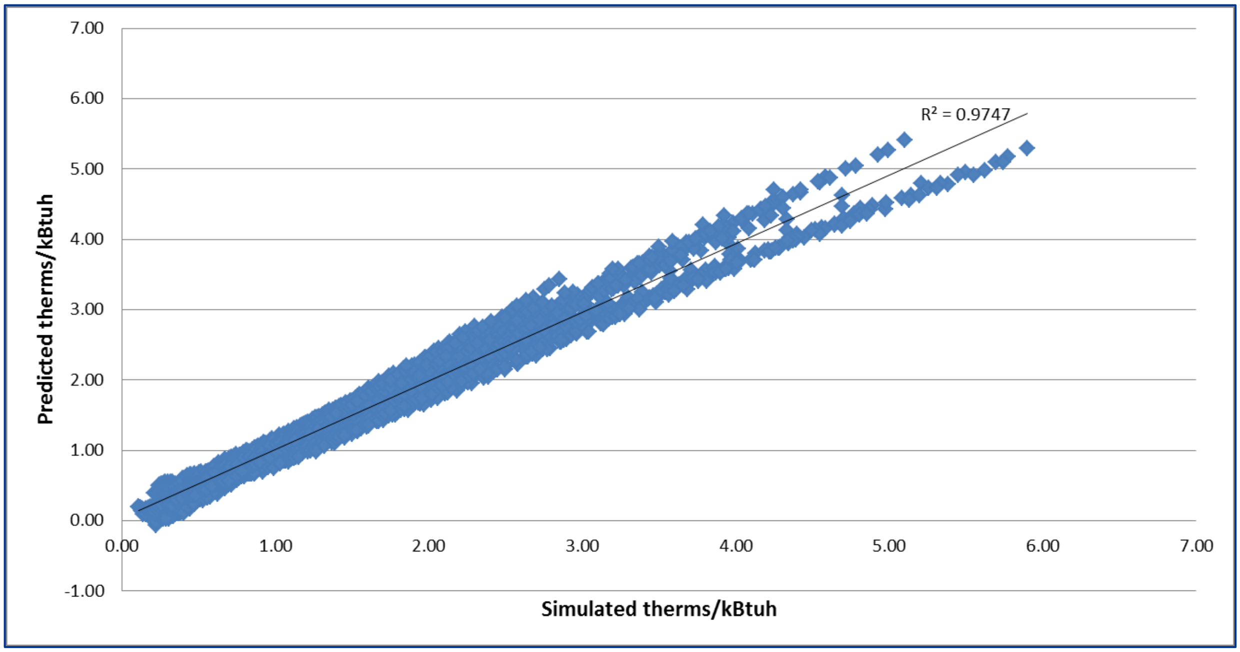


5.3.4 Multivariate bi-quadratic regression models

As described in Section 3, we created bi-quadratic regression models to predict savings at each given set of baseline/post-retrofit conditions for nonresidential boiler measures. More information is provided about the input parameters in APPENDIX B.

The Excel function LINEST was used to generate linear regression model coefficients for the building type/climate zone combination. The generated regression model was used to predict the normalized annual natural gas savings, which was plotted against the simulated annual natural gas savings. Figure 22 shows the plot for large office buildings in climate zone 4.

Figure 22. Predicted vs. simulated natural gas savings for boilers at large office buildings in CZ04



The preceding figure shows that the predicted savings (in therm/kBtuh) using the regression model fits well with the simulated savings performed in eQUEST. The mean bias error is extremely low (<1%) and the coefficient of variation of the root mean square error (CV of RMSE) is 11%. Like all regression models generated for this study, they introduce error in to the predicted savings estimates. This component of uncertainty is not quantified by the Monte Carlo analysis performed by Crystal Ball.

The regression model takes the form as follows for each of four baseline/post-retrofit cases for each of two measures:

$$Y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1,j=1,i\le j}^{i=n,j=n} a_{ij} x_i\, x_j$$

Where

Y represents natural gas savings normalized by boiler capacity, therm/Btuh

X_1 represents Δthermal efficiency, dimensionless

X_2 represents the minimum airflow ratio, dimensionless

X_4[46] represents the boiler sizing ratio, dimensionless

X_5 represents the building vintage bin, dimensionless

The corresponding coefficients for the annual natural gas savings due to boiler retrofits in CZ04 are provided in APPENDIX B.

Table 15 is a correlation table for boiler retrofits that was generated using MS Excel's CORREL function. Such a table is used to determine the extent to which the input parameters influence the savings results similarly on a scale of 0 to 1 where 0 means no correlation and 1 means complete correlation. When two input parameters are found to be highly correlated, they can skew the savings results. As shown in the following table, the input parameters have zero correlation with one another.

Table 15. Correlation of independent variables for boilers at large office buildings in CZ04[47]

Correlation	ΔThermal Efficiency	Minimum Airflow Ratio	Boiler Sizing Ratio	Building Vintage
	X_1	X_2	X_4	X_5
X_1	1			
X_2	0.00000	1		
X_4	0.00000	0.0000	1	
X_5	0.00000	0.0000	0.0000	1

5.3.5 Monte Carlo analysis in Crystal Ball

As described in Section 3, the regression presented in the preceding subsection was entered into the Crystal Ball add-in to determine the range of savings outcomes that could be expected by simulating many combinations of the selected input parameter. These simulations were used to create savings distribution profiles and sensitivity analysis portfolios.

The input parameter distributions can be found in APPENDIX B. Some of the distributions were chosen arbitrarily using practical limitations while others were informed by available data sources including DEER commercial building weights and the California Energy Commission boiler efficiency database. The input parameter distributions have a very significant influence on the uncertainty analysis, specifically the shape

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[46] X_3 was originally used to represent building shell UA, but was ultimately determined to be better represented by building vintage bins. Hence X5$_4$ was ultimately used to represent building vintage bins and X_3 was not used.

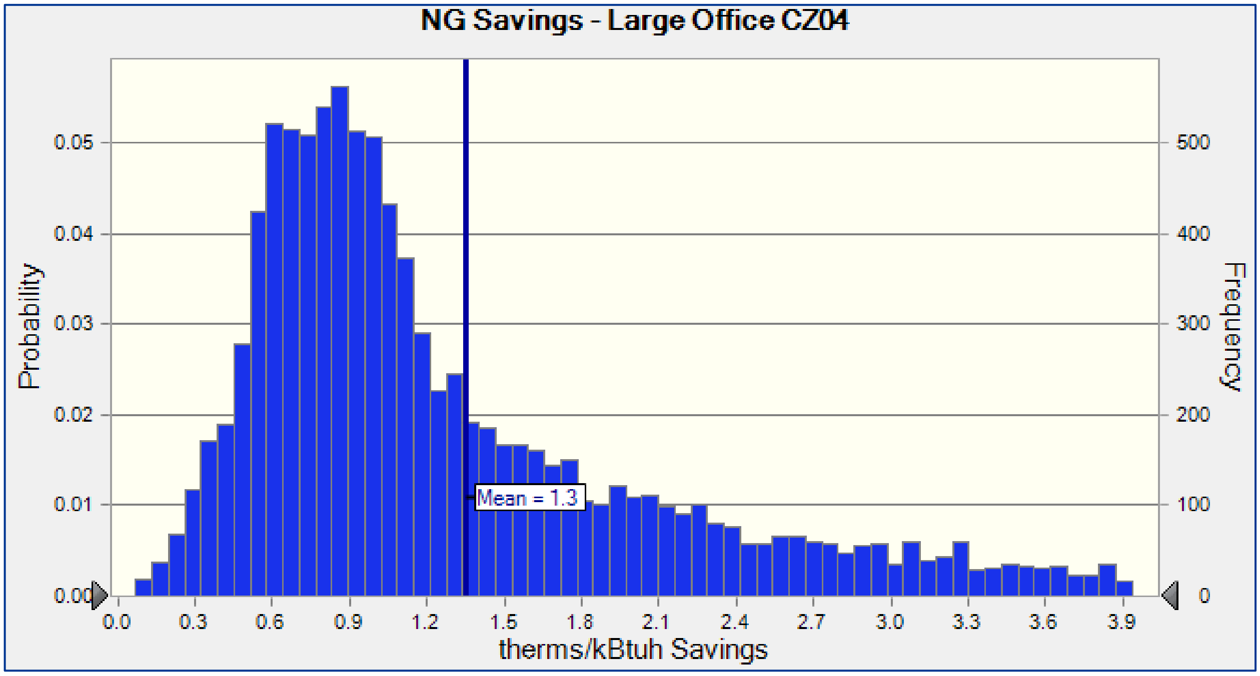
[47] Note the workbook has two "Vintage" variables with a correlation of one. This was performed to expedite the changes made from the previous version which had 2 variables (heat gain and shell UA) to represent vintage. Rather than remove and restructure the workbook, the variables X3 and X5 were set equal to each other (the vintage variable). This correlation table omits the redundant variable.

of the distribution of the energy savings. The assignment of these distributions is critical to controlling the results and isolating the sources of uncertainty.

5.4 Uncertainty analysis results

This section presents the annual natural gas savings identified by the Monte Carlo simulations and the proportions of savings uncertainty that can be attributed to each of the selected input parameters for the Large Office building in climate zone 4. This combination was chosen because it represents the highest proportion of claimed savings in the tracking data. Figure 23 presents the distribution of natural gas savings predicted by the Crystal Ball analysis for the nonresidential hot water boiler implemented in a large office building in climate zone 4. The mean savings is 1.3 therm/kBtuh of boiler input capacity, with a standard deviation of 0.9 therm/kBtuh. This mean savings value is for a hot water, natural-draft boiler with a rated heating-input capacity between 300 and 5,000 kBtuh and a mean average thermal efficiency of 0.88.[48]

Figure 23. Distribution of natural gas savings for boilers at large office buildings in CZ04



The figure shows that, given the distribution and ranges of input parameter values,[49] the savings distribution is not a normal curve. The curve is asymmetric and is skewed to the left of the mean (i.e., a positive skewness with larger distribution with savings smaller than the mean).

Table 16 presents a comparison of the uncertainty analysis results to the DEER database value.[50] A direct comparison was not possible given the current mean value for "delta efficiency" because the uncertainty analysis uses a different "measure" case thermal efficiency than the efficiency used in DEER.

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[48] The mean average delta efficiency used in the CB analysis was 0.13 and the baseline thermal efficiency was 0.75

[49] See APPENDIX B for more information on the distribution of input parameters

Table 16. Uncertainty analysis results for boilers at large office buildings in CZ04

Results	Uncertainty Analysis	DEER
Normalized Annual Natural Gas Savings per kBtuh		
Average Savings, therm/kBtuh	1.3	0.75
Standard Deviation, therm/kBtuh	0.9	N/A
Post Retrofit Efficiency		
“Measure Case” Thermal Efficiency	0.88	0.85

The sensitivity chart, provided in Figure 24, shows the influence of each input parameter on the forecasted savings. The sensitivity of the forecasted savings is largely attributable to the uncertainty of the input parameters. The figure suggests that minimum airflow ratio parameter contributes 82.5% of the variance or uncertainty in the forecasted savings, while the delta thermal efficiency contributes 16.7%. The distant third ranking uncertainty contributor is the sizing ratio input parameter, estimated to contribute 0.8%.

Figure 24. Sensitivity analysis for natural gas savings of boilers at large office buildings in CZ04

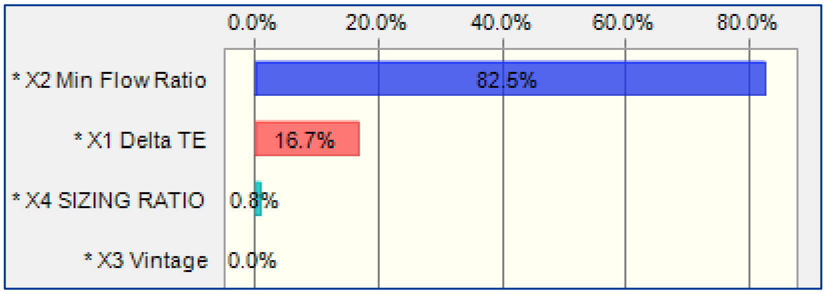

Table 17. Ranked contributors to deemed savings uncertainty for boilers

Input Parameters	Relative Contribution[51] to Variance
Minimum Airflow Ratio	82.5%
Δ Thermal Efficiency	16.7%
Boiler Sizing Ratio	0.8%
Building Vintage Bin weights	0.0%

The results suggest that the minimum airflow ratio is a vitally important parameter (among the parameters chosen) to research in order to reduce the uncertainty in modeled savings estimates for efficient boiler

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[50] READi v.2.3.0; EnergyImpactID ”NG-HVAC-Blr-HW-300to2500kBtuh-85p0ET-Atm”; Version DEER2011; Large Office; PG&E PA; Existing Vintage; CZ04

[51] Absolute values of relative proportions provided herein.

upgrades. This finding has an intuitive relationship to heating energy use because the volume of airflow to zonal terminal boxes at variable air volume (VAV) systems correlates directly to the reheat energy (i.e., boiler load) required to heat the air to zonal set point temperatures. The savings uncertainty of the minimum airflow ratio likely extends to controls (e.g., boiler temperature reset, supply air temperature reset strategies) that can also affect the delivered airflow to terminal boxes and zones.

Relative to the minimum airflow ratio, the vintage and the boiler sizing ratio (i.e., how the rated capacity of the boiler is sized to the building's peak heating load) have a significantly smaller impact on the uncertainty in gas savings for the boiler measure. These findings should not suggest that these are not important parameters for collection; rather, the minimum airflow ratio and delta thermal efficiency have a very high influence on the savings uncertainty compared to the other studied parameters.

Future experiments can include other parameters of interest in to the Monte Carlo simulations to determine their relative significance to savings uncertainty and to other savings parameters.

6 VARIABLE FREQUENCY DRIVES FOR HVAC FANS

The third and final uncertainty analysis undertaken in Year Two of this study pertained to variable frequency drives (VFDs) at HVAC fans. VFDs were selected based upon their prevalence in the 2013-14 and 2015 tracking datasets provided by the CPUC data management team. In this section, we describe the types of VFD measures that are incented, the methodology and input parameters used to determine the deemed savings, and the uncertainty analysis results. At the end, we summarize our findings and present recommendations based upon those findings.

6.1 Measure descriptions

The measure installs a variable frequency drive and associated controls on an existing constant speed, variable flow HVAC supply or return fan. This measure applies to most commercial and industrial facilities. Retrofit-Add-on (REA) is used as the measure installation type. The measure Effective Useful Life was taken as 15 years.

Both workpapers have listed the system requirement and exclusions for this measure. They include the following:

- VFD must be applied to existing HVAC supply or return air fans only.
- Throttling flow control strategies such as inlet guide vanes, or bypass dampers and or discharge dampers, throttling valves must be removed or permanently disabled.
- Fans must be ≤100 horsepower (hp).
- Replacement multiple-speed or variable speed motors (VSM) are not eligible.
- VFDs on cooling towers fans are not eligible.

The energy savings varies with Building Type (BT), building vintage (BV) and climate zone (CZ). The savings were reported per rated fan hp. The energy savings in this workpaper are taken directly from DEER Measure ID D03-051. Since no changes were made to measure code D03-051 under the DEER2014, DEER2011 or the DEER2008 updates, therefore DEER2005 values were used to estimate the savings in the DEER2014 database. DEER 2014 data includes electric demand, electric energy, and gas energy savings with interactive effects, labor costs, equipment useful life, and Net to Gross (NTG) of this measure. However, the PGE workpaper subsequently says that the workpaper does not consider gas savings.

6.2 Workpaper review

The VFD on HVAC fan measure review included the following workpapers:

- SCE13HC050, R2, Jan 29, 2016, Title – Variable Speed Drive on HVAC Fan Control
- PGECOHVC106, R4, 05/08/2014, Title – Variable Frequency Drives (VFDs) for HVAC Fan

Both workpapers provided identical requirements to for compliance with Title 24:

- Direct Expansion (DX) [>=75,000 Btuh] and chilled water [>=1 hp] cooling systems that control the capacity of the mechanical cooling directly based on occupied space temperature shall (i) have a minimum of two stages of fan control with no more than 66% speed when operating on stage 1; and (ii) draw no more than 40% of the fan power at full fan speed, when operating at 66% speed.

- All other systems, including but not limited to DX cooling systems and chilled water systems that control the space temperature by modulating the airflow to the space, shall have proportional fan control such that at 50% airflow, the power draw is no more than 30% of the fan power at full fan speed.
- Systems that include an air side economizer to meet 140.4(e)1 shall have a minimum of two speeds of fan control during economizer operation.
- Installing a VFD is not required to meet performance compliance of the 2013 Title 24 regulations, nor is it a mandatory measure.

The reviewed workpapers assumed the baseline fan control system as discharge damper on forward curved fans. However, in practice, the baseline conditions can have other fan control arrangements such as varying the position of inlet guide vanes, two-speed fans with high and low speed[52] settings, etc. In view of this, the workpaper should have reported savings for different baseline conditions.

The list shown in Table 18 provides the various workpapers that were included in this review:

Table 18. VFDs for HVAC fan workpapers

Workpaper Title	Workpaper Number	Revision No., Date
PG&E		
Variable Frequency Drives (VFDs) for HVAC Fans	PGECOHVC106	R4, May 08, 2014
Variable Frequency Drives (VFDs) for HVAC Fans	PGECOHVC106	R3, Aug 29, 2012
Variable Frequency Drives (VFDs) for HVAC Fans	PGECOHVC106	R3, June 18, 2012
SCE		
Variable Speed Drive on HVAC Supply Fan Control	SCE13HC050	R0, June 19, 2012
Variable Speed Drive on HVAC Supply Fan Control	SCE13HC050	R1, July 10, 2014
Variable Speed Drive on HVAC Supply Fan Control	SCE13HC050	R2, Jan 29, 2016

SCE has a similar workpaper[53] that deals with variable speed motors for commercial building HVAC application. However, this workpaper is for variable speed motors of 10 hp or less in the measure case, while the baseline case refers to non-residential air handler units with permanent split capacitor (PSC) motors. This measure installs variable speed motors (VSM) of 10 hp or less in conjunction with a new air conditioner or heat pump, split or packaged air handling unit. The reported savings for this measure is per each air handling unit. Since, this workpaper measure savings is completely unrelated, no further study of this measure savings were carried out.

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[52] Though two-speed fan motor is not common for most of the IOU programs, however, there are cases where the base case operation is a two-speed and the customer modifies the two-speed operation with a fan motor VFD.

[53] SCE13HC031, R2, Jan 22, 2016 – Air Handler Variable Speed Motor

6.2.1 2004 DEER

The review also included the 2004-2005 Database for Energy Efficiency Resources (DEER) Update Study Final Report, December, 2005. The following assumptions were reported for supply fan VFD measures:

- For the purposes of building simulations, the fans are assumed to be forward-curved centrifugal fans with discharge dampers to control the airflow.
- The oldest vintage prototype includes VAV systems to allow for a comparison between VFD-controlled fans, in the post-retrofit case, and forward-curved centrifugal fans with discharge dampers, in the baseline case.
- No above-code savings were reported for this measure because Title 24 has required VFDs for larger supply fans since 1992.

6.3 Uncertainty analysis steps

6.3.1 VFD tracking data

To begin with, DNV GL used 2013-14 and 2015 tracking data to determine the combinations of major building type and CZs that contributed to the claimed savings. The evaluator found the following:

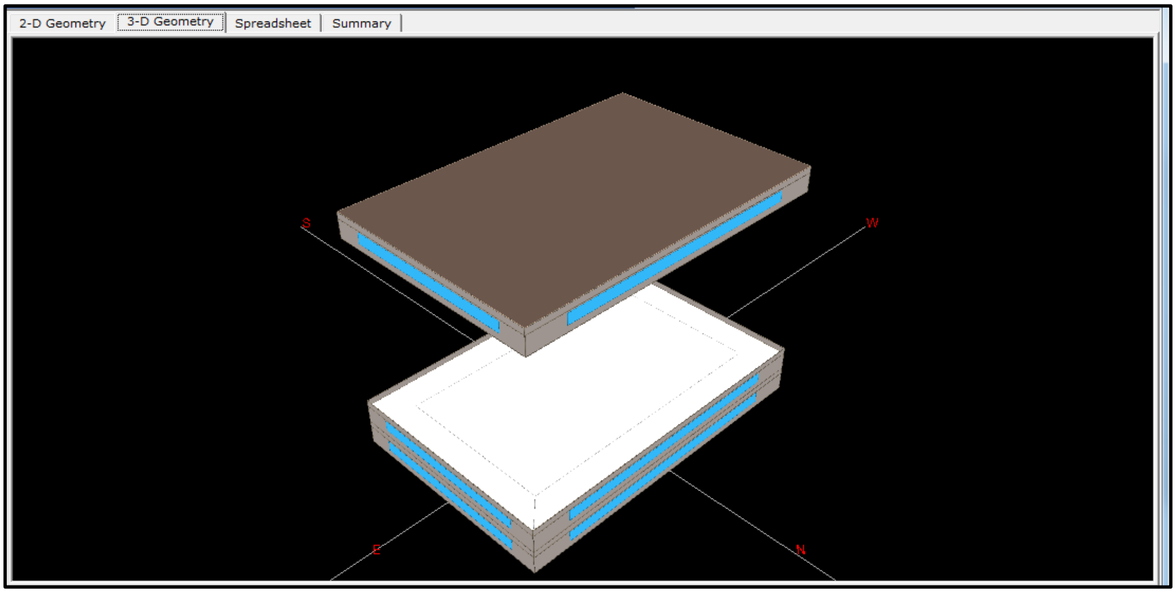
- In the 2013-14 tracking data, the claimed savings at 868 applications were 20,348,106 kWh, 4,113 kW, and 38,443.5 therm.
- In 2015, the total tracking claimed savings were 10,154,964 kWh, 2,610.29 kW, and -13,670.6 therm.

The tracking data also included many VFD savings measures that were not related to the workpaper measure and were submitted through different programs. They included savings for VFDs at a process cooling tower, a parking-garage exhaust fan, a cooling tower, boiler fans, and condenser fans. The tracking data documented the workpaper numbers pertaining to each of the fan VFD measures that were referenced for fans other than HVAC supply fans.

6.3.2 Prototype models for eQUEST

Large office building was selected as the prototype building and was used in this analysis. This building type comprised the largest proportion of the annual electric savings reported for year 2013-14 and year 2015. The prototype building has 10 floors; one AHU for the first floor, one AHU for the top floor and one AHU for second to ninth floors. Besides large office buildings, the other building types that accounted for some high tracking savings included secondary education buildings and hospitals. However, in order to keep the simulation runs limited, only the large office building type was used for the final analysis. Within the most dominant climate zone, CZ03, the building type that accounted for the largest share of the savings was large office buildings.

Figure 25. eQUEST prototype model of large office building



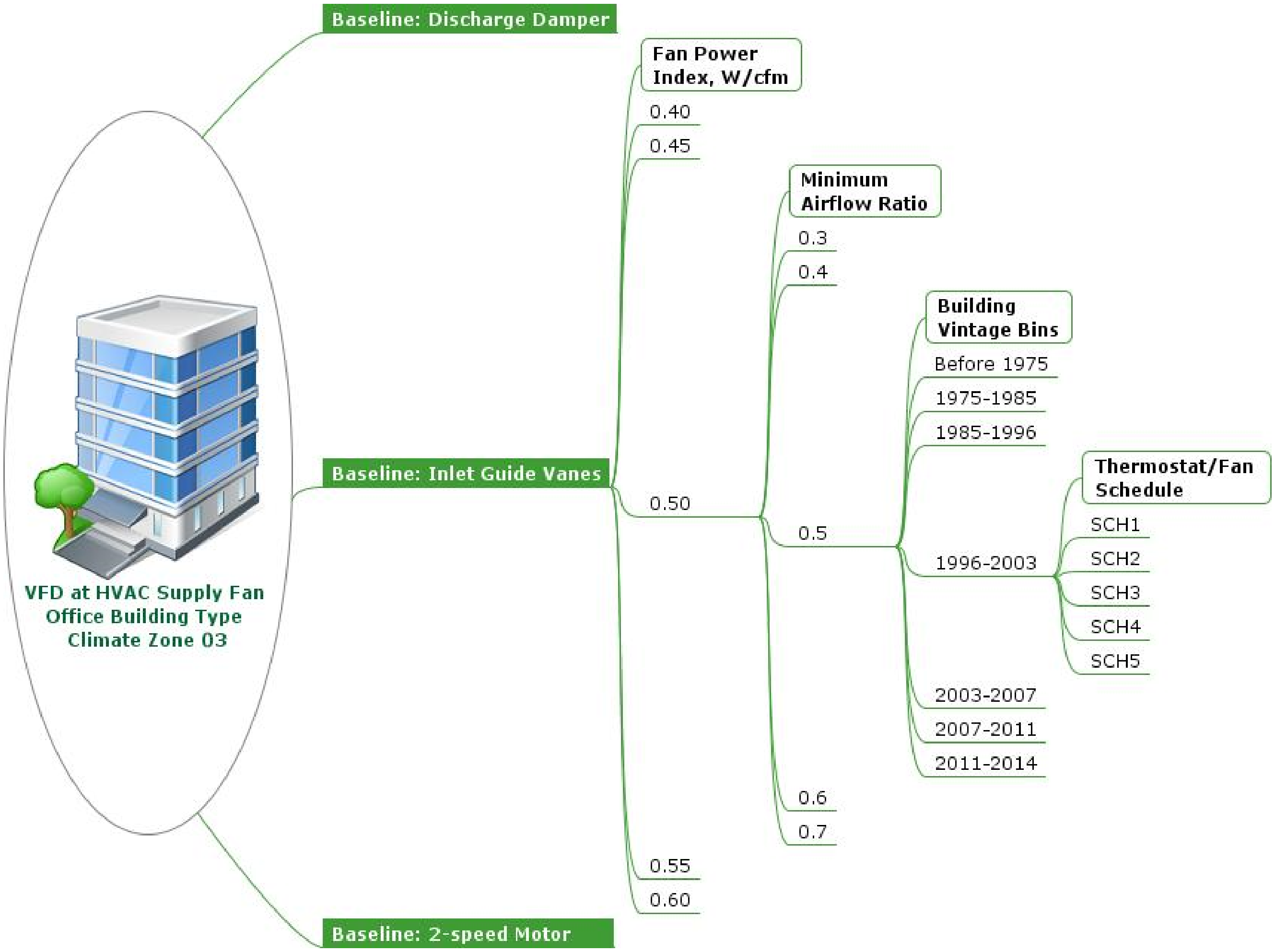
6.3.3 eQUEST batch processing

This study used a batch processing spreadsheet to program a series simulation cases that would be used to research the impact of selected inputs on the deemed energy savings. This study team selected input parameters judged to have a significant effect on the resulting savings. Subsequently, this study team utilized commercial building Packaged VAV (PVAV) prototype models and considered multiple factors that affect the fan power consumptions. The batch runs were comprised of many variations of the following input parameters:

- Baseline fan control strategies
- Fan power indices based on airflow rate (W/cfm)
- Minimum airflow ratios
- Fan operating schedules

The input parameters are shown in the batch run tree provided in Figure 26.

Figure 26. Batch-run tree design for VFDs at HVAC fans



6.3.4 Multivariate bi-quadratic regression models

The analysis included three separate regression models for three separate baseline airflow control strategies used here, i.e. discharge damper, inlet guide vane, and two-speed fan motors[54]. Each regression model used the eQUEST batch run simulation outputs for large office building types in climate zone 03. The models predict the savings for each baseline-case and measure-case input combination as described in Section □3. More information is provided about the input parameters in APPENDIX C.

The figures below; Figure 28, Figure 29, and Figure 30 provide the regression of fan energy savings, in CZ03, for three baseline airflow control types: discharge dampers, inlet guide vanes, and two-speed motors, respectively. The plots for the remaining CZs are not produced in the report as they exhibited the similar trends and characteristics as shown in CZ03 analysis. All three plots show strong linear trends that are easily fitted to regression lines. The baseline airflow control strategy influences the measure savings per

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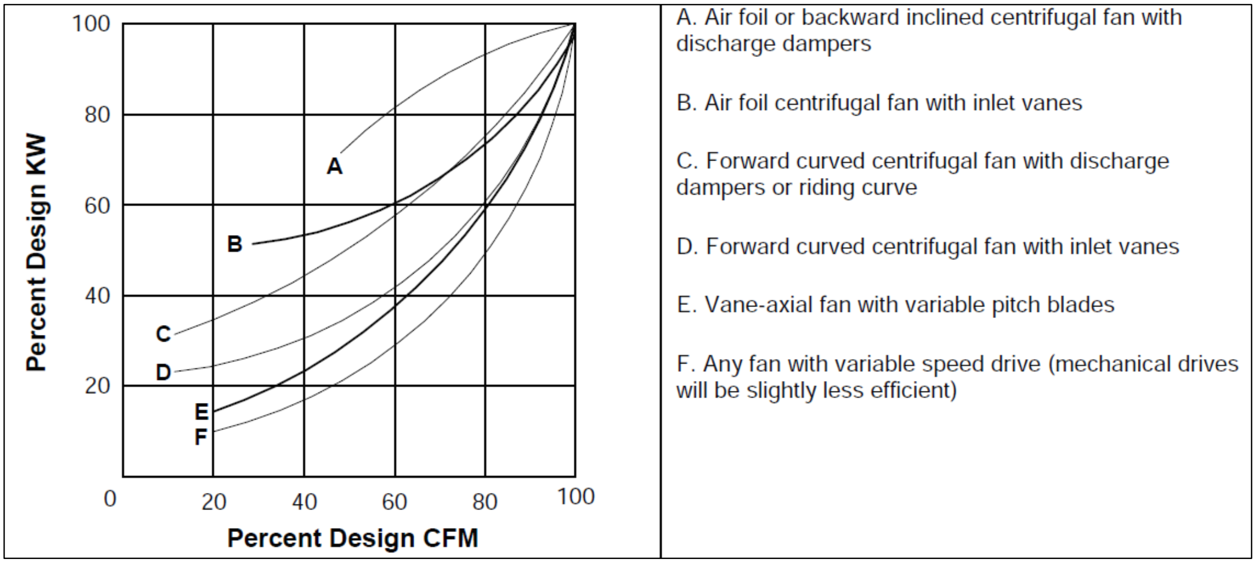
[54] Two-speed motors are sometimes disallowed by IOU programs as eligible baseline conditions.

motor horsepower where a two-speed motor yields the highest savings, discharge dampers yield somewhat less, and inlet guide vanes yield the least.

That the savings for a discharge damper baseline is greater than that for an inlet guide vane baseline is unsurprising—for a given fan type, discharge damper controls always consume more energy than inlet guide vane controls at a given fraction of the system's airflow capacity (see Figure 27). That the savings for a two-speed motor baseline surpassed those of both of the other baseline strategies is a little more surprising. Although Figure 27 does not specifically show the relationship between the fractional power consumption and the fractional airflow rate for a two-speed motor, the fan affinity laws tell us that each 10% reduction in airflow is accompanied by a 27% decrease in energy usage. Hence, the savings yielded by upgrading from a two-speed motor to a VFD control strategy will be heavily influenced by both the ratio of the motor speed at low speed to that at full speed and the extent to which the fan schedule allows the fan motor to operate at low speed. In other words, the more the baseline fan operates at full speed, the greater the savings upon installing a VFD.

Figure 27. Fan performance curves for VAV systems



Source: California Energy Commission, *Nonresidential Compliance Manual*, CEC-400-2013-002-SD, June 2013, p. 4-94.

Figure 28. Discharge damper baseline fan control for VFDs in CZ03

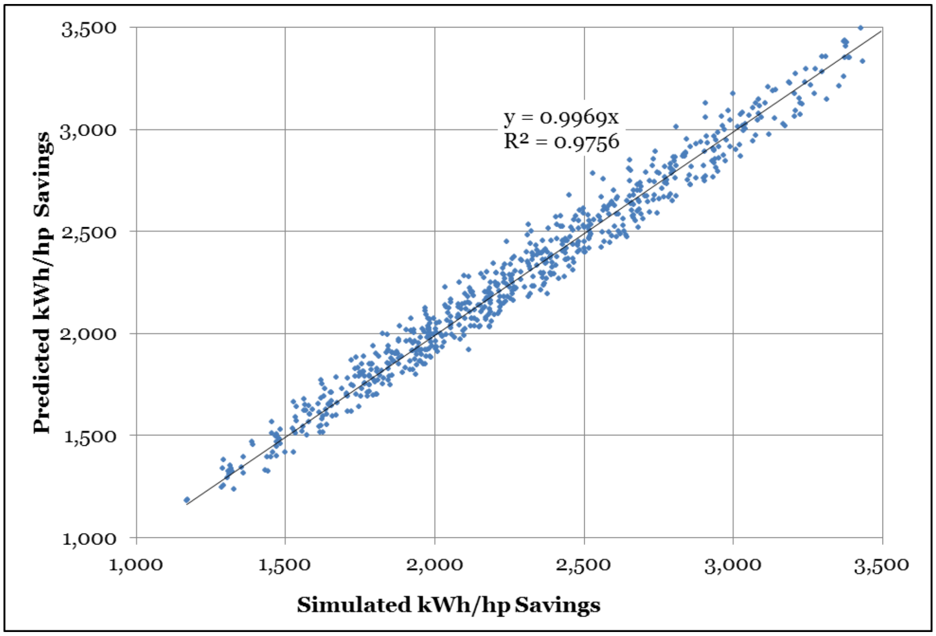


Figure 29. Inlet guide vane baseline fan control for VFDs in CZ03

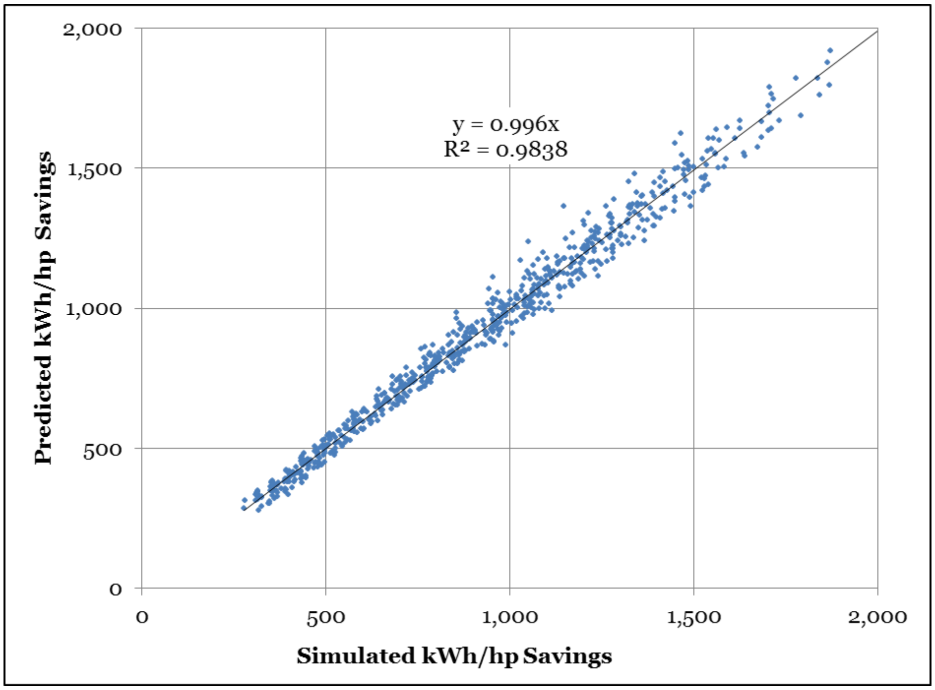
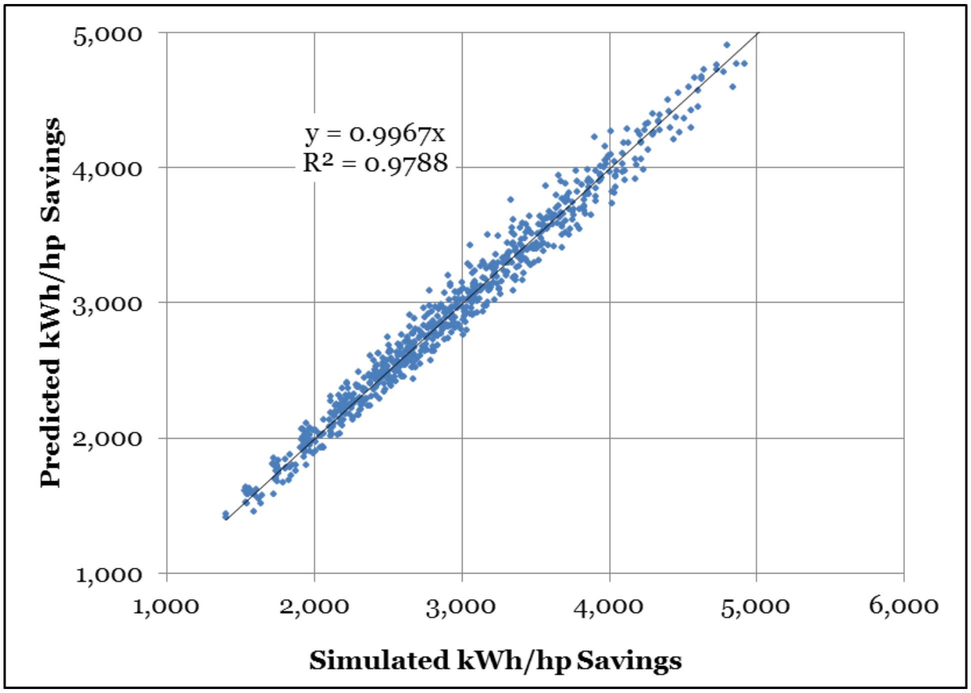


Figure 30. Two-speed motor baseline fan control for VFDs in CZ03



The regression model takes the form as follows for each of three baseline/post-retrofit cases:

$$Y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1, j=1, i \le j}^{i=n, j=n} a_{i,j} x_i \, x_j$$

where

Y represents energy savings, kWh

X_1 represents the fan power index, W/cfm

X_2 represents the minimum airflow ratio, dimensionless

X_4[55] represents the building vintage bin, dimensionless

X_5 represents the fan schedule bin, dimensionless

The corresponding coefficients for the annual electric savings due to the HVAC fan VFD retrofit are provided in APPENDIX C. The coefficient of multiple determination—the R-squared value—associated with each baseline/post-retrofit scenario is also provided. This is used to assess the goodness of fit of the regression to the eQUEST simulation results where an R-squared value of one indicates a perfect fit between the

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[55] X_3 and X_5 were originally used to represent building shell UA, but were ultimately determined to be better represented by building vintage bins. Hence X_4 was ultimately used to represent building vintage bins and X_3 was not used

regression and the results and a zero indicates "no" fit. The R^2 values for the regressions shown in Figure 28 through Figure 30 are all about 0.98—indicating an excellent fit.

The regression coefficients were then used to predict the energy savings of an HVAC fan VFD for each of the three baselines. Table 19 is a correlation table that was generated using the Excel CORREL function. This table is used to determine the extent to which the input parameters influence the savings results similarly on a scale of 0 to 1 where 0 means no correlation and 1 means complete correlation. When two input parameters are found to be highly correlated, they can skew the savings results. As shown in the following table, the input parameters have a low correlation with one another.

Table 19. Correlation table for regression model inputs of HVAC fan VFD measure

Correlation	Fan Power Index, W/cfm	Minimum Airflow Ratio	Building Vintage Bin	Fan Operating Schedule Bin
	X1	X2	X3	X5
X_1	1			
X_2	0.0000	1		
X_3	0.0000	0.0000	1	
X_5	0.0000	0.0000	0.0000	1

There are some simple differences between the workpapers and this study as described below:

- In this study, we normalized the energy savings by the brake horsepower (bhp) of the motor while the workpapers normalized the savings by the rated horsepower of the motor[56].
- To manage the number of simulations, we analyzed large office buildings in CZ03. The same method can easily be replicated, however, for other building types and climate zone combinations.
- We calculated the savings for each of the seven building vintage bins while the workpaper referenced READI reported savings for two building types: new and existing.
- We conducted analyses for three baseline airflow control strategies (discharge dampers, inlet guide vanes, and two-speed fan motors) while the workpaper-reported savings only consider discharge dampers.

6.3.5 Monte Carlo analysis in Crystal Ball

As described in Section 3, the regression presented in the preceding subsection was entered into the Crystal Ball add-in to determine the range of savings outcomes that could be expected by simulating many combinations of the selected input parameter. These simulations were used to create savings distribution profiles and sensitivity analysis portfolios.

The input parameter distributions can be found in APPENDIX C. Some of the distributions were chosen arbitrarily using practical limitations while others were informed by available data sources including DEER

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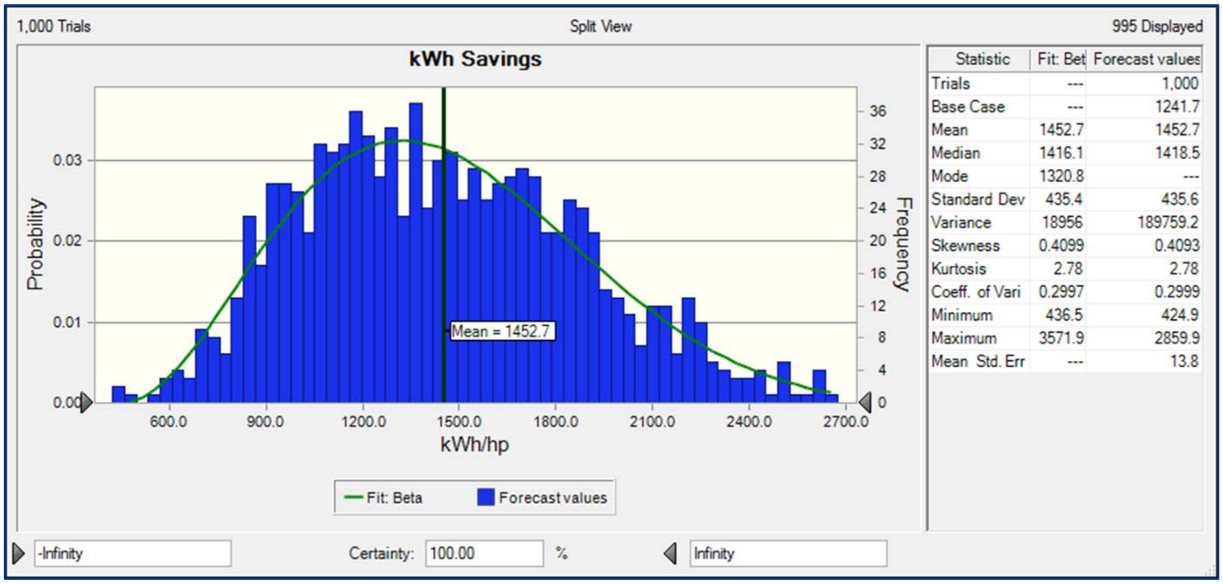
[56] Since motors are manufactured in discrete rated horsepower capacities (5 hp, 7.5 hp, 10 hp, etc.), the installed motor very often has a capacity greater than needed by the system. Hence, the rated motor horsepower is typically greater than its required brake horsepower.

commercial building weights. We analyzed the HVAC fan VFD measure in three different scenarios corresponding to three different baseline airflow control strategies: discharge dampers, inlet guide vanes, and two-speed fan motors. The forecast is defined as the weighted average of the savings across all three airflow control baselines.

6.4 Uncertainty analysis results

A Crystal Ball analysis of a VFD on a supply fan measure at a large office building in CZ03 that generated the annual electric savings distribution as well as the corresponding statistics based on 1,000 Monte Carlo trials as shown in Figure 31. From CZ03 plot, it can be seen that the mean annual electric savings is 1,453 kWh/hp and the standard deviation is 435.4 kWh/hp.

Figure 31. Distribution of savings for VFDs at HVAC fan in CZ03



Statistic	Fit: Bet	Forecast values
Trials	---	1,000
Base Case	---	1241.7
Mean	1452.7	1452.7
Median	1416.1	1418.5
Mode	1320.8	---
Standard Dev	435.4	435.6
Variance	18956	189759.2
Skewness	0.4099	0.4093
Kurtosis	2.78	2.78
Coeff. of Vari	0.2997	0.2999
Minimum	436.5	424.9
Maximum	3571.9	2859.9
Mean Std. Err	---	13.8

-Infinity

Certainty: 100.00 %

Infinity

Table 20 presents a comparison of the uncertainty analysis results to the DEER database value. A direct comparison is not possible because the uncertainty analysis uses the DEER prototypes that used the fan system operating horse power while the DEER data base used the corresponding rated fan motor powers.

Table 20. Uncertainty results for nonresidential HVAC fan VFDs in CZ03

Baseline Condition(s)	Results	Uncertainty Analysis	DEER
Discharge Dampers, Inlet Guide Vanes, and two-speed motors	Average Annual Electric Savings, kWh	1,453	N/A
	Standard Deviation, kWh	435	N/A
Discharge Dampers	Average Annual Electric Savings, kWh	1,512	1,030
	Standard Deviation, kWh	448	N/A

The sensitivity analysis chart provided in Figure 32 and Table 21 shows that the variance of the mean savings is sensitive to the following factors, in decreasing order: 42.4 % due to the fan power index, -28.5% due to the minimum airflow ratio, -13.3% due to the fan sizing factor, and 6.8% due to the fan operating schedule, 6.8. The measure savings uncertainty is not significantly sensitive to the Building Vintage Bin weights. Similarly, fan airflow control strategies have very little impact as well.

Figure 32. Sensitivity analysis for average fan energy savings in CZ03

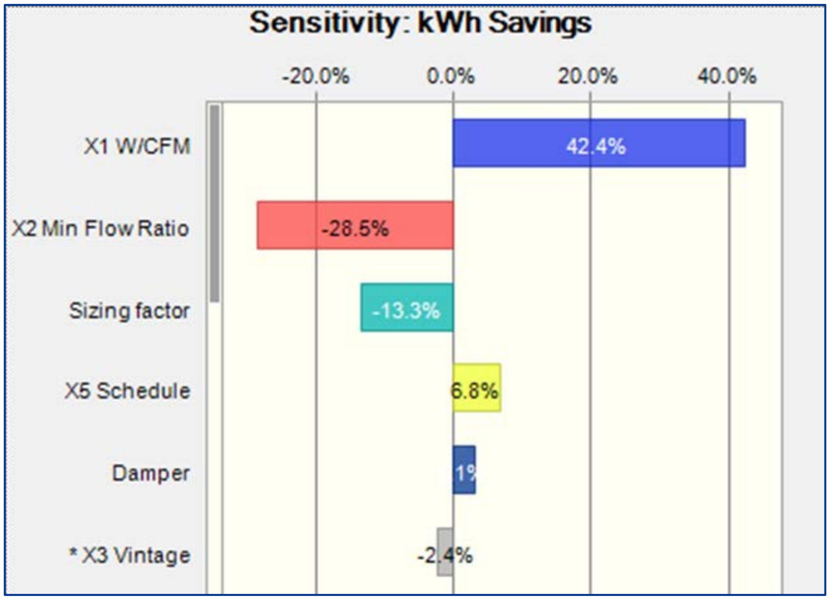


Table 21. Ranked contributors to deemed savings uncertainty for VFDs at HVAC fans

Input Parameters	Relative Contribution[57] to Variance
Fan Power Index (W/cfm)	42.4%
Minimum Airflow Ratio	28.5%
Fan Sizing Ratio	13.3%
Fan Schedule	6.8%
Baseline Airflow Control Strategy	5.1%
Building Vintage Bin weights	3.9%

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[57] Absolute values of relative proportions provided herein.

7 OVERALL FINDINGS AND RECOMMENDATIONS

7.1 Ex ante savings forecasts

For three of the four measures studied, it was possible to directly compare the ex ante savings per DEER to the average ex ante savings forecasts produced by the Monte Carlo simulations as provided in Table 22. Each of the savings forecasts has an associated standard deviation, a common measure of uncertainty. Note that the average savings differ from the DEER estimates in each case. This is a result of using distributions and not point estimates for assumptions. When the range of input parameters has a non-normal distribution around the DEER assumption the mean is shifted. In all cases the DEER estimate is within the uncertainty band of the analysis.

Table 22. Uncertainty analysis savings results for measures studied in Year 2

Deemed Savings Results	Uncertainty Analysis	DEER
High Efficiency Residential Furnace (AFUE 95) in CZ12		
Average Normalized Annual Natural Gas Savings, therm/kBtuh	0.66	0.64
Standard Deviation, therm/kBtuh (percent)	± 0.54 (± 81%)	N/A
Optional VSM at Residential 95 AFUE Furnace without cooling in CZ12		
Average Normalized Annual Electric Savings, kWh/kBtuh	5.29	N/A
Standard Deviation, kWh/kBtuh (percent)	± 3.92 (± 74%)	N/A
Optional VSM at Residential 95 AFUE Furnace with cooling in CZ12		
Average Normalized Annual Electric Savings, kWh/kBtuh	7.61	N/A
Standard Deviation, kWh/kBtuh (percent)	± 4.24 (± 56%)	N/A
High Efficiency Boiler at Office Building in CZ04		
Average Normalized Annual Natural Gas Savings, therm/kBtuh	1.3	0.75
Standard Deviation, therm/kBtuh (percent)	± 0.9 (± 69%)	N/A
VFD for HVAC Fan w/Discharge Dampers at Office Building in CZ03		
Average Annual Electric Savings, kWh	1,512	1,030
Standard Deviation, kWh (percent)	± 448 (± 30%)	N/A
VFD for HVAC Fan w/Multiple Control Strategies at Office Building in CZ03		
Average Annual Electric Savings, kWh	1,453	N/A
Standard Deviation, kWh (percent)	± 435 (± 30%)	N/A

As can be seen upon reviewing Table 22, the standard deviations of the forecasted savings range from 30 percent of the forecasted savings for VFDs for HVAC fans to 81 percent of the forecasted savings for high efficiency residential furnaces. Knowing that their uncertainties are so broad should give readers a new regard for the much narrower uncertainties generally associated with impact evaluation results.

7.2 Sensitivity analyses

From the sensitivity analyses performed for each measure, DNV GL learned which of the studied factors had the greatest influence on the uncertainty of the savings forecasts as shown in Table 23. Knowing which parameters contribute the most to the uncertainty of deemed savings can be used to guide future research.

Table 23. Contributors to deemed savings uncertainty for Year 2 measures studied

Input Parameters	Relative Contribution[58] to Variance
High Efficiency Residential Furnace (AFUE 95) in CZ12	
Heating Setpoint	93.9%
Building Vintage Bin weights	4.0%
Furnace Sizing Ratio	1.3%
Δ Furnace Efficiency	0.4%
Fan Motor/Control Strategy	0.2%
Duct Leakage Proportion	0.1%
Cooling Setpoint	0.1%
Optional VSM for Res. 95 AFUE Furnace without cooling in CZ12	
Minimum Airflow Ratio	35.2%
Fan Control Strategy (FanOn-Auto)	34.8%
Fan Control Strategy (FanOn-FanOn)	14.7%
Fan Control Strategy (Auto-Auto)	10.0%
Post-retrofit Fan Power Index (W/cfm)	3.3%
Baseline Fan Power Index (W/cfm)	1.1%
Thermostat Bin	0.4%
Building Vintage Bin	0.3%
Furnace Sizing Ratio	0.1%
Optional VSM for Res. 95 AFUE Furnace with cooling in CZ12	
Minimum Airflow Ratio	31.9%
Fan Control Strategy (FanOn-Auto)	28.9%
Fan Control Strategy (FanOn-FanOn)	13.5%
Fan Control Strategy (Auto-Auto)	11.4%
Baseline Fan Power Index (W/cfm)	7.1%
Thermostat Usage Bin	4.3%
Building Vintage Bin	2.0%
Furnace Sizing Ratio	0.9%
High Efficiency Boiler at Office Building in CZ04	
Minimum Airflow Ratio	82.5%
Δ Thermal Efficiency	16.7%
Boiler Sizing Ratio	0.8%
Building Vintage Bin weight	0.0%

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[58] Absolute values of relative proportions provided herein.

Input Parameters	Relative Contribution[58] to Variance
VFD for HVAC Fan at Office Building in CZ03	
Fan Power Index (W/cfm)	42.4%
Minimum Airflow Ratio	28.5%
Fan Sizing Ratio	13.3%
Fan Schedule	6.8%
Baseline Airflow Control Strategy	5.1%
Building Vintage Bin weights	3.9%

7.3 Measure-specific recommendations

Strategies that could leverage the findings include:

- The heating setpoint for residential furnaces should be a question on rebate applications or gathered by way of a survey by evaluators and used to true-up savings for a specific program population.
- Data from ongoing studies such as HVAC 6 were used to inform the fan power index (the inverse of fan efficiency). Other data from that study can be used to inform the furnace sizing ratio. While, HVAC 6 was not designed to target these parameters it is an example of leveraging data to reduce ex ante uncertainty.
- The minimum airflow ratio is a simulation input used to capture fan system operation and zonal re-heat for variable air volume systems. The results show that evaluation of boiler measures should not focus as much on verifying installed efficiency, but rather focus on the zonal controls that determine the heating load and influence the total savings.
- For VFD measures, it is important to study the operating conditions (pre- and post-retrofit) that influence fan power index as well as the zonal controls for air distribution.

7.4 Year 3 study recommendations

In Year 3, the study plans to consider one additional measure and apply the updated methodology that uses both building simulations and Monte Carlo simulations. Rather than focusing on unevaluated measures, however, the study plans to shift to evaluated measures and thereby aid future evaluation planning with an eye toward reducing measure-specific uncertainty. Primary measure candidates are the equipment measures covered by HVAC 1 and maintenance measures covered by HVAC 3. Many of the insights gained in the Year 2 report apply directly to high efficiency cooling measures. The 2013-14 report for HVAC 3 determined relatively large ex post uncertainties and the large volume of available implementer data offer a test-bed for additional analysis.

Additionally, the study will consider investigating key methodology steps that influence measure-specific modeled uncertainty. These and other topics that are under consideration for investigation are listed below.

- Introduce explicit uncertainty parameter in Crystal Ball to accommodate and account for the regression model uncertainty or goodness of fit. See 4.3.4.1 for more context on this enhancement.

- Disaggregate the model regression further and investigate impacts of individual vintage characteristics rather than aggregating them as an arbitrary “vintage” uncertainty parameter.
- Investigate impact of adapting uncertainty distribution sets created using discrete parameter and probability values to continuous distribution sets using Crystal Ball distribution tools.
- Research secondary sources to inform the Year 2 commercial measures’ (boilers and fan VFD) uncertainty parameter distribution sets.
- Develop a flowchart to identify how the measure-specific uncertainty analysis can be used in concert with the portfolio-wide uncertainty analyses undertaken by the CPUC.

APPENDIX A. Residential furnace input parameters

The details regarding the input parameters and the regression analysis coefficients used for the uncertainty analysis for both types of retrofits at residential furnaces. In the SFM prototype models, there are many factors having impact on furnace natural gas or electricity consumptions that it is impossible to include all of them in the Crystal Ball analysis. We can only focus on those that are influential to the consumption and have some level of uncertainty. At the same time, we want to emphasis those where the uncertainty can be reduced through survey research or M&V. In addition, the model input parameters should be derived from field observations or measurements, or simple engineering calculations.

Following the principles above, we have selected the following nine input parameters as candidates of regression model inputs. We will introduce each parameter one by one in the following sections including definitions, selected discrete values for batch simulation, and distributions for Crystal Ball analysis.

Furnace AFUE

Residential furnace efficiency is rated by annual fuel utilization efficiency (AFUE). It is defined as the ratio of annual output energy of a furnace to the annual input energy. This metric applies to residential and light commercial boilers and furnaces with an output less than 225 kBtuh for central furnaces and less than 300KBtuh for central boilers.

In eQUEST 3.65, the furnace efficiency input is expressed as heat input ratio (HIR). It is defined as the total natural gas consumption divided by the total heat output in the same unit.

The baseline furnace efficiency requirement is located in Table E-3 or Table E-4 of the 2010 Appliance Efficiency Standards. The minimum AFUE is 80% for units less than 225 kBtuh in input capacity. Considering that most residential furnaces are smaller than 225,000 Btuh, we used 80% AFUE as the baseline efficiency. The qualified central natural gas forced air furnace must have an AFUE rating of 95 percent to 96.9 percent.

Based on the California Title 24 2008, the HIR is calculated by the following formula:

For furnaces with AFUEs not greater than 83.5

$$HIR = one / (0.002907 * AFUE + 0.5787)$$

For furnaces with AFUEs greater than 83.5

$$HIR = one / (0.011116 * AFUE - 0.098185)$$

Table 24 summarizes the HIR values for individual AFUE efficiencies as well as the delta AFUE. For the baseline AFUE of 80, the HIR is equal to 1.2325.

Table 24. AFUE and HIR distributions

Baseline AFUE	Post-retrofit AFUE	ΔAFUE	Post-retrofit HIR
80.0	95.0	15.0	1.0440
80.0	95.5	15.5	1.0380
80.0	96.0	16.0	1.0320
80.0	96.5	16.5	1.0262
80.0	97.0	17.0	1.0203

To define the distribution of the D_AFUE, we collected data from two sources. First, we collected furnace AFUE value from AHRI Directory of Certified Product Performance.[59] This database has rating data of all certified gas furnaces and it reflects the inventory of the available furnace products. In Table 25, there are totally 1,387 natural gas furnace products with the AFUE rating between 95.00 and 96.99. The furnaces with 97.00 AFUE rating are not eligible in accordance with the workpaper. Most furnaces have an AFUE of 95.0, followed by AFUE of 96.0. Only a few furnaces are rated between 96.5 AFUE and 96.99 AFUE.

Table 25. Gas furnace inventory with AFUE between 95 and 97

AFUE	Lower	Upper	Counts	Probability
95.0	95.00	95.25	579	41.7%
95.5	95.25	95.75	229	16.5%
96.0	95.75	96.25	531	38.3%
96.5	96.25	96.75	48	3.5%
97.0	96.75	96.99	0	0.0%

At the same time, we gathered rated AFUE efficiencies from WO032 and HVAC 6 projects. There are a total of 26 samples and the distribution is shown in Figure 33. This plot shows similar distribution compared to the inventory distribution in Table 25. Most units have a rated AFUE of 95 followed by AFUE of 96. Only few units are rated higher than AFUE of 96.5. Considering that the data from local projects should more closely reflect the actual AFUE distribution of installed furnaces, we decided to choose the second source as the Crystal Ball analysis input. Although the sample size is small, it will not have a major impact on the uncertainty analysis because majority of gas savings is contributed by the gap between 80 AFUE and95 AFUE. The variance from 95.0 AFUE to 97.0 AFUE contributes only about 2.1% of total uncertainty, as shown in the Crystal Ball analysis section.

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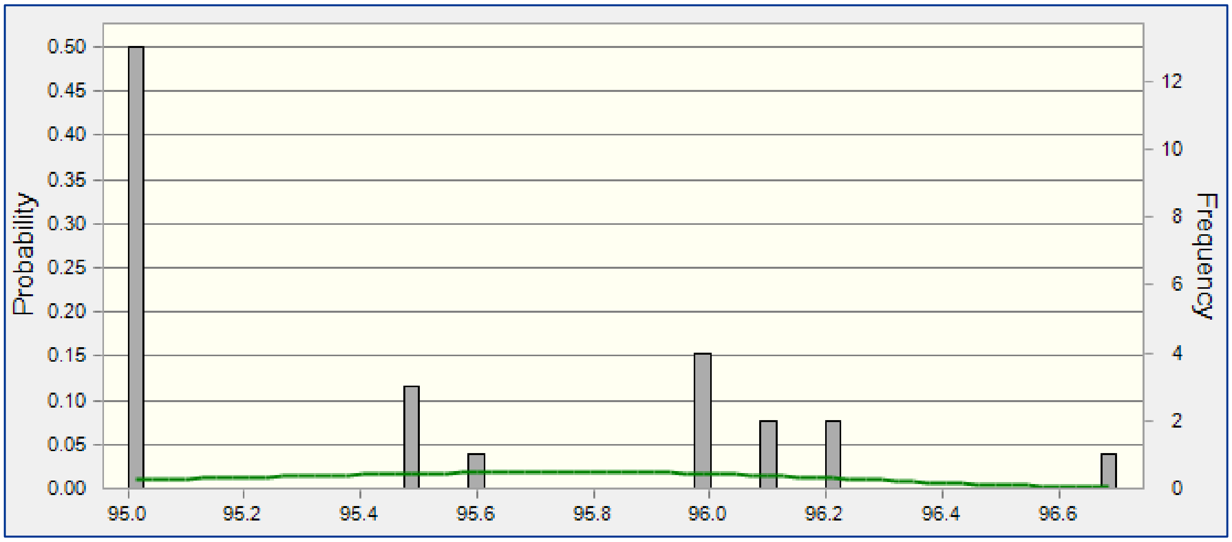
[59] www.ahridirectory.org

Figure 33. Distribution of furnace AFUE Values



Furnace heating capacity

The natural gas savings for 95 AFUE furnace measure and the power savings for ECMs are both normalized by the furnace input capacity in kBtuh. There are four single family houses in each SFM prototype model and each house has one furnace. The two one-story houses have smaller furnaces than the two two-story houses do. To simplify the analysis, this study used the total heating capacity of the four furnaces to normalize the total natural gas and power savings of each run. The total furnace heating capacity for each combo of building vintage and climate zone is shown in Table 26. Note that the values in the table are the total input capacity of four furnaces.

Table 26. Furnace heating capacity by building vintage and climate zone

Building Vintage	Climate Zones							
	01	**02**	**03**	**04**	**05**	**06**	**07**	**08**
Before 1978	162.8	281.9	228.0	217.1	249.2	236.2	179.1	219.2
1978 - 1992	146.5	236.2	195.1	192.7	215.6	231.4	179.3	216.1
1993 - 2001	147.9	242.2	205.2	201.0	225.1	241.7	193.6	227.3
2002 - 2005	153.9	177.1	213.4	209.1	234.2	250.2	200.3	235.2
2006-2009	154.0	177.1	213.4	209.1	234.2	250.2	200.3	235.2
2010 - 2013	154.0	177.1	213.4	209.1	234.2	250.2	200.3	235.2
2014 - 2015	154.0	177.1	213.4	209.1	234.2	250.2	200.3	235.2
	09	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Before 1978	294.3	325.2	343.9	319.5	322.6	487.3	498.3	266.4
1978 - 1992	274.6	300.3	336.3	313.8	321.8	389.4	408.2	224.2
1993 - 2001	220.6	241.6	252.8	235.9	243.2	260.6	279.1	229.2
2002 - 2005	209.9	202.8	213.6	197.7	204.9	296.1	317.8	238.5
2006-2009	209.9	202.8	213.6	197.8	204.9	296.2	317.8	238.5
2010 - 2013	209.9	202.8	213.6	197.8	204.9	296.2	317.8	238.5
2014 - 2015	209.9	202.8	213.6	197.8	204.9	296.2	317.8	238.5

Furnace sizing ratio

Furnace sizing ratio is listed as one significant factor not only because furnace fan horsepower is proportional to the rated fan airflow rate, but also because it impacts fan cycling. If a furnace is oversized, the ECM can still drive the fan at a lower airflow rate to meet actual cooling or heating load requirements. However, the PSC motor can only drive the fan at a preset speed, leading to high fan power. In addition, an oversized furnace tends to cycle more frequently. A Wisconsin study[60] showed that most of the increased run-time for furnaces comes from an increase in the number of cycles the furnace goes through rather than increases in the length of the cycle. More frequently, cycling will lead to furnace performance degradation. It is also important to note that since savings are normalized to furnace capacity, the sizing ratio has a direct effect on the normalized savings. The sizing ratio also has a direct impact on duct leakage since the duct leakage rate is proportional to flow rate.

Most furnaces could meet the design heating load using just the low-fire model of operation. However, there is another consideration in sizing furnaces: setback recovery. Many homeowners employ temperature setbacks. It may take a long time to recover from the setback temperature, however, if the furnace is sized by design conditions. Therefore, in reality, furnaces could be sized in a wide range. There is no consensus on the best oversizing factor. The AFUE rating procedure uses an oversize factor of 70%, based on a national average.[61] A recent meeting of experts in residential furnaces recommended that an oversize factor of 40%

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[60] Scott Pigg, Electricity Use by New Furnaces A Wisconsin field study, October 2003.

[61] ANSI/ASHRAE Standard 103. (2007). Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers. Atlanta: ANSI/ASHRAE.

would be more reflective of current installations.[62] The oversize factor recommended for residential installation by the 2009 Alaska Building Energy Efficiency Standards (BEES) is 25% greater than the heating load, considerably less than 70%. Based on previous survey studies in California, most furnaces are sized up to 150% of design heating load and it is rare that furnaces are undersized. Therefore, we chose a sizing factor range from 100% to 150%.

In the SFM prototype models, MASControl estimates the input heating capacity (HEATING-CAPACITY) and airflow rate (SUPPLY-FLOW) of the furnaces by using a sizing factor (CAPACITY-RATIO) of 130%. When we used the batch-processing spreadsheet to run the SFM models, we changed the SIZING-RATIO to revise the actual sizing factor.

Furnace capacity or airflow rate = Peak load * 130%* SIZING-RATIO

The SIZING-RATIO ranges from 0.8 to 1.2 and the corresponding sizing factor ranges from 104% to 156%. Due to lack of information, we assumed a distribution for the sizing ratio. The sizing ratio, actual sizing factor, and the probabilities are presented in Table 27. We recommend including residential appliance sizing factor in the future residential RASS survey or CLASS study.

Table 27. Distribution of sizing ratio and sizing factor

Sizing Ratio	Sizing Factor	Proportion
0.8	1.04	5%
0.9	1.17	20%
1.0	1.30	50%
1.1	1.43	20%
1.2	1.56	5%

In practice, we can compare the size of the new furnace to the size of the old furnace to determine the sizing ratio. This implies that the old furnace is sized by a factor of 130%. Otherwise, we can use estimate the peak heating load of a residential house following ACCA Manual J[63] and calculate the sizing factor of the installed new furnace.

We recommend studying the residential AC and furnace sizing practices in California to provide substantial and concrete inputs for future uncertainty studies.

Duct leakage

Heat losses through duct leakage are another contributor to space load. Figure 34 is an illustration of duct leakage and heat transfer in a single family house in DOE-2.2.[64] Supply air is leaked to the attic and the conditioned space, while portion of air enters the return duct from the conditioned space and the attic. In the space, the balance portion is made up by airflow infiltration, which increases HVAC unit cooling and heating loads.

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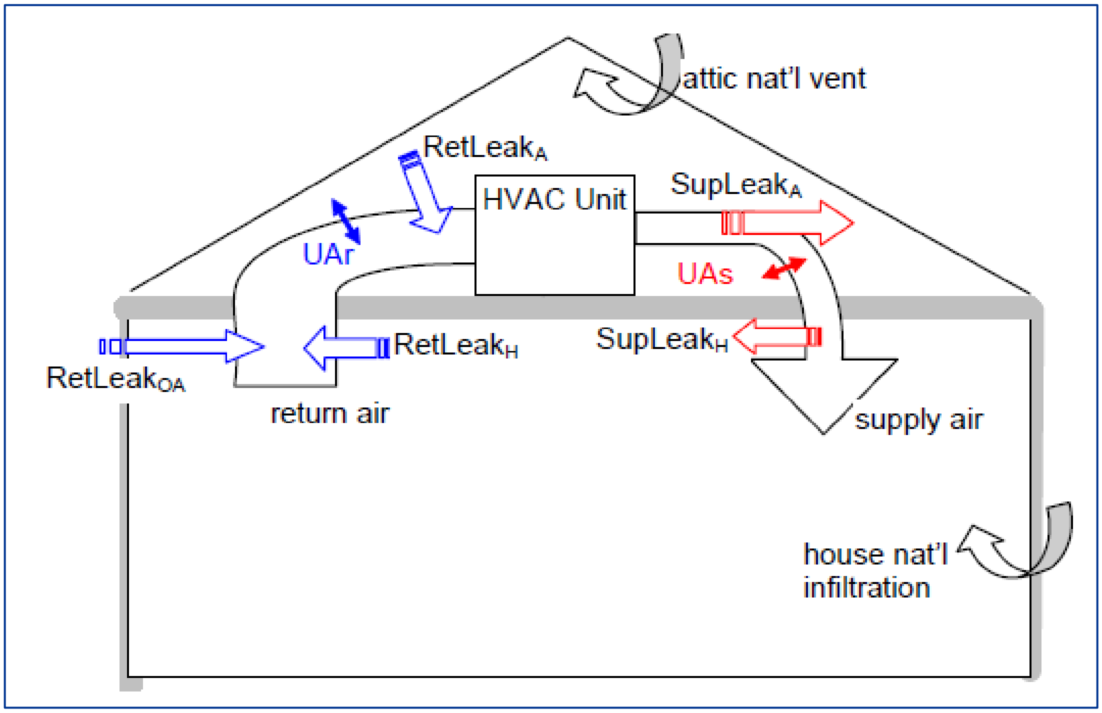
[62] Brand, L. (2012). Expert Meeting Report: Achieving the best installed performance from high-efficiency residential gas furnaces. Des Plaines: Partnership for Advanced Residential Retrofit.

[63] http://www.acca.org/standards/approved-software

[64] Itron, 2005, 2004-2005 Database for Energy Efficiency Resources (DEER) Update Study Final Report. See: http://deeresources.com/files/deer2005/downloads/DEER2005UpdateFinalReport_ItronVersion.pdf

Figure 34. Duct heat loss and gain components considered in DOE-2.2



Source: Itron, 2005.

In all SFM prototype models, the default duct leakage is "40% total air leakage." Of this total, half is supply leakage. For single-story houses, 75% of the supply leakage is assumed to go to the unconditioned attic (SupLeakA), with the remainder leaking to the conditioned spaces (SupLeakH). Return duct leakage in the single family house is assumed to be 80% of the volume of the supply duct leakage. This would imply that 20% of the supply duct loss is made up with airflow (RetLeakOA), but due to interactions with existing natural infiltration, it is assumed that only half of this value (10% of supply duct loss) is actually brought in from the outside. The balance of (supply air lost to attic) minus (outdoor air induced into the space) is return leakage, or air that is sucked into the return ducts from either the attic (RetLeakA) or house (RetLeakH). Since more of the ducts are assumed to be located within the conditioned space for a two-story house, the fraction of total supply leakage that goes to the attic is lowered to 67%.

The equations below show how duct leakage inputs are calculated in the eQUEST prototype models:

DUCT-AIR-LOSS = 0.40*50% (supply)*0.75% (to attic for one-story) =0.150

DUCT-AIR-LOSS = 0.40*50% (supply)*0.67% (to attic for two-story) =0.134

Return duct loss = 0.40*50% (supply)*80% (return) =0.16

DUCT-AIR-LOSS-OA = 0.40*50% (supply)*20% (return) =0.10

In this study, we simplified the problem by assuming the same duct leakage for one-story and two-story houses. Five leakage levels are adopted to describe the impact of duct leakage on energy savings. The probability of the leakage levels are based on a dataset of 6,516 field measurements from a California duct test and seal program (MDSS PGE duct leak distribution analysis dated June 2011). Table 28 presents all duct leakage distributions and corresponding eQUEST inputs. There is no return duct loss keyword defined in the eQUEST model.

Table 28. Duct leakage probabilities and eQUEST model inputs

Duct Leakage	Probability	DUCT-AIR-LOSS	DUCT-AIR-LOSS-OA
0.40	36.6%	0.1500	0.100
0.24	28.2%	0.0900	0.060
0.19	24.6%	0.0713	0.048
0.12	10.5%	0.0450	0.030
0.09	0.1%	0.0319	0.021

Supply fan control

The furnace could operate in four modes: heating mode, cooling mode, ventilation mode, and standby mode. For a furnace with a PSC motor, it has three to five different supply fan speeds to choose from. Most PSC furnaces have fan speed selected at medium-low or medium high at the time of installation. For ECM furnaces, the supply fan speed can modulate based on the furnace mode and system load providing 300 to 400 cfm per ton of airflow. In the ventilation mode, the ECM furnace is generally factory-set at a low airflow and the fan power draw is much lower than that in cooling or heating mode. In the standby mode, all furnaces consume a small amount of power, ranging from 4 to 13 watts.

There are two fan control strategies for both PSC and ECMs: Continuous (FAN-ON) and Intermittent (AUTO). Under the first control strategy, the indoor fan always runs when it is scheduled on by FAN-SCHEDULE or NIGHT-CYCLE-CTRL. Since the fan is scheduled on 24/7, the supply fan will be running continuously. Some home owners prefer this mode for various reasons, such as better air quality and better thermal comfort. Under the AUTO control, the indoor fan operates only for that fraction of the hour required for space heating or cooling. Therefore, the supply fan will be keeping cycling to meet the cooling or heating load when there is a demand. Otherwise, the supply fan will be off.

For the ECM measure, we considered the fan control change between the baseline case and post-retrofit case. Four scenarios are designed: AUTO_PSC vs. AUTO_ECM; AUTO_PSC vs. FAN-ON_ECM; FAN-ON_PSC vs. AUTO_ECM; FAN-ON_PSC vs FAN-ON_ECM. For most areas in California, the period with no cooling or heating load is much longer that the period with load. Therefore, baseline and post-retrofit fan control change has a significant impact on power savings.

A study conducted by the Energy Center of Wisconsin[65] provides furnace fan operation practices in Wisconsin. The findings demonstrate that a considerable number of homeowners (23%) who participated an Energy Star program and purchased ECM furnaces switched from AUTO to FAN-ON mostly because of following HVAC contractors/builders' advice. If the switching is due entirely to installation of the ECM, then the fan power savings are entirely negated because the increase in operating hours more than offsets the

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[65] Scott Pigg, Tom Talerico, Electricity Savings from Variable-Speed Furnaces in Cold Climates. http://www.eceee.org/library/conference_proceedings/ACEEE_buildings/2004/Panel_1/p1_23/paper.

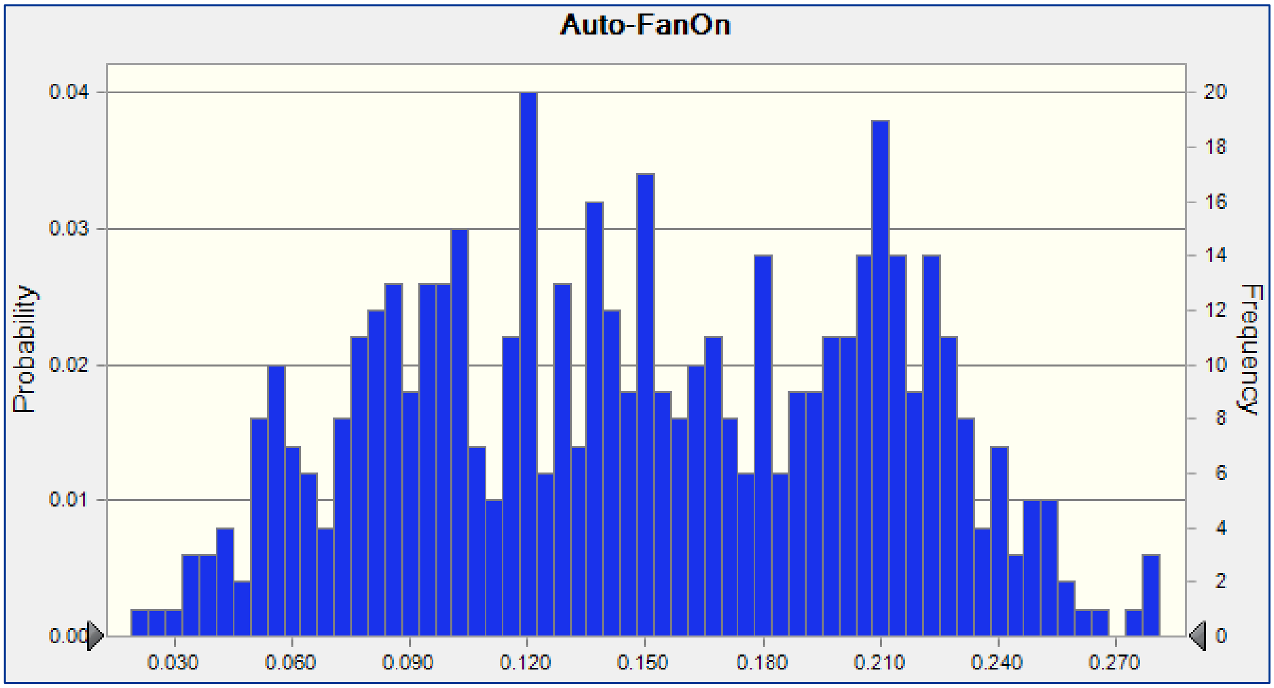
increase in part load efficiency. About 60% homeowners kept AUTO control and 9% kept FAN-ON control after upgrading from PSC motors to ECM m0tors. For non-participants, the ratio is 3% (AUTO to FAN-ON), 92% (AUTO to AUTO), and 3% (FAN-ON to FAN-ON), respectively. The behavior in the non-participant group is quite different from that in the participant group.

At present, due to lack of data in California, we assumed a normal distribution with upper and lower limits for the ratio of each scenario based on the data from Wisconsin. Table 29 summarizes the distribution of each scenario ratio. The ratio of the second scenario is calculated by one minus other three ratios. Scenario one has the highest ratio followed by the Scenario 2. The ratios of the other two scenarios are low. We used Crystal Ball to plot the frequency review of the second scenario ratio as shown in Figure 35.

Table 29. Fan control scenarios and distributions for ECM measure

Scenario	Baseline Control	Post-retrofit Control	Average Ratio	Standard Deviation	Lower Limit	Upper Limit
1	AUTO	AUTO	0.700	0.350	0.600	0.800
2	AUTO	FAN-ON	Calculated by 1-sum of other three ratios			
3	FAN-ON	FAN-ON	0.100	0.050	0.075	0.125
4	FAN-ON	AUTO	0.050	0.025	0.025	0.075

Figure 35. Frequency of ratio of AUTO to FAN-ON scenarios

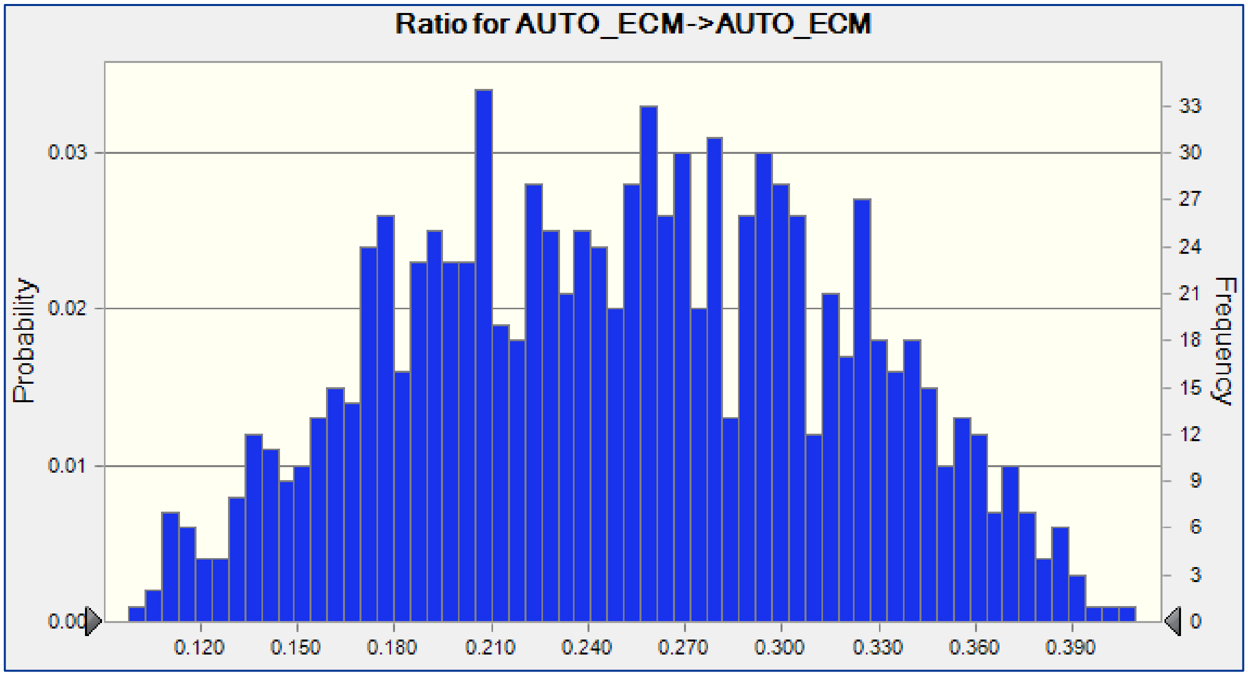


For the 95 AFUE furnace measure, we also designed four scenarios and assigned distributions to the ratio of each scenario in Table 30. Scenario one has the highest ratio followed by the Scenario 3. The ratios of the other two scenarios are low. We used Crystal Ball to plot the frequency review of the ratio for Scenario AUTO_ECM to AUTO_ECM as shown in Figure 36.

Table 30. 95 AFUE furnace retrofit scenarios and distributions

Scenario	Baseline	Post	Average Ratio	Standard Deviation	Lower Limit	Upper Limit
1	AUTO_PSC	AUTO_PSC	0.60	0.3	0.50	0.70
2	FAN-ON_PSC	FAN-ON_PSC	0.10	0.05	0.05	0.15
3	AUTO_ECM	AUTO_ECM	Calculated by 1-sum of other three ratios			
4	FAN-ON_ECM	FAN-ON_ECM	0.05	0.025	0.025	0.075

Figure 36. Frequency of AUTO-ECM to AUTO-ECM scenario ratio



We recommend including fan control survey in the next round of RASS survey or CLASS study. A considerable number of homeowners who purchase ECM furnaces may switch from AUTO to FAN-ON operation, which is highly influential in determining savings..

Supply fan efficiency

In eQUEST, there are two ways to define the power of the supply fan. The first one needs to provide the design full-load fan power in kW per cfm (SUPPLY-KW/FLOW) as well as the corresponding air temperature rise (SUPPLY-DELTA-T). The other method requires total static pressure of the supply fan at design airflow rate (SUPPLY-STATIC) and overall efficiency of the supply fan, motor and drive (SUPPLY-EFF). Pressure losses should include filters, coils, fan housing, and distribution system. The following equation can be used to convert them.

SUPPLY-KW/FLOW = SUPPLY-STATIC inch water ×0.746 / (6356× SUPPLY-STATIC)

This study adopted the first method to define the supply fan power at design airflow rate. eQUEST calculates the airflow rate of the supply fan from zone loads and zone command inputs. The fan power is equal to watt per cfm times the calculated airflow rates.

In the workpaper, the baseline PSC supply fan power is set at 0.650 W/cfm based on a PIER program final report.[66] The post-retrofit ECM fan power is 0.365 W/CFM, which is the DEER default value. Pigg at the Wisconsin Energy Center did two studies, one in 2003[67] and a summary study in 2008.[68] The results show that older PSC (Permanent Split Capacitor) blower motors used 0.517±0.033 W/cfm and that ECMs used 0.320±0.040 W/cfm which close to the DEER assumption of 0.365 W/CFM. If the selected confidence level is 90% and the distribution is a normal distribution, the estimated standard deviation is 0.020 W/cfm for the PSC motors and is 0.024 W/cfm for the ECMs. Pigg also stated that static pressure in the field is considerably higher than that used in the federal test procedure for rating furnaces. The consequence that ECM furnaces use more electricity than their ratings would suggest. Therefore, it is important to determine the static pressure or fan power index based on fan flow and power when comparing the fan power between two types of motors.

Considering the differences in weather conditions and house constructions between California and Wisconsin, we preferred using furnace airflow rate and supply fan power data collected from in-field measurement in HVAC 6 and WO 032 projects. For each unit in these two projects, we looked up the supply fan motor type from the furnace specifications. Totally, there are 45 furnaces with PSC motors and 66 furnaces with ECM or VFD motors. The PSC furnaces have an average supply fan power of 0.49 W/cfm with a standard deviation of 0.14. The power distribution is close to a lognormal distribution shape as shown in Figure 37. The average supply fan power of the ECM or VFD furnaces is 0.45 W/cfm with a standard deviation of 0.12. The closest distribution shape for fan power is a normal distribution as shown in Figure 38.

The fan power data from HVAC 6 and WO032 projects indicate a pretty flat distribution for both types of furnaces. The standard deviations are much higher than those from Pigg's studies (0.020 for PSC motors and 0.024 for ECMs). One possible explanation is that most Wisconsin furnaces are installed in basements while in CA there is a wide variety, many in attics, some in crawl spaces, some in garage, and some in a closet inside the conditioned space. This variety in system configuration will lead to many different static pressure conditions and affect airflow and power.

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[66] Proctor Engineering Group, Ltd., Efficiency characteristics and opportunities for new California homes eco, March 2011

[67] Pigg, Scott. 2003. Electricity use by new furnaces: A Wisconsin Field study, State of Wisconsin, Department of Administration, Division of Energy, October, 2003

[68] Pigg, Scott, Central Air Conditioning in Wisconsin: A Compilation of Recent Field Research, ECW Report Number 241-1, May 2008

Figure 37. Fan power distribution of furnaces with PSC motors

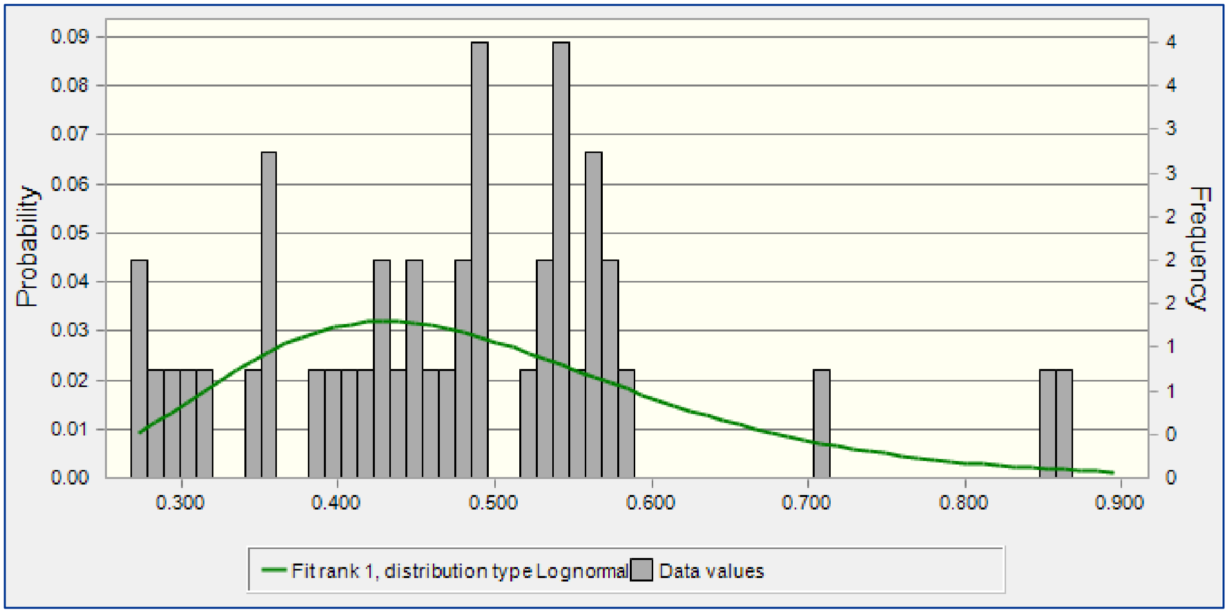
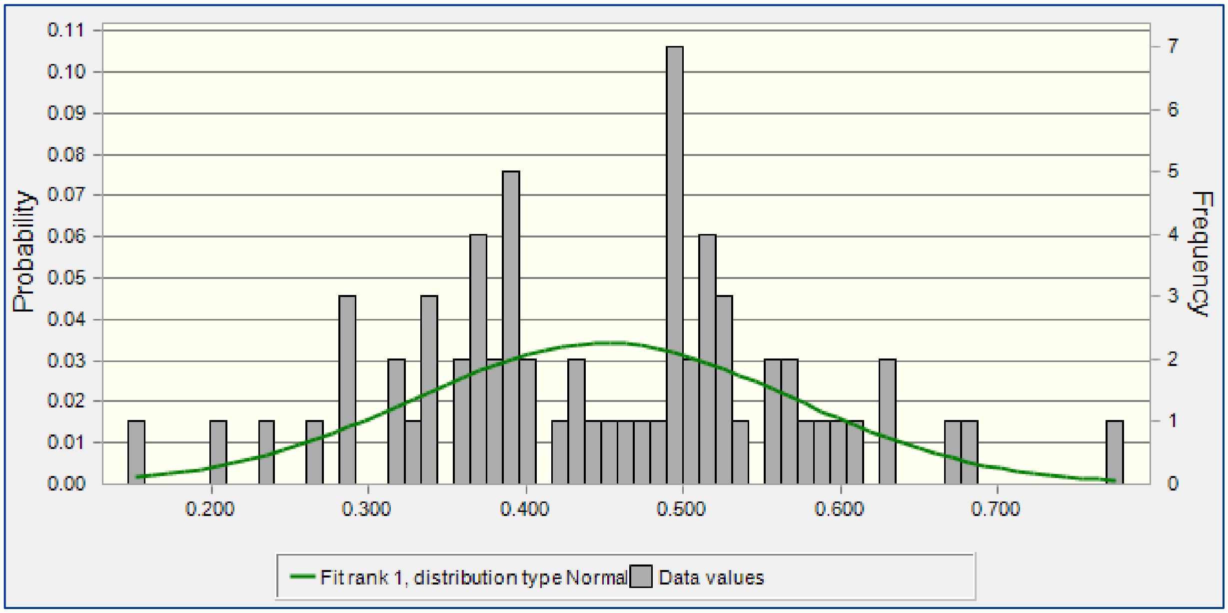
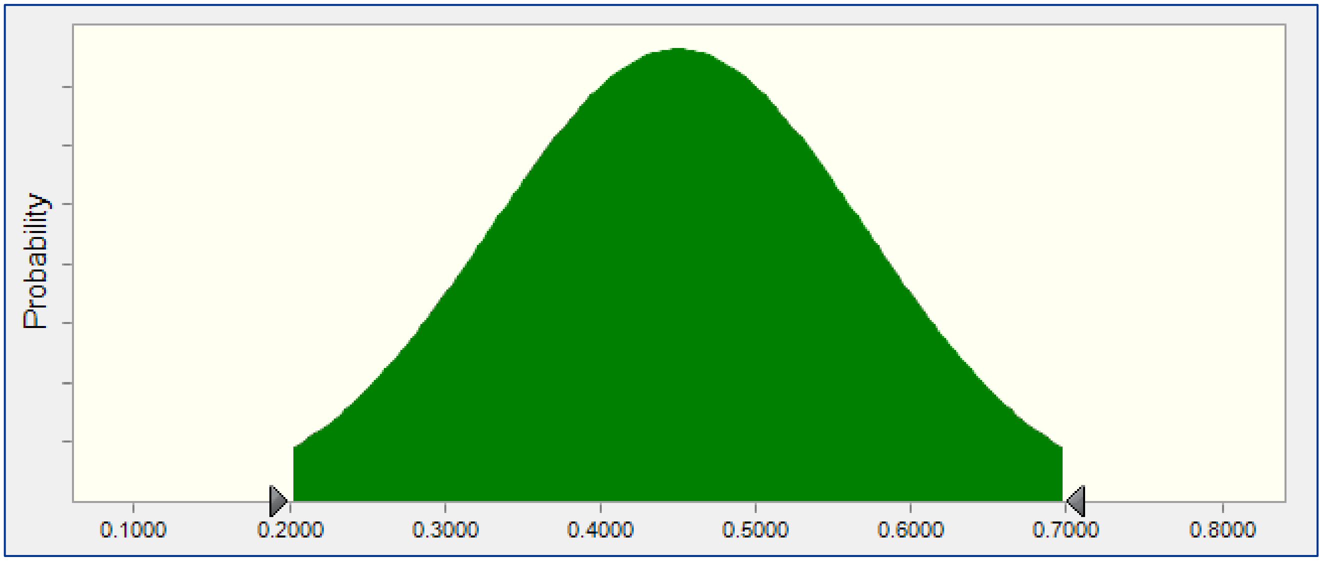


Figure 38. Fan power distribution of furnaces with ECMs



In addition, in California, the difference of average fan powers between PSC motors and ECMs is only 0.04 W/CFM. In contract, the fan power difference in Pigg's study is as large as 0.197 W/CFM. According to the equation 1, the supply fan watt per cfm is determined by the total static pressure of the supply fan at design airflow rate as well as the overall efficiency of the supply fan, motor, and drive. If a PSC motor is replaced with an ECM, the contractor will normally not touch the air duct or the supply fan. The system static pressure as well as fan and motor efficiency will not be changed. However, the contractor could reduce the airflow rate settings at cooling or heating mode, leading to reduced static pressure and supply fan W/CFM. In this study, since we only count power savings due to ECM replacement, we assume that the design airflow rate as well as the supply fan power W/cfm at design airflow rate does not change. Figure 39 is the distribution profile of the supply fan power at design airflow rate in the Crystal Ball analysis.

Figure 39. Distribution profile of supply fan power



eQUEST calculates the part-load power consumption of the supply fan using the fan power vs. part load characteristics corresponding to the control mode selected (FAN-CONTROL). The baseline case has a PSC motor with no airflow control (CONSTANT-VOLUME). The ECM in the post-retrofit case can change airflow by varying motor speed (SPEED). The minimum airflow rate (MIN-FLOW-RATIO and HMIN_FLOW-RATIO) is set at 0.3 for the ECM and at 1.0 for the PSC motor. The maximum airflow rate is set at 1.0 for both motors.

We recommend conducting a study to find out how the fan power, static pressure and airflow rate change after replacing the ECM furnace.

Thermostat heating and cooling setpoints

Thermostat settings are an important factor in determining furnace natural gas and power savings. For SFM prototype models, there are five different default cooling and heating schedules for each of seven building vintage bins and in each of sixteen California climate zones. Each schedule has a fixed temperature setpoint for each of four periods in one day: morning (6 am to 9 am), day (9 am to 5 pm), evening (5 pm to 9 pm), and night (9 pm to 6 am). The weighted average cooling or heating setpoints were calculated using the following equation:

$$T_{average} = (3 * T_{morning} + 8 * T_{day} + 4 * T_{evening} + 9 * T_{night})/24$$

The temperatures used to determine the weighted average heating setpoints used for the eQUEST simulations are provided in Table 31; those for the cooling setpoints are provided in Table 32.

Table 31. eQUEST building simulation heating setpoints

Building Vintage	Thermostat Usage Bin	Heating Temperature Setpoint, °F				
		Morning	Day	Evening	Night	Weighted Average
Before 1975	T1	68	68	68	68	68.0
	T2	65	70	70	65	67.5
	T3	55	55	55	55	55.0
	T4	60	60	60	60	60.0
	T5	65	65	65	65	65.0
1975-1985	T1	65	65	65	65	65.0
	T2	60	60	60	60	60.0
	T3	65	68	68	65	66.5
	T4	65	70	70	65	67.5
	T5	68	68	68	68	68.0
1985-1996	T1	65	70	70	65	67.5
	T2	68	68	68	68	68.0
	T3	68	65	65	68	66.5
	T4	60	60	60	60	60.0
	T5	65	65	65	65	65.0
1996-2003	T1	65	70	70	65	67.5
	T2	68	65	65	68	66.5
	T3	65	65	65	65	65.0
	T4	60	60	60	60	60.0
	T5	68	68	68	68	68.0
2003-2007	T1	65	70	70	65	67.5
	T2	68	68	68	68	68.0
	T3	60	60	60	60	60.0
	T4	68	65	65	68	66.5
	T5	70	65	65	70	67.5
2007-2011	T1	65	70	70	65	67.5
	T2	68	68	68	68	68.0
	T3	60	60	60	60	60.0
	T4	68	65	65	68	66.5
	T5	70	65	65	70	67.5
2011-2014	T1	65	70	70	65	67.5
	T2	68	68	68	68	68.0
	T3	60	60	60	60	60.0
	T4	68	65	65	68	66.5
	T5	70	65	65	70	67.5

Table 32. eQUEST building simulation cooling setpoints

Building Vintage	Thermostat Usage Bin	Cooling Temperature Setpoint, °F				
		Morning	Day	Evening	Night	Weighted Average
Before 1975	T1	80	80	80	80	80.0
	T2	76	83	83	76	79.5
	T3	80	83	83	80	81.5
	T4	83	83	83	83	83.0
	T5	85	85	85	85	85.0
1975-1985	T1	78	78	78	78	78.0
	T2	83	80	80	83	81.5
	T3	80	80	80	80	80.0
	T4	76	83	83	76	79.5
	T5	85	85	85	85	85.0
1985-1996	T1	83	76	76	83	79.5
	T2	78	78	78	78	78.0
	T3	83	80	80	83	81.5
	T4	80	80	80	80	80.0
	T5	76	83	83	76	79.5
1996-2003	T1	74	74	74	74	74.0
	T2	83	76	76	83	79.5
	T3	78	78	78	78	78.0
	T4	83	80	80	83	81.5
	T5	76	83	83	76	79.5
2003-2007	T1	74	74	74	74	74.0
	T2	83	76	76	83	79.5
	T3	78	78	78	78	78.0
	T4	83	80	80	83	81.5
	T5	80	80	80	80	80.0
2007-2011	T1	74	74	74	74	74.0
	T2	83	76	76	83	79.5
	T3	78	78	78	78	78.0
	T4	83	80	80	83	81.5
	T5	80	80	80	80	80.0
2011-2014	T1	74	74	74	74	74.0
	T2	83	76	76	83	79.5
	T3	78	78	78	78	78.0
	T4	83	80	80	83	81.5
	T5	80	80	80	80	80.0

For the purposes of the Crystal Ball analysis, the thermostat schedule weights are calculated from 2009 Residential Appliance Saturation Study (RASS).[69] Figure 40 and Figure 41 show the distribution of heating and cooling setpoints, respectively.

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[69] http://www.energy.ca.gov/appliances/rass/

Figure 40. Average heating setpoint distribution for CZ12

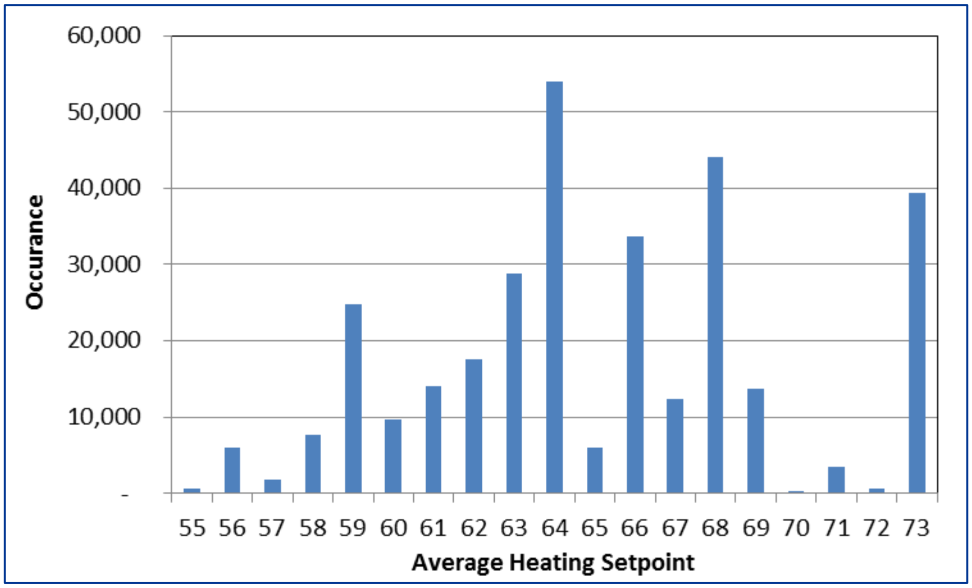
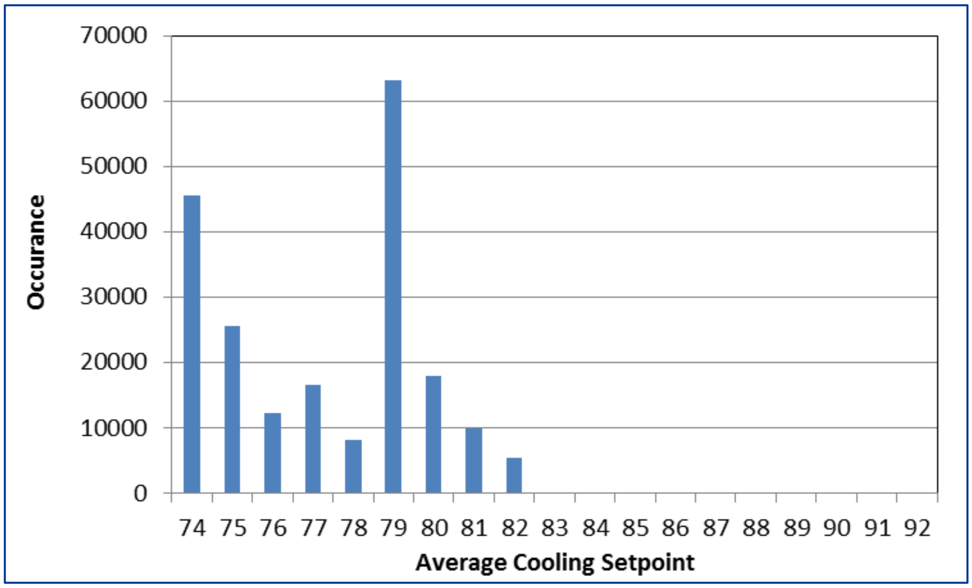


Figure 41. Average cooling setpoint distribution for CZ12



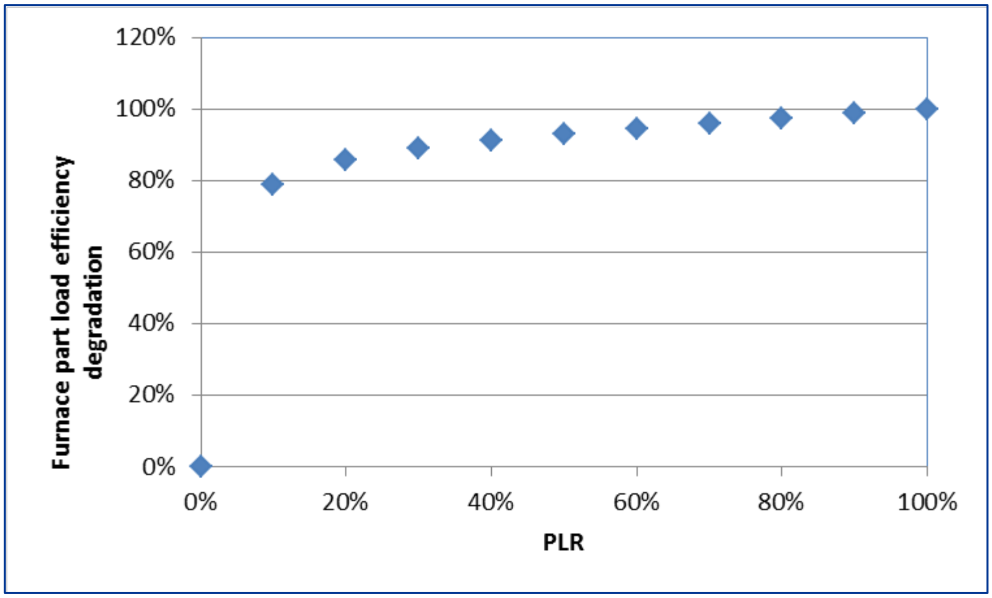
Residential furnace part load performance

Furnaces with 80 AFUE are non-condensing furnaces and those with AFUE higher than 90 are condensing furnaces. eQUEST uses HIR to define the furnace efficiency at full load and provides a curve named FURNACE-HIR-FPLR to describe the furnace performance at part load. MASControl uses the same FURNACE-HIR-FPLR curve for the baseline case (80 AFUE) and the post-retrofit case (>90 AFUE). In the absence of better information, we used the same default curves for both condensing and non-condensing furnaces. Figure 42 shows that the default curve yields a lower efficiency at a lower load.

HIR at part load = HIR at full load * FURNACE-HIR-FPLR

Furnace part load efficiency degradation = PLR / FURNACE-HIR-FPLR (PLR)

Figure 42. Furnace efficiency degradation at part load



Regression model coefficients

The regression model coefficients for the 95 AFUE furnace are provided in Table 33.

Table 33. Regression model coefficients for 95 AFUE furnace measure in CZ12

Coeff.	PSC Motor, Auto-controlled	PSC Motor, Fan On	EC Motor, Auto-controlled	EC Motor, Fan On
a_0	-22.691	-25.397	-25.647	-26.754
a_1	-0.202	-0.241	-0.245	-0.263
a_2	-0.051	-0.133	-0.117	-0.106
a_3	0.530	0.659	0.627	0.651
a_4	0.301	0.355	0.373	0.412
a_6	-2.429	-4.849	-2.326	-2.681
a_7	3.136	3.741	4.705	4.301
$a_{1,1}$	0.000	0.000	0.000	0.000
$a_{1,2}$	0.004	0.005	0.005	0.005
$a_{1,3}$	0.000	0.000	0.001	0.000
$a_{1,4}$	0.000	0.000	0.000	0.000
$a_{1,6}$	0.017	0.049	0.017	0.025
$a_{1,7}$	-0.031	-0.041	-0.044	-0.048
$a_{2,2}$	0.003	0.004	0.004	0.004
$a_{2,3}$	-0.004	-0.003	-0.004	-0.003
$a_{2,4}$	0.000	0.001	0.000	0.000
$a_{2,6}$	0.033	0.073	0.034	0.040
$a_{2,7}$	-0.059	-0.073	-0.086	-0.085
$a_{3,3}$	-0.002	-0.003	-0.002	-0.003
$a_{3,4}$	-0.002	-0.004	-0.003	-0.004
$a_{3,6}$	0.005	0.005	0.005	0.003
$a_{3,7}$	-0.005	-0.006	-0.012	-0.008
$a_{4,4}$	-0.013	-0.019	-0.017	-0.019
$a_{4,6}$	0.005	0.033	0.003	0.009
$a_{4,7}$	0.005	0.007	0.010	0.014
$a_{6,6}$	0.068	-0.235	0.070	0.050
$a_{6,7}$	-0.171	-0.227	-0.280	-0.163
$a_{7,7}$	0.468	0.612	0.765	0.765
Goodness of Fit	**PSC Motor, Auto-controlled**	**PSC Motor, Fan On**	**EC Motor, Auto-controlled**	**EC Motor, Fan On**
R-square	0.9401	0.9578	0.9417	0.9564

APPENDIX B. Boiler input parameters

The details regarding the input parameters and the regression analysis coefficients used for the uncertainty analysis for nonresidential boilers.

Boiler thermal efficiency

Commercial boiler efficiency is rated by several metrics including thermal efficiency. It is defined as a dimensionless performance ratio of the useful heat energy output relative to the heat energy input. This input parameter is the sole parameter that is adjusted in the DEER measure to produce energy savings. In eQUEST, the boiler thermal efficiency input is expressed as heat input ratio (HIR). HIR is equal to the inverse of thermal efficiency.

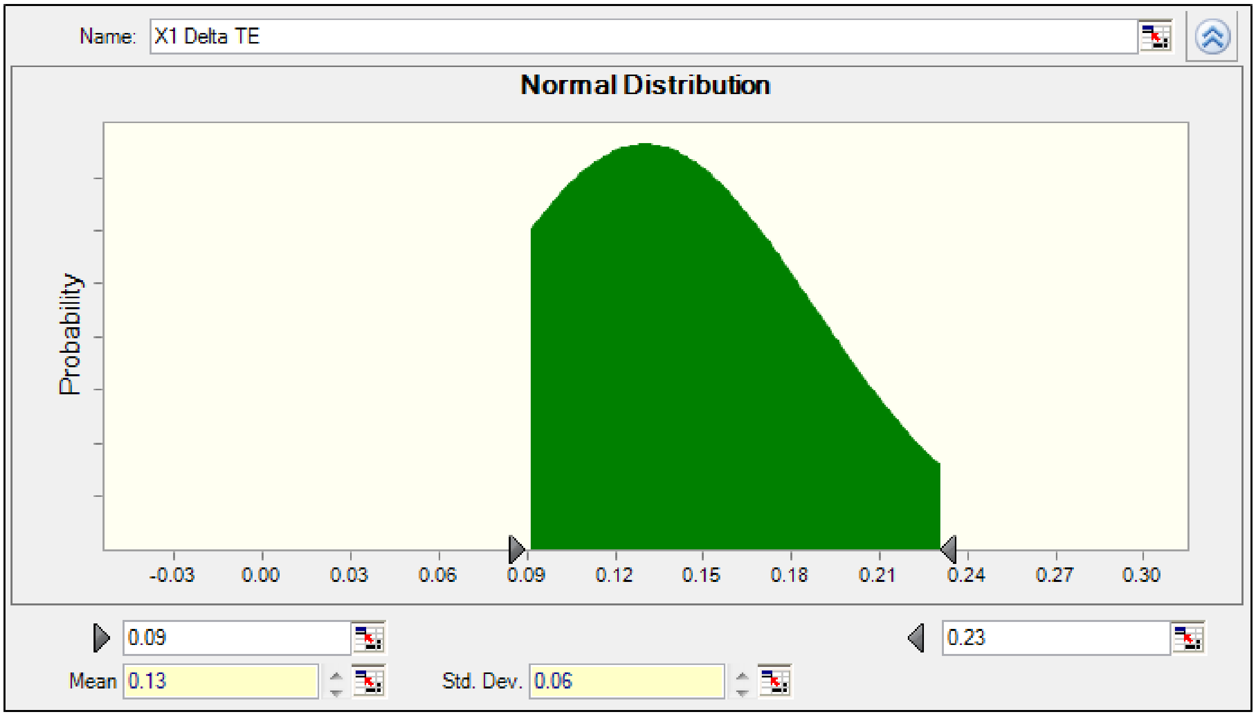
The workpaper review section describes baseline and measure-assumed thermal efficiencies for commercial hot water boilers ranging from 300,000 to 5,000,000 Btuh. The baseline and measure-case thermal efficiencies chosen for batch modeling are presented in Table 34.

Table 34. Thermal efficiency & HIR values for regression model

Thermal Efficiency (TE)	HIR	Delta TE	Note
0.75	1.333	N/A	Based on PG&E workpaper; baseline case = 0.75
0.84	1.190	0.09	Measure qualifying thermal efficiency >= 0.84
0.85	1.176	0.10	Measure case thermal efficiency = 0.85
0.90	1.111	0.15	
0.92	1.087	0.17	
0.94	1.064	0.19	
0.96	1.042	0.21	

The distribution of delta efficiency (Delta TE) was created from one source—the CEC database—queried in May 2016 for natural gas fired hot water boilers with an input capacity ranging between 300 and 2,500 kBtuh (to match the workpaper measure description). From that database, it was determined that the average difference in thermal efficiency from the baseline case efficiency of 0.75 was 0.130 with a standard deviation of 0.057. The upper and lower distribution range was truncated based on the minimum qualifying efficiency (0.84) and the maximum thermal efficiency found in the CEC database (0.98). Figure 43 illustrates the delta thermal efficiency input distribution. This particular analysis was not informed by distribution of sales or weight of program participation. DNV GL recognizes that this distribution is not representative of the boilers that were claimed by the program; however, without program data to inform the distribution, this source was a practical alternative.

Figure 43. Distribution for delta thermal efficiency input



Name: X1 Delta TE

0.09

0.23

Mean 0.13

Std. Dev. 0.06

Boiler heating capacity

The natural gas savings for the commercial hot water boiler measures are normalized by the boiler input capacity in kBtuh. The boiler input capacities vary by building type, climate zone, and vintage. These input values were obtained by collecting the absolute “CAPACITY” keyword value in each of the eQUEST .inp files. The tables below list the applicable boiler input capacities extracted from the eQUEST files. Not all climate zones and building types are displayed; representative climate zones and building types are displayed for illustrative purposes.

Table 35. Boiler input capacity (millions of Btuh) at large office buildings

Large Office	Climate Zones								
Building Vintage	02	03	04	06	08	09	11	12	13
Before 1978	5.674	5.028	5.199	4.796	4.786	5.232	5.920	5.748	5.708
1978 - 1992	3.783	3.190	3.298	2.537	2.787	3.106	3.769	3.668	3.218
1993 - 2001	3.714	3.164	3.214	2.500	2.463	3.186	3.623	3.599	3.369
2002 - 2005	3.091	3.150	3.038	2.003	2.496	2.657	2.926	3.200	3.137
2006-2009	3.202	3.289	3.185	1.971	2.440	2.651	2.930	3.322	3.137
2010 - 2013	2.753	2.982	2.943	1.785	1.940	2.558	2.423	3.323	3.111
2014 - 2015	2.875	2.598	2.630	1.236	1.467	1.957	2.405	3.091	2.819

Boiler capacity sizing ratio

The boiler capacity sizing ratio, or capacity ratio, is the fraction of design heating loop capacity that the boiler is sized to meet. When the DEER prototype models are generated using MASControl there is an intermediate simulation that sizes the boiler to the design heating loop capacity of the building. The DEER team applies a default capacity ratio of 1.3 to the boiler input capacity (i.e., the boiler is oversized by 30 percent). When the final prototype is produced, the absolute boiler input capacity is displayed in the input file, and capacity ratio is reset to 1.0.

The capacity “ratio” was chosen as an input parameter for sensitivity analysis. However, the actual DOE2 input keyword (CAPACITY-RATIO) was not adjusted for the analysis because it is used by the DOE2 program only when the capacity is not specified. Instead of using the keyword CAPACITY-RATIO the absolute capacity value assigned to the DOE2 keyword CAPACITY was modified using a multiplier. In this way, the hot water loop design parameters are left unaffected while the boiler design capacity is changed by the sizing ratio or multiplier. This change is meant to mimic a scenario where a replacement program boiler of a different rated capacity than originally designed for the building is installed.

The capacity of the boiler can have an effect on its efficiency when the boiler is operating in part-load conditions because the efficiency of boilers modeled in eQUEST are dependent on the load the boilers experience i.e. boiler efficiency is a function of it’s part load ratio.

Table 36 and Figure 44 show the range of boiler capacity ratios used in the regression model and sensitivity analysis. Note that the actual capacity ratio is 1.3 times the input parameter value (due to the intermediate sizing run explained above). The table and figure also shows the distribution of values. There was no available boiler sizing data to practically apply to this experiment so a uniform distribution was used[70].

Table 36. Boiler capacity sizing ratio for regression model

Sizing Ratio	Actual Capacity Ratio (based on fraction of design heating loop capacity)	Distribution
0.8	1.04	17%
0.9	1.17	17%
1.0	1.30	17%
1.1	1.43	17%
1.2	1.56	17%
1.3	1.69	17%

The sizing ratios (in the leftmost column) above are applied to the boiler capacity values listed in Table 35.

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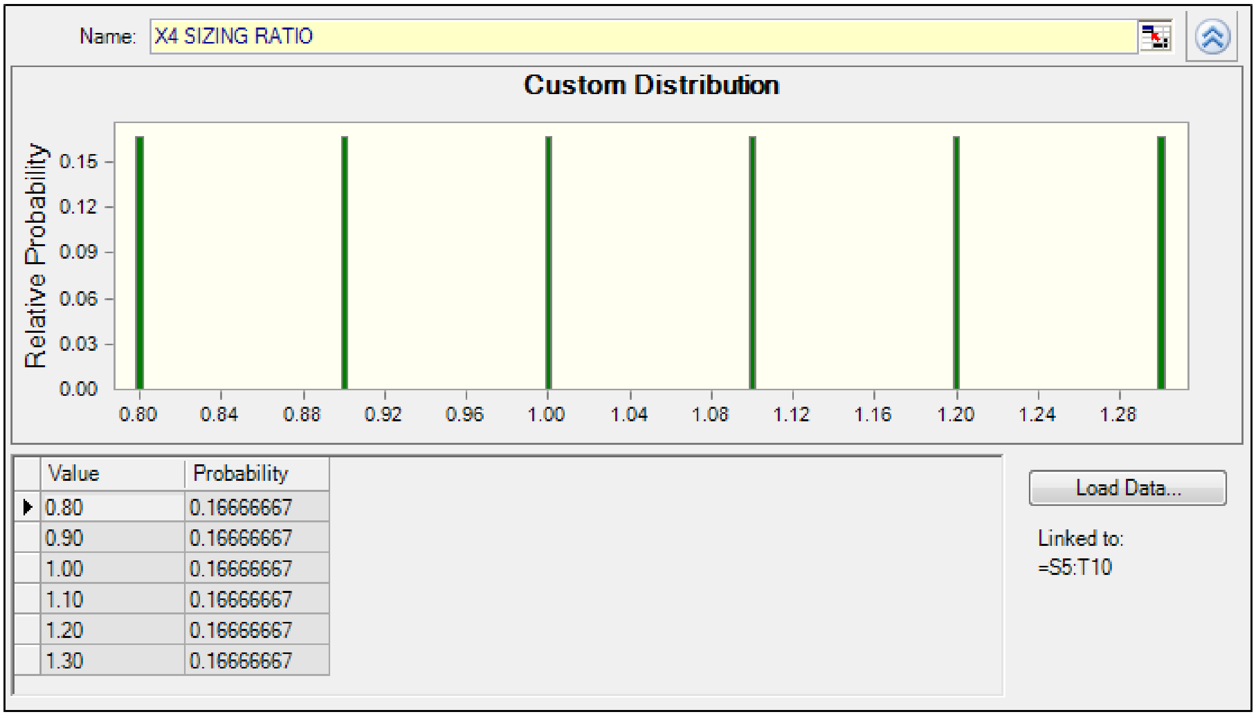
[70] See 7.4 for more information regarding discrete distribution sets

Figure 44. Boiler-capacity-sizing ratio distribution



Name: X4 SIZING RATIO

Value	Probability
0.80	0.16666667
0.90	0.16666667
1.00	0.16666667
1.10	0.16666667
1.20	0.16666667
1.30	0.16666667

Linked to:
=S5:T10

Zonal minimum airflow ratio

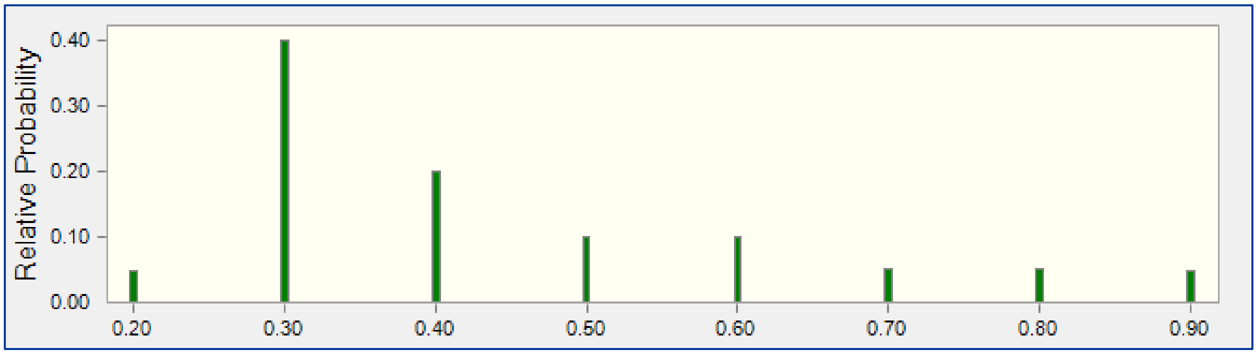
The buildings’ zonal minimum airflow ratios (DOE2 keyword MIN-FLOW-RATIO) were chosen as an input parameter for sensitivity analysis. Both the CPUC and DNV GL believed that the minimum airflow ratio could have a significant impact on the gas savings for the boiler measure. A lower airflow ratio would typically reduce heating energy because a lesser volume of air is necessary to reheat once the zone goes into heating mode.

Table 37 below lists the minimum airflow ratios used in the regression model and sensitivity analysis. All zones within the building had the same minimum airflow ratios applied. This is consistent with large office prototype model which had the same ratio applied to all zones. The distribution of values was chosen arbitrarily although future sources of data could inform the distribution more accurately.

Table 37. Minimum airflow ratio for regression model

Minimum airflow ratio	Proportion, percent
0.2	5%
0.3	40%
0.4	20%
0.5	10%
0.6	10%
0.7	5%
0.8	5%
0.9	5%

Figure 45. Minimum airflow ratio distribution



Nonresidential building vintage bins

Building Vintage is a comprehensive factor chosen for uncertainty analysis that includes many different building characteristics including shell conductivity, shell infiltration, internal heat loads, and equipment controls. Each vintage bin represents typical California building stock that was built in the time range defined by the vintage. Table 38 lists the vintage codes used and their corresponding representative year ranges.

Table 38. Building vintage bin years

Vintage Code	Building Vintage
V75	Before 1978
V85	1978 - 1992
V96	1993 - 2001
V03	2002 - 2005
V07	2006-2009
V11	2010 - 2013
V14	2014 - 2015

The DEER prototypes adjust many building characteristics based on what vintage they are representing. These changes in building characteristics were intrinsically captured by using the DEER prototypes' different vintage levels while developing the regression model for the uncertainty analysis. Table 39 describes the high-level differences across the vintage levels for the large office building.

Table 39. Differences across large office buildings by building vintage bins

Building Vintage	Differences Across Large Office Vintage
Across v75 and v85	R-value; OA Reset on SAT; LPD and radiant fraction; Equip. W/area; Plant equipment capacity; SAT, Duct DT; VAV air volume control; reheat deltaT; Minimum flow ratio
Across v85 and v96	R-value; Glass SC; Pump efficiency; CHW reset; CHW/HW circ. Losses; CT efficiency; fan efficiency; LPD
Across v96 and v03	Glass U; Chiller efficiency; DHW UA and efficiency; Tower fan control; supply air reset controls; LPD; Fan VFD; reheat deltaT; design flow rates
Across v03 and v07	CHW/HW loop flow control; equipment W/area; Pump VFD; Plant equipment capacity; design flow rates
Across v07 and v11	R- value; LPD; Plant equipment capacity; design flow rates; Economizer Control
Across v11 and v14	LPD; Glass U/SC; Pump efficiency; Chiller capacity; fan efficiency; economizer set point;

Each vintage level was arbitrarily assigned a value to represent those vintage differences rather than explicitly assigning values for the regression model. In other words, rather than extracting the absolute values of lighting power density, glazing U/SC values, shell UA values, etc. and assigning them to an input parameter, the entirety of changes across vintage levels were assigned an arbitrary value. Those arbitrary values are insignificant but are listed in Table 40 for completeness.

Table 40. Building vintage bin numbers used for regression

Vintage Code	Assigned Vintage Value
V75	1
V85	2
V96	3
V03	4
V07	5
V11	6
V14	7

In the absence of other sources, we used the nonresidential vintage weights from DEER 2014[71] to calculate the distribution of each vintage. For a given IOU, building type, and location, this file provides the weights based on number of dwellings to be applied to vintage specific results to arrive at an "Existing" vintage result. The data are aggregated to obtain building square footage (in millions of square feet) by vintage and climate zone as shown in Table 41. These weights are used as the distributions of building vintage bins and can be produced by building type and climate zone.

Table 41. Large office building weights by climate zone and building vintage

Building Vintage	Climate Zones								
	02	03	04	06	08	09	11	12	13
Before 1978	6.779	77.240	27.420	98.620	128.042	144.386	2.907	19.449	13.073
1978 - 1992	6.175	69.197	27.530	118.957	149.955	135.762	2.003	17.363	11.335
1993 - 2001	2.891	28.211	14.391	22.110	27.700	22.433	0.833	11.029	3.184
2002 - 2005	1.880	16.702	9.312	11.946	14.989	12.912	0.815	8.297	2.469
2006-2009	0.710	6.493	3.610	5.093	6.847	8.315	0.410	3.387	1.789
2010 - 2013	0.710	6.493	3.610	5.093	6.847	8.315	0.410	3.387	1.789
2014 - 2015	0.355	3.246	1.805	2.547	3.424	4.157	0.205	1.693	0.894

Regression model coefficients

The regression model coefficients for high efficiency boilers are provided in Table 42.

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[71] http://www.deeresources.com/files/DEER2013codeUpdate/download/DEER2014-EnergyImpact-Weights-Tables-v2.xlsx

Table 42. Regression model coefficients for boiler measure savings in CZ04

Coefficient	Value
a_0	-0.675
a_1	1.107
a_2	-2.010
a_4	0.141
a_5	0.544
a_{11}	-10.397
a_{12}	23.437
a_{14}	1.889
a_{15}	-0.860
a_{22}	2.901
a_{24}	0.656
a_{25}	-0.318
a_{44}	-0.148
a_{45}	-0.036
a_{55}	-0.044
Goodness of Fit	**Value**
R-square	0.9747

The preceding coefficients were then used to predict the normalized energy savings due to boiler retrofits.

APPENDIX C. VFD input parameters

The details regarding the input parameters and the regression analysis coefficients used for the uncertainty analysis for VFDs at HVAC fans are provided in the subsections that follow.

Minimum airflow ratio

The analysis utilized five minimum flow ratio for the supply fan (not the fan systems), and they are 0.3, 0.4, 0.5, 0.6, and 0.7. The minimum airflow through the supply fan is the fraction of the fan design flow rate. The default value in eQUEST prototype is 0.3. The assigned flow ratio were applied in the batch run file for both fan level and zone level minimum flow ratios.

Baseline fan control strategy

The analysis used following three baseline fan control strategies:

- Discharge damper, designated as “Dam”
- Inlet guide vanes, designated as “Van”
- Two-speed fan motor, designated as “2SPD”

Although eQUEST offers other fan airflow control strategies for baseline conditions besides those mentioned above, including intermittent or cycling controls, airfoil fans with discharge dampers, airfoil fans with inlet guide vanes, axial fans with variable pitch controls, the analysis did not use them as they are assumed to be less common.

The prototype used varying fan Energy Input Ratio (EIR) functions for the three baseline fan control strategies. The EIR for supply fans with discharge dampers is designated as FC-Fan-w/Dampers, for supply fans with inlet guide vanes as FC-Fan-w/Vanes, and for supply fans with two-speed motors are designated as Any-Fan-w/VFD.

As stated earlier, while the WP savings were reported for fan discharge damper as the baseline control, The DNV GL research team considered three different baseline fan control types and three separate regression models were generated for each base case fan control strategy. Finally, the regression coefficients for each baseline fan control strategy were utilized in the CB analysis by assigning weights for each baseline control type. However, we could not find any direct reference for the percentage distribution of various baseline fan control types. Since no existing studies were available for different baseline fan control type along with their vintages, we adopted an indirect approach and utilized two different resources; DEER buildings vintage distribution and CA HVAC vintage distribution.

DNV GL used an approach which is hybrid of the building vintage distribution and HVAC vintage distribution to determine the different flow control strategy distribution. This is because historically the fan flow control type evolved from the discharge air damper (least efficient) to fan motor VFDs (most efficient) with more recently constructed buildings. Thus, the HVAC systems with v75 vintage group are more likely to see the discharge air damper as their flow control device and progressively they moved to inlet guide vanes from v85 onwards. At the same time, some of the older building that removed their original HVAC systems may have moved to newer flow control strategies. In view of the above, two vintage distributions (Building and HVAC) were used for CB analysis to generate a hybrid distribution for the fan flow control distribution.

The HVAC unit percentages among different vintage groups were documented from the “California Commercial Saturation Study”[72] as summarized in the first two columns of Table 43. Per this study, onsite survey date were collected about 14,302 HVAC units. Of these units, vintage information was either unavailable or inaccessible for 6,436 units. DNV GL assumed that those units with missing information would be divided among the building vintage bins as shown in the latter two columns of Table 43.

Table 43. Distribution of HVAC units by age (n = 14,302)

Year Manufactured	Proportion of HVAC Units in CCSS	Mapping to Building Vintage Bins	Distribution
Before 1990	11%	Before 1978	25%
1990-1999	12%	1978 - 1992	31%
2000-2003	7%	1993 - 2001	12%
2004-2008	13%	2002 - 2005	7%
2009-2013	12%	2006 - 2009	13%
Missing Age Info	45%	2010 - 2013	12%

Source: Itron, 2014.

Subsequently, we documented the DEER building vintage percentage distributions as shown in Table 44. DEER has the building area distribution for different building vintage groups and DNV GL used them to determine their percentages.

Table 44. DEER building distributions in CZ03

Building Vintage Bin	Building Area, million ft^2	Proportion
Before 1978	77.239	37%
1978 - 1992	69.197	33%
1993 - 2001	28.210	14%
2002 - 2005	16.702	8%
2006 - 2009	6.492	3%
2010 - 2013	6.492	3%
2014 - 2015	3.246	2%

It is likely that the actual HVAC system vintage, that represent the flow control distribution as well, will be falling somewhere in between the two distributions shown in Table 43 and Table 44. We subsequently, ran the CB for 10,000 runs to generate the vintage distributions. The results are shown in Table 45. From this, it can be seen that the percentage of units for v75 vintage group is about 43%. Thus, in the final savings analysis, the evaluator used the 43% as the weight for the discharge air damper and 10% as the assumed

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[72] “California Commercial Saturation Survey” by Itron and prepared for the CPUC, July 15, 2014, p 9-33.

weight for two-speed fan control. The remaining percentage (47%) was assumed as the weight for fans with inlet guide vane as their flow control device.

Table 45. Distributions of discharge damper baseline

Statistic	Forecast: v75	Forecast: v85	Forecast: v96	Forecast: v03	Forecast: v07	Forecast: v11
Trials	10,000	10,000	10,000	10,000	10,000	10,000
Base Case	31%	32%	13%	8%	8%	8%
Mean	43%	41%	34%	33%	9%	9%
Median	43%	40%	33%	32%	9%	9%
Standard Deviation	15%	13%	14%	14%	3%	3%
Variance	2%	2%	2%	2%	0%	0%
Skewness	0.2634	0.2045	0.358	0.3895	0.1113	0.1449
Kurtosis	2.65	2.7	2.7	2.73	2.66	2.7
Coeff. of Variation	0.342	0.3226	0.4111	0.4429	0.321	0.3315
Minimum	4%	3%	1%	3%	1%	1%
Maximum	95%	85%	85%	89%	19%	19%
Mean Std. Error	0%	0%	0%	0%	0%	0%

Fan power index (W/cfm)

The analysis considered varying FPI between 0.4 W/cfm to 0.6 W/cfm for both baseline and measure conditions. Based on Title 24 limitation on FPI, for constant volume fan system, the total fan power index at design conditions for each fan system with total horsepower over 25 hp shall not go beyond 0.8 W/cfm and the same for VAV system shall not go beyond 1.25 W/cfm. These defined FPI includes the fan power from supply fans, return fans, relief/exhaust fans, and fan-powered VAV boxes. The analysis considered that of the total system horsepower, the supply fan horsepower is about 50% and all remaining fans contribute the rest 50%. Based on this analysis, the upper and lower limit of FPI were set at 0.4 W/cfm (=0.8/2 W/cfm) and 0.6 W/cfm (=1.25/2 W/cfm).

- The analysis used five different FPI values in steps and they are 0.4 W/cfm, 0.45 W/cfm, 0.5 W/cfm, 0.55 W/cfm, and 0.6 W/cfm. For each combination, both baseline and post-retrofit models used the identical FPI values. Further, as the FPI is related to the temperature rise across the supply fan, the analysis revised the fan Delta T (ºF) in the prototype eQUEST models. The analysis used the following equation to calculate the Delta T (ºF) for each W/cfm value the batch run used.
- $\text{Delta T } (^\circ\text{F}) = \left(\frac{W}{cfm}\right) x \left(3.412 \frac{Btu}{W}\right) x\ (1.08)\ x\ 85\%$
- The above equation assumes that about 85% of the total fan FPI will be used to increase the air temperature across the fan.

Heating/cooling temperature & fan schedule

The analysis used five cooling and heating temperature schedules as shown in Table 46.

Table 46. Parameters of HVAC schedules

Schedule	Cooling Setpoints, °F		Heating Setpoints, °F		Fan Operation	
	Occupied	Unoccupied	Occupied	Unoccupied	Start Time	Stop Time
SCH1	76	86	72	62	8:00 am	5:00 pm
SCH2	76		72		7:00 am	6:00 pm
SCH3	76		72		6:00 am	8:00 pm
SCH4	76		72		5:00 am	9:00 pm
SCH5	76		72		4:00 am	10:00 pm

Thus, the analysis utilized varying weekdays fan operating hours along with the eQUEST prototype model's default cooling and heating temperature setpoints to derive five different schedules for the batch runs. The default fan operating hours in the prototype eQUEST models is from 7 am to 6 pm (Monday through Saturday). Further, the prototype models used similar operating schedules along with default cooling setpoint (76 oF) and default heating setpoint (72 oF) from Monday through Saturday and called it is the weekday schedule. Similarly, the prototype models used un-occupied cooling setpoint (86 oF) and un-occupied heating setpoint (62 oF) along with no fan operation for Sunday and holidays and called it the weekend schedule. The unoccupied cooling and heating setpoints were also used during the unoccupied hours of the weekday schedule.

Supply fan power estimate

The workpaper measure savings are reported per horsepower of the supply fan. Looking at the workpaper-reported measure impact savings in READI 2.3.0, though the fan motor powers are designated as system rated hp, however, the fractional values appearing for each line item suggests that the horsepower values used for normalized savings reporting (kWh/hp, kW/hp and therm/hp) are not rated hp. The analysis of the brake horsepower utilized two separates approaches to derive the total fan system brake horsepower and compared the values obtained. Refer to Table 17 and Table 18 below.

First, the eQUEST prototype model used for this analysis (OfL building type with PVAV system type) contains three fan systems; Sys(G), Sys(M), and Sys(T), that server the three floors (Ground, Middle and Top) of the prototype model. The analysis used the model .SIM files to find out the design flow rates at all three floors for all prototype models for all seven building vintage bins and for all three CZs (w03, w08, and w13). Refer to Table 17 below. The total building design flow was calculated as the summation of all three system design flow rates. Finally, the total design flow rate is multiplied with the fan power index (0.0004 kW/CFM) to derive the fan system power (kW). The total design break horsepower was calculated by dividing 0.746 (conversion factor for kW and hp) and multiplying an assumed average motor efficiency (92%). With this approach, the derived motor horsepower were between 76 hp to 173 hp for CZ w03, between 80 hp to 186 hp for CZ w08, and between 82 hp to 188 hp for CZ w13. Refer to Table 47 below.

Second approach used to determine the total fan system horsepower was rather straight forward. The analysis used the .SIM files for all seven vintage bins at three CZs and added the design system powers of all three systems [Sys(G), Sys(M), and Sys(T)]. These calculated total building system power (kW) were converted into the break horse power by multiplying the same assumed motor efficiency (92%) and dividing the conversion factor (0.746). With this approach, the derived motor horsepower were between 76 hp to

173 hp for CZ w03, between 79 hp to 184 hp for CZ w08, and between 81 hp to 186 hp for CZ w13. Refer to Table 48 below. Thus, the motor brake horsepower calculated through two separate approaches were found comparable.

DNV GL found that brake horsepower values given in READI 2.3.0 impact savings table were significantly higher than those calculated from the prototype model .SIM file. The values given in READI are not available for all seven building vintage groups, rather classified for total three new building types, one each at CZ03, CZ08 and CZ13 and seven existing buildings. The total system break horse power values were between 247 hp to 281 hp. Since the READI reported motor powers were higher than that derived through the prototype models therefore, the normalized savings (kWh/hp, kW/hp, and therm/hp) determined through this analysis were higher than that reported in READI impact savings.

Table 47. Fan power derived from system airflow rates

Building Vintage	Airflow, cfm				Calculated Brake Hp
	Ground Floor	Middle Floors	Top Floor	Total	
CZ03					
v75	26,223	288,635	36,079	350,937	173
v85	23,495	251,505	31,438	306,438	151
v96	18,466	195,478	24,435	238,379	118
v03	17,509	182,209	22,776	222,494	110
v07	17,480	177,832	22,229	217,541	107
v11	17,225	175,151	21,894	214,270	106
v14	12,071	125,714	15,714	153,499	76
CZ08					
v75	28,676	308,820	38,602	376,098	186
v85	25,541	268,567	33,571	327,679	162
v96	20,100	209,273	26,159	255,532	126
v03	18,941	193,773	24,222	236,936	117
v07	18,911	189,341	23,668	231,920	114
v11	18,499	185,029	23,129	226,657	112
v14	13,018	132,970	16,621	162,609	80
CZ13					
v75	29,611	312,445	39,056	381,112	188
v85	26,311	271,666	33,958	331,935	164
v96	19,280	198,012	24,751	242,043	119
v03	17,257	175,604	21,950	214,811	106
v07	17,225	171,134	21,392	209,751	103
v11	16,818	166,860	20,857	204,535	101
v14	13,429	135,029	16,879	165,337	82

Table 48. Fan power levels per eQUEST SIM files

Building Vintage	Brake Horsepower, hp			
	Ground Floor	Middle Floors	Top Floor	Total
CZ03				
v75	10.5	115.5	14.4	173
v85	9.4	100.6	12.6	151
v96	7.4	78.2	9.8	118
v03	7.0	72.9	9.1	110
v07	7.0	71.1	8.9	107
v11	6.9	70.1	8.8	106
v14	4.8	50.3	6.3	76
CZ08				
v75	11.4	122.3	15.3	184
v85	10.1	106.4	13.3	160
v96	8.0	82.9	10.4	125
v03	7.5	76.7	9.6	116
v07	7.5	75.0	9.4	113
v11	7.3	73.3	9.16	111
v14	5.2	52.7	6.58	79
CZ13				
v75	11.7	123.7	15.5	186
v85	10.4	107.6	13.4	162
v96	7.6	78.4	9.8	118
v03	6.8	69.5	8.7	105
v07	6.8	67.8	8.5	102
v11	6.7	66.1	8.26	100
v14	5.3	53.5	6.7	81

Regression model coefficients

The regression model coefficients for HVAC fan VFDs are provided in Table 49.

Table 49. Regression model coefficients for VFD measure savings in CZ13

Coefficient	Discharge Damper Baseline	Inlet Guide Vane Baseline	Two-speed Motor Baseline
a_0	-1,060.405	-515.452	-1,332.302
a_1	5,726.817	3,731.058	8,164.770
a_2	5,995.719	2,657.281	7,071.415
a_4	-6.314	-31.685	40.398
a_5	-59.621	-14.666	-73.523
a_{11}	67.520	-36.978	-46.774
a_{12}	-4,575.531	-4,794.799	-8,000.691
a_{14}	-144.148	-63.227	-154.368
a_{15}	159.242	68.974	211.236
a_{22}	-4,961.537	-1,702.186	-5,089.865
a_{24}	45.001	95.045	73.379
a_{25}	-88.306	-97.684	-167.852
a_{44}	2.428	-0.397	-3.705
a_{45}	-2.653	-1.017	-3.495
a_{55}	4.215	2.505	6.362
Goodness of Fit	**Discharge Damper Baseline**	**Inlet Guide Vane Baseline**	**two-speed Motor Baseline**
R-square	0.9841	0.9902	0.9874

APPENDIX D. Public-review period comments and responses

Numerous comments were received from two members of the public, Robert Mowris, P.E., of Robert Mowris Associates, and Abram Conant, of Proctor Engineering Group, Ltd. DNV GL responses are provided in Table 50.

Table 50: Draft Report Comments from Members of the Public and DNV GL Responses

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
1	Robert Mowris, P.E.	Robert Mowris Associates	4.4.1 95 AFUE furnace retrofits	AFUE 95 Furnace – Slide 8 of the HVAC4 presentation shows 93.9% of the furnace uncertainty is due to the heating setpoint. The eQuest average heating setpoints ranged from 55 to 73°F based on the 2009 RASS. The lower limits used for the heating setpoint input parameters should be increased to eliminate occupants with very low probability of using their furnace or purchasing an AFUE 95 furnace. The eQuest simulations should have used narrower heating setpoint tolerances of 64 to 72°F (i.e., 68 +/-4°F) to evaluate the uncertainty associated with more representative heating setpoints for customers who would have a higher probability of purchasing an AFUE 95 furnace versus a standard furnace.	The range from RASS was used and the probabilities from RASS should also be used in revisions to ensure the uncertainty represents a statewide range. Surveys and analysis of rebate program participants could be used to augment the range in the future and can be made as a recommendation. The proposed range is not linked to a source and thus we cannot assume all program participants use setpoints in the range of 64 to 72°F. Furthermore, we have no data to support the argument that program participants behave differently than the RASS survey participants.
2	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3 eQUEST batch processing	AFUE 95 Furnace – USDOE is proposing a new furnace efficiency standard of AFUE 92.1 The HVAC4 study should have included the proposed USDOE AFUE 92 standard in the uncertainty analysis (Table 14, page 4-8) since this could have a large impact on savings compared to other input parameters. [1] https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=59&action=viewlive http://www.achrnews.com/articles/129036-doe-proposes-national-92-afue-standard http://www.achrnews.com/ext/resources/2015/03-2015/03-09-2015/furnaces_nopr_tsd_2015-02-13.pdf http://energy.gov/sites/prod/files/2016/09/f33/Residential Furnaces SNOPR.pdf	Since this standard is still in draft form, DNV GL did not use this information. Of course, assuming a baseline AFUE of 92 would reduce program savings. Code changes were not considered for this study.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
3	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3.1 95 AFUE furnace retrofits	AFUE 95 Furnace – Prior to performing thousands of eQuest simulations, the HVAC4 study should have performed 16 simulations for each climate zone using weighted building prototypes to evaluate uncertainty for a wider range of input parameters. This would eliminate input parameters such as fan motor/control strategy, duct leakage proportion, and cooling setpoint. Cooling setpoint should have been eliminated without any simulations.	We respectfully disagree. We decided to select just one climate zone CZ12 and keep as many as possible input parameters in this study to explore the relative uncertainties from various sources. We have considered as wide as possible of a range of relevant input parameters. Per a request from the IOUs, we have run the analysis for CZ08 and there are minor differences of the uncertainty analysis results between CZ12 and CZ08. We did not run all climate zones because most zones had far fewer claims that did not justify the time required to run all climate zones.
4	Robert Mowris, P.E.	Robert Mowris Associates	4.4.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM – Page 31, first paragraph states the following. "*The PSC-motorized furnace has a high airflow rate and the fan will keep cycling to meet the load. The fan run-time will be shorter than that of an ECM-motorized furnace. In the heating mode, the ECM furnace is cycling to maintain the space temperature and the resulting annual electric savings are very low.*" These findings are based on incorrect modeling input assumptions. The airflow (cfm) should be fixed for both PSC and EC motors (see "Flow Parameters" and "Design cfm"). The inputs for "Fan Power and Control" and "Design kW/cfm" must be changed so that the EC motor power is reduced by 35% compared to the PSC baseline (as noted below). Retrofitting an air handling unit (AHU) with an EC motor will not provide variable heating capacity for the furnace or variable cooling capacity for the air conditioner.	In fact, what was previously called the "ECM Retrofit" in our draft report *should* have been called the "Variable-speed motor option." We have revised the measure name to reflect this in hopes that it is clearer for readers. To reiterate, the VSM is not offered as a standalone retrofit, but as an optional upgrade to the AFUE 95 furnace retrofit. We have removed the quoted text shown to the left In addition, we revised our eQUEST inputs so that the range of minimum airflow ratios was narrower. This eliminated the anomaly of negative savings caused by the fan running at very low speeds for unreasonably long annual hours.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
5	Robert Mowris, P.E.	Robert Mowris Associates	4.4.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM – Page 33, provides the following findings. "*Table 9 shows the annual electric savings distribution for this specific scenario; the savings are positive, but only 50 kWh. The PSC-motorized furnace has a high airflow rate and the fan will keep cycling to meet the load. The fan run-time will be shorter than that of an ECM-motorized furnace. In the heating mode, the ECM furnace is cycling to maintain the space temperature and the resulting annual electric savings are very low. There is a penalty of 2,025 kWh on cooling. The hourly data show that the annual total airflow cubic feet per year of the PSC furnace is only 69% of that of the ECM furnace; most of the difference occurs during the cooling season. At present, it is not fully understood what causes such a large airflow difference. We will contact the DEER team to investigate further.*" The airflow difference is caused by not fixing the airflow (cfm) inputs for both the PSC and EC motor simulations (see "Flow Parameters" and "Design cfm" above). Fixing the airflow will eliminate the "cooling penalty" and provide a cooling benefit. Table 9 provides negative cooling savings of -2,025 kWh/yr (i.e., negative 28.4%) and only 50 kWh/yr fan savings for the EC motor (i.e., 7.5%). Laboratory tests indicate the EC motor is 35% more efficient than the PSC motor in terms of W/cfm. The findings presented in Table 9 indicate errors with the input assumptions noted above. Laboratory tests indicate that installing an EC motor will reduce heat added to the air by approximately 0.43°F which will increase sensible cooling capacity by 2% and reduce heating capacity by 1% (heating impact is lower due to the higher average furnace heat exchanger temperature rise of 35°F compared to the lower direct expansion evaporator temperature split of approximately 20°F). Based on laboratory test data the EC motor difference for cooling should be 2% with savings of 143 kWh/yr. The difference for ventilation fan should be 35% or 235 kWh/yr. The total difference should be 378 kWh/yr. This represents a savings increase of 656% savings compared to findings presented in Table 9 (i.e., 378/50-1=6.56).	In the baseline and post-retrofit models previously used, the design airflow rate (SUPPLY-FLOW) was left blank so that eQUEST would automatically make that determination. That led to the fan running at very low speeds for far too many hours during the year. In response to this comment, we revised our analysis by modifying the ranges of the baseline and post-retrofit minimum airflow ratios. In doing so, the anomalous simulation behavior was eliminated and the annual electric savings were no longer negative.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
6	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM – Slide 10 of the HVAC4 presentation shows 59.2% of the ECM uncertainty is from the assumed supply fan power index (W/cfm). The assumed PSC fan power index is 0.65 W/cfm and the assumed ECM fan power index is 0.365 W/cfm indicating a fan power index ratio of 56%.[2] Laboratory tests at Intertek on split-system HVAC systems were performed with PSC and EC motors at constant external static pressure (ESP, inches of water column, IWC) and constant airflow (CFM).[3] The fan power indices at constant airflow were 0.561 W/cfm for PSC and 0.382 W/cfm for EC motors indicating a fan power index ratio of 68%. The fan power indices at constant ESP were 0.461 W/cfm for PSC and 0.299 W/cfm for EC motors indicating a fan power index ratio of 65%. The difference between the HVAC4 assumed power index ratio and the laboratory power index ratios are 14 to 18% depending on constant airflow versus constant static pressure. The laboratory test data should be included in the HVAC4 study, but the fan power index ratio should be an input parameter instead of the fan power index. Tighter tolerances on the fan power index ratio should reduce uncertainty. [2] Fan power index ratio is the ratio of the EC motor power index to the PSC motor power index. [3] Verified, Inc. 2012. Draft Evaluation Report: Lab Tests of a Residential 3-Ton Split System Air Conditioner under Typical Installed Conditions, CPUC, 2012 (Verified 2012). http://deeresources.com/index.php/deer-versions/deer2018	The 59.2% contribution from fan power index (W/cfm) is largely due to the distribution of this variable used by our analysis. Since we assumed the same W/cfm for the EC motor and PSC motor, the resulting savings are due to the part-load power used by the EC motor at partial airflow conditions. We agree that the savings due to motor efficiency difference were not considered during our analysis. We have since revised our analysis, the reported results, and the report conclusions accordingly.
7	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM - Slide 10 of the HVAC4 presentation shows 16% of the ECM uncertainty is from the furnace sizing ratio. The furnace sizing ratio input parameter should be changed to “design ESP” or “cooling capacity sizing ratio” since airflow (cfm) and blower motor horsepower are more dependent on ESP and cooling capacity (in tons). Most HVAC systems are sized based on cooling loads and airflow required to meet the design cooling load. The blower motor horsepower is selected based on the design static pressure to provide the design airflow.	This comment is being considered for the report as the slides will not be revised. Many homes in CA have no cooling (about 40% from RASS), so the furnace sizing ratio remains a relevant parameter.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
8	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM – Slide 10 of the HVAC4 presentation shows 13.1% of the ECM uncertainty is from the fan-motor control strategy. The high level of uncertainty is due to the “always on” input parameter which should be eliminated since this fault represents another measure with low frequency of occurrence (i.e., unlikely to happen in either case).	This comment is being considered for the report as the slides will not be revised. The frequency is based on the only study found related to fan control strategies. No data were available to be sure that it was nonexistent. A study conducted by the Energy Center of Wisconsin provides furnace fan operation practices in Wisconsin. The findings demonstrate that a considerable number of homeowners (23%) who participated an Energy Star program and purchased ECM furnaces switched from AUTO to FAN-ON mostly because of following HVAC contractors/builders’ advice.
9	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM - Slide 10 of the HVAC4 presentation shows 10.2% of the ECM uncertainty is from the heating setpoint. The heating setpoint input parameter should be revised. The eQuest simulations should have used a narrower range of heating setpoints from 64 to 72°F (i.e., 68 +/-4°F) and range of cooling setpoints from 72 to 80°F (i.e., 76 +/-4°F) to determine the uncertainty associated with more representative setpoints.	See the response to Comment #1. While it is true that more than 90% of the RASS responses were within the range of 72 to 80°F, we must consider the full range of values.
10	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM – Slide 10 of the HVAC4 presentation shows 0.2% of the ECM uncertainty is from the duct leakage and duct leakage was varied from 9 to 40%. The low level of uncertainty associated with duct leakage is counterintuitive since duct leakage will influence operational times similar to a wide range for heating or cooling setpoints. The 0.2% uncertainty associated with duct leakage should be reviewed to ensure the eQuest simulations are properly modeling the duct leakage input parameters.	This comment is being considered for the report as the slides will not be revised. When we revised the analysis approach for this option, we replaced the duct leakage proportions—as an input parameter—with minimum airflow ratios. Hence, this comment is no longer very relevant. We agree, however, that the very low contribution to the savings uncertainty due to duct leakage was counterintuitive.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
11	Robert Mowris, P.E.	Robert Mowris Associates	unknown	ECM- Page 3-7 of the HVAC4 study states that "*the fan power index (W/cfm) and airflow (cfm) would vary with changes to outside weather conditions and motor operation,*" and recommends using eQuest to simulate variable speed operation as "*far preferable to using the full-load hours for a fixed fan motor speed*." While variable speed/torque EC motors have been available since the early 1990s, virtually all PSC motors and most constant-torque EC motors installed as a retrofit in programs are fixed-speed motors with taps to adjust torque. The term "constant torque" defines the type of ECM programmed to provide constant power to the motor.[4] Constant-torque EC motors have multiple taps to provide programmed levels of torque similar to the taps (referred to as "speeds taps") on a PSC induction motor. Constant torque allows the ECM to maintain the torque delivered to the motor as external static pressure (ESP) increases due to particle accumulation on air filters. PSC motors will decrease in torque when static pressure increases, causing the airflow to decrease as well. When torque is maintained, airflow does not decrease as much. For an ECM, this decreases the impact ESP has on reducing airflow, providing better performance and efficiency. The ECM has a programmed limit of operation to protect from damage, due to the energy it must use to maintain torque at high external static pressures. If the system's maximum total ESP is exceeded, torque will not be maintained, however the motor will deliver as much torque as possible without damaging the motor. [4] The "constant-torque" EC motor was originally introduced in 2006 by Regal-Beloit (formerly GE and now Genteq). See Regal-Beloit. 2007. The ECM Textbook. http://www.prokupmedia.com/seminarfiles/ecm_textbook.pdf. Mohalley. C. Understanding ECM Motors. ISBN 978-1-61607-191-2. http://www.rses.org/store/item.aspx?itemid=2144& https://yorkcentraltechtalk.wordpress.com/2012/10/27/x-13-motors-what-are-they/ http://www.achrnews.com/articles/112674-comparing-motor-technologies	We have been unable to locate the referenced quotes in the report.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
12	Robert Mowris, P.E.	Robert Mowris Associates	4.3.3.2 Optional variable-speed motor (previously titled ECM retrofits)	ECM - The Table 9 Refrigerant Impact Factor Distributions is based on field data and is out of date. The values in Table 9 have been replaced with new DEER2018 values based on comments provided by RMA and Intertek laboratory test data (see Table 15, pages 31-36, Resolution E-4795 Approved by CPUC on 8-16-16).[5] [5] http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M165/K012/165012114.PDF	The proposed DEER change and ensuing response came about too late to be considered by this report.
13	Robert Mowris, P.E.	Robert Mowris Associates	5.4 Uncertainty analysis results	Boiler – Slide 12 of the presentation shows 82.95% of the uncertainty is from the minimum airflow ratio (MAR) input parameter. MAR is a separate energy efficiency measure not relevant to all boiler installations. As noted in the HVAC4 study, MAR is relevant to variable air volume (VAV) systems, and most VAV systems use MAR controls to save energy. Efficient boilers are installed on many different building types to improve hot water and HVAC system efficiency. Buildings with constant volume HVAC systems would save more energy with an efficient boiler and even more energy with a VAV system, but this is like comparing apples to oranges. The boiler measure savings should be based on climate zone, building type/vintage, HVAC system type, and control strategy. These are unique applications for an efficient boiler measure and not input parameters that cause uncertainty. Relevant input parameters that cause uncertainty for efficient boiler savings are: thermal efficiency ratio, operational hours, sizing ratio, turn-down ratio, end use supply temperature, and standby losses. Too many simulations were performed with incorrect input parameters.	The boiler simulations were based on DEER prototypes with built-up systems and utility boilers as their space heating source. The HVAC system type and control strategy, for the purposes of this research study, were inherently set by the DEER prototype. The uncertainty in the MAR relates to the uncertainty of the loads calculated by the DEER prototypes, so it is related to the uncertainty of the DEER prototypes in general, and is not specific to the parameters addressing boiler efficiency. We wanted to explore the uncertainty in a range of parameters affecting both the measure efficiency and the loads presented to the boiler by the prototypes.
14	Robert Mowris, P.E.	Robert Mowris Associates	General	The HVAC4 study indicates plans to use the same approach to evaluate deemed measure uncertainty for unitary systems (<65 kBtu/h), air-cooled chillers, and refrigerant charge adjustment. Performing thousands of eQuest simulations with questionable or irrelevant input parameters for these and other deemed measures is unnecessary.	The team is working to define relevant input parameters for the Year 3 analysis. The work is necessary because the current practice is to assign judgement-based uncertainty values to deemed measures without any ability to target specific parameters in evaluations or larger studies. Since all weather-dependent measure savings are expected to make use of DEER eQUEST simulations or DEER methods, these types of analyses become relevant.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
15	Robert Mowris, P.E.	Robert Mowris Associates	General	The HVAC 4 study should adhere to the American Evaluation Association (AEA) guidelines for data-based systematic inquiry, competence, integrity, respect, and responsibility for all stakeholders. The study should have included a collaborative process to solicit comments and suggestions from colleagues, program implementers, and industry experts to examine the input parameters and the research plan to produce reliable and credible results per AEA guidelines.	The research plan was publically vetted and, prior to that, vetted with the IOUs through the HVAC PCG. This process applies to all CPUC projects and deliverables. Since this is not an evaluation—but a research study, instead—AEA evaluation standards are not particularly relevant.
16	Robert Mowris, P.E.	Robert Mowris Associates	General	Based on the lack of adherence to the CPUC California Evaluation Framework and AEA guidelines and lack of vetting of input parameters, the HVAC4 study should be rejected. Future studies should be competitively bid to a wider group of qualified HVAC industry experts, engineers, evaluators, and building scientists who understand how to measure, evaluate, and simulate HVAC energy efficiency measure savings and uncertainties.	The research plan was publically vetted and, prior to that, vetted with the IOUs through the HVAC PCG. This process applies to all CPUC projects and deliverables including the Year 1 report and this report. The CPUC Evaluation Framework was followed in spirit, but the uncertainty chapter focuses on sample-based evaluation and billing analysis error. AEA also focuses on sampling uncertainty and bias and in no way addresses this situation. Since there is currently no framework for determining the uncertainty of deemed savings, this report and the resulting comments have demonstrated the importance of this novel study.
17	Abram Conant	Proctor Engineering Group, Ltd.	General	Reliance on unproven simulation models over facts, data, and scientific analysis by individuals with expertise on the measures being studied is an ongoing problem fostered by CPUC policy over the past decade. It has never been proven that the models accurately predict energy use representative of CA buildings, it has never been proven that they accurately predict energy savings for all measures, and it is even less certain that they respond in a realistic way to a wide range of inputs as are applied in these studies. It is disappointing that policy decisions continue to be based on information that is not proven to be meaningful, and not merely a artifact of the simulation model calculations and inputs.	The approach for this study must consider the current context. Related studies were used to define inputs. Since all weather-dependent measure savings are expected to make use of DEER eQUEST simulations or DEER methods, these types of analyses are relevant in the current context. We will recommend that—whether eQUEST or other tools are used—an analysis of uncertainty must accompany the point estimate deemed savings. Furthermore, evaluation results, along with relative precisions, should be used in savings updates in spite of their uncertainty.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
18	Abram Conant	Proctor Engineering Group, Ltd.	4.2 Workpaper review	Section 4.2.2 ECM Retrofits is an excellent illustration of meaningless outputs produced by flawed simulation modeling. The measure titled "ECM Retrofit" in this study and the referenced workpaper is a brushless permanent magnet D type motor designed to be a drop in replacement for the Permanent Split Capacitor (PSC) motors that are prevalent in existing furnaces. As a replacement part, the retrofit motors are designed to function similarly to the PSC motors that they replace, but a higher efficiency. There are at least 5 brands of brushless permanent magnet replacement motors on the market, and all are designed to do the same job as the PSC motors they replace. The following findings in this study represent a fundamental misunderstanding and misrepresentation of the measure by the simulation modeling process.	In fact, what was called the "ECM Retrofit" in our report *should* have been called the "variable-speed BPM motor option." This option is not offered as a standalone retrofit, but as an optional upgrade to the AFUE 95 furnace retrofit. We have revised the measure description in the report to make this clearer to readers.
19	Abram Conant	Proctor Engineering Group, Ltd.	4.2.2	The first paragraph on page 31 says: *"The PSC-motorized furnace has a high airflow rate and the fan will keep cycling to meet the load. The fan run-time will be shorter than that of an ECM-motorized furnace. In the heating mode, the ECM furnace is cycling to maintain the space temperature and the resulting annual electric savings are very low."* This makes no sense. Replacing the fan motor does not transform the furnace into a variable capacity furnace or the air conditioner into a variable capacity air conditioner. The pre/post retrofit fan speeds are similar, heating and cooling capacities are unchanged, and so the furnace and air conditioner cycling characteristics will be unchanged except as influenced by the reduced amount of heat produced by the fan motor inefficiencies.	In fact, what was called the "ECM Retrofit" in our report *should* have been called the "Variable-speed motor option." This option is not offered as a standalone retrofit, but as an optional upgrade to the AFUE 95 furnace retrofit. We have revised the measure description in the report to make this clearer to readers. We agree that the quoted text could have been worded better. We have removed the quoted text.
20	Abram Conant	Proctor Engineering Group, Ltd.	4.2.2	The first paragraph on page 31 says: *"There is a penalty of 2,025 kWh on cooling."*, and Table 9 shows higher cooling energy use resulting in increased total annual energy use of 1,974 kWh. This makes no sense. The notion that replacing a fan motor with a more efficient product that moves the same amount of air at reduced Watt draw will somehow increase cooling energy use by 28% is absurd. It is an artifact of the modeling process, and a gross misrepresentation of the measure.	Modeling uncertainty is, in fact, entirely relevant when considering the current context. It is reasonable to recommend either collecting better input data or revising the current modeling approach.

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
21	Abram Conant	Proctor Engineering Group, Ltd.	4.2.2	The first paragraph on page 31 says: *"The hourly data show that the annual total airflow cubic feet per year of the PSC furnace is only 69% of that of the ECM furnace; most of the difference occurs during the cooling season. At present, it is not fully understood what causes such a large airflow difference. We will contact the DEER team to investigate further."* This indicates that the study team was aware that the model outputs were flawed. Therefore, the appropriate conclusion would be that the simulation model doesn't accurately represent the measure. Producing uncertainty estimates based on obviously flawed results is not good science, and continuing to pretend that these results are meaningful because they came out of a DEER model is bad policy.	Modeling uncertainty is, in fact, entirely relevant when considering the current context. It is reasonable to recommend either collecting better input data or revising the current modeling approach. Without this analysis, issues such as this might never be revealed.
22	Abram Conant	Proctor Engineering Group, Ltd.	4.2.2	The last paragraph on page 30 says: *"It is easy to understand that all fan power savings are negative for the Auto-FanOn scenario. However, 90% are negative for the Auto-Auto scenario if a PSC motor is replaced with a ECM."* This is the type of damaging misrepresentation that has become all too common as policy has increasingly prioritized the use of unproven and unreliable DEER models over real world data and analysis by technical experts. The DEER models themselves may well be the single greatest source of uncertainty in deemed measure savings estimates, as evidenced by the > 30% error in cooling energy use outputs in the example discussed on pages 30 and 31.	Modeling uncertainty is, in fact, relevant when considering the current context. It is reasonable to recommend either collecting better input data or revising the current modeling approach. Without this analysis, issues such as this might never be revealed.