Study of Deemed HVAC Measures Uncertainty Year 3 Report (HVAC4)

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1 EXECUTIVE SUMMARY

The California Public Utilities Commission (CPUC) engaged DNV GL in early 2014 to study the uncertainty of energy savings for selected energy efficiency measures for heating, ventilation, and air-conditioning systems (HVAC). A deeper understanding of the extent and drivers of energy savings uncertainty may lead to improvements in savings estimation and portfolio planning. In the third year of this study, DNV GL investigated three types of HVAC measures promoted through California's 2013-14 and 2015 rebate programs:

- **Unitary systems**, which combine heating, cooling, and fan components to deliver temperature- and humidity-controlled air to conditioned building spaces. HVAC4 focused on small and medium-sized, high-efficiency[1] unitary HVAC systems at small office buildings.[2] The study addressed units in two areas within California that have similar temperatures and average rainfall (climate zones [CZ]): CZ08 and CZ12.
- **Air-cooled chillers**, which provide cold water to cool the air used to condition building spaces. HVAC4 focused on high-efficiency,[1] air-cooled chillers of all sizes at large office buildings in CZ03 and CZ08.
- **Refrigerant charge adjustment** (RCA), which is a quality maintenance process to restore the amount of refrigerant in a unitary system to the manufacturer-recommended level.

This report presents this year's study results.

1.1 Research objectives

The study, called HVAC4, had three objectives related to the measures described above:

- Develop a method to assess the uncertainty of the pre-determined (or "deemed") savings values
- Quantify this uncertainty using recent field and laboratory measurement data
- Identify the savings parameters with the greatest influence on the uncertainty of measure-level savings

Note that the CPUC maintains a repository of deemed measure savings values in the Database for Energy Efficiency Resources (DEER). DNV GL relied on DEER for the deemed savings values and associated assumptions for this study.

The HVAC4 study also aimed to support broader CPUC efforts related to the Portfolio Parameter Prioritization Project (P4). P4's objective is to help prioritize evaluation activities around measures or parameters with the highest level of savings uncertainty. P4 uses a database tool to estimate the uncertainty of savings associated with major measure groups at the measure level and the portfolio level.[3] The tool relies on a combination of field-measured uncertainties developed by program evaluation studies and those obtained through interviews with subject matter experts to generate a prioritized list of measures with uncertain savings. Commission staff use this list to prioritize evaluation efforts to address measures that introduce the most uncertainty to portfolio-level savings. The CPUC can potentially use the uncertainty analysis developed in this study in place of expert interview results for relevant measures and inform the data collection needed to reduce those uncertainties.

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[1] Of the three high-efficiency tiers defined for unitary systems and chillers, Tier 2 was studied.

[2] For the purposes of this study, small systems are less than 55 kBtuh and medium systems are between 65 to 134 kBtuh.

[3] The CPUC Portfolio Parameter Prioritization Project (P4) Uncertainty Analysis Tool creates and reports an uncertain measures list annually. See: http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6339

1.2 Research approach

DNV GL relied on the following approaches to support HVAC4:

- For unitary systems and air-cooled chillers, DNV GL used two types of computer software to assess the uncertainty of the energy savings: a building energy modelling tool and a Monte Carlo simulation tool.[4] We used field data from two recent impact evaluation reports, including one that addressed the California investor-owned utilities' (IOU)[5] 2015 upstream HVAC programs (HVAC1)[6] and another that addressed the IOUs' 2015 commercial quality maintenance programs (HVAC3).[7]
- For the RCA measure, DNV GL used a Monte Carlo simulation tool to assess the uncertainty of common performance metrics of unitary systems. We used laboratory data from a recent HVAC laboratory testing study (HVAC5)[8] and field data from the HVAC3 study. Instead of estimating the resulting mean annual savings—as we did for the first two measures—we estimated the measure effects on three key unitary system performance metrics:
    - Energy efficiency ratio (EER), a measure of air-conditioning unit efficiency when operating at full load
    - Net total cooling capacity, a measure of heat energy removed from air (including dehumidification) by an air-conditioning unit
    - Net sensible cooling capacity, a measure of heat energy removed from air (excluding dehumidification) by an air-conditioning unit

In general, we tailored our analysis approach for each measure by using the available data to inform the ranges of operating conditions modelled.

1.3 Key findings

Key findings from the HVAC4 study include:

- **Unitary systems:**
    - For small unitary systems, the mean annual savings were 33 to 45% lower than those in DEER. The leading contributors to savings uncertainty included: whether units had one- or two-speed fans, whether units had economizers (devices to improve energy efficiency), and how closely building cooling load[9] matched the system cooling capacity—called the cooling sizing ratio.
    - For medium unitary systems, the mean annual savings were 13 to 14% higher than those in DEER. The leading contributors to savings uncertainty were the cooling sizing ratio and the thermostat setting for cooling.

[4] 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 an analyst runs a Monte Carlo simulation, 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).

[5] California's IOUs include Pacific Gas & Electric Company, San Diego Gas and Electric Company, Southern California Edison, and Southern California Gas Company.

[6] CPUC 2016. Impact Evaluation of 2015 Upstream HVAC Programs (HVAC 1). http://www.calmac.org/publications/HVAC1_Upstream_HVAC_NTG_Report_FinalPublic.pdf

[7] CPUC 2016. Impact Evaluation of 2015 Commercial Quality Maintenance Programs (HVAC3). www.calmac.org/publications/HVAC3_2015_Impact_Report.pdf

[8] Laboratory HVAC Testing Research for 2013-14 (HVAC5): An Introduction and Data Dictionary. DNV GL, RMA (2017). http://calmac.org/publications/HVAC5_2013-14_Introduction_and_Data_Dictionary.pdf

[9] Cooling load refers to amount of heat energy that a system needs to remove from a space—in other words, how much the system needs to cool the space—to maintain the temperature within the range selected by the occupants.

- **Air-cooled chillers:**
  - The mean annual energy savings were 58 to 79% lower than those in DEER. The leading contributors to savings uncertainty included the full-load efficiency rating, the thermostat settings for cooling the conditioned space, and the minimum condenser[10] temperature setting of the chiller.
- **Refrigerant charge adjustment:** For the performance metrics that we studied—EER, net total cooling capacity, and net sensible cooling capacity—we found the following:
  - Improvements were much lower than assumed by DEER except for pre-RCA units that had highly undercharged refrigerant circuits.[11] There were even instances when EER decreased following RCA.
  - Improvements were much lower than assumed by DEER for units with two compressors and thermal expansion valves[12] (TXV); they were significantly better for single-compressor units without TXV.
  - The uncertainty of the improvement to EER due to RCA was driven by the extent of the pre-RCA charge offset and the amount of outdoor air introduced into the unit through the economizer.[13]

Overall, we found that other measure assumptions more heavily influence energy savings than the current ex ante parameters used, such as building vintage. Using the results described, DEER savings estimates could be improved.

1.4 Recommendations

To leverage these findings, the Commission staff may choose to use the deemed savings forecasts and sensitivity analyses to determine which additional data should be gathered to reduce future savings uncertainty. IOU programs or CPUC consultants could likely gather such new data with minimal incremental cost by either modifying future HVAC rebate applications to gather basic data or during future evaluations. Furthermore, the results provide analysis-based inputs to the P4 tool. To achieve these objectives, we provide the following list of measure-specific and portfolio-level strategies:

For unitary systems, our recommendations include:

- Because the resulting mean energy savings for small units were substantially lower than those reported by DEER, program administrators should reconsider the assumptions and inputs used to estimate their savings. Other 2013-15 HVAC report results support this recommendation.
- Across all combinations of unitary system sizes and climate zones analyzed, cooling sizing ratio and the thermostat setting for cooling were moderate to strong contributors to savings variance. These outranked the influence of duct leakage rate, economizer high-temperature limit, and building vintage. The CPUC evaluation research Roadmap leads should consider future efforts that aim to reduce the uncertainty of these inputs to affect the greatest reduction in savings uncertainty.
- While it is well understood that a correctly-functioning economizer greatly influences the energy efficiency of a unitary system, we learned that a poorly performing economizer also diminishes or eliminates the efficiency benefits yielded by RCA. IOUs may need to reconsider assumptions regarding economizer effects on unitary systems based on the results produced by this and other 2013-15 HVAC Roadmap reports.

[10] A condenser is a device within the chiller that condenses a refrigerant vapor to its liquid state by cooling it. As it does so, the condenser takes the heat that the refrigerant gave off and removes it from the conditioned space.

[11] For the RCA measure, a pre-treatment refrigerant charge level that differs from that recommended by the manufacturer by at least 20% is classified as "high overcharged" or "high undercharged;" those that deviate by less than 20% are classified as "typical overcharged" or "typical undercharged."

[12] A thermal expansion valve is a device that automatically regulates the flow of refrigerant in the air conditioner, and is used to compensate for improper refrigerant charge levels.

[13] An economizer is a system of interlocking dampers used to regulate the amount of outdoor air introduced into the unit.

For air-cooled chillers, our recommendations include:

- Given that the mean savings were found to be substantially lower than those deemed, the savings for the upcoming DEER update should be reviewed.
- Given the influence of the minimum condenser temperature and other setpoints on savings variance, programs should consider developing a retro-commissioning measure to guide temperature setpoints for space-conditioning applications.
- The part-load efficiency qualification path results in some chillers with full-load efficiency below that required by Title 24 and, hence, yields negative energy savings during full-load periods of operation.

For the refrigerant charge adjustment (RCA) measure, our recommendations include:

- Study results support re-designing the measure so that contractors are trained to treat all non-RCA faults *before* adjusting the level of refrigerant charge.
- Pre-RCA adjustment factors used for EER, net total cooling capacity, and net sensible cooling capacity should be reviewed based upon this and other 2013-15 HVAC Roadmap reports.
- Program administrators should consider offering refrigerant-line repair as a measure or emphasizing replacement of old units that have a history of low refrigerant charge. They should also target refrigerant charge adjustments on units without thermal expansion valves or units with multiple compressors.
- Given that economizer faults or sub-optimal economizer settings have significant influence on savings uncertainty, additional research is appropriate. Furthermore, contractor training programs may help participants to achieve optimal economizer settings and reduce faults.

Regarding Year 3 findings to be considered for incorporation into the P4 tool, our recommendations include:

- While we do not know whether or how P4 will evolve to make use of HVAC4 results, evaluation research Roadmap leads should have a role in its development.
- The P4 database team should consider increasing the resolution of P4 to include building types and climate zones.
- The P4 database team should consider adding a field for the HVAC4-derived standard deviation of the mean, ex ante, unit energy savings.

2 INTRODUCTION

The California Public Utilities Commission (CPUC) and DNV GL agreed 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 energy savings uncertainty that could be applied to many different HVAC measures. During Year 1 and Year 2 of this study, 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. During Year 3, we included measures that had been evaluated because the evaluations, themselves, offered a rich dataset to inform the uncertainty analyses—the results of which can help plan future evaluation efforts aimed at reducing the remaining uncertainty.

For many energy efficiency measures, utilities assign a predetermined savings value per installed measure or measure-unit, which are called deemed savings. Subsequent to implementing such measures, many energy efficiency programs are evaluated to determine the extent to which the deemed 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 deemed 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 will study those parameters that have the greatest influence on the savings uncertainty.

2.1 Background information

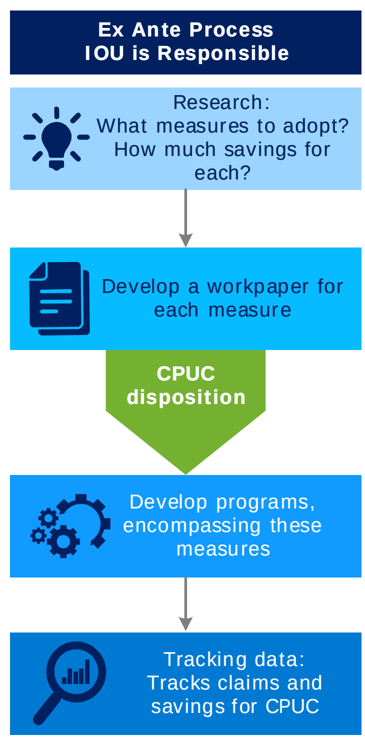
Prior to the launch of every energy efficiency rebate program, the IOUs in California—Pacific Gas and Electric Company (PG&E), Southern California Edison (SCE), Southern California Gas (SCG), and San Diego Gas and Electric Company (SDG&E)—describe how the energy savings will be determined for each measure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

For many types of energy efficiency measures, per-unit energy savings are assigned to measures prior to the program's start based on factors such as the building type, climate zone, and system operation characteristics that affect measure performance. These measures are called deemed measures, and their savings are intended to represent average 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, their savings are also often predetermined (deemed).

Figure 1. Ex ante process



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

1. Database for Energy Efficiency Resources (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)
   d. For non-residential measures, building characteristics data are drawn from a variety of sources including the Commercial Market Share Tracking (CMST) Study, Commercial Saturation Study (CSS), Commercial End-Use Study (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 IOUs submit claims quarterly to the CPUC to track program progress and for the annual program savings reconciliation process. The submitted claims are processed through quality checks and appended with several descriptive fields before being integrated into a tracking database. The savings recorded in the tracking database are referred to as the ex ante savings,[14] 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 evaluation contractors selected by the CPUC. For 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 2, 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,[15] or impacts.

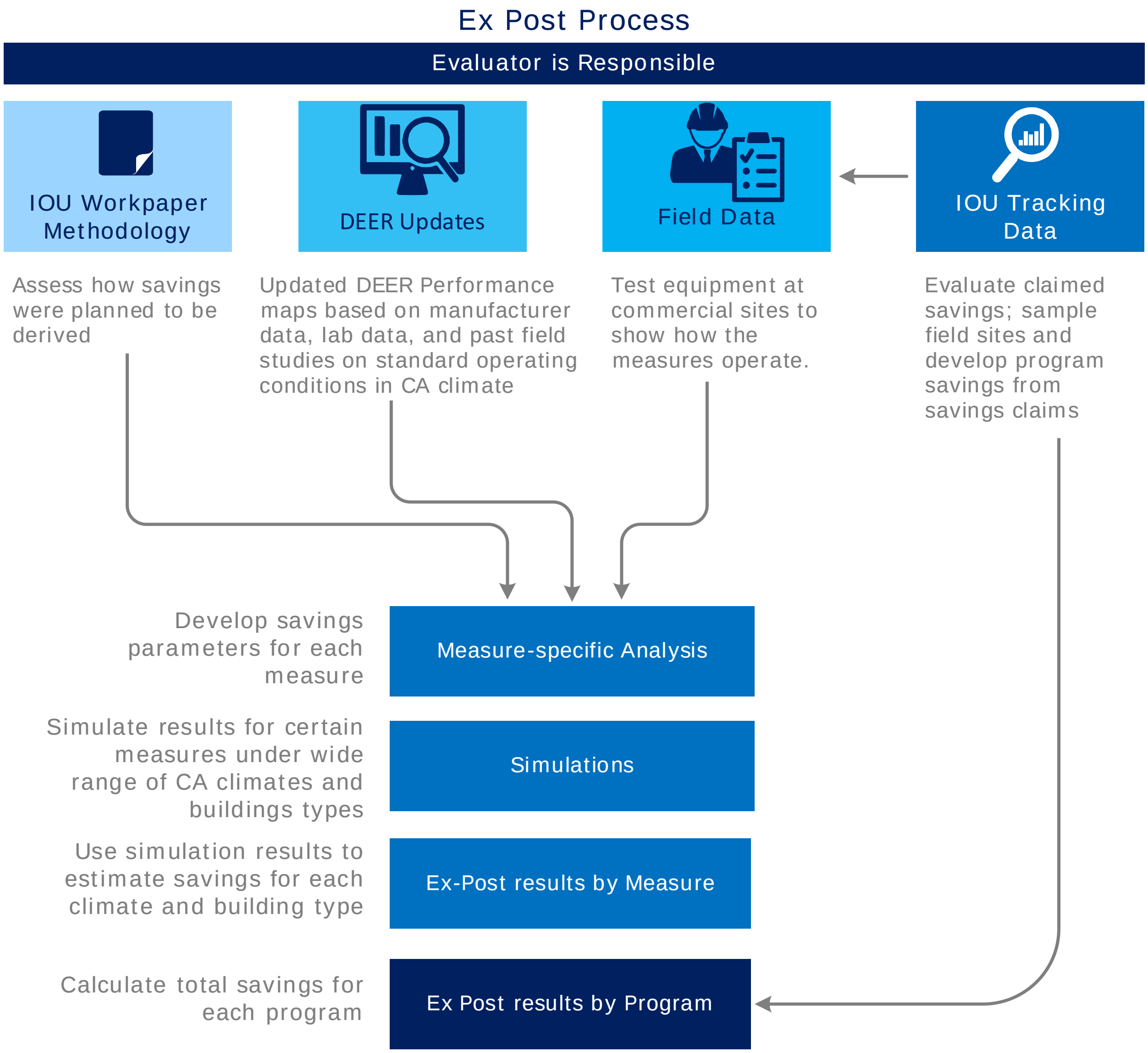
To determine the project-specific ex post savings, DNV GL applies a measurement and verification (M&V) process using an agreed-upon level of rigor that is appropriate for the evaluation budget. The project-level M&V process often includes a site visit or telephone interview to achieve some or all of 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

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

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

are used to estimate the ex post retrofit-savings across all measures in the program(s) covered by evaluation activity.

Figure 2. Estimation of ex post retrofit-savings



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, IOUs, program implementation contractors, and IOU ratepayers. Hence, Evaluators' Protocols[16] 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,

[16] California Public Utilities Commission. April 2006. *California Energy Efficiency Study Team Protocols: Technical, Methodological, and Reporting Requirements for Study Team Professionals* (commonly referred to as Evaluators' Protocols).

peak demand savings, and annual natural gas savings—evaluators are required to report some or all of the following precision ex post metrics:

- 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. This stimulates much discussion 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.[17] Through this study, we set out to develop tools to assess the uncertainty of deemed savings. This year's effort emphasized leveraging both the methodology developed during Year 2 and the results yielded by other evaluations and studies in the HVAC Roadmap. This study allowed us to assess savings uncertainty after incorporating recent ex-post evaluation results, thus providing information on remaining uncertainty useful for future evaluation planning.

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 estimate, 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 Year 3 study tasks

DNV GL performed the following tasks to complete the uncertainty analysis study during Year 3:

1. Reviewed the HVAC Roadmap tracking data to identify relevant deemed HVAC measures and ranked their contribution to the portfolio savings.
2. Selected the measures to study.
3. Performed an in-depth review of the sources of the ex ante savings to assess the savings methodology and sources of the input parameters.

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

4. Performed an in-depth review of the results of ex post evaluations and other research performed in the HVAC Roadmap.
5. Created a model of the energy consumption or savings that used the same input parameters used by the IOUs. Ran 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.
6. Established a process and format for integration of the HVAC4 results for Years 1 through 3 to the Portfolio Parameter Prioritization Project (P4) Uncertainty Analysis Tool.
7. Prepared this report that presents uncertainty analysis results and 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 3 of this study.
- Section 4, "NONRESIDENTIAL UNITARY SYSTEMS" describes the methods and references used to determine the ex ante savings for nonresidential unitary systems of one building type at two climate zones, 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 AIR-COOLED CHILLERS" describes the methods and references used to determine the ex ante savings distributions for air-cooled chillers at large office buildings in one climate zone and small office buildings in another.
- Section 6, "NONRESIDENTIAL RCA MEASURE" describes the methods and references used to determine the distribution of the post-treatment Energy Efficiency Ratio (EER), net cooling capacity, and net sensible cooling capacity.
- Section 7, "INTEGRATION OF HVAC4 RESULTS INTO P4 TOOL" describes the method for incorporating the relative precision of the ex ante savings into the portfolio-wide uncertainty analysis.
- Section 8, "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, "NONRESIDENTIAL UNITARY SYSTEM 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, "NONRESIDENTIAL AIR-COOLED CHILLER INPUT PARAMETERS AND RESULTS FOR TIERS 1 & 3" 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, “NONRESIDENTIAL RCA ,” 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 COMMENT AND RESPONSE,” provides the public comment received and DNV GL’s response.
- APPENDIX E, “APPENDIX AC – IESR STANDARDIZED RECOMMENDATIONS,” provides a summary table of the findings and recommendations delivered within this report.

3 UNCERTAINTY ANALYSIS METHOD

Over the course of the three-year study, the team developed uncertainty analysis methods to produce savings distributions and uncertainty metrics as well as to determine the relative influence of key input parameters for some influential HVAC measures. The uncertainty analysis method underwent continuous development over the course of the project. 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.

In Year 2, 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[18] simulations. In this Year 3 report, we relied on this simulation and Monte Carlo approach as well as a new approach for refrigerant charge adjustment (RCA) that focused on the uncertainty of building simulation inputs using HVAC5 lab data and HVAC3 field data.

The simulation and Monte Carlo method developed and used by DNV GL is shown in Figure 3 and is described in greater detail below:

1. Building Prototypes. We used MASControl,[19] the CPUC's tool for 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 and 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,[20] 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

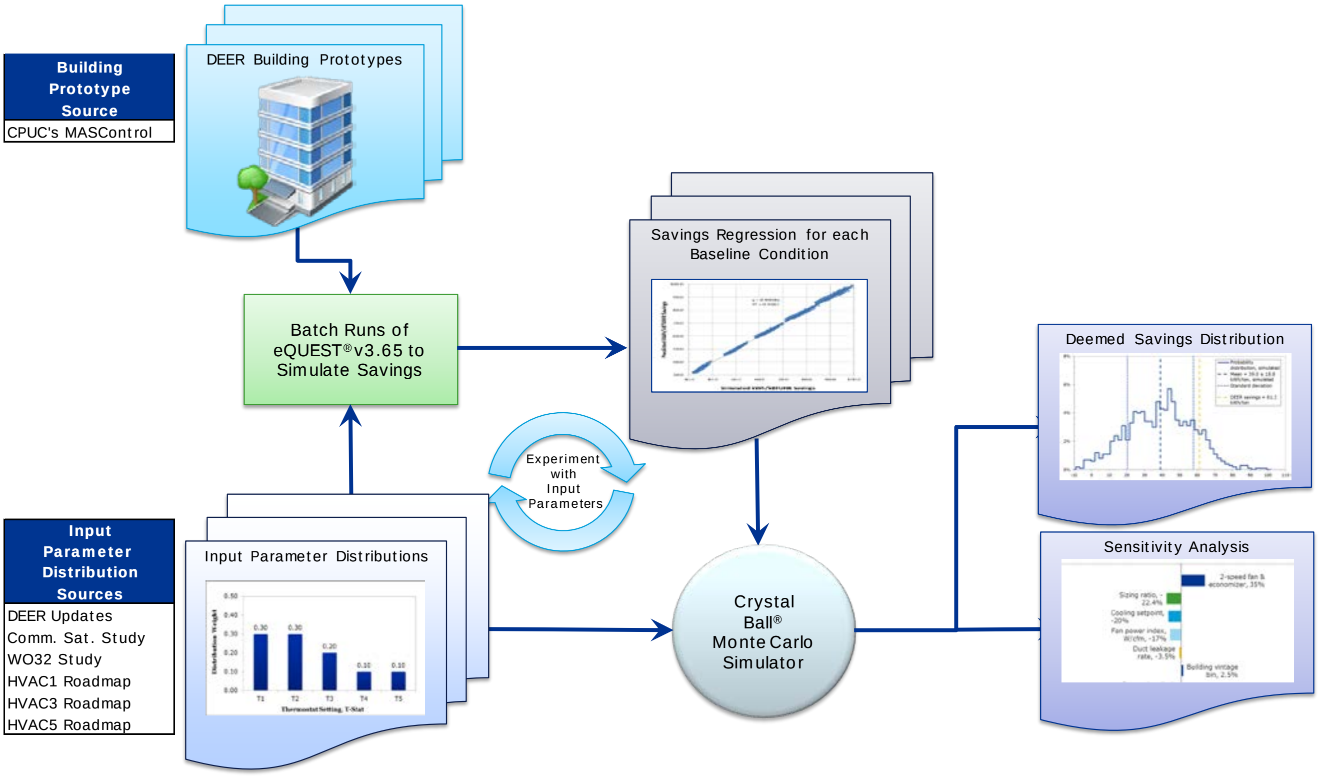
18 Monte Carlo simulation was named for Monte Carlo, Monaco, where the primary attractions are casinos offering games of chance. Games of chance, such as roulette wheels, dice, and slot machines, exhibit random behavior. The random behavior in games of chance resembles how Monte Carlo simulation randomly 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).

19 http://www.doe2.com/download/DEER/MAStool/

20 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/

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.

Figure 3. Graphical representation of eQUEST-based uncertainty analysis method



4. Multivariate Quadratic Regression Analysis. We then developed a post-modelling Excel workbook 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 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. The coefficients are represented by a_0 through a_n and $a_{1,1}$ through $a_{n,n}$ as shown in the following equation:

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

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.[21,22] 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.[23]

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 (illustrated in Figure 3) 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 3. These results show which input parameters are most worthy of additional study to reduce the uncertainty of the deemed savings distributions.

As previously indicated, the third measure selected for study the year, the RCA measure, warranted an approach that neither used the deterministic equations provided by IOU workpapers (as in Year 1) or the batch-runs of eQUEST analyses to produce regression equations (as in Year 2). Instead it used an approach that incorporated the laboratory data gathered during the 2013-2014 HVAC5 study and the field data gathered during the 2013-2014 and 2015 HVAC3 evaluations to produce regression equations for Crystal Ball simulations. In this instance, the analysis did not explore the uncertainty of deemed measure savings; instead, it quantified the uncertainty of three key equipment-performance parameters that greatly influence the energy savings due to quality maintenance of rooftop air conditioning: Energy Efficiency Rating (EER), net sensible cooling capacity, and total cooling capacity.

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[21] 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

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

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

4 NONRESIDENTIAL UNITARY SYSTEMS

The unitary systems measure was selected for uncertainty analysis based upon its prevalence in the 2015 IOU program tracking data provided by the CPUC data management team. While this measure was evaluated in HVAC1, this is such an important measure in the HVAC portfolio that further study was warranted in HVAC4. In this section, we describe the deemed measure, the methodology, and input parameters used to determine the savings uncertainty and sensitivity and the uncertainty analysis results. At the conclusion of this section, we summarize our findings and recommendations based upon those findings.

4.1 Measure description

A non-residential unitary system—sometimes called a package system or rooftop unit (RTU)—is an HVAC system that combines multiple components into one cabinet. They are usually installed on rooftops and can vary in size from 24 kBtu/h to 760 kBtu/h. The system components include a system fan, direct-expansion cooling coil, heating element (burners or coils), heat exchanger, condenser coil, condenser fan, and a duct system to circulate the conditioned air to the building. Unitary systems having a cooling capacity greater than 55 kBtu/h (slightly under five tons) are also required by code to have an integrated economizer.

Under DEER 2015 guidelines, three or four above-code efficiency tiers exist, depending on unit capacity, for the unitary system measure. This analysis examined the uncertainty of Tier-2-equivalent unitary systems for two ranges of cooling capacity: less than 55 kBtu/h (using the SEER efficiency rating) and 65 kBtu/h to 134 kBtu/h (using the EER efficiency rating). The baseline efficiency for systems under 55 kBtu/h is 14 SEER without economizer while a Tier-2 unit is rated at 16 SEER without economizer. The baseline efficiency for systems between 65 kBtu/h to 134 kBtu/h is rated at 11 EER with economizer while the Tier-2 unit is rated at 12 EER with economizer.

4.2 Unitary system tracking data

This uncertainty analysis investigation focused on unitary systems “installed” at the small office building prototype model in CZ08 and CZ12—the most prevalent measure installation application from the 2013-15 upstream HVAC program years. DEER 2015 savings values for these specific measure applications are presented below in Table 1.

Table 1. Selected unitary system measure characteristics

DEER 2015 Measure ID	Baseline: Pre-existing or Standard	Building Type	Climate Zone	DEER 2015 Annual Savings, kWh/ton
NE-HVAC-airAC-Pkg-lt55kBtuh-16p0seer	Standard	Small office	8	328
NE-HVAC-airAC-Pkg-lt55kBtuh-16p0seer		Small office	12	322
NE-HVAC-airAC-SpltPkg-65to109kBtuh-12p0eer	Standard	Small office	8	61
NE-HVAC-airAC-SpltPkg-65to109kBtuh-12p0eer		Small office	12	53

4.3 Uncertainty analysis steps

The initial step involved in the uncertainty analysis was the development of a regression to predict savings using the results of parametric energy-simulation models that were informed by program data distributions, as available. A data array was then generated consisting of variable input values, the products of two input-variable value combinations (i.e., second order interactions), and model output kWh savings. From this array, second-order polynomial (quadratic) regression expression-coefficients were developed using the LINEST function in Excel. This expression efficiently characterized modeled savings impacts resulting from varying each model input. The regression expression was loaded into the Crystal Ball platform together with discrete values and an associated probability distribution for each input variable to simulate the resulting range of savings outcomes. These simulations were used to create savings distribution profiles and the relative contribution of each parameter to the overall uncertainty.

4.3.1 eQUEST prototype batch processing

As described in Section 3, we used the savings results produced by the eQUEST batch runs to create multivariate quadratic regression models for annual electric savings for each equipment size category and in each climate zone.

Six energy simulation modeling input variables were selected for the investigation of energy savings uncertainty of Tier-2 unitary systems. The input variables were chosen based on their influence on energy consumption. If there are no data available for selected variables, assumed distributions will be used as an alternative. The input variables are as follows:

- Supply fan power index (W/cfm), using data yielded by the 2015 HVAC1 upstream program impact evaluation[24]
- Duct leakage rate (percent), using a discrete value distribution based on engineering judgement
- Cooling capacity sizing ratio (percent), using a discrete value distribution based on engineering judgement
- Prototype-building vintage bins were used to account for shifts in building characteristics that have occurred over time. These include characteristics such as lighting power density and the rate at which heat flows (described as U-factor or UA[25]) through building components such as windows, walls, doors, and ductwork.
- Space cooling setpoint (degree Fahrenheit, °F), with data sourced from the 2015 HVAC3 quality maintenance program impact evaluation[26]
- Economizer control's high-temperature limit (°F), with data yielded by the 2015 HVAC3 quality maintenance program impact evaluation

[24] CPUC 2016. Impact Evaluation of 2015 Upstream HVAC Programs (HVAC 1). http://www.calmac.org/publications/HVAC1_Upstream_HVAC_NTG_Report_FinalPublic.pdf

[25] U-factor represents the rate at which heat is transferred through building components, in Btu/hr-ft^2-°F. It is the inverse of the better-known R-factor. UA represents the product of the U-factor and the surface area, in ft^2, of a given building component.

[26] CPUC 2016. Impact Evaluation of 2015 Commercial Quality Maintenance Programs (HVAC3). www.calmac.org/publications/HVAC3_2015_Impact_Report.pdf

The regression model takes the form as follows for each of the baseline/post-retrofit cases for each measure at each building vintage bin:

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

where

Y represents energy savings, kWh

X_1 represents the supply fan power index, watt/cfm

X_2 represents the duct leakage, percent

X_3 represents the cooling-capacity sizing ratio, dimensionless

X_4 represents the building model vintage bin, dimensionless

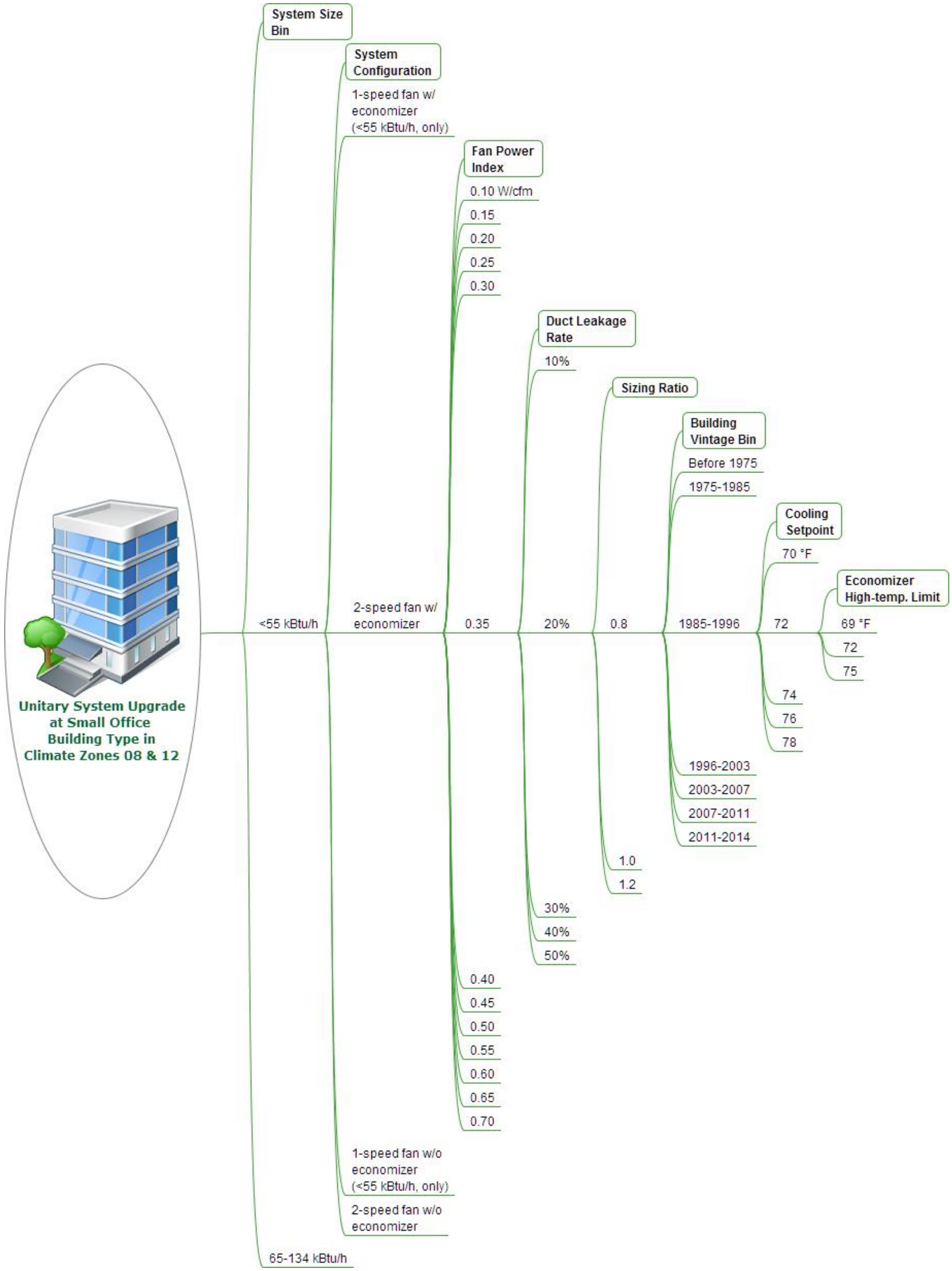
X_5 represents the cooling setpoint, °F

X_6 represents the economizer control high-temperature limit, °F

The corresponding coefficients (a_0, a_1, etc.) for this measure are provided in APPENDIX A. A graphical depiction of the various combinations of input parameters is provided in Figure 4. For each combination of input values run through Crystal Ball, the annual energy savings results from each of the regression models are weighted by an assumed prevalence of each system configuration[27] and, then, aggregated to provide an annual energy savings value. For unitary systems under 55 kBtu/h, four configurations are defined based on the four possible combinations of two system features: fan mode (1 speed vs 2 speed) and whether the system has a functioning economizer. Details can be found in Table 2. For unitary systems between 65 kBtu/h and 134 kBtu/h, two configurations are defined and details can be found in Table 3.

[27] Configurations for units under 55 kBtu/h included combinations of one- and two-speed fans at systems with or without functioning economizers.

Figure 4. Input parameters of eQUEST batch runs for unitary system simulations



4.3.1.1 Unitary systems under 55 kBtu/h

The baseline efficiency for a unit less than 55 kBtu/h is 14 SEER whereas the Tier-2 unit is rated at 16 SEER. The regression models generate simulated energy savings output values for a specific combination of modeling assumption and input parameter values. Each regression model calculates the savings due to upgrading to the measure system configuration and efficiency (16 SEER, Tier-2) from the baseline system configuration and efficiency—a 14 SEER unitary system with a one-speed supply fan and no economizer. Twenty-eight regression models were developed for this equipment class, each representing the savings expected for unique combinations of measure system configurations and building vintage bins. For each pair of baseline/measure runs with an economizer, the economizer functionality was held constant (i.e., if the economizer had not been functioning properly in the measure case, the baseline case was also assumed to not be functioning properly).

The annual energy savings output results from each of the regression models are multiplied by variable weighting distributions representing the assumed prevalence of that system configuration and the sum of these weighted savings values calculated to arrive at a single weighted annual energy savings result. The weighting distribution characteristics are informed by the 2015 HVAC1 Upstream Program Evaluation Report findings on unitary system fan speeds and economizer failure rates, and by our engineering judgment. The regression model characteristics and weighting for this equipment size class are presented below in Table 2.

Table 2. Measure unit configurations and weights for units under 55 kBtu/h

Measure Configuration	Weight Mean	Weight Standard Deviation	Weight Lower Bound	Weight Upper Bound
1-speed fan w/economizer	60%	30%	50%	70%
2-speed fan w/o economizer	5%	5%	0%	10%
2-speed fan w/economizer	15%	15%	10%	20%
1-speed fan w/o economizer	The weighting value for this configuration is equal to one minus the sum of all other weights, or 0, whichever is greater			

APPENDIX A provides more details about each input parameter used to run the eQUEST models.

4.3.1.2 Unitary systems between 65 kBtu/h and 134 kBtu/h

For 65 to 134 kBtu/h-sized unitary systems, the baseline unit has an efficiency rating of 11 EER; the Tier-2 unit has a rating of 12 EER. The baseline unitary system configuration is a unit with a 2-speed supply fan and an economizer. Fourteen regression models were developed for this equipment class, one for each system type and building vintage bin combination. Both configurations involved 2-speed supply fans, but one was modeled with an economizer and one without. As with the smaller systems, for each pair of baseline/measure runs with an economizer, the economizer functionality was held constant. The overall annual energy savings represent a weighted average of the regression model outputs; the weights equal the assumed prevalence of each system configuration. As is the case for the smaller equipment-size category, the weights of the system configurations and operating conditions are informed by a combination of the CPUC 2015 Impact Evaluation of Upstream Programs (HVAC1) report findings and our engineering judgment. The regression model characteristics and weighting for this equipment size class are presented in Table 3.

Table 3. Measure unit configurations and weights for units 65 kBtu/h to 134 kBtu/h

Measure Configuration	Weight Mean	Weight Standard Deviation	Weight Lower Bound	Weight Upper Bound
2-speed fan with economizer	0.750	0.750	0.650	0.850
2-speed fan w/o economizer	The weighting value for this configuration is equal to one minus the sum of all other weights, or 0, whichever is greater			

4.3.2 Monte Carlo analysis in Crystal Ball

Crystal Ball is a spreadsheet-based risk analysis program 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, Crystal Ball performs Monte Carlo simulations to generate hundreds or thousands of scenarios and produce the distribution profile of the forecast. Crystal Ball 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 Crystal Ball 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 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 Unitary systems under 55 kBtu/h

The resulting forecast is defined as the weighted average of the savings of the four scenarios. These weights are provided in Table 3 and in Table 37 of APPENDIX A. Table 4 presents the mean annual energy saving and standard deviation of the annual savings for system less than 55 kBtu/h in CZ08 resulting from this uncertainty analysis alongside the DEER 2015 measure energy savings value, while Figure 5 illustrates the probability distribution of annual savings distribution resulting from the analysis.

The uncertainty analysis produced a mean annual energy savings of 218.2 kWh/ton with a standard deviation of ±29.4 kWh/ton. The savings ranged from 137.7 kWh/ ton to 324.4 kWh/ ton. As a comparison, the DEER measure savings value is 327.8 kWh/ton, slightly above the upper end of the range of savings probability produced by this analysis.

Table 4. Savings and uncertainty of units under 55 kBtu/h at a small office building in CZ08

Annual Savings Ratio	Uncertainty Analysis	DEER
Normalized Annual Electric Savings, kWh/ton		
Mean annual savings	218.2	Tier-2 2015: 327.8
Standard deviation of mean annual savings	± 29.4	n/a

Figure 5. Distribution of savings for units under 55 kBtu/h at a small office building in CZ08

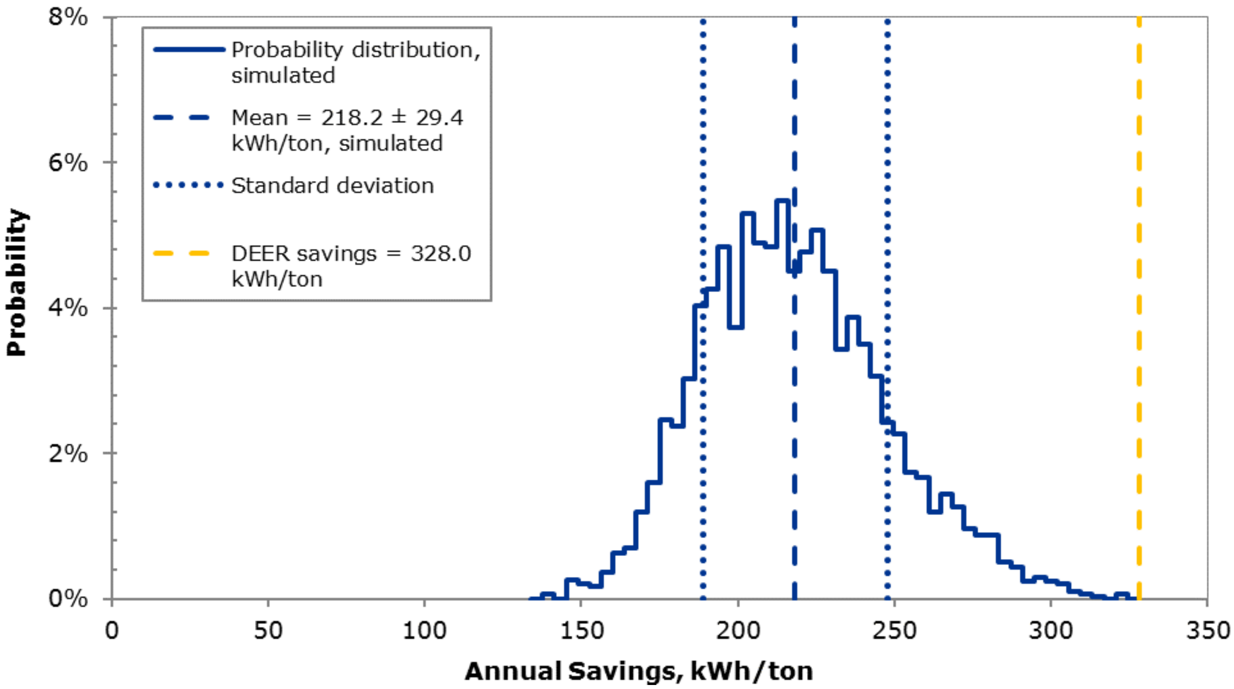


Table 5 presents the uncertainty analysis input variable ranked by the magnitude of their relative contribution to the savings variance for less than 55 kBtu/h systems in CZ08, while Figure 6 illustrates these relative contributions graphically.

The 1-speed fan & economizer configuration weight (21%), fan power index (21%), and the cooling setpoint (20%) input parameters were the top three positive contributors to variance in savings, collectively representing a 62% relative contribution. The relatively high sensitivity to fan power index suggests that attention should paid towards achieving installation of units with low static pressure and therefore a low fan power index. The range of the fan power indices used is based on HVAC 1 studies and is relatively wide; more data are needed to understand the probability distribution of this input parameter. Similarly, the analysis shows that the presence of an economizer, relative to a baseline unit which does not have an economizer, can greatly increase unit savings. The high sensitivity of savings due to the cooling setpoint shows that this input has a large impact on the cooling load imposed on the unit, which will impact measure savings.

In the study, the baseline and post fan power indexes are set identical. The higher the fan power index is, the more cooling load and more savings. As a result, fan power index has a positive correlation with savings. The cooling sizing ratio was the greatest negative contributor to savings variance at -13%, and this suggests that correct sizing of units has a non-trivial impact on achieved savings. The analysis also shows that, relative to a 1-speed fan baseline, there is an energy tradeoff for a 2-speed fan, as evident by the lower positive contribution to savings variance for the 2-speed fan & economizer configuration (12%) compared to the single speed equivalent and also seen in the minor contribution (0.5%) to savings resulting from the 2-speed fan & no economizer configuration. Part of reason is because of lower weight on 2-speed fan configuration.

Table 5. Contributors to savings uncertainty at units under 55 kBtu/h at small office building in CZ08

Input Parameters	Relative Contribution to Savings Variance
1-speed fan w/economizer weight, percent	21%
Fan power index, W/cfm	21%
Cooling setpoint, °F	20%
Cooling sizing ratio, dimensionless	-13%
2-speed fan w/economizer weight, percent	12%
Economizer high-temperature limit, °F	5.5%
Duct leakage rate, percent	5.2%
Building vintage bin	-1.1%
2-speed fan w/o economizer weight, percent	0.5%

Figure 6. Contributors to savings uncertainty for less than 55 kBtu/h RTU at small office building in CZ08

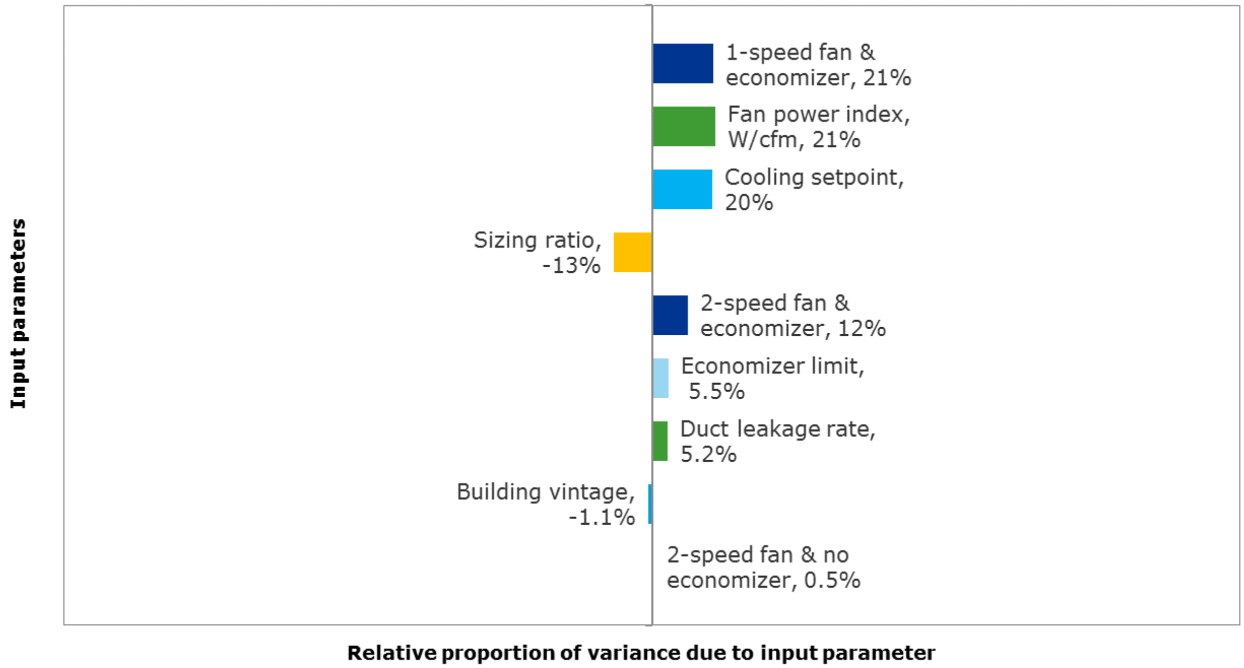


Table 6 presents the mean annual energy saving and standard deviation of the annual savings for system less than 55 kBtu/h in climate zone 12 (CZ12) resulting from this uncertainty analysis alongside the DEER 2015 measure energy savings value, while Figure 7 illustrates the probability distribution of annual savings distribution resulting from the analysis. The uncertainty analysis produced a mean annual energy savings of 178.0 kWh/ton with a standard deviation of ±29.2 kWh/ton. The savings ranged from 95.6 kWh/ ton to 285.3 kWh/ ton. As a comparison, the DEER measure savings value is 322.2 kWh/ton; this is well above the upper end of the range of savings probability produced by this analysis.

Table 6. Savings and uncertainty of units under 55 kBtu/h at small office building in CZ12

Annual Savings Ratio	Uncertainty Analysis	DEER
Normalized Annual Electric Savings, kWh/ton		
Mean annual savings	178.0	Tier-2 2015: 322.2
Standard deviation of mean annual savings	± 29.2	n/a

Figure 7. Distribution of savings at units under 55 kBtu/h at small office building in CZ12

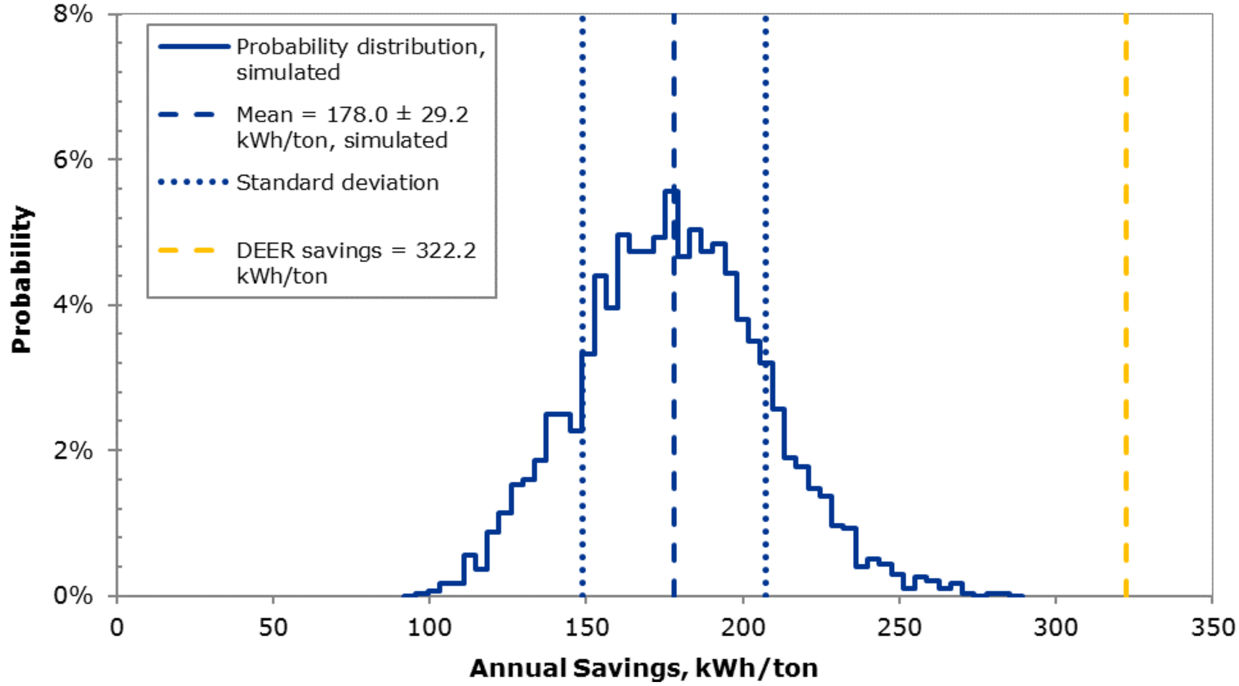


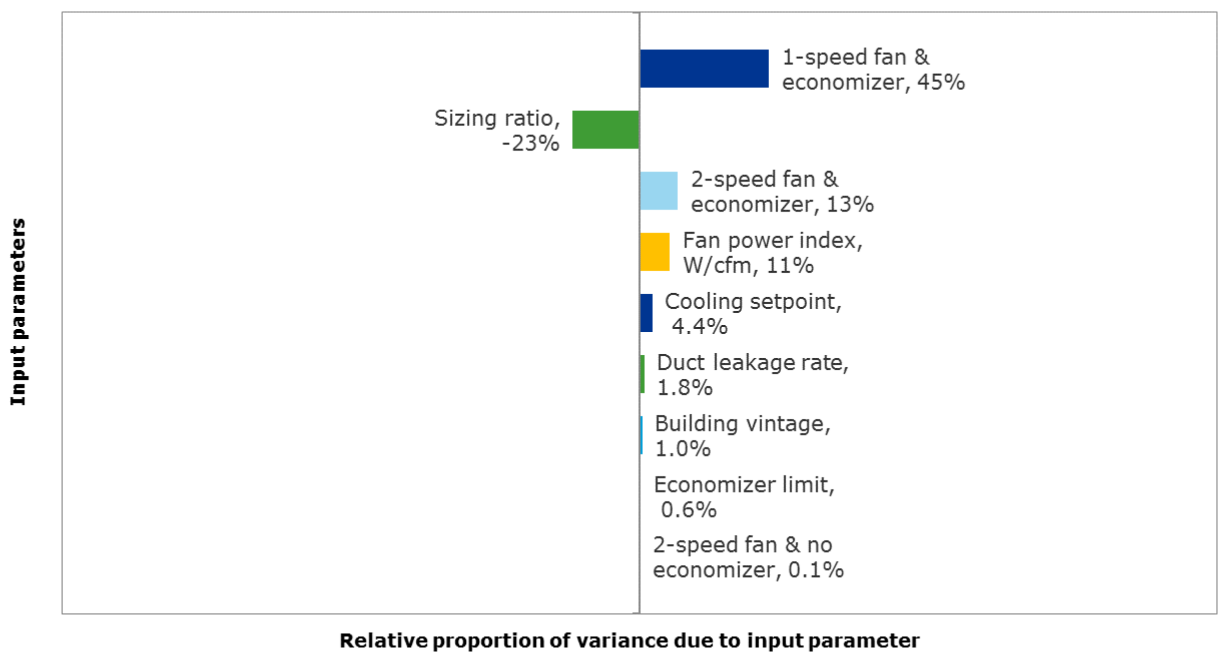
Table 7 presents the uncertainty analysis input variable ranked by the magnitude of their relative contribution to the savings variance for less than 55 kBtu/h systems in CZ12, while Figure 8 illustrates these relative contributions graphically.

The 1-speed fan & economizer configuration weight (45%) and cooling sizing ratio (-23%) had significant contributions to saving variance, accounting for over 68% of total variance in the CZ12 application. As with the CZ08 application, in CZ12 we see that the presence of an economizer, relative to a baseline unit which does not have an economizer, can greatly increase unit savings. The cooling setpoint (4.4%) and fan power index (11%) inputs exhibited less contribution to savings variance in CZ12 than in CZ08. The duct leakage rate (1.8%), building vintage (1.0%), economizer high-temperature limit (0.6%), and the 2-speed fan w/o economizer configuration weight (0.1%) all exhibited minor contributions to savings variance.

Table 7. Contributors to uncertainty at units under 55 kBtu/h at small office building in CZ12

Input Parameters	Relative Contribution to Savings Variance
1-speed fan w/economizer weight, percent	45%
Cooling-sizing ratio, dimensionless	-23%
2-speed fan w/economizer weight, percent	13%
Fan power index, W/cfm	11%
Cooling setpoint, °F	4.4%
Duct leakage rate, percent	1.8%
Building vintage bin	1.0%
Economizer high-temperature limit, °F	0.6%
2-speed fan w/o economizer weight, percent	0.1%

Figure 8. Contributors to uncertainty at units under 55 kBtu/h RTU at small office building in CZ12



4.4.2 Unitary systems between 65 kBtu/h and 134 kBtu/h

The resulting forecast is defined as the weighted average of the savings of the two scenarios. These weights are provided in Table 3. Table 8 presents the mean annual energy saving and standard deviation of the annual savings for 65 kBtu/h to 134 kBtu/h systems in CZ08 resulting from this uncertainty analysis alongside the DEER 2015 measure energy savings value, while Figure 9 illustrates the probability distribution of annual savings distribution resulting from the analysis. The uncertainty analysis produced a mean annual energy savings of 69.8 kWh/ton with a standard deviation of ±12.7 kWh/ton. The savings ranged from 36.4 kWh/ ton to 124.3 kWh/ ton. As a comparison, the DEER measure savings value is 61.3 kWh/ton, nearly identical to the mean savings produced by this analysis.

Table 8. Savings of units between 65 kBtu/h and 134 kBtu/h at small office building in CZ08

Annual Savings Ratio	Uncertainty Analysis	DEER	
Normalized Annual Electric Savings, kWh/ton			
Mean annual savings	69.8	Tier-2 2015:	61.3
Standard deviation of mean annual savings	± 12.7		n/a

Figure 9. Distribution of savings of units between 65 and 134 kBtu/h at small office in CZ08

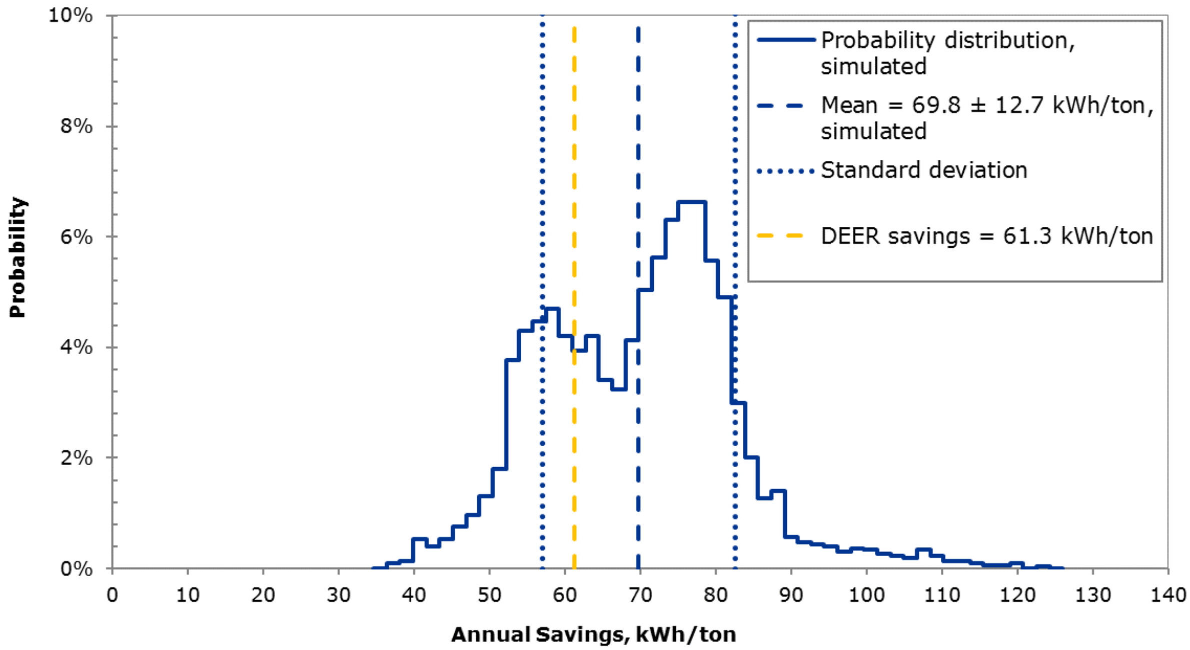


Table 9 presents the uncertainty analysis input variable ranked by the magnitude of their relative contribution to the savings variance for the 65 kBtu/h to 134 kBtu/h systems in CZ08 while Figure 10 illustrates these relative contributions graphically. The bimodal distribution is due to the existence of two economizer configurations.

The cooling sizing ratio (-42%) and cooling setpoint (-34%) inputs had significant, negative contributions to savings variance for the 65 kBtu/h to 134 kBtu/h systems in CZ08. The fan power index (12%) input was the greatest positive contributor to savings variance, although this impact was reduced relative to the sensitivity results for the less than 55 kBtu/h systems in CZ08. The contribution of the 2-speed fan with economizer configuration weight (-7.2%) input was moderate but negative, because greater electrical energy savings is achieved due to compressor efficiency when an economizer is not present or functioning properly for both measure and base cases, relative to measure and base configurations with working economizers. The building vintage (3.6%), duct leakage rate (-1.8%), and economizer high temperature limit (0.2%) inputs had only minor contributions to savings variance.

Table 9. Contributors to savings uncertainty of units between 65 kBtu/h and 134 kBtu/h at small office building in CZ08

Input Parameters	Relative Contribution to Savings Variance
Cooling sizing ratio, dimensionless	-42%
Cooling setpoint, °F	-34%
Fan power index, W/cfm	12%
2-speed fan w/economizer weight, percent	-7.2%
Building vintage bin	3.6%
Duct leakage rate, percent	-1.8%
Economizer high temperature limit, °F	0.2%

Figure 10. Contributors to savings uncertainty of units between 65 kBtu/h and 134 kBtu/h at small office building in CZ08

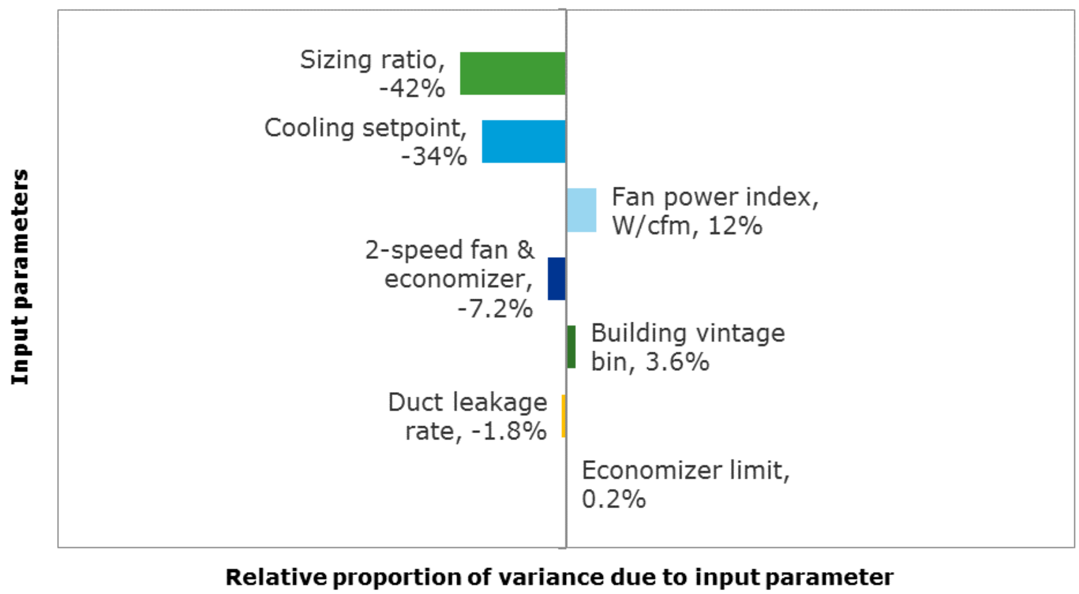


Table 10 presents the mean annual energy saving and standard deviation of the annual savings for 65 kBtu/h to 134 kBtu/h systems in CZ12 resulting from this uncertainty analysis alongside the DEER 2015 measure energy savings value, while Figure 11 illustrates the probability distribution of annual savings distribution resulting from the analysis. The uncertainty analysis produced a mean annual energy savings of 59.8 kWh/ton with a standard deviation of ±10.1 kWh/ton. The savings ranged from 32.3 kWh/ ton to 106.6 kWh/ ton. As a comparison, the DEER measure savings value of 53.0 kWh/ton, similar to the mean savings produced by this analysis.

Table 10. Savings and uncertainty of units between 65 kBtu/h and 134 kBtu/h at small office building in CZ12

Annual Savings Ratio	Uncertainty Analysis	DEER
Normalized Annual Electric Savings, kWh/ton		
Mean annual savings	59.8	Tier-2 2015: 53.0
Standard deviation of mean annual savings	± 10.1	n/a

Figure 11. Distribution of savings of units between 65 kBtu/h and 134 kBtu/h at small office building in CZ12

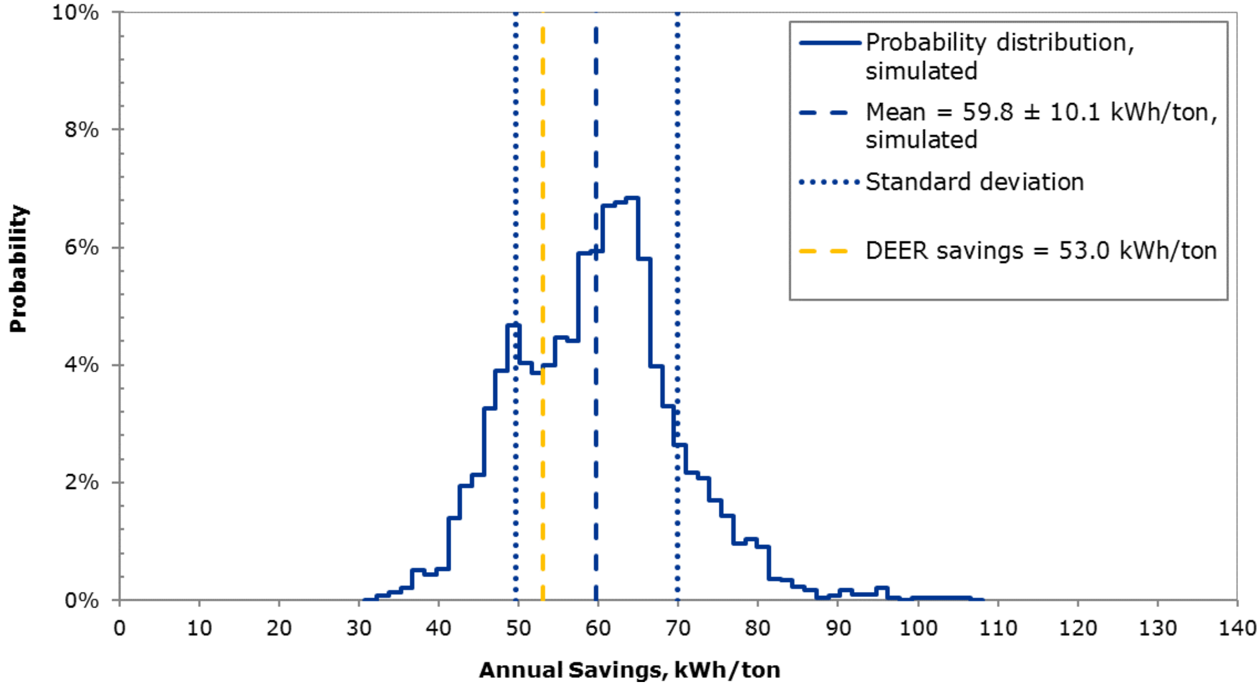


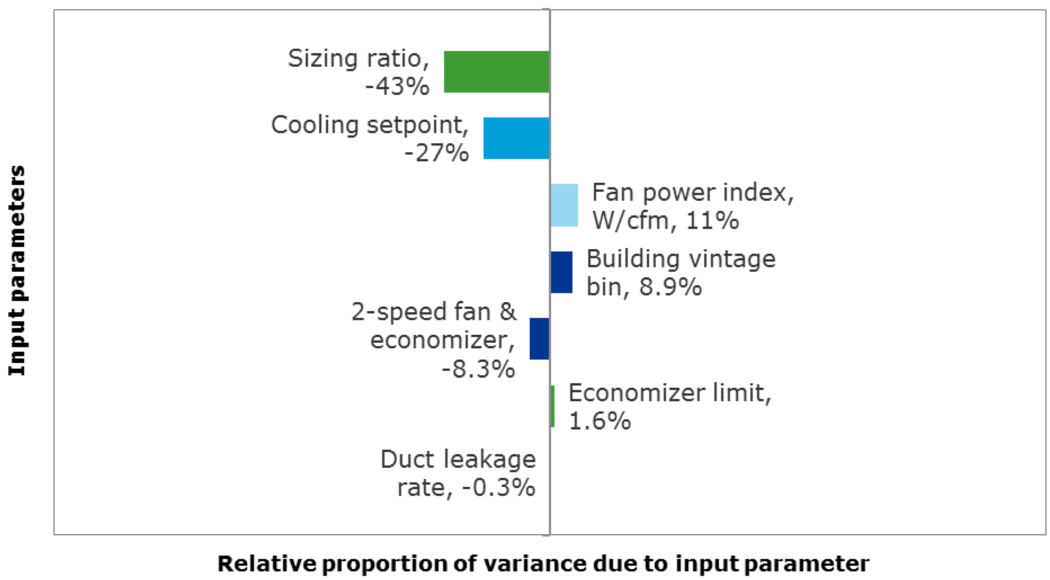
Table 11 presents the uncertainty analysis input variable ranked by the magnitude of their relative contribution to the savings variance for the 65 kBtu/h to 134 kBtu/h systems in CZ08 while Figure 12 illustrates these relative contributions graphically.

As was the result in CZ08, the cooling sizing ratio (-43%) and cooling setpoint (-27%) inputs also had significant, negative contributions to savings variance for the 65 kBtu/h to 134 kBtu/h systems in CZ12. The fan power index (11%) input was the greatest positive contributor to savings variance, and was of a similar magnitude to the result for the less than 55 kBtu/h systems in CZ12. The building vintage bin exhibited a moderate, positive contribution to savings variance (8.9%), and while difficult to fully define, this increase in per ton savings likely driven by the decreasing unit capacities with increasing (later) building vintage bins. The contribution of the 2-speed fan with economizer configuration weight (-8.3%) input was again moderate but negative. The duct leakage rate (-0.3%), and economizer high temperature limit (1.6%) inputs had only minor contributions to savings variance.

Table 11. Contributors to uncertainty of units between 65 kBtu/h and 134 kBtu/h at small office building in CZ12

Input Parameters	Relative Contribution to Savings Variance
Cooling sizing ratio, dimensionless	-43%
Cooling setpoint, °F	-27%
Fan power index, W/cfm	11%
Building vintage bin	8.9%
2-speed fan w/economizer weight, percent	-8.3%
Economizer high-temperature limit, °F	1.6%
Duct leakage rate, percent	-0.3%

Figure 12. Contributors to savings uncertainty of 65 kBtu/h to 134 kBtu/h RTU at small office building in CZ12



4.5 Conclusions and recommendations

The findings of the unitary systems uncertainty analyses are as follows:

- The DEER deemed savings for unitary systems less than 55 kBtu/h were considerably higher than the mean savings yielded by the simulations. In both simulations for unitary systems of this size, the DEER savings values lie just beyond the upper limit of the simulated probability distribution range and well beyond one standard deviation away from the associated mean savings.
- The DEER deemed savings for unitary systems between 65 and 134 kBtu/h were generally in alignment with the uncertainty analysis results for those measures, falling within one standard deviation of the simulated mean savings.

- The cooling sizing ratio input exhibited moderate to strong negative contribution to savings variance, indicating that normalized savings decreases with unit oversizing.
- The fan power index input exhibited moderate to strong positive contribution to savings variance, indicating that—for unitary systems with high static pressure and correspondingly high fan power—the increased fan-motor waste heat increases the cooling load and yields greater savings (due to the increased cooling performance of the measure unit).
- When the baseline condition does not include an economizer, as is the case for those units less than 55 kBtu/h, an economizer on the measure unit greatly increases the savings. This finding is supported by the strong, positive contributions to savings variance of the one- and two-speed fan and economizer-configuration weight inputs.
- The one-speed fan configurations had greater positive contributions to savings variance relative to like two-speed fan configurations. This is probably a result of the higher distribution weighting of the one-speed fan configurations relative to the two-speed fan configurations.
- The cooling setpoint input's contribution to savings variance was strong and negative for unitary systems between 65 and 134 kBtu/h in both climate zones, while it was strong and positive for unitary systems less than 55 kBtu/h in CZ08 but only moderate and positive for those in CZ12. In general, a higher setpoint would reduce the cooling load and therefore reduce the savings, indicated by the negative contributions to savings variance in the larger units, but there is also an increase in savings potential with the higher setpoint as it affords increased opportunity for free cooling by the economizer, as indicated by the positive contributions to savings variance in the smaller units.
- The duct leakage rate, building vintage bin, and economizer high temperature limit inputs exhibited moderate to weak contributions to savings variance across measures and climate zones.

Recommendations for unitary systems include:

- The assumptions used by the DEER and Ex Ante Review teams to develop savings values for the less than 55kBtu/h unitary systems should be reevaluated in light of the data and results produced by this and the other 2013-15 CPUC HVAC reports.
- Across the different unitary sizes and climate zone combinations explored in this analysis, the cooling sizing ratio, cooling setpoint, and fan power index inputs exhibited moderate to strong contributions to saving variance. The DEER and the Ex Ante Review teams should aim to reduce the uncertainty of the inputs showing moderate to strong contributor to variance to reduce the overall uncertainty of the savings estimates. More data collections are needed to reduce the uncertainty.
- The presence of a correctly-functioning economizer can have large impacts on energy consumption and on the savings realized by the improved mechanical cooling unit efficiency. The DEER and Ex Ante Review teams should aim to refine their inputs and assumptions around the installation and functionality of economizers at unitary systems, again using data and results produced by this and the other 2013-15 CPUC HVAC reports, to further reduce uncertainty and refine the savings estimates.

5 NONRESIDENTIAL AIR-COOLED CHILLERS

In this section, we discuss the uncertainty of savings for the types of deemed, nonresidential, air-cooled chillers incentivized in the 2013, 2014, and 2015 program years and commonly used for space cooling. Air-cooled chillers were studied in the 2013-14 Impact Evaluation of Upstream HVAC Programs (HVAC1) where they were found to have the lowest realization rate of all measure groups at 18%.[28] The data and findings from the HVAC1 report are the source for many of the inputs into this uncertainty analysis. This report section 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 section, we summarize the findings and present our recommendations.

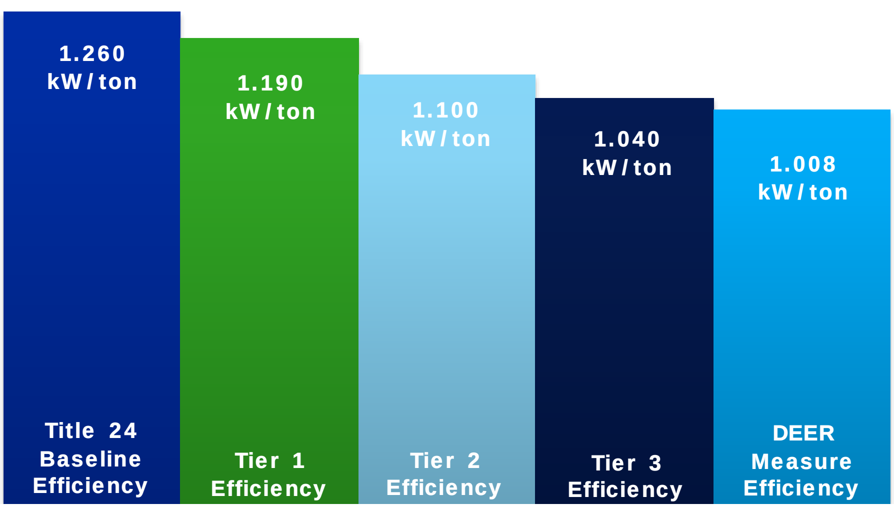
5.1 Measure description

Air-cooled chiller measures yield savings due to installing constant-speed, air-cooled chillers with efficiency levels that exceed the California Title 24 energy code requirements. The programs recognize three efficiency tiers for air-cooled chillers:

- Tier-1 Chiller: Minimum full-load cooling efficiency of 10.07 EER (1.19 kW/ton) or integrated part-load value $(IPLV)_{EER}$[29] of 14.29 (0.84 kW/ton)
- Tier-2 Chiller: Minimum full-load cooling efficiency of 10.90 EER (1.10 kW/ton) or $IPLV_{EER}$ of 15.00 (0.80 kW/ton)
- Tier-3 Chiller: Minimum full-load cooling efficiency of 11.50 EER (1.04 kW/ton) or $IPLV_{EER}$ of 16.00 (0.75 kW/ton)

The workpaper savings were derived from the DEER savings after applying estimated scaling factors for the different measure chiller efficiency tiers. Figure 13 illustrates the relative efficiency levels of the baseline and measure unit efficiency levels.

Figure 13. Full-load chiller efficiency levels[30]



[28] Impact Evaluation of 2013-14 Upstream HVAC Programs (HVAC1), California Public Utilities Commission, pp.48.

[29] Integrated Part Load Value (IPLV) is a performance characteristic developed by the Air-Conditioning, Heating and Refrigeration Institute (AHRI) to describe the performance of a chiller capable of capacity modulation as per AHRI Standard 550/590-2003.

[30] For PG&E's calculations, all efficiencies—with the exception of the DEER measure efficiency—were rounded to 1/100 kW/ton whereas SCE used efficiencies rounded to 1/1,000 kW/ton.

5.2 Ex ante savings review

DNV GL identified and reviewed two workpapers pertaining to the measure: one from PG&E (PGECOHVC120 Air-Cooled Packaged Chillers Rev 3, 8/28/12) and one from SCE (SCE13HC030 Air-Cooled Packaged Chillers Rev 0, 5/30/2012).[31] Since both workpapers build on the 2011 DEER values, a discussion about the DEER measures precedes the workpaper descriptions.

5.2.1 2011 DEER measure

The DEER measure codes for two types of air-cooled chillers—reciprocating- and screw-type chillers—are D03-41 and D03-114, respectively. That said, the PG&E and SCE workpapers deviate from the DEER savings values by applying scaling factors. Both workpapers defend the deviations using the following reasons:

- DEER savings are based on installing a chiller with an efficiency of 11.9 EER (1.008 kW/ton) that yields savings equaling 20% of the baseline energy consumption. The workpaper reported finding, however, only one manufacturer's chillers meet the required efficiency. Hence, it was concluded that the DEER savings do not adequately reflect products currently on the market.
- DEER savings are based on the difference in efficiency from installing air-cooled chillers comprised of either reciprocating- or screw-type compressors. The workpaper reported finding, however, that the majority of air-cooled chillers available in the market contained either screw- or scroll-type compressors and that only a very small percentage contained reciprocating compressors.

For these reasons, both the PG&E and SCE workpapers use deemed annual electric savings and peak demand savings that are lower than both the 2011 DEER and 2014 DEER savings.

5.2.2 PG&E workpaper

The workpaper assumed a Replace-on-Burnout (ROB) type of retrofit and, hence, used the minimum chiller efficiencies required by 2008 Title 24[32,33] as the baseline condition. For air-cooled chillers with condensers of all capacities, PG&E's program uses a baseline full-load coefficient of performance (COP) of 2.8 (1.26 kW/ton) or a baseline part-load $IPLV_{COP}$ of 3.05 (1.15 kW/ton). Using these baselines, full-load unit energy savings were determined for 11 building types across nine climate zones for both Tier-1 and Tier-2 chillers. The unit energy annual savings were reported in kWh/ton and the peak demand unit energy savings were reported in kW/ton.

Using full load chiller efficiency, PG&E established scaling factors—by which the annual and peak demand DEER savings were multiplied—based on the equation that follows and as shown in Table 12:

PG&E's scaling factor, by tier $$= \frac{Title\ 24\ Efficiency - Minimum\ Program\ Efficiency_{Tier}}{Title\ 24\ Efficiency - DEER\ Measure\ Efficiency}$$

[31] Both workpapers are located at: http://www.deeresources.com/index.php/non-deer-work-paper-values-13-14.

[32] Title 24, TABLE 112-D WATER CHILLING PACKAGES – MINIMUM EFFICIENCY REQUIREMENTS was referenced for air-cooled chillers with and without condensers. In this edition of Title 24, $IPLV_{COP} = 0.10COP_{100\%} + 0.42COP_{75\%} + 0.45COP_{50\%} + 0.12COP_{25\%}$. Subsequent editions used $IPLV_{EER} = 0.10EER_{100\%} + 0.42EER_{75\%} + 0.45EER_{50\%} + 0.12EER_{25\%}$.

[33] Later workpaper revisions are based on 2013 Title 24.

Table 12. PG&E workpaper scaling factors

Description	Tier-1	Tier-2	Tier-3	Units
Scaling Factor	0.278	0.635	0.873	dimensionless

For each efficiency tier, these scaling factors were used to scale the 2011 DEER measure savings, for both annual electric and peak demand savings.

5.2.3 SCE workpaper

Again, the baseline used for air-cooled chillers was the 2008 Title 24 minimum efficiency standard of 2.8 COP and 3.05 $IPLV_{COP}$. For 2013-14 program years, the measure case must meet either the EER or the IPLV requirements described in Section 5.1. The SCE workpaper justifies accepting units that meet either the minimum full-load or the minimum part-load efficiency requirement by pointing out that manufacturers usually design units to emphasize one efficiency type or the other. Hence, those units that have very high part-load efficiency may fall slightly short of the full-load efficiency requirement, but are still a suitable choice at more moderate climate zones.

The program delivery method is “Upstream Programs – Upstream incentives.” The incentives are paid by the upstream prescriptive program at all building and vintage types for ROB cases. The workpaper savings values were taken from 2011 DEER using the following measure codes: NE-HVAC-Chlr-AirPkgRecip-AllSizes-1p008kwpton and NE-HVAC-Chlr-AirScrew-AllSizes-1p008kwpton. As was the case for the PG&E workpaper savings, SCE scaled the DEER measure savings using a scaling factor to account for the difference between the DEER measure efficiency and the program measure efficiency tiers.

To determine the annual savings for EER-qualifying measures, SCE established scaling factors—by which the annual DEER savings were multiplied—based on the equation that follows:

$$\text{SCE's scaling factor, by tier} = \frac{Title\ 24\ Efficiency - Average\ Program\ Efficiency_{Tier}}{Title\ 24\ Efficiency - DEER\ Measure\ Efficiency}$$

The primary difference between these equations and those used by PG&E is that SCE used the average efficiency across each tier in place of PG&E’s use of the minimum efficiency of each tier.

In contrast, savings for IPLV-qualifying units were calculated by multiplying the annual cooling-load hours, in hours, by ΔkW/ton. The annual cooling-load hours were derived using DEER 2008 MASControl files. Then, to establish a single savings value for each building-type/climate-zone combination, a weighted average of the EER-qualifying savings and the IPLV-qualifying savings was taken using an assumed proportion of each qualifying category.

The scaling factors used by SCE are provided in Table 13.

Table 13. SCE workpaper scaling factors

Description	Tier-1	Tier-2	Tier-3	Units
Scaling Factor	0.399	0.733	0.857	dimensionless

For all units, whether EER-qualifying or IPLV-qualifying, peak demand savings were determined by multiplying the SCE scaling factors by the DEER 2011 peak demand values (DEER11 v4.0 & DEER08 MASControl Files).

5.2.3.1 SCE tracking data analysis

Data from the 2010-12 SCE Upstream HVAC Programs show that the average efficiency for equipment submitted in Tiers 1-3 are higher than the minimum qualifying efficiency requirements. For example, a Tier-1, EER-qualifying chiller has a minimum requirement of 10.07 EER, but program data show that such installed equipment has an average EER of 10.37. Similarly, a Tier-3, IPLV-qualifying chiller has a minimum tier requirement of 16 IPLV, but program data show that such installed equipment has an average IPLV of 17.30.

5.3 Uncertainty analysis steps

As was the case for the referenced workpapers and the DEER savings values and prototypes, this uncertainty investigation focused on the savings resulting from the full-load efficiency and operation of chillers. Although a more recent workpaper added methodology to determine the savings resulting from the part-load efficiencies and operations of chillers,[34] our analysis does not consider those. This is an important distinction because the full-load savings are significantly lower than the part-load savings.

Unlike our analysis for other measures, there were no opportunities to draw from field or laboratory measurement data gathered in other HVAC Roadmap evaluations since chillers were evaluated using inspections-only during the 2013-14 program years. Instead, it was necessary to rely upon the engineering judgment of DNV GL and CPUC consultants to inform the distributions of input parameters.

5.3.1 eQUEST-prototype batch processing

We simulated energy savings directly from prototype models using a batch process. This method provided an efficient method of producing modeled savings across a wide range of simulation model inputs. The analysis focused on the two most prevalent program building-type/climate-zone combinations: a large office building type in Climate Zone (CZ) 03 in PG&E territory and a small office building type in CZ08 in SCE territory. Building vintage bin 2002-05 was selected for analysis as significant variations by building vintage bin were not anticipated.

The seven model input variables with the greatest impact on modeled savings were chosen to be investigated for this analysis. The model input variables are:

- Chiller minimum ratio: the minimum fraction of rated load at which the chiller can operate continuously
- Minimum condensing temperature: the minimum allowable condensing temperature setpoint
- Chilled-water supply temperature reset range
- Cold duct-supply air temperature reset range
- Building temperature cooling temperature schedules

[34] PGECOHVC120 Air-Cooled Packaged Chiller, Revision # 4, 07/14/2014

- Chiller sequencing strategies
- Full-load chiller efficiency, using the conversion of EER into the dimensionless Electrical Input Ratio (EIR) eQUEST variable[35]

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

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 electric savings, which was plotted against the simulated annual electric savings.

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

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

Where

Y represents annual electric savings normalized by chiller capacity, kWh/ton

X_1 represents the building temperature cooling/heating temperature schedules

X_2 represents the chiller minimum ratio

X_3 represents the minimum condensing temperature

X_4 represents the chilled water (CHW) supply temperature reset range

X_5 represents the cold duct supply air temperature reset range

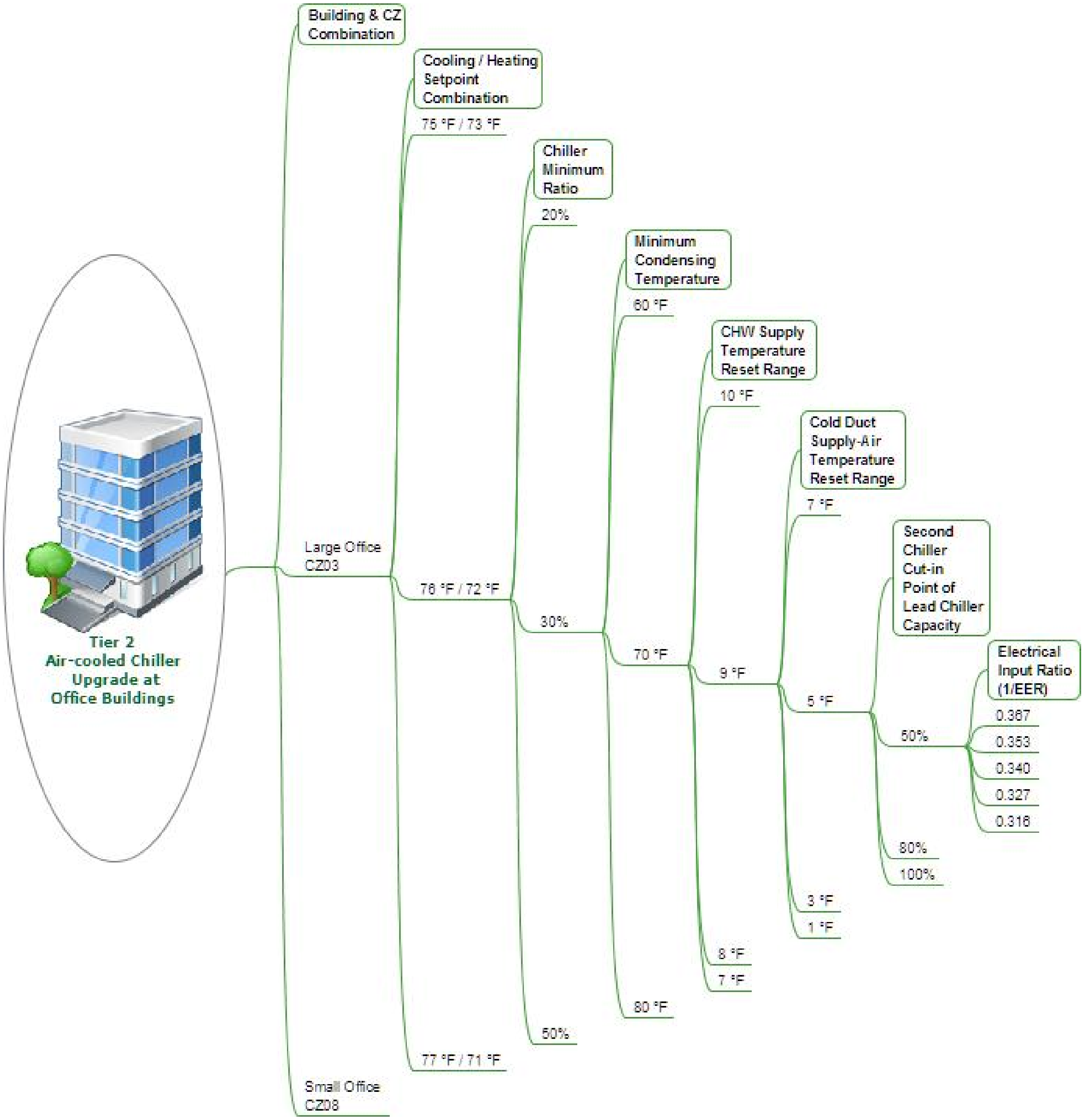
X_6 represents the chiller sequencing strategies

X_7 represents the full-load chiller efficiency (EIR).

The corresponding coefficients for this measure are provided in APPENDIX A. A graphical depiction of the various combinations of input parameters is provided in Figure 14.

[35] The distributions of tier-level, full-load efficiencies were based upon the Upstream Chiller Applications data for 2013-2014 Upstream Program for three-phase, air-cooled chillers—as embedded in the SCE workpaper Revision 1. Tier-level efficiency distributions were calculated using the data for eligible and approved applications for both SCE and PG&E with a sales date from 1/1/2013 to 2/4/2014 for units qualifying under EER, under IPLV, or under both EER and IPLV.

Figure 14. Input parameters of eQUEST batch runs for air-cooled chillers



5.3.2 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, in this case, nearly 6,500 combinations of the selected input parameters. These simulations were used to create savings distribution and sensitivity analysis profiles.

The seven input parameter distributions and weights can be found in APPENDIX A. The distributions and weightings were chosen using practical limitations and expected operating conditions based on the experience of DNV GL staff and CPUC advisors. While the mean values of the input parameter distributions have a significant influence on the average savings yielded by the uncertainty analysis, they also greatly influence the shape of the distribution of the energy savings. The assignment of these distributions is critical to determining the overall uncertainty in the results and tabulating the relative contribution of each input to the overall uncertainty.

5.4 Uncertainty analysis results

Uncertainty and sensitivity analyses were conducted for two specific cases: constant-speed, air-cooled chillers in a prototypical large office building in CZ03—to represent a PG&E program case—and for constant-speed, air-cooled chillers in a prototypical small office building in CZ08—to represent an SCE program case. The results of these analyses are presented in the following sections. Although analyses were performed for Tier-1, Tier-2, and Tier-3 chillers, we present the results for Tier-2 chillers in this section; those for Tier-1 and Tier-3 chillers are provided in APPENDIX B.

5.4.1 Air-cooled chillers at large office buildings in CZ03

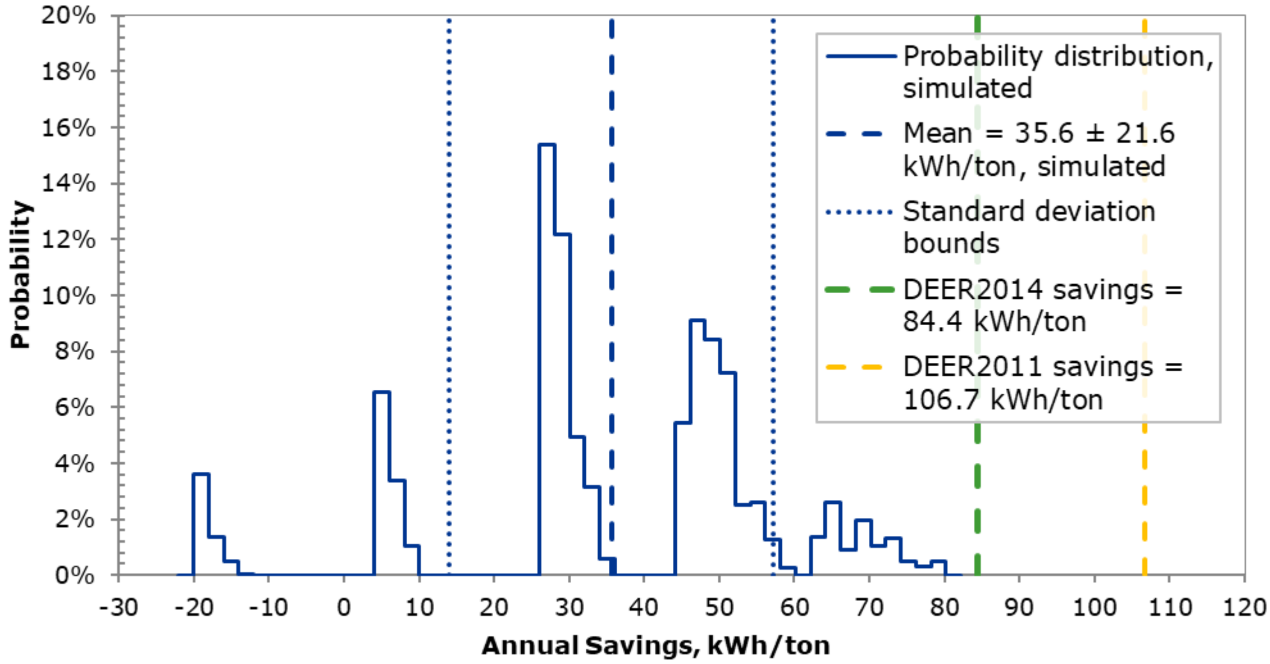
For a Tier-2 chiller measure at the large office building type in CZ03, the uncertainty analysis produced a mean annual energy savings of 35.6 kWh/ton and a standard deviation of ± 21.6 kWh/ton. The savings ranged from -20.0 kWh/ton to 80.2 kWh/ton. To allow for a comparison of these results to DEER savings, the DEER 2011 and DEER 2014 savings were multiplied by PG&E's Tier-2 scaling factor to yield 106.7 kWh/ton and 84.4 kWh/ton, respectively.[36] We applied the PG&E scaling factor to this measure application, large office in CZ03, because it was the most prevalent building type/ climate zone combination in the tracking data for PG&E's program and because CZ03 lies entirely within PG&E's service territory. A summary of the Crystal Ball results is presented in Table 14 and the probability distribution of the resulting savings are shown in Figure 15.

Table 14. Savings and uncertainty of Tier-2 air-cooled chillers at large office buildings in CZ03

Tier-2 Measure Efficiency Results	Uncertainty Analysis Savings	Scaled DEER2011 Savings	Scaled DEER2014 Savings
Normalized Annual Electric Savings, kWh/ton			
Mean annual savings	35.6	106.7	84.4
Standard deviation of mean annual savings	± 21.6	n/a	n/a

[36] The uncertainty analysis results are compared to the full load (EER) component of the DEER2011 and 2014 measure savings values, but modified using PG&E's Tier-2 adjustment factor of 0.635. The earlier version (R3) of the workpapers were based on DEER2011 savings values, while an updated version (R4) of the workpapers are based on DEER2014 values. The decrease in savings from DEER2011 to DEER2014 measures reflects a change from 2008 Title 24 code minimum efficiency to the 2013 Title 24 value, which slightly increases the code baseline chiller efficiency.

Figure 15. Probability distribution of annual savings of Tier-2 air-cooled chillers at large office buildings in CZ03



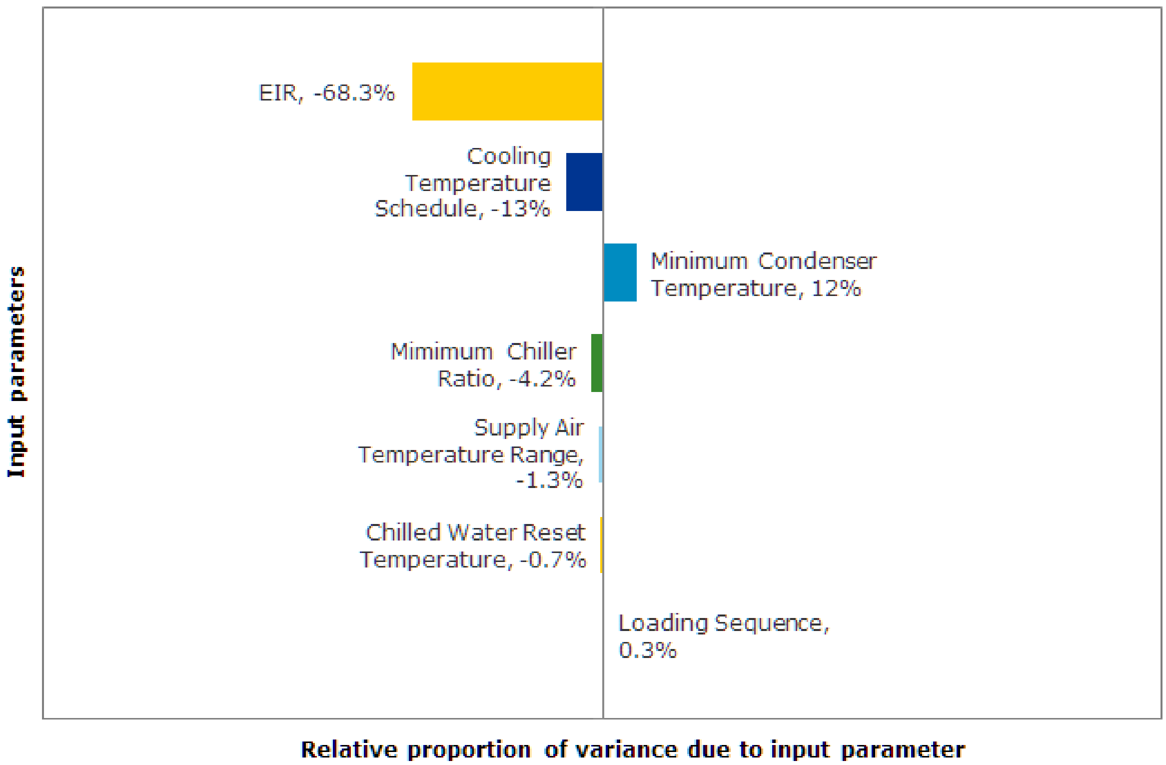
The results of the uncertainty analysis show a broad range of probable energy savings based on the input parameter variables and distributions tested. The workpaper-adjusted DEER 2011 savings value falls well outside the upper bounds of the results, while the workpaper-adjusted DEER 2014 savings value lies near the upper range of the uncertainty analysis distribution and well outside of one standard deviation from the mean savings value result.

The sensitivity analysis results are shown in Table 15 and Figure 16, ranked by the relative contribution of each modeled input parameter to the total savings variance. The EIR full-load cooling efficiency (-68%), the cooling temperature schedule (-13%), and the minimum condensing temperature (12%) were the leading contributors to savings variance. These were followed by the minimum chiller ratio (-4.2%). The supply air-temperature range, the chilled-water reset temperature, and the chiller loading sequence contributed little to the variance of the savings.

Table 15. Ranked contributors to variance for Tier-2 air-cooled chillers applied to large office building type in CZ03

Input Parameters	Relative Contribution to Savings Variance
Full-load cooling efficiency (EIR)	-68%
Cooling temperature schedule bin	-13%
Minimum condenser temperature, °F	12%
Minimum chiller ratio, dimensionless	-4.2%
Supply-air temperature range, °F	-1.3%
Chilled-water reset temperature, °F	-0.7%
Loading-sequence bin	0.3%

Figure 16. Tier-2 Air-cooled chiller relative sensitivity of input parameters on annual energy savings uncertainty for air-cooled chillers applied to large office building type in CZ03



5.4.2 Air-cooled chillers at small office buildings in CZ08

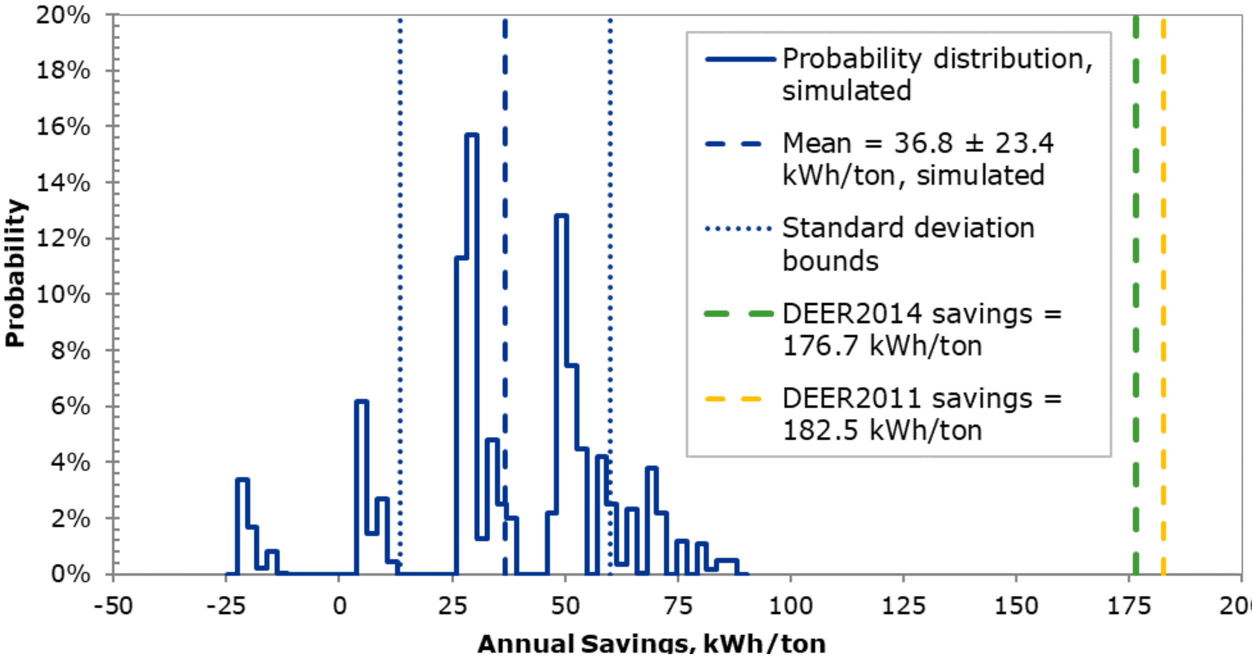
For a Tier-2 chiller at a small office building type in CZ08, the uncertainty analysis produced a mean annual energy savings of 36.8 kWh/ton. The savings ranged from -22.6 kWh/ ton to 88.1 kWh/ ton with a standard deviation of ± 23.4 kWh/ton.

To allow for a comparison of these results to DEER savings, the DEER 2011 and DEER 2014 savings were multiplied by SCE's Tier-2 scaling factor to yield 182.5 kWh/ton and 176.7 kWh/ton, respectively.[37] We applied the SCE scaling factor to this measure application—at a small office building type in CZ08—because it was the most prevalent building type/climate-zone combination in the tracking data for SCE's program and CZ08 lies entirely within SCE's service territory. A summary of the Crystal Ball results is presented in Table 16 and the probability distribution of the resulting savings are shown in Figure 17.

Table 16. Savings and uncertainty of Tier-2 air-cooled chillers at small office buildings in CZ08

Results	Tier-2 Uncertainty Analysis	Tier-2 Scaled DEER2011	Tier-2 Scaled DEER2014
Normalized Annual Electric Savings, kWh/ton			
Mean annual savings	36.8	182.5	176.7
Standard deviation of mean annual savings	± 23.4	n/a	n/a

Figure 17. Probability distribution of annual savings of Tier-2 air-cooled chillers at small office buildings in CZ08



The results of the uncertainty analysis for the measure at a small office building in CZ08 show a broad range of savings with a somewhat skewed distribution of probable energy savings based on the distributions of input parameters tested. In this case, however, the SCE-adjusted DEER 2011 and DEER 2014 measure

[37] The uncertainty analysis results are compared to the full load (EER) component of the DEER2011 and 2014 measure savings values, but modified using SCE's Tier-2 adjustment factor of 0.733. The earlier version (R0) of the workpapers were based on DEER2011 savings values, while an updated version (R1) of the workpapers are based on DEER2014 values. The decrease in savings from DEER2011 to DEER2014 measures reflects a change from 2008 Title 24 code minimum efficiency to the 2013 Title 24 value, which slightly increases in the code baseline chiller efficiency.

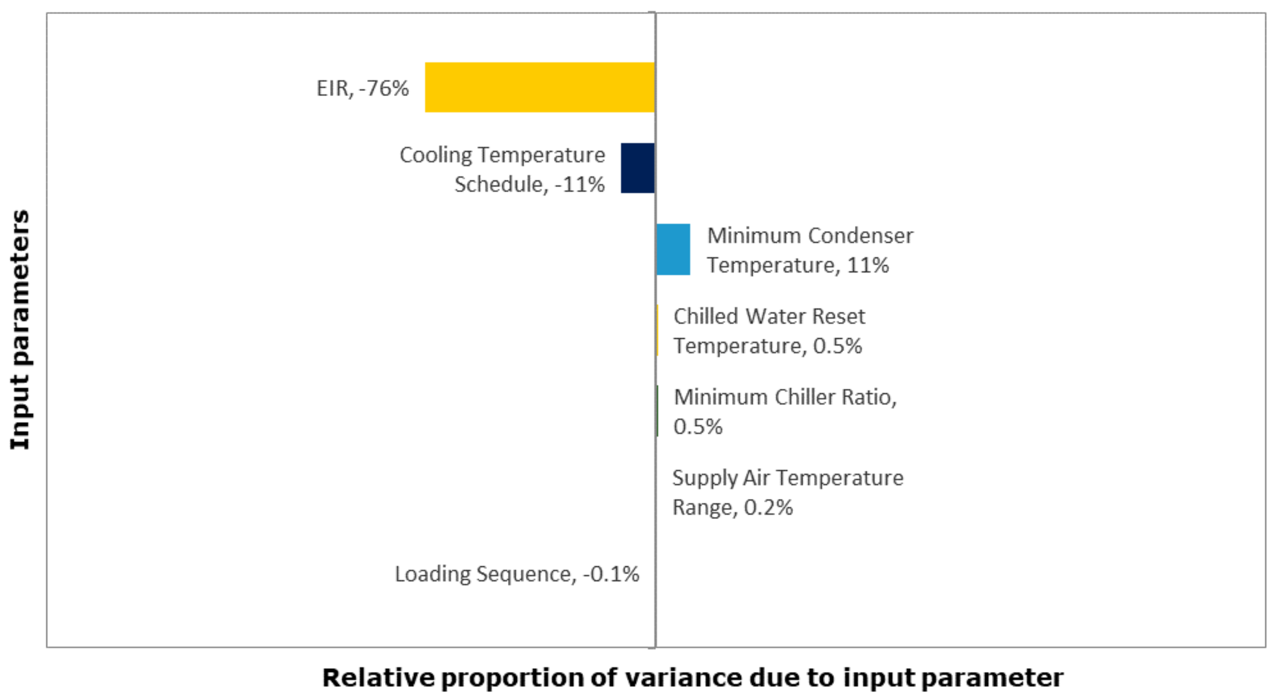
savings values nearly twice the upper bounds of the savings distribution produced by the uncertainty analysis.

The sensitivity analysis results are shown in Table 17 and Figure 18, ranked in order of their magnitude of relative contribution to the savings variance. The full-load cooling efficiency, using EIR, (-76%), the cooling-temperature schedule (-11%), and the minimum condensing temperature (11%) were the leading contributors to savings variance. In this case, the chilled-water reset temperature, the minimum chiller ratio, the supply-air temperature range, and the chiller loading sequence contributed minimally to the variance of savings.

Table 17. Ranked contributors to variance for Tier-2 air-cooled chillers at small office building in CZ08

Input Parameters	Relative Contribution to Savings Variance
Full-load cooling efficiency (EIR)	-76%
Cooling-temperature schedule bin	-11%
Minimum condenser temperature, °F	-11%
Chilled-water reset temperature, °F	0.5%
Minimum chiller ratio, dimensionless	0.5%
Supply-air temperature range, °F	0.2%
Loading-sequence bin	-0.1%

Figure 18. Sensitivity of input parameters for Tier-2 air-cooled chillers at small office building in CZ08



5.5 Conclusions and recommendations

The findings of the air-cooled chiller uncertainty analyses are as follows:

- Both the DEER2011 and DEER2014 deemed savings for Tier-2 chillers were considerably higher than those yielded by the simulations, however this analysis is intended to highlight the uncertainty of savings and drivers of savings variance, not to supplant the chiller measure savings evaluated under the 2013-14 Impact Evaluation of Upstream HVAC Programs (HVAC1).
- Among the seven input parameters studied, the full-load cooling efficiency (EIR) and the cooling temperature schedule are the leading drivers of uncertainty around the simulated annual savings for air-cooled chillers, with the cooling efficiency far outweighing the combined contributions to variance from all of the other input parameters.
- The part-load (IPLV) efficiency qualification pathway results in some tier-qualifying chiller units having full-load efficiency ratings that are below the Title-24 code minimum. In these instances, the energy savings at full-load operation is negative when compared to this baseline.
- This analysis also highlights the limitations of the DEER savings calculation in assessing part-load characteristics due to lack of data to support efficiency performance curves that deviate from the generic eQUEST model curve.

Recommendations for air-cooled chillers include:

- Given that the mean savings produced by the uncertainty analyses were significantly lower than the workpaper-adjusted DEER2014 savings, consider revising the deemed annual unit energy savings.
- Consider adding a retro-commissioning measure to guide building equipment managers around those operating setpoints most critical to energy savings outcomes.
- Presently, EER and IPLV values are not collected by tracking data. Instead, they are clustered by tiers. Furthermore, chillers were not evaluated for the most recent program cycle and there are no recent field data. Hence, there is an absence of EER and IPLV data for program participants. Going forward, we recommend gathering these values in the tracking data.
- For future evaluation cycles, consider feasibility of gathering information about critical operating setpoints—including the chilled-water supply temperature, the space-cooling setpoint, and the minimum condensing temperature of the chiller—to reduce uncertainty of annual savings. Of course, better still would be to gather this information in the program tracking data or through other research efforts.

6 NONRESIDENTIAL RCA MEASURE

This section presents very different types of uncertainty analyses pertaining to the nonresidential refrigerant charge adjustment (RCA) measure for air-cooled, direct expansion (DX) air conditioning units. RCA is typically bundled in Quality Maintenance (QM) programs such as AirCare Plus by PG&E. Unlike the two previous sections, this analysis does not rely on eQUEST prototypes or simulations to inform the inputs to the Monte Carlo simulations. Instead, it makes use of RCA data—from both laboratory and field testing—gathered through recent studies. Another key difference is that these analyses do not explore the uncertainty of the annual savings yielded by the RCA measure, but instead estimate the uncertainty in the measure effects on three key equipment performance factors: energy efficiency (EER), total cooling capacity, and sensible cooling capacity.

The RCA analysis approach was chosen for the following reasons:

- The HVAC3 evaluation determined that—although QM measures, overall, yielded a high realization rate—the RCA measure group had a low realization rate. The high realization rate for QM measures was due, in part, to the high realization rates of condenser coil cleaning and economizer repair. These findings spurred us to investigate the interaction of other QM measures on the efficacy of RCA treatments.[38]
- The HVAC5 study offered a rich dataset to inform the assessment of the key performance outcomes.[39]
- It is a maintenance/treatment measure that is applied to existing units with varying pre-existing conditions which individually and in combination affect the unit's performance.
- Unlike other measures, negative savings are possible if faults are incorrectly diagnosed or incorrectly treated; such occurrences can be a primary source of savings uncertainty.
- The measure, itself, differs from other typical deemed measures in that no equipment replacement occurs (e.g., standard efficiency chiller being replaced with a high-efficiency chiller).
- In a prior program cycle evaluation,[40,41] there was considerable savings uncertainty resulting from the refrigeration charge correction and the suitability of available methods for measuring refrigerant charge. After the sensitivity to the RCA charge offset, itself, the next two factors to which the savings are sensitive include the metering device used and presence of other performance faults (including improper airflow, economizer functionality, and condenser- and evaporator-coil fouling).

Before implementing RCA, diagnostic tests must be administered to determine whether RCA treatment is required. Since these tests do not normally measure refrigerant charge levels directly (e.g., evacuate the system and weigh the refrigerant), pre-existing conditions—including other performance faults (e.g., dirty coils, non-condensables)—combine to influence diagnostic measurements and their accuracy. The efficacy of

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[38] Impact Evaluation of 2015 Commercial Quality Maintenance Programs (HVAC3), DNV GL (2017). http://calmac.org/publications/HVAC3_2015_FINAL_Impact_Report.pdf

[39] Laboratory HVAC Testing Research for 2013-14 (HVAC5): An Introduction and Data Dictionary. DNV GL, RMA (2017). http://calmac.org/publications/HVAC5_2013-14_Introduction_and_Data_Dictionary.pdf

[40] HVAC Impact Evaluation FINAL Report ("WO32"), DNV GL (2015). http://calmac.org/publications/FINAL_HVAC_Impact_Evaluation_WO32_Report_28Jan2015_Volume1_Report.pdf

[41] In addition to WO32, the "Evaluation Measurement and Verification of the California Public Utilities Commission HVAC and High Impact Measures and Specialized Commercial Contract Group Programs" (http://calmac.org/publications/Vol_1_HVAC_Spec_Comm_Report_02-10-10.pdf) also investigated uncertainty of contractor measurements

the RCA measure depends not only on correct diagnostic measurements to determine if an adjustment is necessary, but on the pre-existing conditions of the unit, including the presence of other faults.

6.1 Measure description

The RCA measure typically consists of performing system diagnostic tests on air-cooled DX units to determine if they are correctly charged, and making charge adjustments as indicated by the tests. Evaluation and research studies have provided direct measurement of charge amounts compared to factory charge for packaged systems. If the first "test-in" measurement determines that the charge is incorrect, technicians add or remove charge and retest the system until the correct level is reached. A final "test-out" measurement is performed to document that the charge is correct.

The ex ante savings for nonresidential RCA at direct-expansion (DX) units are provided by DEER (2011). The DEER savings were established for four baseline refrigerant-charge offset bins: "Typical undercharged," "Typical overcharged," "High undercharged," and "High overcharged." Post-treatment, the unit's charge is restored to factory levels and thereby regains the presumed nominal efficiency. The DEER RCA-measure assumptions were derived, in part, from field-measurement data used inform the measure effects upon key input parameters due to a refrigerant charge adjustment.[42]

6.2 Ex ante savings review

DNV GL explored the derivation of the ex ante savings by reviewing RCA workpapers published by the IOUs, and analyzing the DEER prototypes and the database software (e.g., READi and MASControl) used to quantify and publish the deemed measure savings.

In order for DNV GL to determine which input parameters to adjust to drive the measure savings, the DEER 2011 database tool, READI v.2.1.0, and the Measure Analysis Software (MASControl v.3.00.20) tool were used to reproduce the RCA measure impacts and the associated eQUEST prototype models. The models were then compared to determine which input parameter values differed between the baseline and measure models. These differences are provided in Table 18 to provide a benchmark for the extent to which the key parameters were expected to shift.

The listed scaling factors are applied to the baseline models' eQUEST input parameters to de-rate the nominal capacity and efficiency of prototype models' DX units. For example, the baseline case representing a DX unit that is overcharged by 20% or more is assumed to have a cooling efficiency that is 35.8% less efficient than the measure case, and total and sensible cooling capacities that are 17.4% and 11.1% less than the measure case, respectively[43].

[42] "RCA_DataforRefrigerantChange-CoolingOnly_081004.xls" includes 65 residential (< 5 ton) units and 5 nonresidential units.

[43] The capacity of the base model DX unit is smaller relative to the nominal capacity. The efficiency (EIR) value of the base model is larger (less efficient) relative to the nominal efficiency.

Table 18: DEER RCA measure key input parameter adjustments[44]

Measure Description	DEER Measure Description	DEER Measure ID	Total Cooling Capacity Scaling Factor [COOLING-CAPACITY]	Sensible Cooling Capacity Scaling Factor [COOL-SH-CAP]	Efficiency (EIR) Scaling Factor[45] [COOLING-EIR]
Undercharge, typical	Charge increased by less than 20%	D-08-NE-HVAC-RefChg-Inc-typ	0.884	0.912	1.117
Undercharge, high	Charge increased by 20% or more	D-08-NE-HVAC-RefChg-Inc-high	0.839	0.907	1.156
Overcharge, typical	Charge decreased by less than 20%	D-08-NE-HVAC-RefChg-Dec-typ	0.902	0.951	1.153
Overcharge, high	Charge decreased by 20% or more	D-08-NE-HVAC-RefChg-Dec-high	0.826	0.889	1.358

6.3 Uncertainty analysis methodology

Unlike most of the HVAC4 uncertainty analyses, the RCA regression models were developed using related laboratory and field data rather than using DEER prototypes and eQUEST simulations. Furthermore, while the rest of the HVAC4 analyses studied annual savings uncertainty, this study looks at the measure effects on three key performance indicators: EER, net cooling capacity, and net sensible cooling capacity. The predictions are compared to the adjustment factors that DEER uses for the deemed RCA measure. The process included the following steps:

- Laboratory- or field-data selection and analysis
- Multivariate quadratic regression analysis
- Monte Carlo simulations

Limitations to the data and regression analyses include:

- The HVAC5 lab dataset do not completely cover the range of load and ambient conditions that are simulated in the eQUEST models. For example, the eQUEST models use DX cooling performance curves to calculate the instantaneous efficiency and capacity of the units given the conditions (e.g., outside dry-bulb temperature [DBT], building cooling loads) at the time. We were limited to estimating uncertainty around a specific point on the curve – in this case 95 °F outside DBT.
- Although a rich dataset, some combinations of input parameters are not available in the HVAC5 data. This limitation led to the use of different input parameters for the thermal expansion valve (TXV) unit vs. the fixed orifice, non-TXV unit regression models.
- HVAC5 tests are generally full-load, steady-state tests. The modeling required to calculate energy consumption and savings from the full load test data was not done.

44 A nominally charged unit has COOLING-CAPACITY, COOL-SH-CAP, and COOLING-EIR input parameter values equal to 1.000.

45 This value accounts for the improved compressor efficiency, only; the condenser fan efficiency changes are accounted for by the "OUTSIDE-FAN-ELEC" parameter in eQUEST.

6.3.1 HVAC5 laboratory data analysis

HVAC5 lab data were used to develop the regression models that would later be entered into Crystal Ball for uncertainty analysis. Unlike the eQUEST batch processing method, where any eQUEST input parameter can be chosen for manipulation, using lab data limited the regression models to those conditions and faults (input parameters) in place during the testing.

HVAC5 lab tests results were revised to measure efficiencies and capacities intrinsic to the equipment; that is, measurements were based on conditions at the coil inlet rather than those at the return air inlet (doing otherwise would have effectively measured system-wide efficiencies and capacities). This distinction is important because the intrinsic equipment efficiencies and capacities effectively isolate the test units from any other cooling/heating loads affecting the conditioned spaces. For example, the "indoor" test chamber is held at constant dry- and wet-bulb temperatures for each set of experiments by non-test HVAC units to eliminate the influence of the test unit's contribution to the load. These testing conditions reveal somewhat counterintuitive results such as increased efficiency and capacity with increased (95 °F) proportions of outdoor air (i.e., higher economizer position). More information about the HVAC5 lab data can be found in the HVAC5 summary report.[46]

Most multi-fault tests were performed at 95 °F outdoor DBT and 75 °F indoor DBT. These conditions are similar to those required for AHRI full-load efficiency tests to rate air conditioning units[47]. DNV GL held constant these ambient conditions throughout the regression models because multi-fault testing data at other outdoor/indoor conditions were limited. Choosing the 95 °F/75 °F conditions offered the largest inclusion of multi-fault test data.

The following table illustrates the fault conditions that were investigated during the uncertainty analyses. These faults comprise the regression models' input parameters. More information regarding the input parameters' distributions are provided in APPENDIX C.

Table 19: Laboratory test faults concurrent with RCA

Fault used as regression input parameter	Test Range	
	RTU5: 3-ton, non-TXV, single-stage unitary syst.	RTU2: 7.5-ton, TXV, dual-stage unitary system
Refrigerant Charge Offset	-40% to 40%	
Condenser Coil Blockage	0% to 80%	
Evaporator Coil Blockage	0% to 50%	
(Failed) Economizer Damper Position[48]	Fully closed to fully open	
Fan airflow (% based on 400 cfm/ton)	N/A[49]	Approximately 65% to 110%

The HVAC5 tests measured key RTU performance metrics while manipulating the severity or combination of the faults listed shown in Table 19. The performance metrics (e.g., EER in Btu/W-hr, cooling capacity in

[46] Laboratory HVAC Testing Research for 2013-14 (HVAC5): An Introduction and Data Dictionary. DNV GL, RMA (2017). http://calmac.org/publications/HVAC5_2013-14_Introduction_and_Data_Dictionary.pdf

[47] AHRI rating conditions are 95 °F outdoor dry-bulb temperature, 80 °F entering dry-bulb temperature, and 67 °F entering wet-bulb temperature

[48] While the lab tests did not specifically treat the economizer damper position as a fault, DNV GL chose to use this test condition as a "failed" economizer damper fault and measure its impact on the refrigerant charge fault.

[49] Note that some faults were not tested/measured for some RTUs. The "N/A" designates that no data were available for that fault type & RTU combination.

Btu/h, fan airflow rate in cfm) were normalized based on a baseline test designed to represent a RTU of nominal performance. The baseline test characteristics are summarized in Table 20.

Table 20: Baseline RTU characteristics

Faults	RTU5: 3-ton, non-TXV, single-stage unitary system	RTU2: 7.5-ton, TXV, dual-stage unitary system
Refrigerant Charge (% of factory charge)	100%	
Condenser Coil Blockage	0%	
Evaporator Coil Blockage	0%	
Economizer Outside Air Damper Position (% open)	"1 finger" (38.75%)[50]	10%[51]
Fan airflow (% based on 400 cfm/ton)	N/A	~100%

Note that the baseline economizer damper position is 10% or "1 finger," depending on the RTU. These values were chosen to represent the minimum outside-air requirements typical of commercial buildings at which RTUs could be installed. While neither this "fault" nor the uncertainty analysis represent the effects of outside air on RTU run-times (due to increased cooling load on unit) and energy consumption, they do illustrate specific application performance effects and potential interactive effects of multi-fault scenarios.[52]

6.3.2 Multivariate quadratic regression models

The Excel function LINEST was used to generate linear regression model coefficients for the multi-fault combinations. Regression models developed for the RCA measure predict normalized net cooling capacity, net sensible cooling capacity, and energy efficiency ratio (EER) of two representative rooftop units.

The regression models take the form as follows for pre-/post-treatment cases:

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

Where input variables are as shown in Table 21:

Table 21: Regression model variable definitions

Variable	RTU5: 3-ton, non-TXV, single-stage unitary system	RTU2: 7.5-ton, TXV, dual-stage unitary system
Y	Normalized net cooling capacity, net sensible capacity, or EER, dimensionless	
X_1	Refrigerant charge offset, %[53]	
X_2	Condenser coil blockage, %	
X_3	Evaporator coil blockage, %	Fan airflow (relative to 400 cfm/ton), %

50 The RTU5 unit was not tested with the outside air damper position at 10%. The minimum position that was tested was the "1 finger" position, or 38.75% open.

51 This "fault" condition represents a failed economizer; however, the original purpose of the economizer fault tests was to measure the actual outside air fraction relative to the outside air damper position.

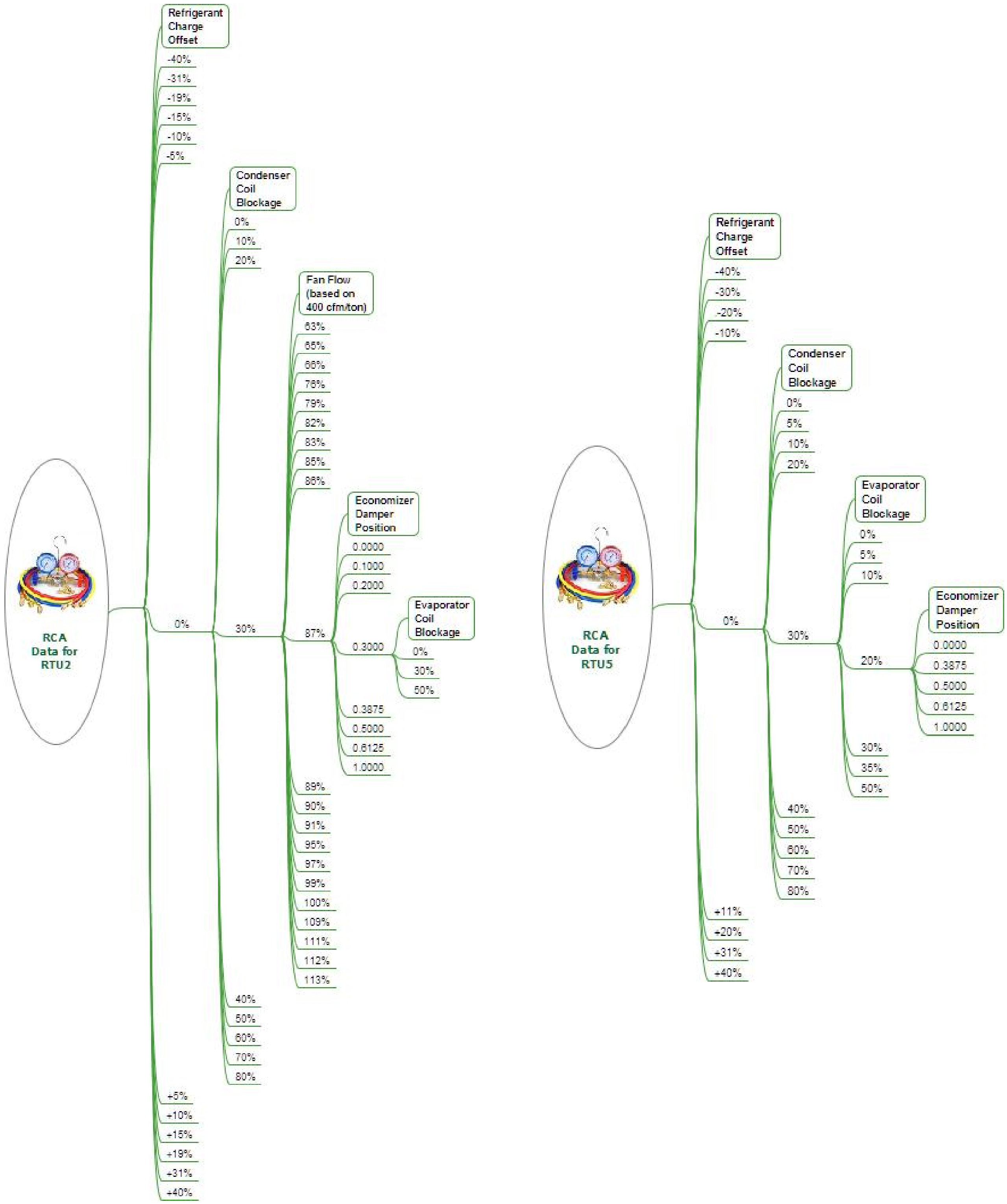
52 Increasing outside air increases the cooling load across RTU evaporator coil (due to increased ΔT) and effectively increases the efficiency of the unit. On the other hand, the RTU run-time will be extended because more (warmer) outside air needs to be conditioned to satisfy indoor air setpoints.

53 For RTU2 – the multi-stage/circuit unit – X_1 represent charge offset of both circuits

Variable	RTU5: 3-ton, non-TXV, single-stage unitary system	RTU2: 7.5-ton, TXV, dual-stage unitary system
X_4	Economizer outside air damper position, from 0 (closed) to 1 (fully open)	
X_5	n/a	Evaporator coil blockage, %

The regression model coefficients (a_0, a_i, etc.) for the parameters predicting RTU5 and RTU2 capacity and efficiency were developed as part of the HVAC5 lab data analysis and are provided in APPENDIX C. A graphical depiction of the various combinations of input parameters is provided in Figure 19. Note that the matrix of input parameter values was not complete i.e., every value of one input parameter did not have the complete set of listed values from the other input parameters. This was because the regression data set was limited to whatever data was available in the HVAC5 lab data.

Figure 19: Input parameter values used for RTU2 and RTU5 regression models



6.3.3 Monte Carlo analysis in Crystal Ball

As described in Section 3, the RTU5 and RTU2 regressions were next used to run Monte Carlo simulations to determine the range of outcomes that could be expected by simulating many combinations of selected input parameters. These simulations were used to create probability distribution profiles for three performance metrics: EER, net cooling capacity, and net sensible cooling capacity. The input parameter distributions used for these simulations are provided in APPENDIX C. Some of the distributions were chosen arbitrarily using engineering judgement while others were informed by available data sources including HVAC3 field measurements.

The Crystal Ball analyses were grouped into three experiments, each drawing from HVAC Roadmap datasets to yield a variety of comparisons. These experiments are described as follows:

- **Experiment 1** considers the hypothetical instances of each representative RTU (RTU5 and RTU2) for which the DEER deemed RCA-measure savings are claimed for RCA treatment. This experiment is designed to illustrate the shifts in the key performance metrics that occur when the RCA treatment is performed in the presence of other pre-existing faults that remain untreated. As described in Table 22, the experiment (referred to as 1AB) simulates the percent differences of the key performance metrics of the RTUs at the two described equipment states (referred to as states 1A and 1B).
- **Experiment 2** considers the effects of first treating the non-RCA faults before performing the RCA treatment. The experiment simulates the key performance metrics for the RTU states by drawing from HVAC3 field data to characterize three equipment states as described in Table 22. From these, the percent differences of the key performance metrics resulting from going from state 2A to state 2B (referred to as experiment 2AB), from state 2B to state 2C (referred to as experiment 2BC), and from state 2A to state 2C (referred to as experiment 2AC).
- **Experiment 3** considers the effects of quality maintenance treatments (coil cleaning, economizer repair, and RCA). It considers the "post" case to have field-observed test-out distributions for the RCA and economizer position input parameters. Coil cleaning is assumed perfectly treated and fan airflow % retains its pre-treatment distribution.

Table 22. Overview of RCA experiments for RTU5 and RTU2

RTU State	Data Source(s)	Description of State	Experiment Case
Experiment 1			
1A	HVAC5	RTU prior to the treatment of a variety of faults	1AB (Cases are appended with -IT, -IH, -DT, or -DH[54])
1B		RTU following the RCA treatment, but leaving all non-RCA faults untreated	

[54] These codes mimic those used by DEER such that IT, IH, DT, and DH describe charge that is "typical undercharged," "high undercharged," "typical overcharged," and "high overcharged," respectively.

RTU State	Data Source(s)	Description of State	Experiment Case	
Experiment 2				
2A	HVAC5 & HVAC3	RTU prior to the treatment of a variety of faults	2AB-I 2AB-D	2AC-I 2AC-D
2B		RTU following non-RCA fault treatments (assumed to be perfectly executed)		
2C		RTU following RCA-treatment to match results observed in HVAC3	2BC-I 2BC-D	
Experiment 3				
3A	HVAC5 & HVAC3	RTU prior to the treatment of a variety of faults	3AB-I 3AB-D	
3B		RTU following all treatments (except fan airflow faults)		

The Monte Carlo forecasts are generated as the percent differences between various states described.

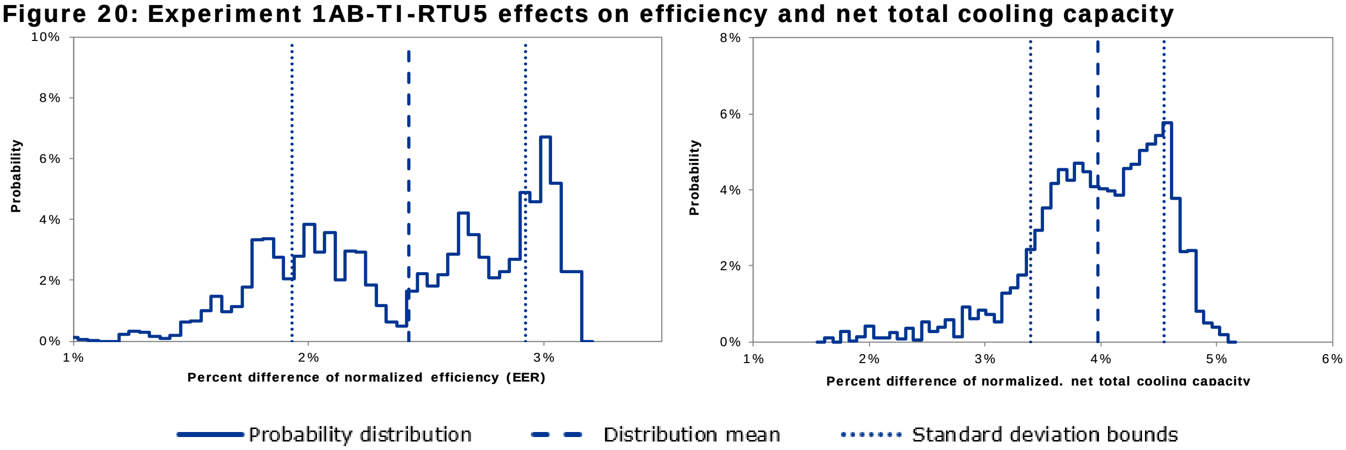
6.4 Uncertainty analysis results

This section presents comparative uncertainty analysis experiment results from many Monte Carlo simulations. As previously explained, the section does not report deemed measure savings uncertainty; rather, the experiment results provide illustrative evidence of multi-fault impacts on key efficiency and performance indicators: EER, net cooling capacity, and net sensible cooling capacity.

6.4.1 Experiment 1: Multi-fault uncertainty using DEER RCA assumptions

This first experiment hypothesizes typical program-participating RTU conditions that undergo "perfect" RCA treatment only. The analysis attempts to illustrate how the uncertainty associated with RTU performance improvement from RCA treatment is affected by other faults that are not addressed or accounted for.

Figure 20: Experiment 1AB-TI-RTU5 effects on efficiency and net total cooling capacity

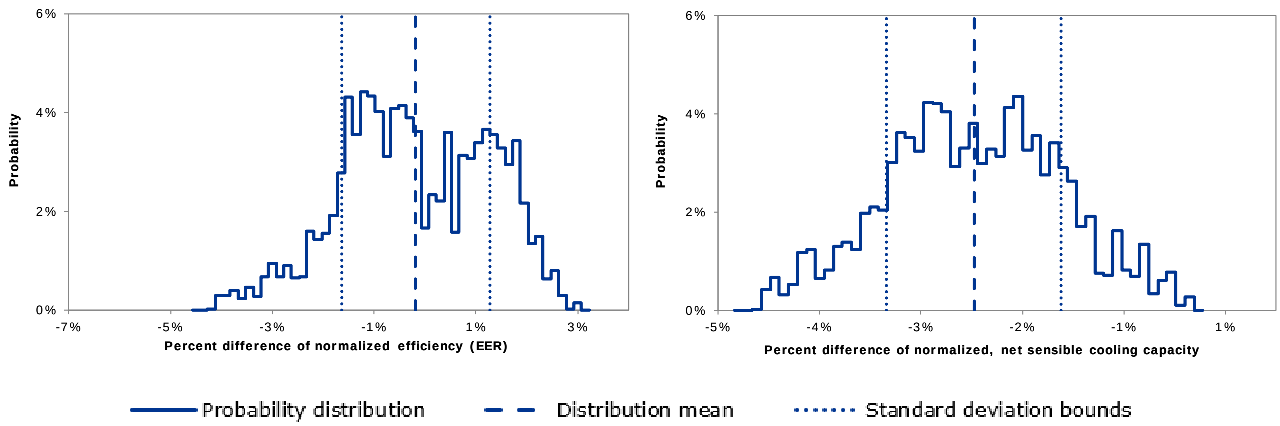


The experiment results illustrate the performance-metric effects of RCA treatment specific to deemed refrigerant charge offset assumptions. The ranges of the simulation results are caused by the assumed distributions for the non-RCA faults. The experiment figures' horizontal axes represent the percent difference of a given performance metric between the state 1A and state 1B (i.e., a positive mean indicates that, on average, the corresponding performance metric increases).

Figure 20 illustrates the typical undercharge treatment effects on RTU5's normalized EER and net sensible cooling capacity. By adjusting the refrigerant charge offset from -12% to 0%—while all other faults remain untreated—the mean normalized EER and net sensible cooling capacity increase by 2.4% and 4.0%, respectively.

Figure 21 illustrates the simulated effects that a high overcharge treatment has on the normalized efficiency and net sensible cooling capacity of RTU2 (multi-stage TXV) while other multi-fault conditions are present. By adjusting the refrigerant charge offset from 32% to 0% while keeping all other faults un-treated, the mean normalized efficiency and net sensible capacity were predicted to decrease by -0.2% and -2.0%, respectively. The corresponding standard deviations were predicted to be ±1.4% and ±0.9%, respectively. Figure 21 also shows that—in the presence of other faults—the performance metrics shown might even deteriorate due to RCA at overcharged multi-stage, TXV units.

Figure 21: Experiment 1AB-HD-RTU2 effects on efficiency and net sensible cooling capacity



The forecast results for experiment 1AB are tabulated in Table 23 and Table 24, categorized by RTU. The tables present the mean average percent difference (between states 1A and 1B) and the standard deviation of the percent difference for the normalized efficiency (EER), net total cooling capacity (TC), and net sensible cooling capacity (SC).

Table 23: Experiment 1AB performance metrics results for RTU5 (single-stage, non-TXV)

Experiment	Mean Average Percent Difference ± Standard Deviation		
	EER	Net Total Cooling Capacity	Net Sensible Cooling Capacity
1AB-TI-RTU5 (undercharge, typical)	2.4% ± 0.5%	4.0% ± 0.6%	3.5% ± 0.6%
1AB-HI-RTU5 (undercharge, high)	12.1% ± 1.4%	18.8% ± 1.7%	15.3% ± 1.9%
1AB-TD-RTU5 (overcharge, typical)	-0.3% ± 0.6%	-1.2% ± 0.6%	-1.4% ± 0.7%
1AB-HD-RTU5 (overcharge, high)	3.8% ± 1.9%	2.4% ± 2.1%	0.5% ± 2.0%

Table 24: Experiment 1AB performance metrics results for RTU2 (multi-stage TXV)

Experiment	Mean Average Percent Difference ± Standard Deviation		
	EER	Net Total Cooling Capacity	Net Sensible Cooling Capacity
1AB-TI-RTU2 (undercharge, typical)	4.6% ± 0.9%	6.2% ± 0.7%	3.8% ± 0.3%
1AB-HI-RTU2 (undercharge, high)	20.3% ± 3.9%	26.2% ± 3.1%	15.2% ± 1.0%
1AB-TD-RTU2 (overcharge, typical)	-2.0% ± 0.6%	-3.3% ± 0.5%	-2.0% ± 0.3%
1AB-HD-RTU2 (overcharge, high)	-0.2% ± 1.4%	-3.8% ± 1.0%	-2.0% ± 0.9%

For both RTU5 and RTU2, the results suggest that even with other faults present, correctly diagnosing and addressing undercharged circuits will almost certainly have positive performance impacts. The results also generally agree with recent studies that have shown that the performance metrics (efficiency and cooling capacity) of units with overcharged circuits, whether TXV or non-TXV, are not significantly affected by correctly diagnosing and treating overcharged units.[38,39] These Monte Carlo simulations suggest that, when non-RCA faults remain untreated, the following results:

- The greatest performance-metric improvements result from correctly treating highly-undercharged circuits on both TXV and non-TXV units.
- Performance can be diminished when treating typically overcharged units on both TXV and non-TXV units.
- Moderate performance-metric improvements result from correctly treating typically undercharged or highly overcharged circuits on both TXV and non-TXV units.
- When RCA treatment is certain (i.e., when the refrigerant charge is known and is corrected to factory charge), the standard deviations of the performance-metric changes are relatively narrow.

6.4.2 Experiment 2: Multi-fault uncertainty using HVAC3 findings for RCA

Experiment 2 differs from experiment 1 as follows:

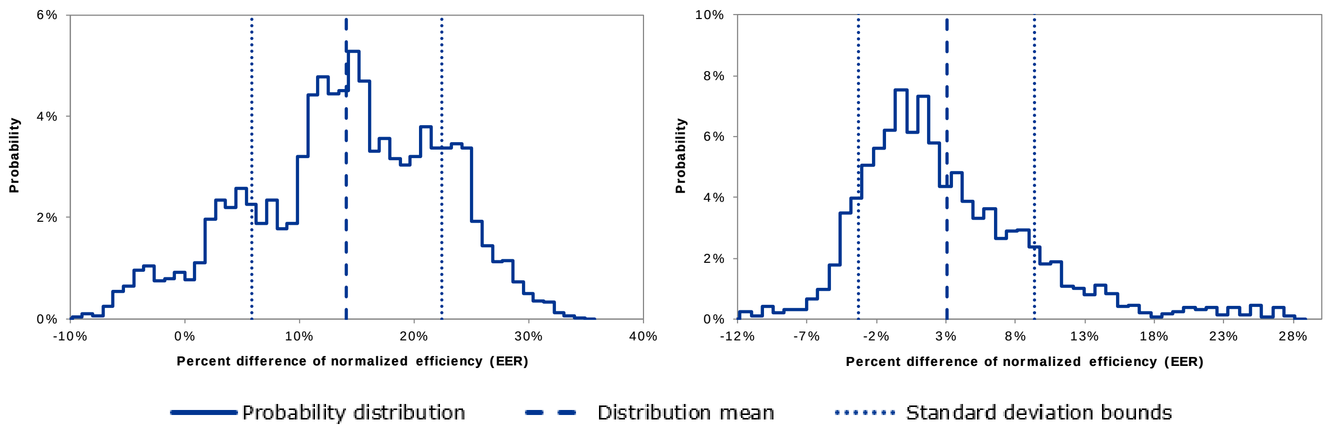
- Three states, detailed in Table 22, are used:
  - State 2A occurs before any faults have been treated
  - State 2B occurs after non-RCA faults have been “perfectly” treated
  - State 2C occurs after RCA-treatment was performed—and to the same degree as was observed during HVAC3 field measurements
- The performance-metric effects due non-RCA faults are isolated and measured by effectively removing the faults perfectly and uniformly (i.e., no distribution).
- For the perfect fault treatment values, see the baseline RTU characteristics in Table 20. For coil fouling faults, perfect treatment equates to 0% blockage; perfect air flow treatment equates to 100% (based on 400 cfm/ton); and perfect economizer minimum damper position equates to 10% (RTU2) or “1 finger” (RTU5).

- HVAC3 field measurement data are used to inform the refrigerant charge input parameter distributions for pre-RCA treatment and post-RCA treatment (i.e., the RCA fault is not treated perfectly).

For the last bullet, the HVAC3 field data were used because they showed that post-RCA charge levels were rarely equal to the factory charge as the DEER measure and Experiment 1 assumes. This experiment accounts for this finding and illustrates its relative impact to the uncertainty distribution of unit efficiency and net cooling capacity.

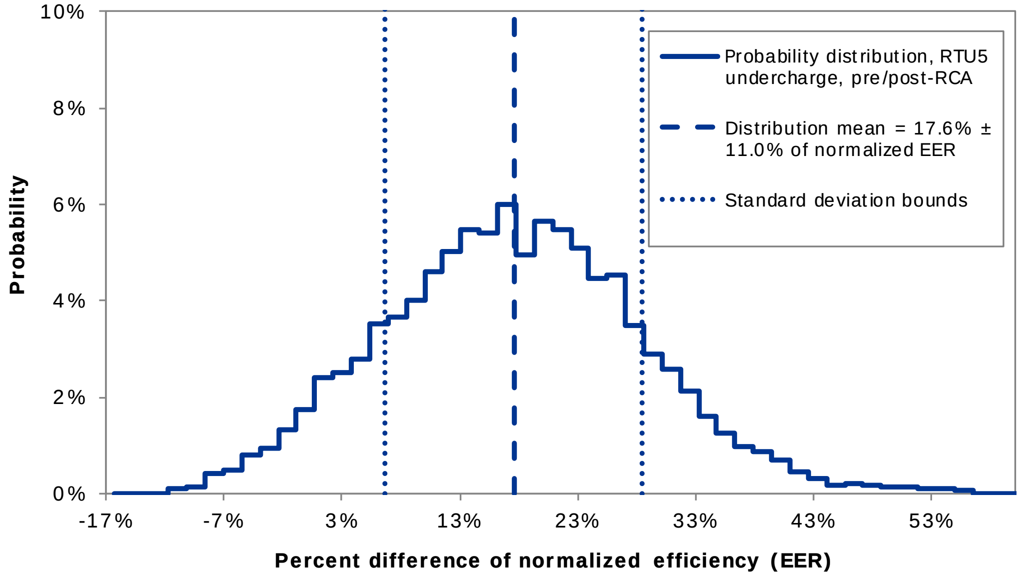
Figure 22 presents two charts. On the left is the percent difference of EER between state 2A and 2B for RTU5; on the right is that between states 2B and 2C. Figure 23 presents the percent difference between the pre-treatment forecast and the post-RCA forecast for RTU5 efficiency. Figure 23 can be thought of as the total impact of perfectly treating non-RCA faults and treating the RCA fault as effectively as the RCA treatments observed in the test-in/test-out measurements from HVAC3.

Figure 22: Effects on EER of experiments 2AB-I-RTU5 and 2BC-I-RTU5



The average efficiency impact of treating non-RCA faults on representative single-stage non-TXV units is 14.1% with a standard deviation of ±8.3%. The average efficiency impact of treating the RCA fault on a unit that has been treated for the other non-RCA faults is 3.1% with a standard deviation of ±6.3%. These findings are illustrated in Figure 22.

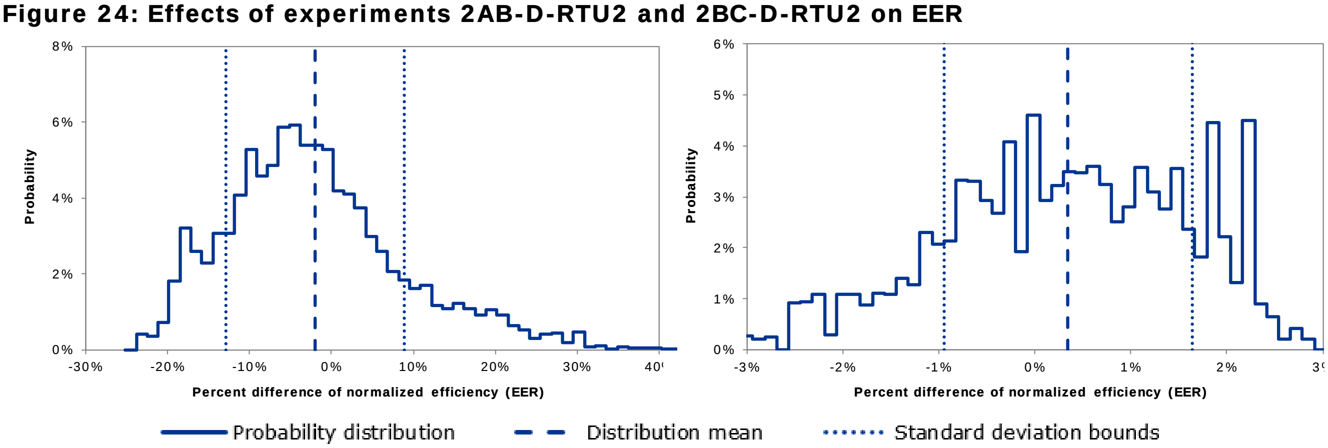
Figure 23: Overall effects of experiment 2AC-I-RTU5 on EER



The two figures in Figure 22 and that in Figure 23 suggest that addressing non-RCA faults, first, can reduce the uncertainty of the performance-metric effects due to RCA treatment.

Figure 24 presents the percent differences in EER from experiments 2AB-D-RTU2 and 2BC-D-RTU2 for the multi-stage, TXV unit. Further, Figure 25 presents the percent differences in EER from experiment 2AC-D-RTU2 to show the total effects of all treatments, combined.

Figure 24: Effects of experiments 2AB-D-RTU2 and 2BC-D-RTU2 on EER



The left chart in Figure 24 represents the efficiency effects profile associated with non-RCA treatments on a multi-stage, TXV unit that is overcharged. The wide standard deviation indicates that there is significant uncertainty around the EER effects for treating non-RCA faults. Recall that for RTU2, the non-RCA faults that were addressed included condenser and evaporator coil fouling, fan airflow speed, and the minimum economizer damper position. Addressing these faults on an overcharged unit can have beneficial or deleterious efficiency effects.

The right chart in Figure 24 illustrates how the probability distribution profile narrows significantly when providing RCA-treatment *following* correcting all non-RCA faults. That said, the percent difference of EER due to RCA-treatment is rather small and the profile suggests that treating an overcharged TXV unit could yield small positive or negative performance-metrics effects.[55]

The cumulative effect, as illustrated in Figure 25, shows a wide range of EER effects when treating RTUs with common faults, including refrigerant charge offset. The mean percent difference of EER is -1.5% and a standard deviation of 11.0%. The results for Experiment 2 are listed in Table 25 and Table 26 for RTU5 and RTU2, respectively.

Figure 25: Effects of overall experiment 2AC-D-RTU2 on EER

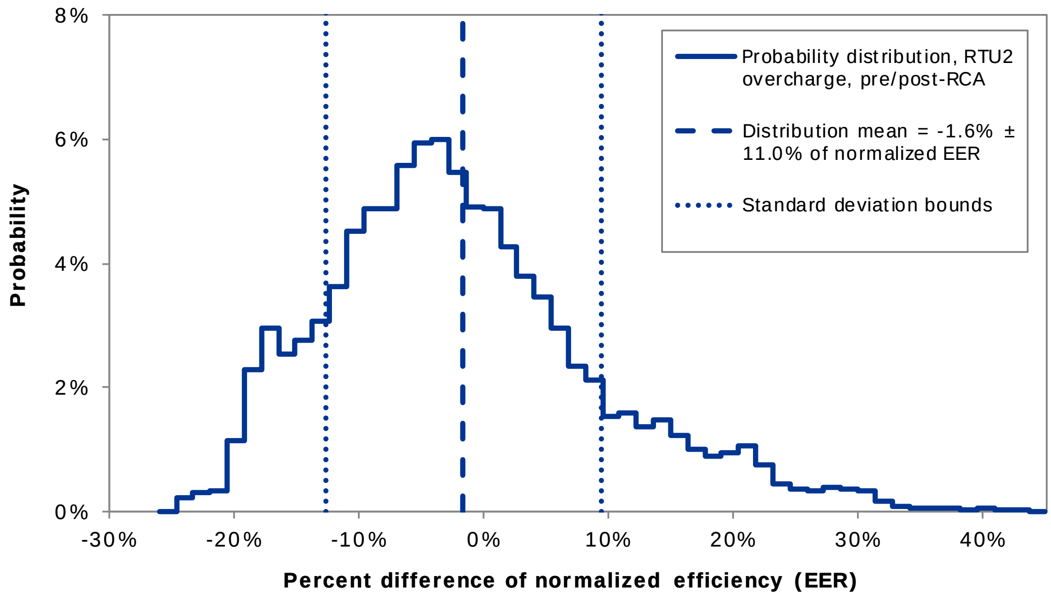


Table 25: Experiment 2 performance-metrics effects for RTU5 (single-stage, non-TXV)

Experiment	Baseline Charge Offset	Mean Average Percent Difference ± Standard Deviation		
		EER	Net Total Cooling Capacity	Net Sensible Cooling Capacity
2AB-I-RTU5	Undercharged	14.1% ± 8.3%	6.9% ± 5.1%	5.6% ± 3.6%
2BC-I-RTU5		3.1% ± 6.3%	5.0% ± 10.3%	3.9% ± 8.2%
2AC-I-RTU5		17.6% ± 10.9%	12.1% ± 11.2%	9.7% ± 8.5%
2AB-D-RTU5	Overcharged	16.0% ± 9.2%	9.6% ± 6.3%	7.7% ± 4.8%
2BC-D-RTU5		0.2% ± 1.3%	0.0% ± 1.0%	0.2% ± 1.2%
2AC-D-RTU5		16.0% ± 9.2%	9.8% ± 6.3%	8.0% ± 4.9%

[55] Based on treating an overcharged TXV unit with current diagnostic methods used in quality maintenance programs evaluated under HVAC3. The post-RCA charge offset distribution is informed by weigh-in weigh-out field measurements made on approximately 27 TXV circuits

Table 26: Experiment 2 performance-metrics effects for RTU2 (multi-stage, TXV)

Forecast	Baseline Charge Offset	Mean Average Percent Difference ± Standard Deviation		
		EER	Net Total Cooling Capacity	Net Sensible Cooling Capacity
2AB-I-RTU2	Undercharged	-3.6% ± 11.9%	-4.8% ± 7.1%	2.1% ± 7.7%
2BC-I-RTU2		5.7% ± 6.1%	6.9% ± 7.5%	4.0% ± 4.2%
2AC-I-RTU2		1.8% ± 13.6%	1.8% ± 9.9%	6.2% ± 9.0%
2AB-D-RTU2	Overcharged	-1.9% ± 11.0%	-3.5% ± 6.2%	2.9% ± 7.8%
2BC-D-RTU2		0.4% ± 1.3%	0.4% ± 2.2%	0.2% ± 1.3%
2AC-D-RTU2		-1.5% ± 11.0%	-3.1% ± 6.5%	3.2% ± 7.9%

General findings of this experiment are:

- The performance-metrics effects on multi-stage, TXV units due to non-RCA treatments are smaller than (and in some cases, negative) those for single-stage, non-TXV units.
- The widest ranges of effects resulted from non-RCA fault repairs for both non-TXV and TXV units.
- For units where non-RCA faults are treated first, undercharged units experience greater performance-metrics improvements from RCA-treatments than overcharged units.
- The wide standard deviations reported for the 2BC experiments are likely the result of having a distribution of post-RCA treatment charge offsets. The HVAC3 test-in/test-out field data indicated that units that underwent RCA-treatment were commonly not adjusted to factory charge. This point is illustrated in Table 27.

Table 27: Average charge level pre- and post-RCA treatment

Charge State, Metering Device	Pre-treatment	Post-treatment
Overcharged, non-TXV	9%	11%
Overcharged, TXV	9%	10%
Undercharged, non-TXV	-17%	-11%
Undercharged, TXV	-14%	-4%

6.4.3 Experiment 3: Multi-fault uncertainty using refrigerant charge field measurements

Experiment 3 is an extension of Experiment 2, but hypothesizes typical program-participating RTU conditions that undergo fault treatments relating to the fault conditions described for RTU5 and RTU2. The experiment is intended to cover pre- and post-treatment conditions that were observed in the HVAC3 evaluation field measurements. Experiment 3 differs from Experiment 2 in the following ways:

- The non-RCA faults—except the fan airflow fault—and the RCA fault are assumed to be treated simultaneously where the forecast compares the pre-treatment conditions to the post-treatment conditions.

- The distribution for the fan airflow input parameter does not differ between pre- and post-treatment conditions because the QM programs evaluated by HVAC3 did not include a treatment to adjust fan airflow in response to such faults.
- HVAC3 field data are used to inform the economizer-repair treatment rate. In other words, the post-treatment economizer minimum position is not set perfectly. Rather, the post-treatment economizer position is defined by a weighted distribution of failed positions and the assumed minimum position. The net effect of the economizer repair treatment was to slightly reduce the failed economizer position (i.e., outside air fraction decreases).

Condenser/evaporator coil treatments were assumed to be treated "perfectly" and the Crystal Ball inputs for these faults are point values rather than distributions. The experiment's unit states are outlined in Table 22. More information regarding specific input parameter distributions and input values can be found in APPENDIX C.

Figure 26 presents the percent difference of EER and net total cooling capacity for experiment 3AB-I-RTU5. The forecasted differences show significant improvements of 15.3% and 10.7% to EER and net total cooling capacity, respectively. However, the range is wide and the standard deviations are 11.5% for both efficiency and net total cooling capacity.

Figure 26: Effects on EER and net total cooling capacity of experiment 3AB-I-RTU5

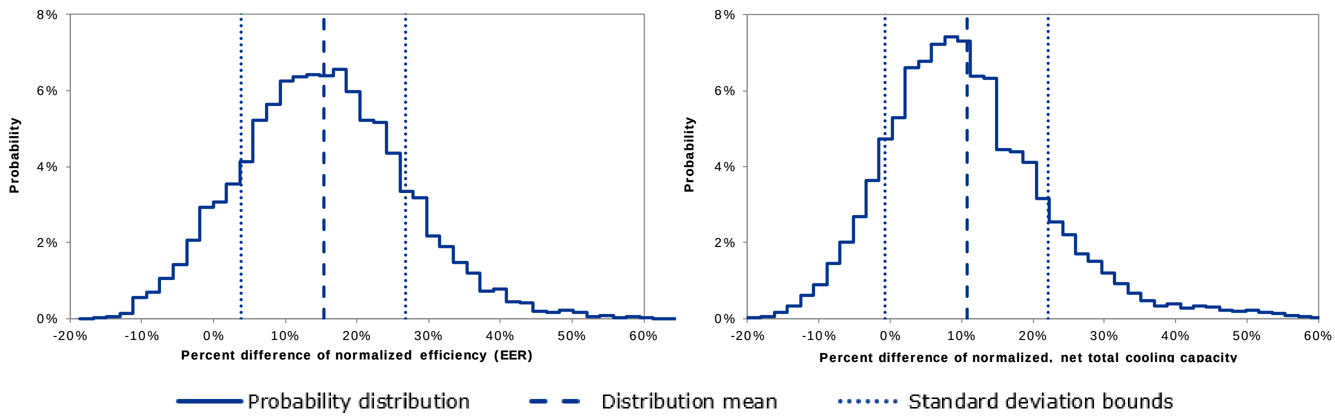
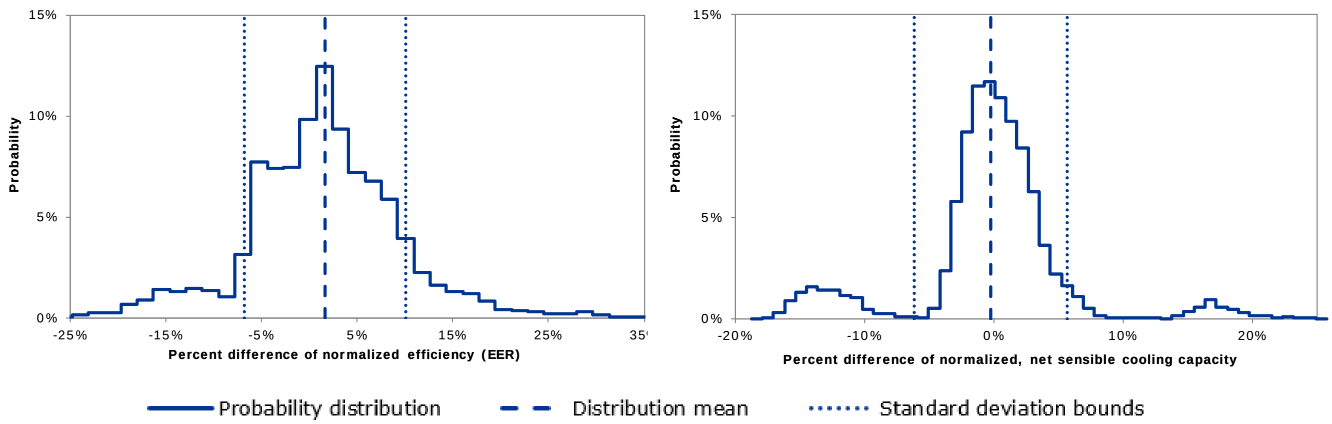


Figure 27 presents the percent difference of EER and net sensible cooling capacity that result from experiment 3AB-D-RTU2. These are far smaller than resulted from experiment 3AB-I-RTU5 with a small beneficial EER improvement of 1.6% and a small and deleterious reduction of net sensible cooling of -0.2%. The associated standard deviations (8.5% and 5.9%, respectively) are wide relative to the mean average impacts.

Figure 27: Effects on EER and net sensible cooling capacity of experiment 3AB-D-RTU2



The results for experiment 3AB are provided in Table 28 and Table 29 for RTU5 and RTU2, respectively.

Table 28: Experiment 3 uncertainty forecast results for RTU5 (single stage non-TXV)

Forecast	Mean Average Percent Difference ± Standard Deviation		
	EER	Total Capacity	Sensible Capacity
Undercharged	15.3% ± 11.5%	10.7% ± 11.5%	8.4% ± 8.7%
Overcharged	13.8% ± 9.9%	8.3% ± 6.9%	6.4% ± 5.3%

Table 29: Experiment 3 uncertainty forecast results for RTU2 (multi-stage TXV)

Forecast	Mean Average Percent Difference ± Standard Deviation		
	EER	Total Capacity	Sensible Capacity
Undercharged	5.4% ± 10.5%	3.8% ± 10.5%	2.9% ± 7.3%
Overcharged	1.6% ± 8.5%	-1.5% ± 7.4%	-0.2% ± 5.9%

Based on the experiment 3 figures above, the forecasts suggest that RCA treatment and other related fault treatments can have varying effects on units typically owned by participants of QM programs. This is evident in the forecast ranges and standard deviation values which often exceeded the mean average impact.

The results suggest that:

- Cumulative treatments (non-RCA plus RCA) performed on representative undercharged non-TXV participant units have a relatively high likelihood of beneficial effects but the magnitude of those are less certain.
- High uncertainty of impact exists for cumulative treatments on representative TXV units, especially for overcharged circuits.

6.4.3.1 Sensitivity analysis results

Table 30 and Table 31 provide the results of the sensitivity analyses around the changes to EER and net total cooling capacity that results from experiment 3AB-I-RTU5.

Table 30: Experiment 3AB-I-RTU5 ranked contributors to variance of change to EER

Input Parameters	Relative Contribution to Variance of EER
Pre-treatment economizer position, percent	-41%
Pre-treatment charge offset, percent	-22%
Condenser coil blockage rate, percent	14%
Post-treatment economizer position, percent	9.6%
Post-treatment charge offset, percent	7.0%
Evaporator coil blockage rate, percent	6.4%

Table 31: Experiment 3AB-I-RTU5 ranked contributors to variance of change to net total cooling capacity

Input Parameters	Relative Contribution to Variance of Net Total Cooling Capacity
Pre-treatment charge offset, percent	-53%
Pre-treatment economizer position, percent	-19%
Post-treatment charge offset, percent	17%
Post-treatment economizer position, percent	5.5%
Evaporator coil blockage rate, percent	3.7%
Condenser coil blockage rate, percent	1.6%

The contributors to variation in the above tables assist in assigning the percentage of uncertainty in the target forecast that is caused by the respective input parameter assumptions. Assumptions with a positive contribution imply that an increase in the assumption value is associated with an increase in the forecast value. Negative contributions indicate the opposite association. The relationship between parameter assumption and forecast is stronger when the absolute value of the contribution to variance is larger.

For example, the larger the condenser and evaporator coil blockage rates are in the pre-treatment case, the larger the forecast of the percent difference between the pre-treatment and post-treatment cases. They have a contribution of 14% and 6.4%, respectively, to the variation in change of EER, as shown in Table 30.

The charge offset and economizer position parameters have to be interpreted differently than the coil blockage rates because they are described by different distributions for both the pre-treatment and post-treatment cases (the coil blockage rates are treated perfectly in the post-treatment cases so do not have distributions in the post-treatment case).

The pre-treatment charge offset contributed -22% to the variation in change of EER. This means as the value of the pre-treatment charge offset increases (which in the case of the undercharged scenario, becomes less negative), the forecast value (the percent change between pre- and post-treatment) decreases. In other words, as the severity of the undercharged offset decreases, the impact the charge offset has on EER reduces. However, since the forecast value is the difference between pre- and post-treatment parameter conditions, the opposite effect occurs with the post-treatment charge offset. As the (undercharged) post-treatment charge offset becomes less negative (increases closer to zero), the forecast value increases. The post-treatment charge offset contributed 7.0% to the variation in change of EER.

The ranked contributors show that the forecasts have a pronounced sensitivity to economizer position and charge offset. However, these were also the faults that were not treated perfectly (in experiment 3); rather, they used the HVAC3 test-out results to inform their post-treatment distributions.[56] Due to the nature of how coil fouling magnitude was measured in HVAC3, the coils were assumed to be perfectly clean after treatment.[57] Still, note that the charge offset and economizer parameter's contribution to variance decreased from pre- to post-treatment, indicating that the range of forecast uncertainty decreased because of the fault treatments.

6.4.4 Results across experiments

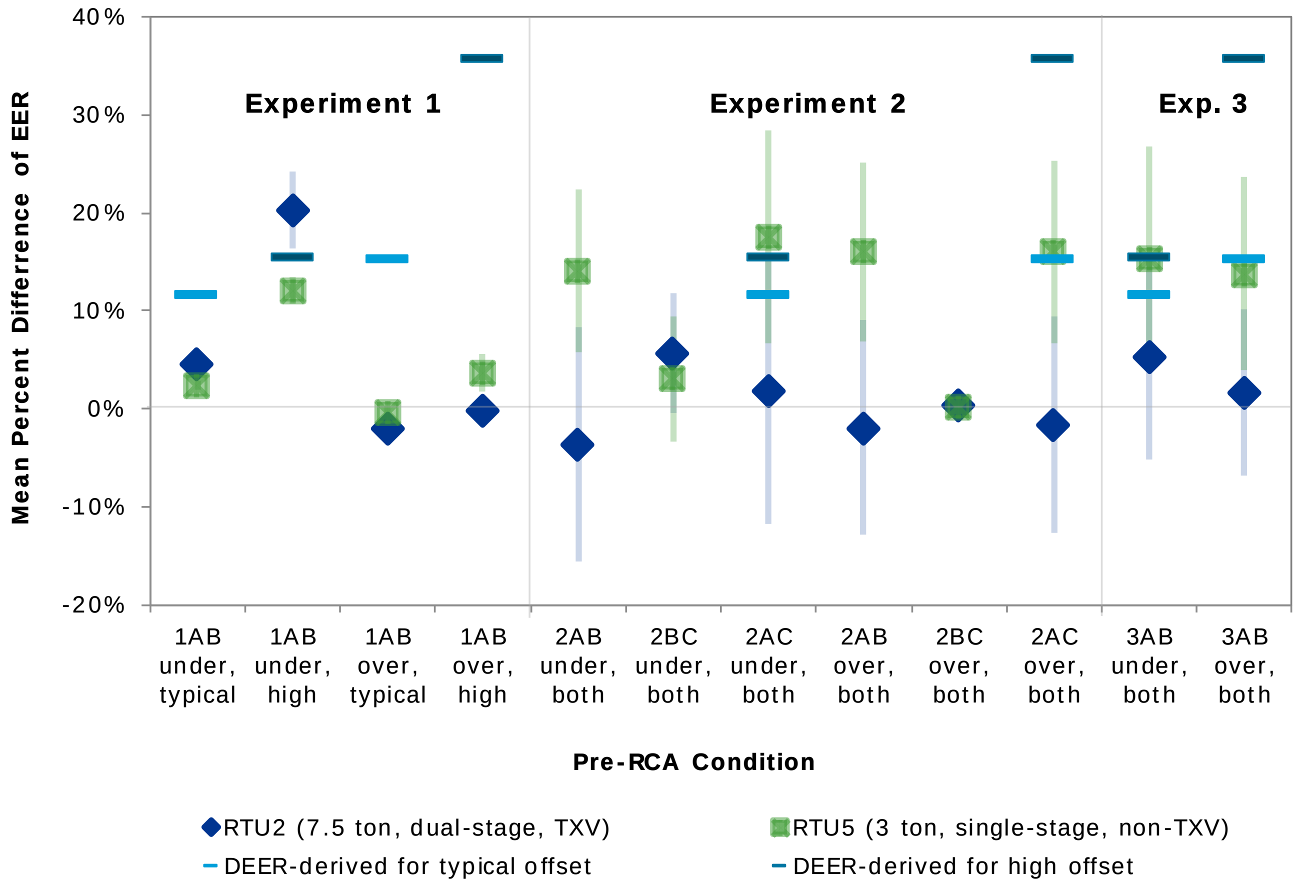
The results of the uncertainty analyses show a broad distribution of probable performance-metrics effects. Experiment 1 highlights the uncertainty that non-RCA faults introduce to the performance-metrics effects of perfect RCA treatment. Experiment 2 illustrates the impact uncertainties around field-measured test-in/test-out RCA treatments and isolates the uncertainty of non-RCA faults being treated perfectly on units that have varying levels of charge offsets and non-RCA faults. Experiment 3 attempts to utilize all known HVAC3 RTU field data to inform pre- and post-treatment scenarios and describe the profiles of the changes to the key performance metrics.

The mean percent differences of EER for all experiments are shown in Figure 28. For the Experiment 1 series, only the highly undercharged RTU2 case (7.5-ton, dual-stage, TXV unit) outperformed the DEER-derived improvements; all of the rest of the cases were significantly lower than DEER-derived improvements. For Experiments 2 and 3, the results for RTU2 fell far short of the DEER-derived improvements. Furthermore, only the undercharged RTU5 cases (3-ton, single-stage, non-TXV unit) met or exceeded the DEER-derived improvements. The results are similar to those observed for net total and net sensible cooling capacities and are provided in APPENDIX C.

[56] This is evident based on the charge offset and economizer input parameters (Crystal Ball uses the term "assumption definitions") having pre-treatment and post-treatment definitions. Since the other faults were treated perfectly, their post-treatment definition is a known 0% so they do not have Crystal Ball assumption definitions.

[57] There is no established protocol to follow to make field measurements on existing units to determine the nominal "benchmark" for a clean condenser or evaporator coil.

Figure 28. Mean percent differences and standard deviations of EER for all experiments



The uncertainty analysis builds on HVAC3 and HVAC5 findings by using non-RCA fault test data to determine how sensitive RCA-treatment benefits are to combinations of faults and the ranges of fault levels observed the HVAC3 data. Some of the high-level findings are as follows:

- Experiment 1 yielded narrow distributions around relatively small mean efficiency and capacity improvements.
  - Only highly undercharged units were found to achieve greater than 5% performance-metrics benefits from RCA treatment. The treatment effects on typical overcharged units were a “wash” and sometimes led to small negative effects.
  - “Perfect” RCA outcomes (no non-RCA faults were treated/adjusted but they existed) is main cause of tight distribution and highest degree of certainty of effects (among the three experiments).
- Experiments 2 and 3 have broader distributions around greater increases in efficiency and cooling capacity:
  - While HVAC3 data showed many post-treatment units still have charge offsets (i.e., treatment is not perfect), these do not explain wide forecasts of effects to key performance metrics.

- When non-RCA faults are treated before RCA faults, the average changes to the performance metrics are on par with those observed in experiment 1, except that the distributions are much wider (due to the imperfect treatment and the distribution of pre- and post-RCA charge offsets).
- As was reported by HVAC3, greater performance benefits are realized by non-RCA fault treatments than RCA.

6.5 Conclusions and recommendations

Uncertainty analysis results corroborated the narrative of the HVAC3 evaluation results quite well. Recall that HVAC3 recommended that the RCA measure continued for DX circuits where refrigerant charge is low or empty. From HVAC4, we can provide the following additional recommendations:

- Addressing other non-RCA faults appears to be more beneficial than addressing the charge offset fault, itself. This is especially true for units with TXV devices and for overcharged units.
  - With the exception of very low charge levels, consider focusing efforts on addressing non-RCA faults before refrigerant offsets.
- Only units with egregious charge offsets and non-RCA faults are expected to be significantly impacted by adjusting the charge to factory levels.
  - Target older, non-TXV units or units with multiple circuits.
  - Consider expanding services to repair refrigerant lines or targeting replacement of units that have an established track record of low refrigerant charge.
- The failed economizer damper position has a distinct impact on unit performance.[58] While large temperature differentials across the evaporator coil (e.g., when >95 °F outdoor air flows over the coil) increase both the unit efficiency and its cooling capacity, the additional run-time needed to meet the added cooling load increases energy consumption. That said, the sensitivity of efficiency and capacity to the economizer damper position was notable in the uncertainty analysis results, as shown in Table 30 and Table 31.[59]
  - Economizer impact continues to be a large source of uncertainty and we recommend continued investigation and training around economizer functionality and reasons for failure or unintentional operation.

[58] This analysis was performed using HVAC5 laboratory data where the reference outdoor air temperature was 95 °F DBT.

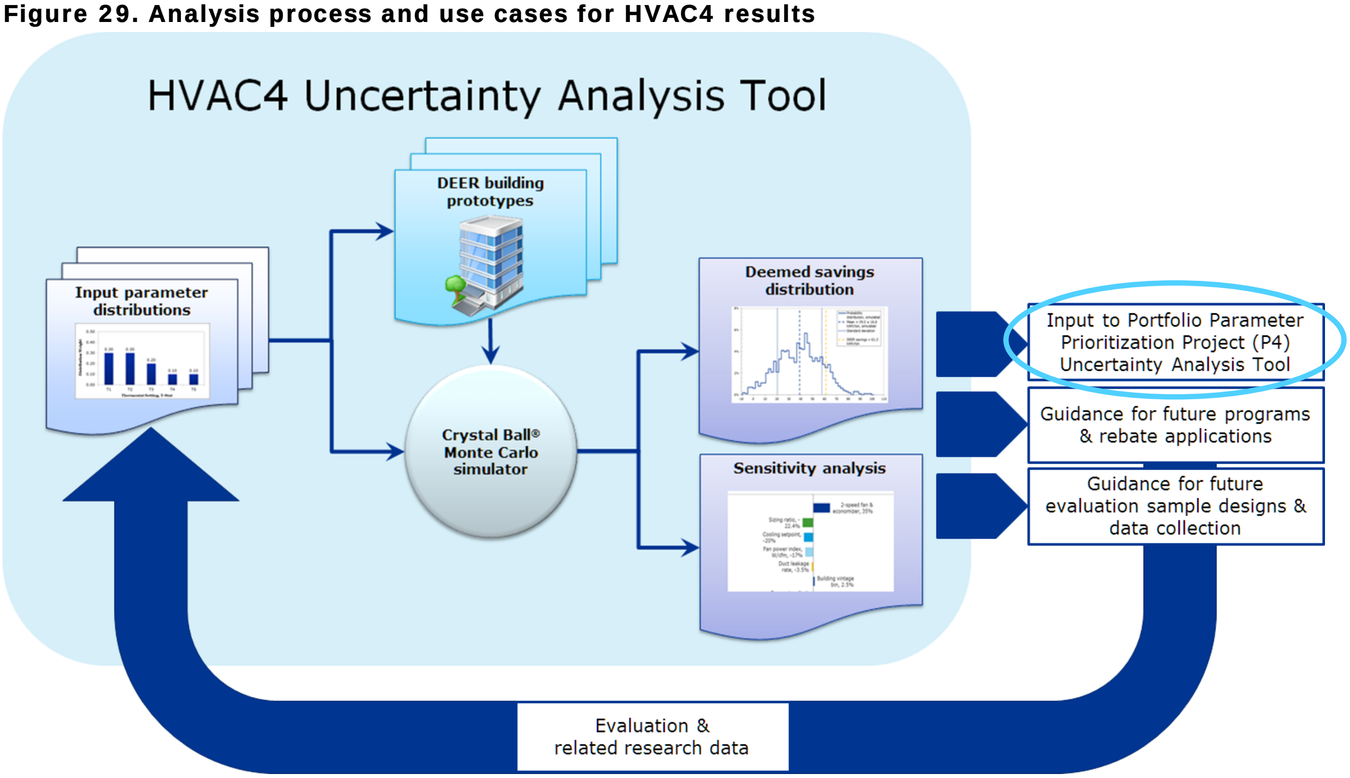
[59] The Crystal Ball outputs are the fractional differences between the modeled pre- and post-treatment performance parameters (efficiency and net cooling capacity) in the form: -1*(Pre – Post)/Pre. Since the pre- and post-treatment models use different assumed distributions to describe the pre- and post-treatment conditions of the input parameters (e.g., distribution of delta charge offsets), each of those distributions—even though they describe the same input parameter—contributes differently to the variance of the uncertainty forecasts.

7 INTEGRATION OF HVAC4 RESULTS INTO P4 TOOL

In addition to the primary objectives of estimating uncertainties for select measures, this HVAC4 study seeks to inform inputs into the CPUC Portfolio Parameter Prioritization Project (P4) Uncertainty Analysis Tool that is used to develop the ESPI uncertain measure list and inform the evaluation priorities in the EM&V Plan. The CPUC runs the analysis annually based on the most recent savings claims. P4 allows users to query a statewide database of claimed measures from the Energy Division's Central Server (EDCS) SQL server to obtain estimated errors associated with the claimed savings of the measures. It attempts to match the claimed measure by program and measure group to the estimated errors from evaluation results. If a match is found, the claimed measure is joined to the estimated errors for that program and measure group. If no match is found in evaluation results, a match is made using the estimated errors for measure groups obtained through surveys of stakeholders and subject matter experts. This query process produces a table in the Uncertainty Analysis Tool. In 2017, the CPUC also developed a table to accept ex post evaluation uncertainty typically included only in written reports. The format aligns with the standard impact results reporting.

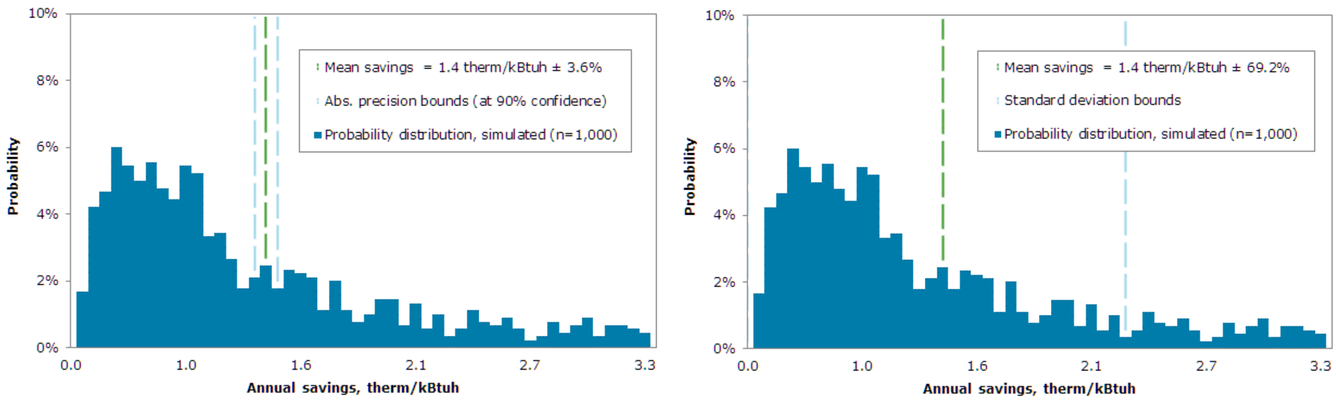
For Year 3, this study added the goal of providing the ex ante savings uncertainty analysis results as inputs to the P4 tool as shown in Figure 29. The results of the HVAC4 analysis could replace the estimated errors from the subject matter expert surveys, especially for measure groups where no evaluation estimates and uncertainties are reported. To do so, it will be necessary to develop a table to deliver ex ante uncertainty, such as the HVAC4 results, that can be imported into the P4.

Figure 29. Analysis process and use cases for HVAC4 results



One challenge of integrating the results of HVAC4 into the P4 database is that the current ex post inputs include relative precision of the unit energy savings rather than the associated relative standard deviation. For evaluations where sample sizes tend to be fairly small, collecting and using relative precision is appropriate as these are often as high as 10%. Since the Monte Carlo simulations typically number anywhere from 1,000 to 10,000 to generate a simulated mean savings, the resulting relative precision of the mean savings is often a fraction of those for ex post savings. Figure 30 provides examples of both the absolute precision bounds, in the graph on the left, and the standard deviation bounds, in the graph on the right, for an analysis performed during Year 2 of HVAC4.

Figure 30. Simulated annual natural gas savings for nonresidential boilers (n=1,000)



Based on the preceding charts, for the Year 3 results, we replaced relative precision with relative standard deviation of the ex ante savings to better represent the underlying distributions of the simulated savings.

7.1 Conclusions and Recommendations

We recommend that CPUC structure a table for ex ante uncertainty results, similar to the HVAC4 results, that is modeled after the evaluation uncertainty P4 tables called the "All Things Reported (ATR)" P4 tables. Having a similar table structure for ex ante and ex post uncertainty would facilitate matching claimed measures to estimated errors at a level of granularity comparable to the uncertainty analysis conducted under HVAC4. The proposed structure would also require adding several fields to a "master uncertainty table" so the estimated errors could be updated as results become available from evaluations or studies like HVAC4, where subsets of measure groups have been evaluated.

To incrementally update estimated errors for subsets of program and measure group combinations, we propose including the following inputs in a master uncertainty table:

- Building type
- Climate zone
- Measure group
- Program

8 OVERALL FINDINGS AND RECOMMENDATIONS

8.1 Ex ante savings forecasts

For unitary systems and air-cooled chillers, it was possible to directly compare the deemed savings per DEER model to the average savings forecasts produced by the Monte Carlo simulations provided in Table 32. Each of the savings forecasts has an associated standard deviation, a common measure of uncertainty. Note that the average savings differ significantly from the DEER estimates in every 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 other than medium unitary systems, the DEER estimates lie outside the uncertainty bands of their respective savings analyses. Those analysis results that exceeded DEER estimates are highlighted in green. While it would be premature to recommend that the average deemed savings values determined by this study be considered to replace those presently in use, further discussion with the Ex Ante Review Team is warranted.

Table 32. Savings uncertainty for unitary systems and air-cooled chillers.

Deemed Savings Results	Uncertainty Analysis	DEER
Unitary systems under 55 kBtu/h at small office building in CZ08		
Average normalized annual electric savings, kWh/ton	218.2	2015 Tier-2: 327.8
Standard deviation, percent	± 13%	N/A
Unitary system under 55 kBtu/h at small office building in CZ12		
Average normalized annual electric savings, kWh/ton	178.0	2015 Tier-2: 322.2
Standard Deviation, percent	± 16%	N/A
Unitary system 65 kBtu/h - 134 kBtu/h at small office building in CZ08		
Average normalized annual electric savings, kWh/ton	69.8	2015 Tier-2: 61.3
Standard deviation, percent	± 18%	N/A
Unitary system 65 kBtu/h - 134 kBtu/h at small office building in CZ12		
Average normalized annual electric savings, kWh/ton	59.8	2015 Tier-2: 53.0
Standard deviation, percent	± 17%	N/A
Air-cooled chiller at large office building in CZ03		
Average normalized annual electric full-load savings, kWh/ton	35.6	2011 Tier-2: 106.7[60] 2014 Tier-2: 84.4
Standard deviation, percent	± 21.6%	N/A
Air-cooled chiller at small office building in CZ08		
Average normalized annual electric full-load savings, kWh/ton	36.8	2011 Tier-2: 182.5[60] 2014 Tier-2: 176.7
Standard deviation, percent	± 23.4%	N/A

[60] The Tier-2 DEER Savings for Large Office Building in CZ03 are workpaper-adjusted by PG&E; those for Small Office Building in CZ08 are workpaper-adjusted by SCE.

In all cases—other than large unitary systems—the DEER deemed savings exceed the mean savings output by HVAC4 analyses. Also, the standard deviations range from 4.5% for air-cooled chillers at large office building in CZ03 to 18% for large unitary systems (65 kBtu/h – 134 kBtu/h) at small office buildings in CZ08.

For the RCA measure, three main experiments were performed using HVAC5 laboratory data and HVAC3 field data as shown in Table 33. For nearly all comparisons with DEER assumptions, the analyses showed that the assumptions about how much EER is improved by the RCA measure are too high. Those EER-improvement analysis results that are nearly equal to or higher than assumed by DEER are highlighted in green.

Table 33. Change to energy efficiency rating (EER) due to RCA measure experiments

Percent Difference of Energy Efficiency Rating, EER	Uncertainty Analysis Standard Deviation, Percent		DEER
	RTU2	RTU5	
Typical undercharged using HVAC5 laboratory data (1AB-IT)			
Percent difference of EER	4.6%	4.0%	11.7%
Standard deviation, percent	0.9%	0.6%	N/A
High undercharge using HVAC5 laboratory data (1AB-IH)			
Percent difference of EER	20.3%	18.8%	15.6%
Standard deviation, percent	4.0%	1.7%	N/A
Typical overcharge using HVAC5 laboratory data (1AB-DT)			
Percent difference of EER	-2.0%	-1.2%	15.3%
Standard deviation, percent	1.0%	0.6%	N/A
High overcharge using HVAC5 laboratory data (1AB-DH)			
Percent difference of EER	-0.2%	2.4%	35.8%
Standard deviation, percent	1.0%	2.1%	N/A
Undercharged using HVAC3 field data for pre-RCA and HVAC5 laboratory data (2AC-I)			
Percent difference of EER	1.8%	1.8%	11.7% to 15.6%
Standard deviation, percent	14%	9.9%	N/A
Overcharged using HVAC3 field data for pre-RCA and HVAC5 laboratory data (2AC-D)			
Percent difference of EER	-1.5%	-3.1%	15.3% to 35.8%
Standard deviation, percent	11%	6.5%	N/A
Undercharged using HVAC3 field data for pre- and post-RCA and HVAC5 laboratory data (3AB-I)			
Percent difference of EER	5.4%	15.3%	11.7% to 15.6%
Standard deviation, percent	10.5%	11.5%	N/A
Overcharged using HVAC3 field data for pre- and post-RCA and HVAC5 laboratory data (3AB-D)			
Percent difference of EER	1.6%	13.8%	15.3% to 35.8%
Standard deviation, percent	8.5%	9.9%	N/A

8.2 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 34. Knowing which parameters contribute the most to the uncertainty of deemed savings can be used to guide future research.

Table 34. Contributors to deemed savings uncertainty for Year 3 measures studied

Input Parameters	Relative Contribution[61] to Variance
Unitary systems under 55 kBtu/h at small office building in CZ08	
1-speed fan w/economizer weight, percent	21%
Fan power index, W/cfm	21%
Cooling setpoint, °F	20%
Cooling sizing ratio, dimensionless	13%
2-speed fan w/economizer weight, percent	12%
Economizer high-temperature limit, °F	5.5%
Duct leakage rate, percent	5.2%
Building vintage bin	1.1%
2-speed fan w/o economizer weight, percent	0.5%
Unitary systems under 55 kBtu/h at small office building in CZ12	
1-speed fan w/economizer weight, percent	45%
Cooling sizing ratio, dimensionless	23%
2-speed fan w/economizer weight, percent	13%
Fan power index, W/cfm	11%
Cooling setpoint, °F	4.4%
Duct leakage rate, percent	1.8%
Building vintage bin	1.0%
Economizer high-temperature limit, °F	0.6%
2-speed fan w/o economizer weight, percent	0.1%
Unitary systems between 55 kBtu/h and 134 kBtu/h at small office building in CZ08	
Cooling sizing ratio, dimensionless	42%
Cooling setpoint, °F	34%
Fan power index, W/cfm	12%
Building vintage bin	7.2%
2-speed fan w/economizer weight, percent	3.6%
Economizer high temperature limit, °F	1.8%
Duct leakage rate, percent	0.2%
Unitary systems between 55 kBtu/h and 134 kBtu/h at small office building in CZ12	
Cooling sizing ratio, dimensionless	43%
Cooling setpoint, °F	27%
Fan power index, W/cfm	11%
Building vintage bin	8.9%
2-speed fan w/economizer weight, percent	8.3%
Economizer high temperature limit, °F	1.6%
Duct leakage rate, percent	0.3%

[61] Absolute values of relative proportions provided herein.

Input Parameters	Relative Contribution[61] to Variance
Air-cooled chillers at large office building in CZ03	
Full-load cooling efficiency (EIR)	-68%
Cooling temperature schedule bin	-13%
Minimum condenser temperature, °F	12%
Minimum chiller ratio, dimensionless	--4.2%
Supply-air temperature range, °F	-1.3%
Chilled-water reset temperature, °F	-0.7%
Loading-sequence bin	-0.3%
Air-cooled chillers at small office building in CZ08	
Full-load cooling efficiency (EIR)	-76%
Cooling-temperature schedule bin	-11%
Minimum condenser temperature, °F	-11%
Chilled-water reset temperature, °F	0.5%
Minimum chiller ratio, dimensionless	0.5%
Supply-air temperature range, °F	0.2%
Loading-sequence bin	-0.1%
Change in EER due to RCA per experiment 3AB-I-RTU5	
Pre-treatment economizer position, percent	41%
Pre-treatment charge offset, percent	22%
Condenser coil blockage rate, percent	14%
Post-treatment economizer position, percent	9.6%
Post-treatment charge offset, percent	7.0%
Evaporator coil blockage rate, percent	6.4%
Change in net total cooling capacity due to RCA per experiment 3AB-I-RTU5	
Pre-treatment charge offset, percent	53%
Pre-treatment economizer position, percent	19%
Post-treatment charge offset, percent	17%
Post-treatment economizer position, percent	5.5%
Evaporator coil blockage rate, percent	3.7%
Condenser coil blockage rate, percent	1.6%

For unitary systems, the findings include:

- For both small and large units, the cooling sizing ratio is often one of the top drivers of savings uncertainty.
- For small units with economizers, it is important to understand the proportions of systems with 1-speed fan motors.
- For large units, the fan power ratio is a significant driver of savings uncertainty.

For air-cooled chillers, the findings include:

- Both the DEER2011 and DEER2014 deemed savings for Tier-2 chillers were considerably higher than those yielded by the simulations.
- Among the seven input parameters studied, the full-load cooling efficiency (EIR), the cooling temperature schedule, and the minimum condenser temperature were the leading driver of the annual savings uncertainty for air-cooled chillers.

Some of the high-level findings for refrigerant charge adjustment are as follows:

- On units with multiple fault conditions that undergo hypothetical RCA treatments where charge correction is known, only highly undercharged units were found to achieve greater than 5% performance-metrics benefits from RCA treatment. The treatment effects on typical overcharged units were a very nearly zero and sometimes led to small negative effects.
- When non-RCA faults are treated before RCA faults, the average changes to the performance metrics are on par with those observed in experiment 1, except that the distributions are much wider (due to the imperfect treatment and the distribution of pre- and post-RCA charge offsets).
- As was reported by HVAC3, greater performance benefits are realized by non-RCA fault treatments than RCA.

8.3 Measure-specific recommendations

For unitary systems, recommendations include the following:

- The assumptions used by DEER and the Ex Ante Review Team to develop savings values for the less than 55kBtu/h unitary systems should be reevaluated in light of the data and results produced by this and the other 2013-15 CPUC HVAC reports.
- Across the different unitary sizes and climate zone combinations explored in this analysis, the cooling sizing ratio, cooling setpoint, and fan power index inputs exhibited moderate to strong contributions to saving variance, whereas inputs such as duct leakage rate, economizer high temperature limit, and building vintage generally had weaker contributions to the variance. The DEER and the Ex Ante Review Team should aim to reduce the uncertainty of the inputs showing moderate to strong contributor to variance to reduce the overall uncertainty of the savings estimates.
- The presence of a correctly functioning economizer can have large impacts on energy consumption by the unitary system and on the savings achieved through the increased mechanical cooling unit efficiency. The DEER and the Ex Ante Review Team should aim to refine their inputs and assumptions around the distributions of installation and functionality of economizers on these unitary systems, again using data and results produced by this and the other 2013-15 CPUC HVAC reports, to further reduce uncertainty and refine the savings estimates.

For chillers, recommendations include the following:

- Given that the mean savings produced by the uncertainty analyses were significantly below the workpaper-adjusted DEER2014 values, consider revising the deemed annual unit energy savings.
- Consider adding a retro-commissioning measure to guide building equipment managers around operating setpoints that are critical to energy savings.

- Presently, EER and IPLV values are not collected by tracking data—they are clustered by tiers, but that does not provide adequate resolution. Furthermore, chillers were not evaluated for the most recent program cycle and there are no field data. Hence, there is an absence of EER/IPLV data for program participants. Going forward, we recommend gathering these values in the tracking data.
- The part-load efficiency (IPLV) qualification pathway results in some qualifying chillers with full-load efficiencies (EER) that are below the Title 24 code requirement. This results in negative savings during full-load periods of operation.
- For future evaluation cycles, consider feasibility of gathering information on critical operating setpoints—including the chilled water supply temperature, the space cooling setpoint, and the chiller minimum condensing temperature—to reduce uncertainty of annual savings. For the RCA measure, some of the more important recommendations include the following:
- Programs should prioritize addressing other non-RCA faults since doing so is more beneficial than addressing the charge offset fault, itself. This is especially true for units with TXV devices and for overcharged units.
- The combination of HVAC4 and HVAC3 findings suggest improved savings certainty for high undercharged, non-TXV units. Programs should target older, non-TXV units or units with multiple circuit because primary HVAC3 site data shows that older non-TXV units and multi-circuit units can be more susceptible to refrigerant loss or lack of thorough diagnostics (on the second circuit).
- Programs should consider expanding services to repair refrigerant lines or targeting replacement of units that have an established track record of low refrigerant charge.
- The DEER team should consider revising the ex ante savings for the refrigerant charge measure.
- The failed economizer damper position has a distinct impact on unit performance. While large temperature differentials across the evaporator coil (e.g., when greater than 95 °F outdoor-air flows over the coil) increase both the unit efficiency and its cooling capacity, the additional run-time needed to meet the added cooling load increases energy consumption. That said, the sensitivity of efficiency and capacity to the economizer damper position was notable in the uncertainty analysis results, as shown in Table 30 and Table 31. Economizer impact continues to be a large source of uncertainty and we recommend continued investigation and training around economizer functionality and reasons for failure or unintentional operation.

8.4 HVAC portfolio-wide recommendation

To make use of the uncertainty analyses performed by HVAC4, we recommend that the CPUC develop an input table for the P4 tool to gather the mean simulated savings and the associated standard deviations, for each measure studied, by building type and climate zone.

APPENDIX A. NONRESIDENTIAL UNITARY SYSTEM INPUT PARAMETERS

The details regarding the input parameters and the regression analysis coefficients used for the uncertainty analysis for both size categories of unitary system retrofits. We set out to focus on those parameters that are most 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 used the following 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.

Regression model configurations and weights

The values used for this input parameter, measure configuration weighting, describe the distribution characteristics used to define the variation in the weighting of savings for the unitary measure configurations (see Table 35 and Table 36), and were informed by the 2015 Upstream program (HVAC1) evaluation results and engineering judgement.

Table 35. Regression model configurations and weights for units 65 to 134 kBtu/h

Measure Configuration	Weight Mean	Weight Standard Deviation	Weight Lower Bound	Weight Upper Bound
2-speed fan, economizer	0.750	0.750	0.650	0.850
2-speed fan, no economizer	The weighting value for this configuration is equal to one minus the sum of all other weights, or 0, whichever is greater			

Table 36. Regression model configurations and weights for units less than 55 kBtu/h

Measure Configuration	Weight Mean	Weight Standard Deviation	Weight Lower Bound	Weight Upper Bound
1-speed fan, economizer	60%	30%	50%	70%
2-speed fan, no economizer	5%	5%	0%	10%
2-speed fan, economizer	15%	15%	10%	20%
1-speed fan, no economizer	The weighting value for this configuration is equal to one minus the sum of all other weights, or 0, whichever is greater			

Fan power index

The unitary system savings analyses used the following distributions of fan power indices provided in Table 37 and Table 38.

Table 37. Fan power index (X_1) distribution for unitary systems <55kBtu/h

Fan Power Index, W/cfm	Proportion
0.10	14%
0.15	11%
0.20	10%
0.25	9%
0.30	16%
0.35	12%
0.40	4%
0.45	6%
0.50	4%
0.55	1%
0.60	9%
0.65	0%
0.70	5%

Table 38. Fan power index (X_1) distribution for unitary systems 65 to 134 kBtu/h

Fan Power Index, W/cfm	Proportion
0.10	10%
0.15	17%
0.20	6%
0.25	9%
0.30	11%
0.35	8%
0.40	10%
0.45	9%
0.50	2%
0.55	6%
0.60	6%
0.65	3%
0.70	3%

Duct leakage rate

The unitary system savings analyses used the following distributions of duct leakage rates provided in Table 39.

Table 39. Duct leakage rate (X_2) distributions for unitary systems

Duct Leakage Rate, percent	Proportion
0.10	10%
0.20	15%
0.30	35%
0.40	35%
0.50	5%

System sizing ratio

The unitary system savings analyses used the following distributions of system sizing ratio as provided in Table 40.

Table 40. System sizing ratio (X_3) distributions for unitary systems

Sizing ratio	Proportion
0.8	5%
1.0	70%
1.2	25%

Building vintage

Prototype-building vintage bins are used to account a lot of building characteristics, including building shell UA, duct work UA, glazing properties, lighting power density, and so on. Duct UA is one example.The unitary system savings analyses used the following distributions of duct heat transfer coefficient (UA), by climate zone, as provided in Table 41 and Table 42.

Table 41. Duct heat transfer coefficient (X_4) by building vintage bin in CZ08

Building Vintage Bin	Duct UA Value
v75	864
v85	564
v96	228
v03	123

Building Vintage Bin	Duct UA Value
v07	65
v11	65
v14	33

Table 42. Duct heat transfer coefficient (X_4) by building vintage bin in CZ12

Building Type Vintage	Duct UA Value
v75	189
v85	124
v96	82
v03	49
v07	23
v11	23
v14	11

System sizing ratio

The unitary system savings analyses used the following distribution of cooling setpoints as provided in Table 43.

Table 43. Cooling setpoint (X_5) distribution for unitary systems

Cooling Setpoint, °F	Proportion
70	8%
72	32%
74	35%
76	15%
78	10%

Economizer temperature limit

The unitary system savings analyses used the following distribution of high-temperature limits for systems with economizers as provided in Table 44.

Table 44. High-temperature limit (X_6) distribution at unitary systems with economizers

Economizer high-temperature limit, °F	Proportion
69	25%
72	50%
75	25%

APPENDIX B. NONRESIDENTIAL AIR-COOLED CHILLER INPUT PARAMETERS AND RESULTS FOR TIERS 1 & 3

This appendix presents the details of the air-cooled chiller input parameter distributions and additional supporting details regarding that uncertainty analysis.

Cooling and heating setpoint temperatures

The values used for this input parameter, the cooling and heating setpoints for space conditioning (see Table 45), were established based on engineering judgement.

Table 45. Cooling / heating setpoint temperature combination (X_1) distribution

Schedule	Cooling, Setpoint °F	Heating Setpoint, °F	Proportion
1	75	73	20%
2	76	72	30%
3	77	71	50%

Chiller minimum ratio

This input parameter, the minimum turndown ratio, is defined as the minimum fraction of rated load at which the chiller can operate continuously. This inputs are varied as shown in Table 46.

Table 46. Chiller minimum turndown ratio (X_2) distribution for air-cooled chillers

Min. Chiller Turndown Ratio	Proportion
20%	20%
30%	60%
50%	20%

Minimum condensing temperature

This input parameter, the minimum condensing temperature, is a system-dependent variable that is defined as the minimum temperature at which the condenser will turn the high-pressure, superheated vapor discharged by the chiller compressor into 100% saturated vapor. This inputs are varied as shown in Table 47.

Table 47. Minimum condensing temperature (X_3) distribution for air-cooled chillers

Min. Condensing Temperature, °F	Proportion
60	15%
70	60%

Min. Condensing Temperature, °F	Proportion
80	25%

Chiller water supply temperature reset range for air-cooled chillers

This input parameter is used to establish the reset range of the chilled water supply temperature, or the difference between maximum and minimum supply water temperature resets. The distribution of the values used in the analysis are as shown in Table 48.

Table 48. Chilled-water supply temperature reset range (X_4) input values for air-cooled chillers

Chilled Water Supply Temperature Reset Range[62]	Proportion
∆ 10 °F	10%
∆ 9 °F	30%
∆ 8 °F	40%
∆ 7 °F	20%

Cold duct supply air temperature

This input parameter is used to establish the reset range of the cold duct temperature, or the difference between maximum and minimum supply air temperature resets. The distribution of the values used in the analysis are as shown in Table 49.

Table 49. Cold duct supply air temperature reset range (X_5) distribution

Cold Duct Supply Air Temp. Reset Range	Proportion
∆ 7 °F	10%
∆ 5 °F	30%
∆ 3 °F	40%
∆ 1 °F	20%

Chiller staging strategy

This input parameter is used to establish and define the sequencing strategy of the chiller systems. The second chiller cut-in point is defined as the percent of nameplate cooling capacity of the lead chiller at which the second chiller turns on. The distribution of the values used in the analyses are as shown in Table 50.

[62] Delta between maximum and minimum chilled water reset temp.

Table 50. Chiller staging strategy (X_6) distribution by building type and climate zone

Second Chiller Cut-in Point, Percent	Effective Lead Chiller Nameplate Capacity, Btu/h		Proportion
Climate Zone	CZ03	CZ08	
Building Prototype	Large Office Building	Small Office Building	
50%	1,200	100	50%
80%	1,920	160	25%
100%	2,400	200	25%

Full-load chiller efficiency

This input parameter is used to establish the ranges of chiller efficiency, within each program-defined tier, at full load under test rating conditions. EER, or energy efficiency ratio is the quotient of the cooling capacity delivered by the system, in Btu/h, over the electrical energy input into the system, in watts. EIR, or electrical input ratio, is the dimensionless inverse of EER and is used by eQUEST to define the full-load performance of cooling equipment. The distribution of the values used in the analyses are as shown in Table 51.

Table 51. EIR (X_7) distribution by chiller efficiency tier

Efficiency Tier	EIR	Proportion
Tier 1	0.351	1%
	0.343	15%
	0.335	51%
	0.327	18%
	0.320	14%
Tier 2	0.367	6%
	0.353	11%
	0.340	38%
	0.327	36%
	0.316	10%
Tier 3	0.338	25%
	0.312	45%
	0.290	0%
	0.270	28%
	0.253	3%

Correlation of independent variables for air-cooled chillers

Table 52 is a correlation table for Tier-2 air-cooled chillers 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 -1 to 1 where 0 means no correlation, 1 means complete positive correlation, and -1 means complete negative 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 little to no correlation with one another.

Table 52. Correlation of independent variables for air-cooled chillers at large office buildings in CZ03

Correlation	Schedule	Min ratio	Min Cond. Temp	CHW Reset Range	Cold Duct SAT Reset Range	Sequence (Max Load)	EIR
	X_1	X_2	X_3	X_4	X_5	X_6	X_7
X_1	1						
X_2	-0.0003	1					
X_3	-0.0004	-0.0003	1				
X_4	0.0004	0.0004	0.0004	1			
X_5	0.0004	0.0004	0.0004	-0.0005	1		
X_6	0.0001	0.0000	0.0001	-0.0001	-0.0001	1	
X_7	0.0004	0.0004	0.0004	-0.0005	-0.0005	-0.0001	1

Results for Tier-1 air-cooled chillers

Figure 31. Probability distribution of annual savings of Tier-1 air-cooled chillers at large office buildings in CZ03

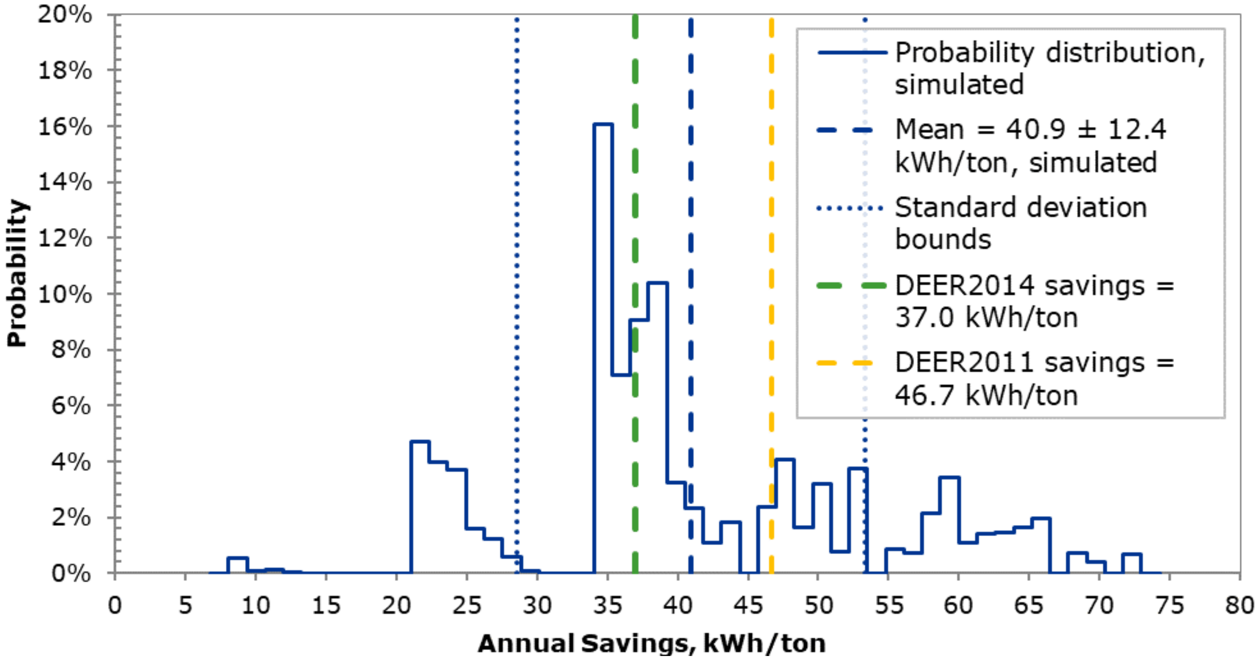


Figure 32. Ranked contributors to variance for Tier-1 air-cooled chillers applied to large office building type in CZ03

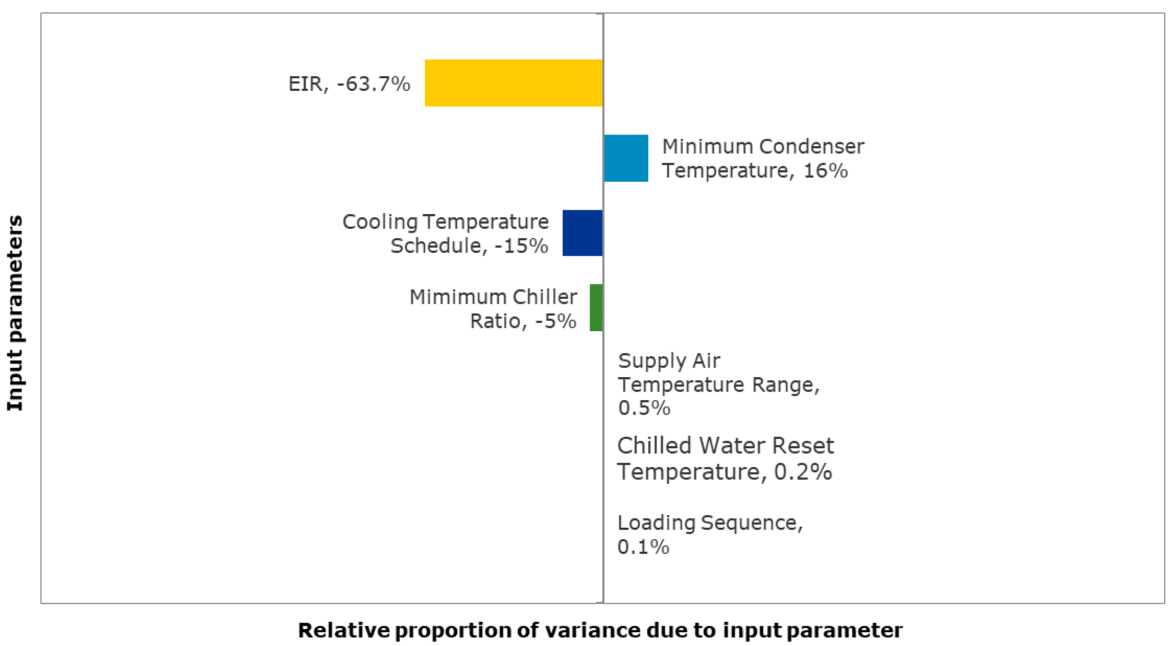


Figure 33. Probability distribution of annual savings of Tier-1 air-cooled chillers at small office buildings in CZ08

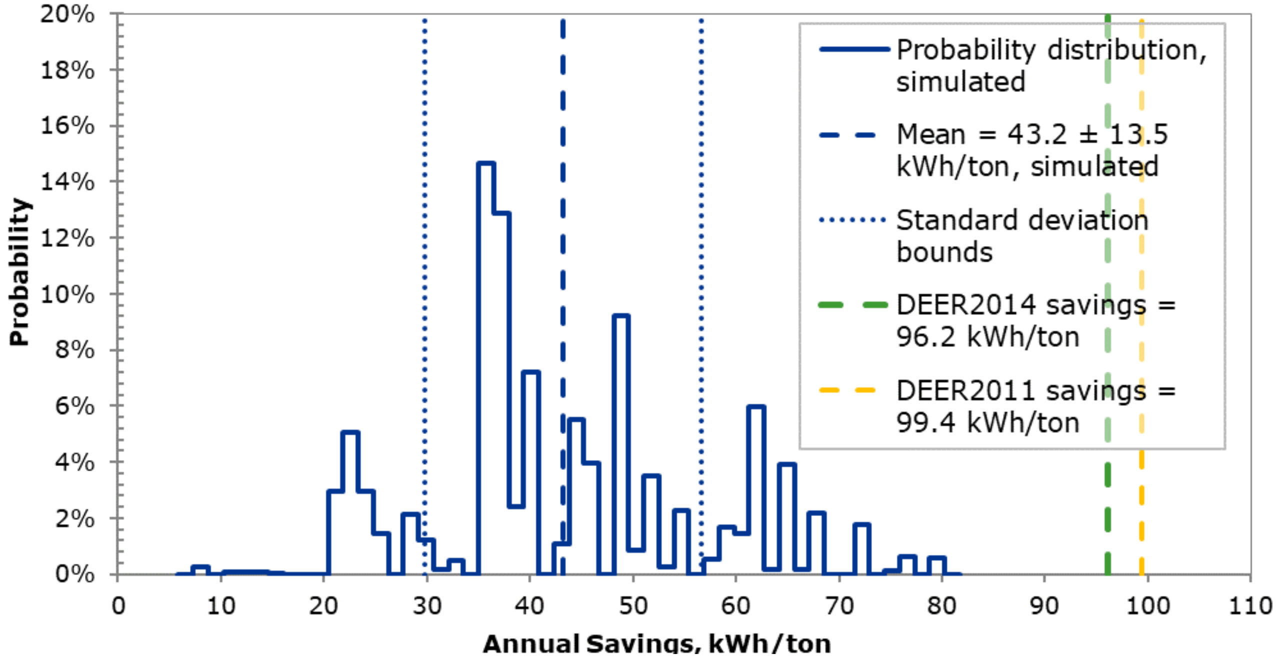
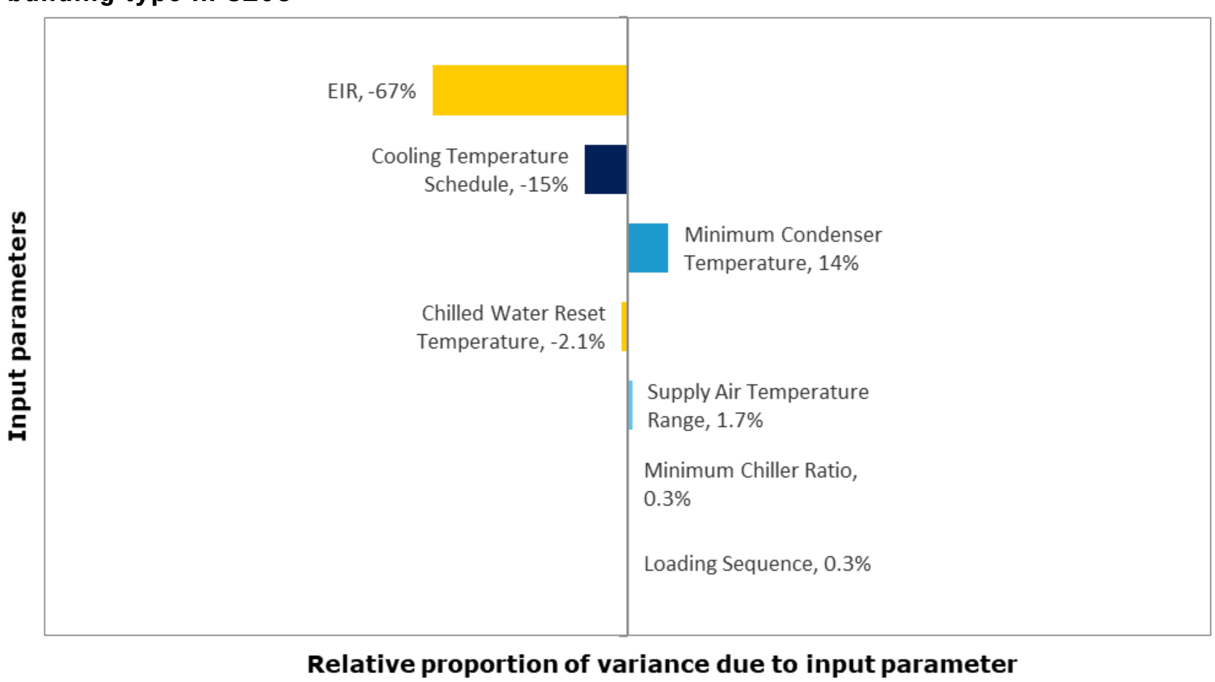


Figure 34. Ranked contributors to variance for Tier-1 air-cooled chillers applied to small office building type in CZ08



Results for Tier-3 air cooled chillers

Figure 35. Probability distribution of annual savings of Tier-3 air-cooled chillers at large office buildings in CZ03

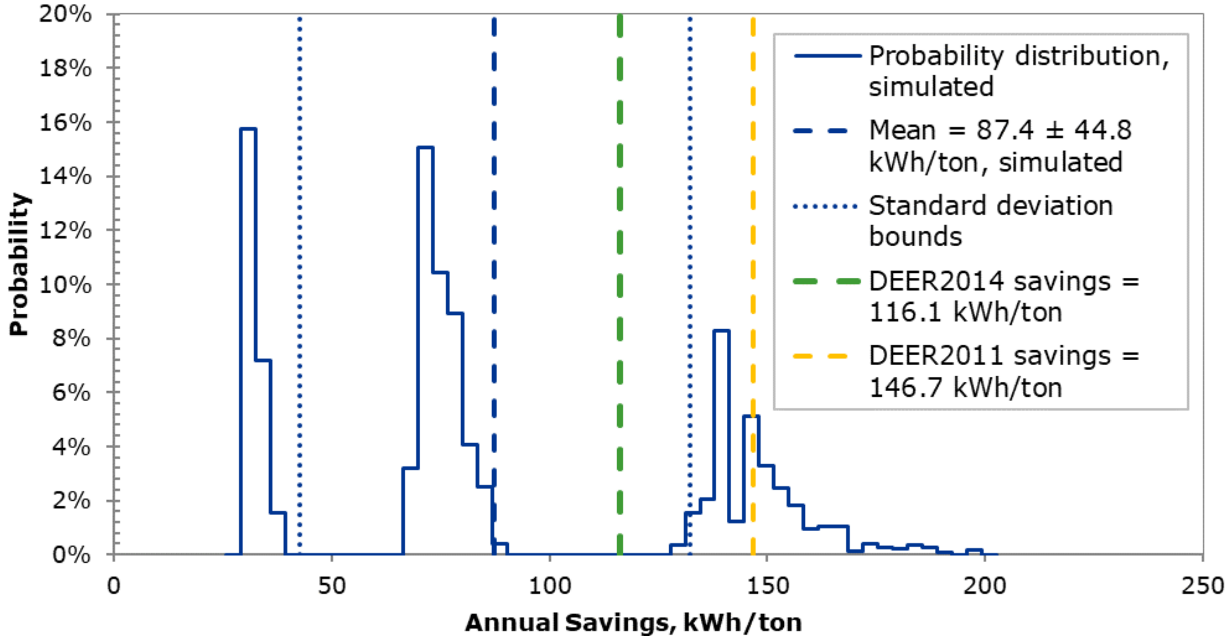


Figure 36. Ranked contributors to variance for Tier-3 air-cooled chillers applied to large office building type in CZ03

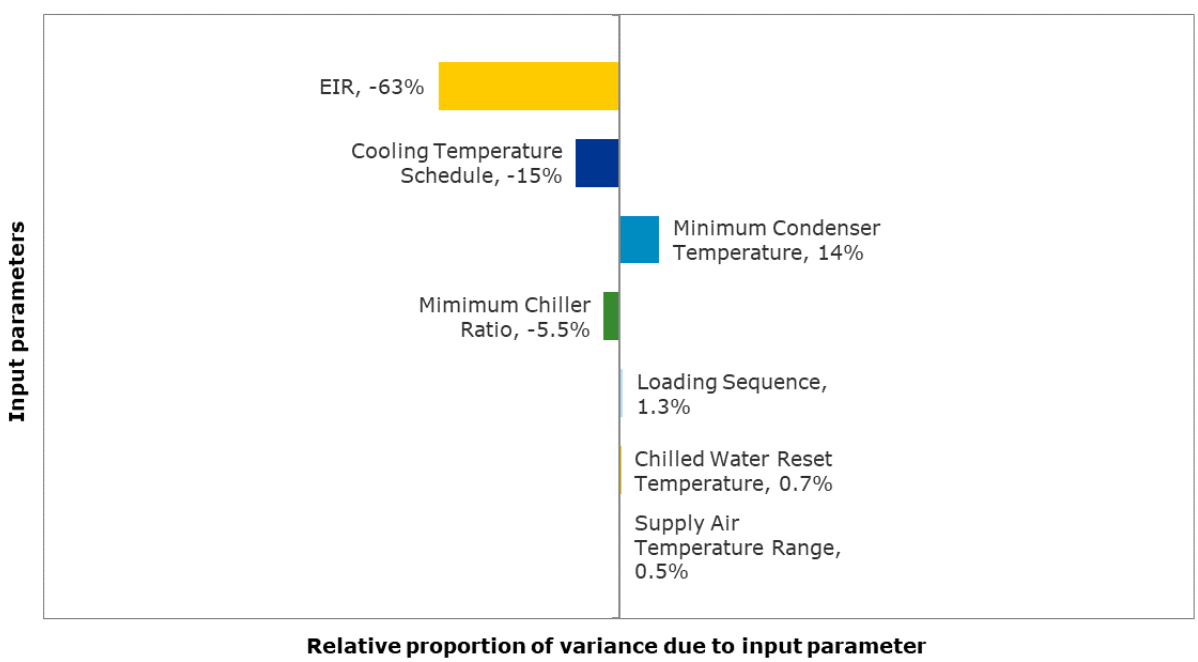


Figure 37. Ranked contributors to variance for Tier-3 air-cooled chillers applied to small office building type in CZ08

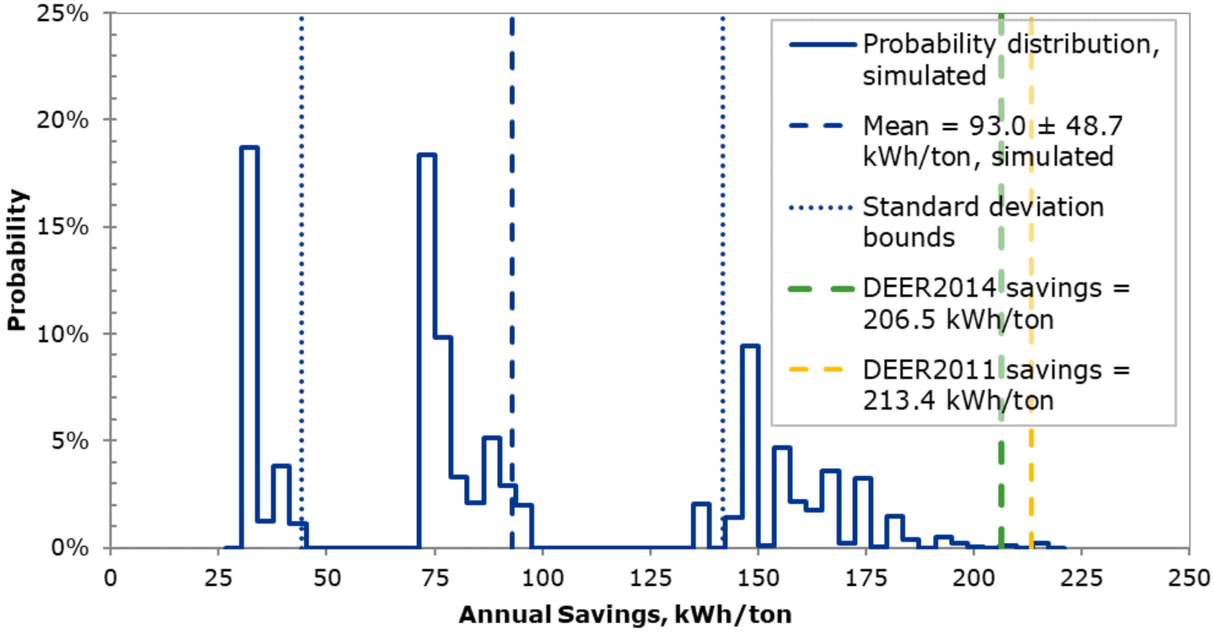
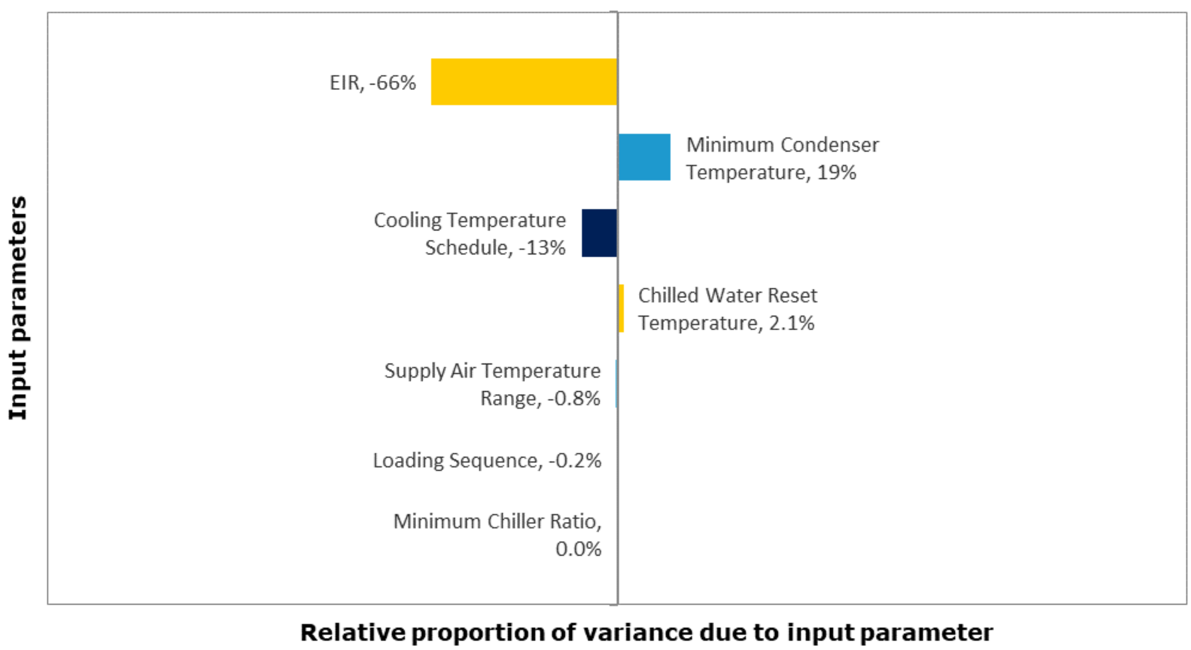


Figure 38. Ranked contributors to variance for Tier-3 air-cooled chillers applied to small office building type in CZ08



APPENDIX C. NONRESIDENTIAL RCA ASSUMPTIONS

The details regarding the experiment assumptions, the input parameters, and the regression analysis coefficients used for the uncertainty analysis for the RCA measure are presented in this appendix. All input parameters are performance faults that were directly assessed during HVAC5 lab tests. They are also commonly observed field conditions.

Experiment Assumptions and Conditions

Experiment 1

The DEER RCA measure group has two different charge adjustment levels for undercharged and overcharged systems. Each group is categorized by whether the charge offset is “Typical” or “High.” The measure assumes the RTU is brought to “perfect” factory charge by the treatment (i.e., the post-RCA charge offset is 0% of the nominal factory charge level). The measure groups and the specific pre-RCA and post-RCA offset values assumed by the measure are shown in Table 53.

Table 53: DEER RCA measure groups and representative charge offset value

RCA DEER Measure Group	Charge Offset, State 1A	Charge Offset, State 1B	Delta Charge	Experiment Sub-case
Typical Undercharge (<20%)	-12%	0%	Δ +12%, typical increase	1AB-IT-RTU5
				1AB-IT-RTU2
High Undercharge (≥20%)	-32%	0%	Δ +32%, high increase	1AB-IH-RTU5
				1AB-IH-RTU2
Typical Overcharge (<20%)	12%	0%	Δ -12%, typical decrease	1AB-DT-RTU5
				1AB-DT-RTU2
High Overcharge (≥20%)	32%	0%	Δ -32%, high decrease	1AB-DH-RTU5
				1AB-DH-RTU2

Experiment 1AB uses the specific DEER measure charge offset values (i.e., assumes no uncertainty for charge offset) as inputs for the Crystal Ball uncertainty analysis but other fault input parameters use pre-treatment distributions that were developed from HVAC3 field measurements for condenser coil cleaning, evaporator coil cleaning, and failed economizer outside air damper position.[63] The experiment’s pre- and post-treatment conditions for RTU5 and RTU2 are outlined in Table 54 and Table 55, respectively. More information regarding specific custom distributions and input values can be found in APPENDIX C.

Table 54: Experiment 1AB--RTU5[64] (single stage, non-TXV) conditions**

Faults	State 1A	State 1B
Refrigerant Charge Offset (%)	±12% or ±32%	0%

[63] The fault distribution for fan airflow % was assigned arbitrarily as discussed in APPENDIX C.

[64] Asterisks (*) are intended to represent wild characters that can be either TI, HI, TD, or HD that represent that the system was “typical undercharged,” “high undercharged,” “typical overcharged,” or “high overcharged.”

Faults	State 1A	State 1B
Condenser coil blockage (%)	pre-treatment custom distribution	
Evaporator coil blockage (%)	pre-treatment custom distribution	
Failed economizer damper position (% of open)	pre-treatment custom distribution	

Table 55: Experiment 1AB--RTU2 (multi-stage, TXV) conditions**

Faults	State 1A	State 1B
Refrigerant Charge Offset (%)	±12% or ±32%	0%
Condenser Coil Blockage (%)	pre-treatment custom distribution	
Evaporator coil blockage (%)	pre-treatment custom distribution	
Failed economizer damper position (% of open)	pre-treatment custom distribution	
Fan Airflow, normalized by 400 cfm/ton (%)	pre-treatment custom distribution	

Experiment 2

The experiment's case conditions are outlined in Table 56. More information regarding specific input parameter distributions and input values can be found in the appendix sub-sections that follow.

Table 56: Conditions of States for Experiment 2

Faults	State 2A, (All Faults Untreated)	State 2B (Non-RCA faults treated)	State 2C (Imperfect RCA treatment)
Refrigerant Charge Offset (%)	Pre-RCA custom distribution (differ between for RTU5 and RTU2)		Post-RCA custom distribution (differ between RTU5 and RTU2)
Condenser coil blockage (%)	Pre-treatment custom distribution	0%	
Evaporator coil blockage (%)	Pre-treatment custom distribution	0%	
Failed economizer damper position (% of open)	Pre-treatment custom distribution	"1 finger"[65] for RTU5 10% for RTU2[66]	
Fan Airflow (% of 400 cfm/ton) – RTU2 only	Pre-treatment custom distribution	100%	

Experiment 3

Table 57 describes the conditions of the two equipment states that preceded the RCA measure.

[65] Economizer opening of "1 finger," or 38.75%, was chosen as the nominal minimum economizer outside air damper position only because HVAC5 data did not include a test involving air damper position at 10% for RTU5—the position chosen for the RTU2 nominal conditions. The "1 finger" position was the closest to a typical "minimum" outside air position.

[66] Ten percent outside air damper position was chosen to be the nominal position based on outside air requirements for typical building RTUs that participate in IOU QM programs.

Table 57: Conditions of experiment 3 states

Faults	State 3A, Pre-treatment	State 3B, Post-treatment
Refrigerant Charge Offset (%)	pre-treatment custom distribution (differ between RTU5 and RTU2)	post-treatment custom distribution (differ between RTU5 and RTU2)
Condenser coil blockage (%)	pre-treatment custom distribution	0%
Evaporator coil blockage (%)	pre-treatment custom distribution	0%
Failed economizer damper position (% of open)	pre-treatment custom distribution	post-treatment custom distribution
Fan airflow (% of 400 cfm/ton) – RTU2 only	pre-treatment custom distribution	

Refrigerant charge offset

Refrigerant charge offset is defined as the percent difference between the nominal factory refrigerant circuit weight and the refrigerant weight that was measured pre- or post-RCA treatment. For example, a refrigerant circuit may have a factory "charge" of 100 ounces. If the measured charge is 90 ounces, the refrigerant circuit is 10% undercharged [(90 - 100) / 100 = -10%]. If the measured charge is 140 ounces, the refrigerant circuit is 40% overcharged [(140 – 100) / 100 = 40%].

This input parameter is the indirect metric used in the deemed DEER measure. Prior field and lab testing attempted to correlate charge offset to system performance like EER and capacity. Those system performance metrics are used in the RCA DEER measure eQUEST models to produce energy savings. The deemed RCA measure assumes that post-treatment charge offset is 0% ("perfect" factory level charge) and thus the post-treatment equipment performance is at nominal factory values.

The distribution of refrigerant charge offset was created from weigh-in/weigh-out data collected under the HVAC3 evaluation. During that evaluation, several nonresidential roof top units (RTUs) that had been RCA-treated had their refrigerant circuits evacuated and refrigerant weight directly measured.

The program assumes that the RCA-treatment adds or removes refrigerant in order to adjustment levels to the nominal factory charge. The program recorded the amount of refrigerant added or removed to reach factory levels so the pre-treatment refrigerant levels are also known.

Crystal Ball was used to attempt to automatically fit a probability distribution to the weigh-in/weigh-out refrigerant charge data. The data did not fit well to any distributions in the Crystal Ball library, so custom discrete distributions (i.e., field data points were given equal probability) were generated to describe different unit configurations (e.g., TXV, non-TXV, single stage, multi-stage). Figure 39, Figure 40 illustrate the general shape of the distribution for RTU5 (non-TXV, single stage) and RTU2 (TXV, multi-stage) pre- and post-RCA conditions for undercharged circuits. Table 58 contains the distribution data points for all refrigerant charge categories. Table 59 contains the average values of the distribution data points for all the refrigerant charge categories.

Figure 39: Distribution for RTU5 undercharged pre-condition, state 2A-I-RTU5

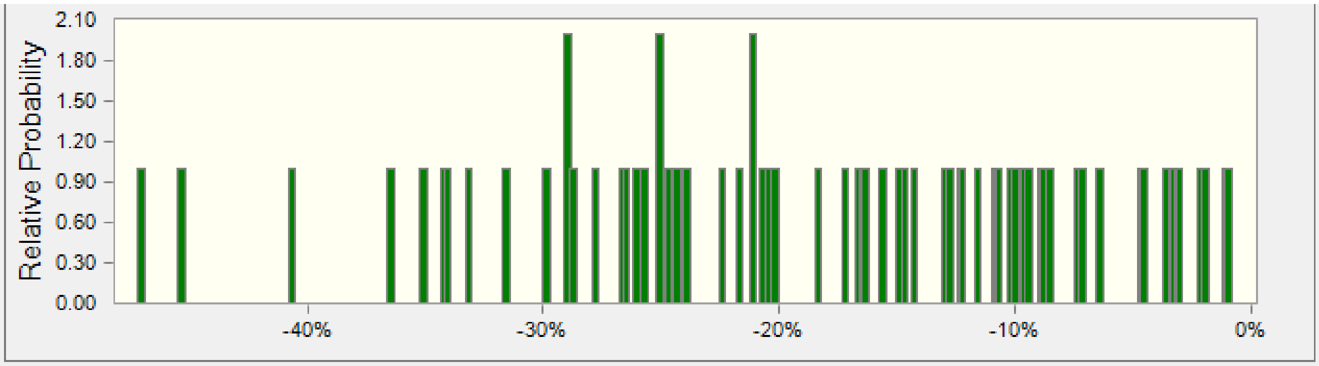


Figure 40: Distribution for RTU5 undercharged post-condition, state 2C-I-RTU5

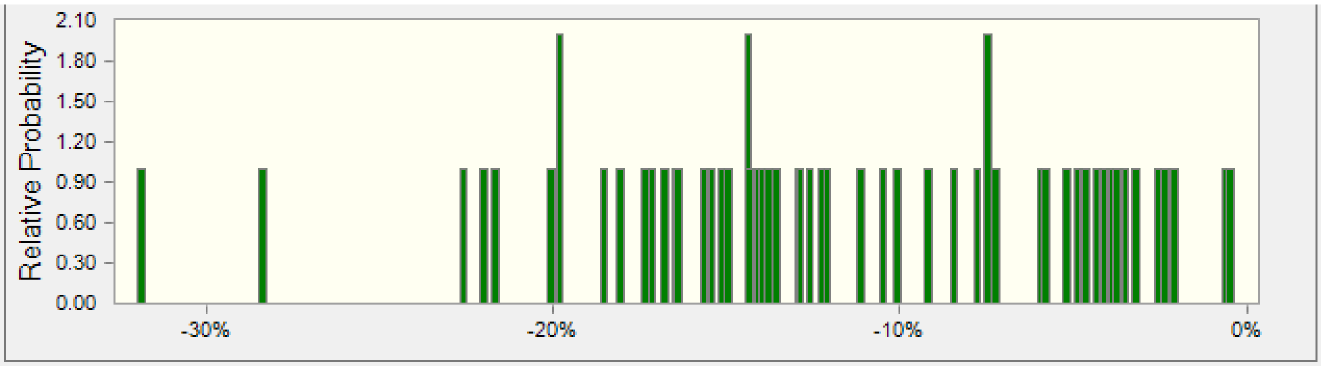


Figure 41: Distribution for RTU2 undercharged pre-condition, state 2A-I-RTU2

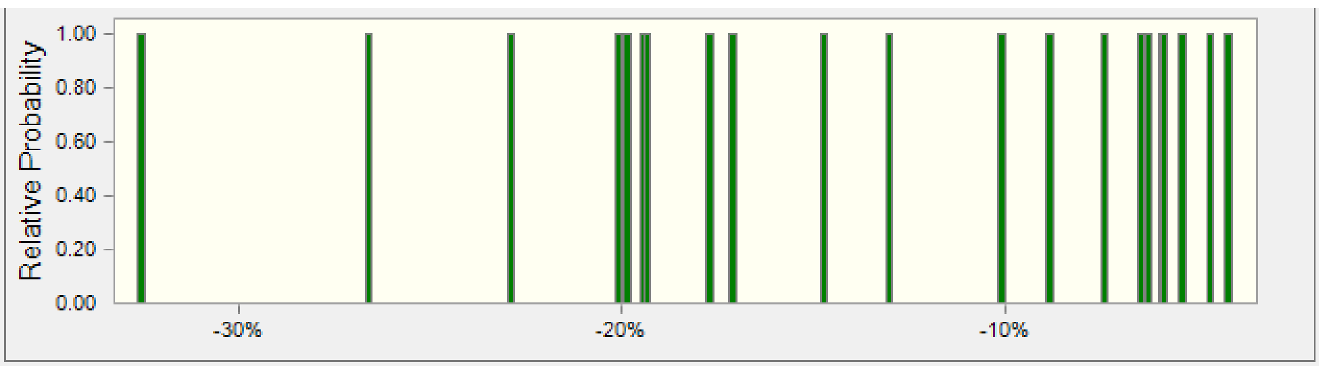


Figure 42: Distribution for RTU2 undercharged post-condition, state 2C-I-RTU2

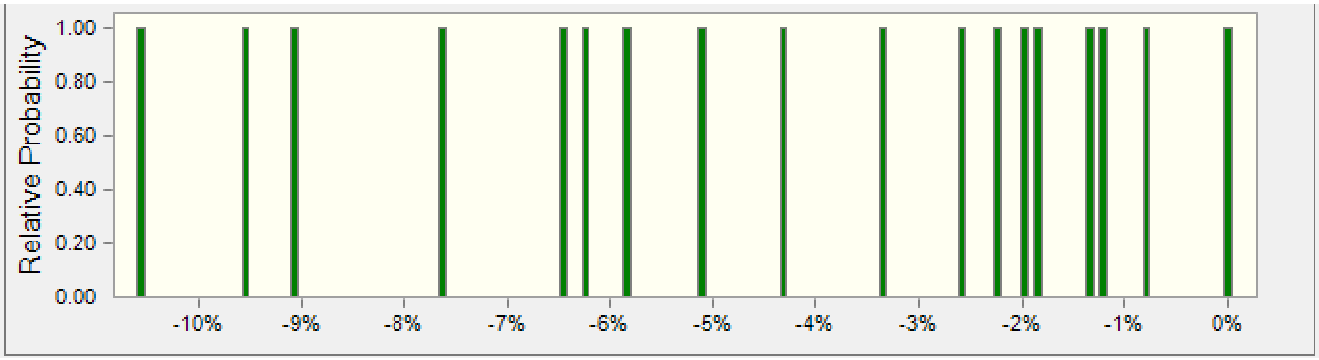


Figure 43: Distribution for RTU5 overcharged pre-condition, state 2A-D-RTU5

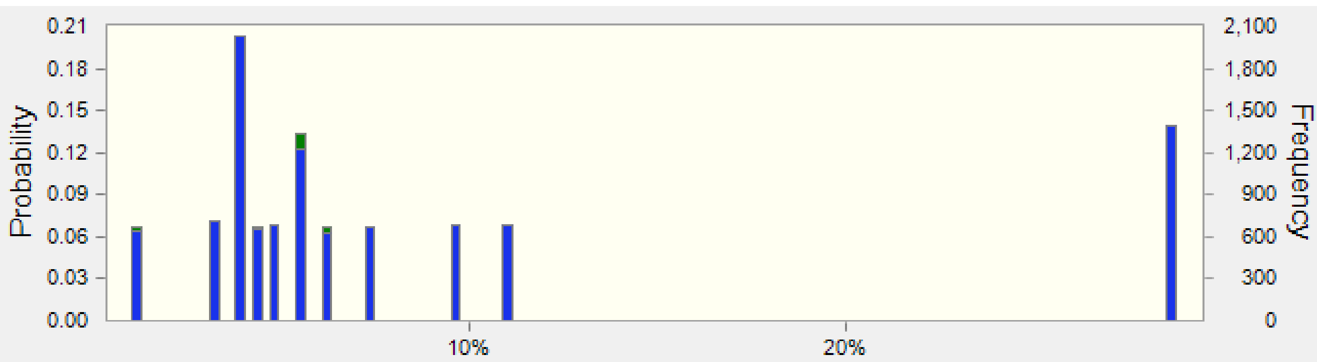


Figure 44: Distribution for RTU5 overcharged post-condition, state 2C-D-RTU5

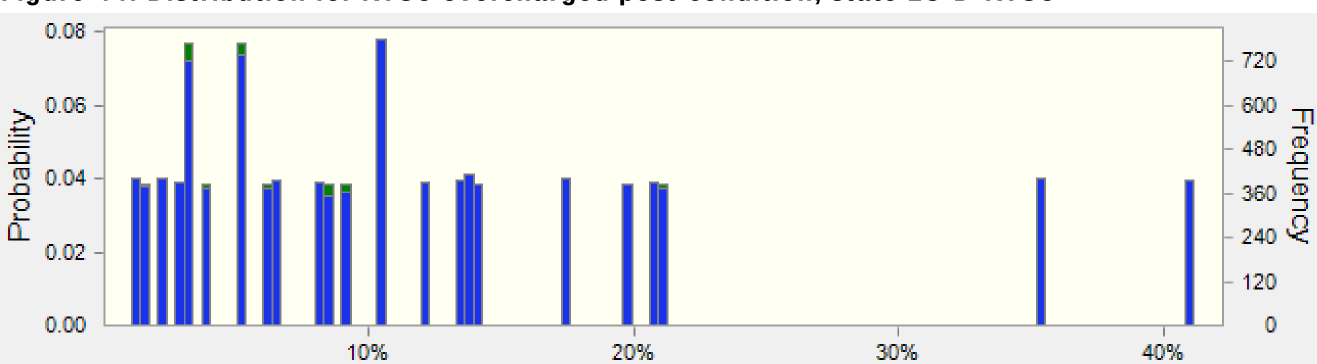


Figure 45: Distribution for RTU2 overcharged pre-condition, state 2A-D-RTU2

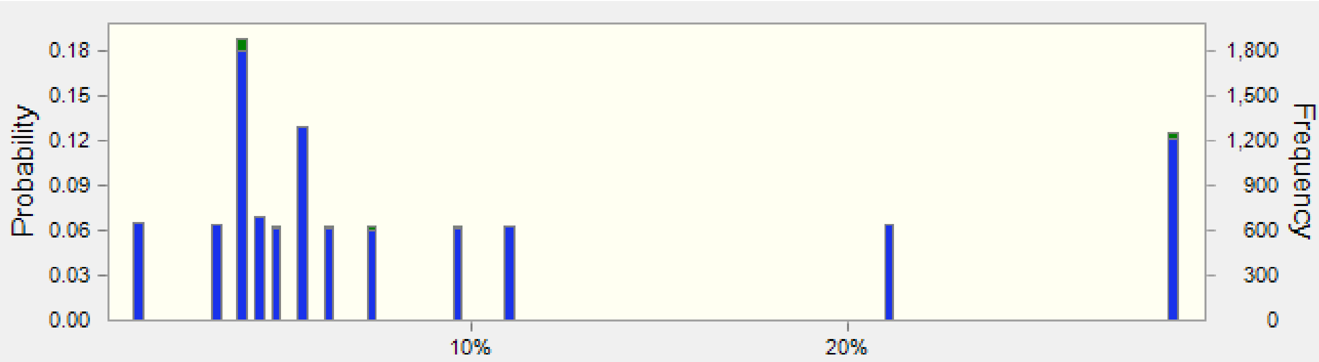


Figure 46: Distribution for RTU2 overcharged post-condition, state 2C-D-RTU2

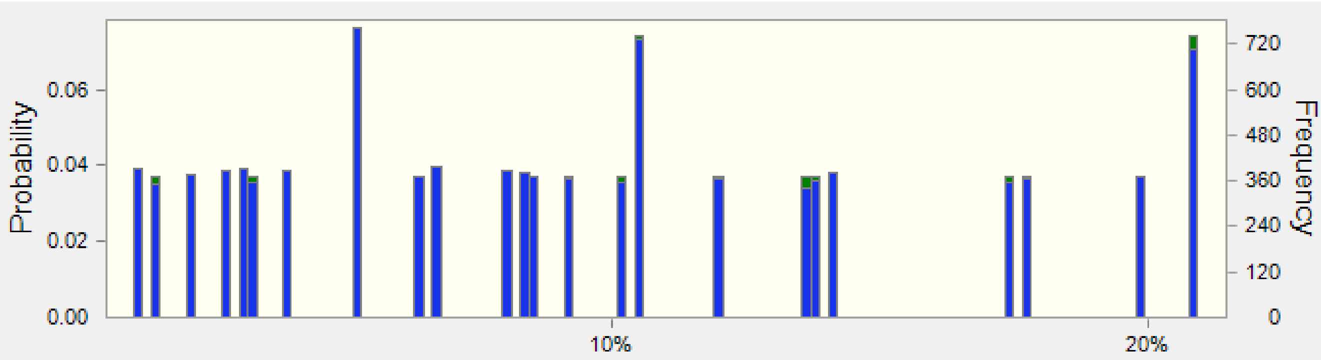


Table 58: Distributions of refrigerant charge categories

Pre-measure				Post-measure			
RTU5 (non-TXV, single)		RTU2 (TXV, multi)		RTU5 (non-TXV, single)		RTU2 (TXV, multi)	
Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge
-41%	6%	-4%	6%	-22%	4%	-3%	18%
-32%	3%	-5%	3%	-12%	14%	-3%	8%
-36%	29%	-20%	29%	-13%	41%	-6%	10%
-6%	10%	-6%	10%	-10%	2%	-6%	4%
-9%	4%	-19%	4%	-14%	3%	-8%	14%
-5%	7%	-6%	7%	-2%	5%	-6%	2%
-5%	5%	-6%	5%	-10%	35%	-1%	3%
-15%	4%	-10%	4%	-8%	17%	-9%	5%
-2%	4%	-18%	4%	-13%	9%	0%	17%
-9%	11%	-5%	11%	-5%	14%	-2%	9%
-3%	1%	-7%	1%	-6%	12%	-2%	14%

Pre-measure				Post-measure			
RTU5 (non-TXV, single)		RTU2 (TXV, multi)		RTU5 (non-TXV, single)		RTU2 (TXV, multi)	
Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge
-7%	29%	-9%	29%	0%	11%	-1%	12%
-3%	4%	-6%	4%	-2%	8%	-5%	11%
-1%	5%	-15%	5%	-4%	3%	-2%	8%
-16%	6%	-13%	6%	-4%	20%	-1%	3%
-17%		-20%	21%	-4%	21%	-4%	20%
-11%		-27%		-1%	6%	-10%	21%
-9%		-17%		-28%	14%	-11%	6%
-11%		-19%		-32%	7%		14%
-33%		-33%		-23%	5%		7%
-7%		-23%		-15%	1%		5%
-47%				-16%	21%		1%
-35%				-17%	8%		21%
-26%				-11%	3%		8%
-26%				-16%	1%		3%
-2%				-16%	11%		1%
-25%				-17%			11%
-20%				-14%			
-24%				-14%			
-22%				-15%			
-24%				-22%			
-21%				-20%			
-4%				-14%			
-21%				-20%			
-34%				-14%			
-28%				-4%			
-29%				-18%			
-25%				-3%			
-29%				-5%			
-25%				-15%			
-12%				-12%			
-29%				-17%			
-9%				-4%			
-11%				-7%			
-22%				-7%			

Pre-measure				Post-measure			
RTU5 (non-TXV, single)		RTU2 (TXV, multi)		RTU5 (non-TXV, single)		RTU2 (TXV, multi)	
Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge
-18%				-9%			
-30%				-5%			
-5%				-8%			
-27%				-4%			
-17%				-4%			
-12%				-5%			
-2%				-16%			
-12%				-19%			
-16%				-3%			
-13%				-13%			
-10%				-6%			
-10%				-7%			
-26%				-4%			
-9%				-14%			
-15%				-20%			
-2%				-4%			
-13%				-14%			
-14%				-17%			
-10%							
-3%							
-16%							
-21%							
-20%							
-11%							
-26%							
-34%							
-45%							
-1%							

Table 59: Average of refrigerant charge categories

Pre-measure				Post-measure			
RTU5 (non-TXV, single)		RTU2 (TXV, multi)		RTU5 (non-TXV, single)		RTU2 (TXV, multi)	
Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge	Under-charge	Over-charge
-17%	9%	-14%	9%	-11%	11%	-4%	10%

Condenser coil blockage

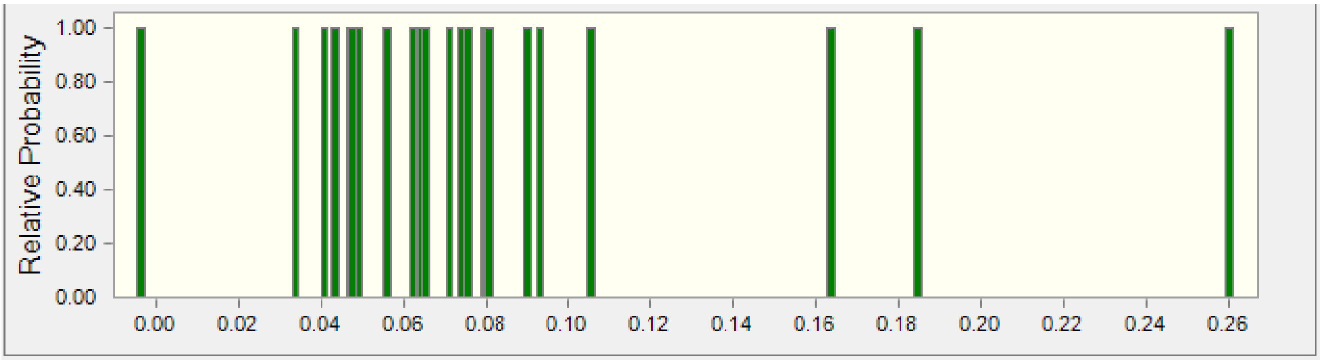
Condenser coil blockage was one of the main maintenance faults tested in HVAC5. Pre-treatment coil blockage levels were also indirectly measured (using change in discharge pressure) during HVAC3 field data collection. After coil cleaning is performed, the coils are assumed to be perfectly clean (0% blockage) and no distribution is necessary for the post-treatment case. The pre-treatment condenser coil blockage distribution was fit to a custom distribution (all data points given the same probability) using 25 data points. The data points represent coils cleaned during the HVAC3 ride-along field data collection effort. Custom distribution is illustrated in Figure 47.

Figure 47: Distribution for condenser coil blockage input, state 2A

Evaporator coil blockage

Evaporator coil blockage was another of the main maintenance faults tested in HVAC5. Pre-treatment coil blockage levels were indirectly measured (using change in total air flow) during HVAC3 field data collection. After evaporator coil cleaning is performed, the coils are assumed to be perfectly clean (0% blockage) and no distribution is necessary for the post-treatment case. The pre-treatment evaporator coil blockage distribution was fit to a custom distribution using 23 data points. The data points represent coils cleaned during the HVAC3 ride-along field data collection effort. The custom distribution is illustrated in Figure 48.

Figure 48: Distribution for evaporator coil blockage input, state 2A



Failed economizer damper position

The economizer position input parameter represents the outside air damper position (from 0 – fully closed, to 1 – fully open) of unit economizer dampers that have failed (i.e., damper remains in broken, fixed position regardless of conditions). While the damper position was adjusted in HVAC5 lab tests, the primary goal of these tests was not to measure performance impacts but to measure outside air fractions.

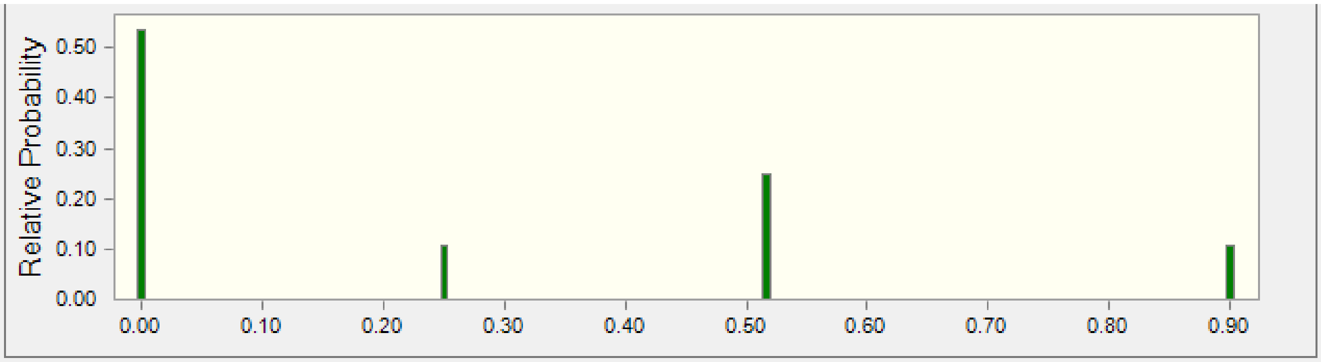
The boundary for measuring system performance includes outside air impacts to conditioned air psychrometric conditions (i.e., airside enthalpy calculations using mixed air conditions). The testing conditioned chambers were also controlled for fixed dry- and wet-bulb temperature setpoints i.e., the testing unit does not necessarily satisfy cooling load – there are control RTUs that ensure indoor chambers maintain their testing setpoint temperatures. Because of the performance calculation boundary and controlled indoor/outdoor chamber conditions, unit tests where outside air dampers are open have higher measured efficiency than unit tests where the damper is closed.

The distribution of failed economizer damper positions references failed economizer position observations collected during the HVAC3 field data collection effort. It is a custom, discrete value distribution where qualitative descriptors needed to be converted in to specific position values. Table 60 and Figure 49 show the economizer position descriptors, corresponding input parameter values, and the discrete distribution for the pre-treatment scenario.

Table 60: Distribution for pre-treatment economizer outside-air damper position, state 2A and 2B

OA Damper Position	Input Parameter Value	Distribution (%)
Closed	0.000	54%
Minimum	0.250	11%
Partial	0.516	25%
Open	0.900	11%

Figure 49: Distribution for pre-treatment economizer outside air damper position, states 2A and 2B

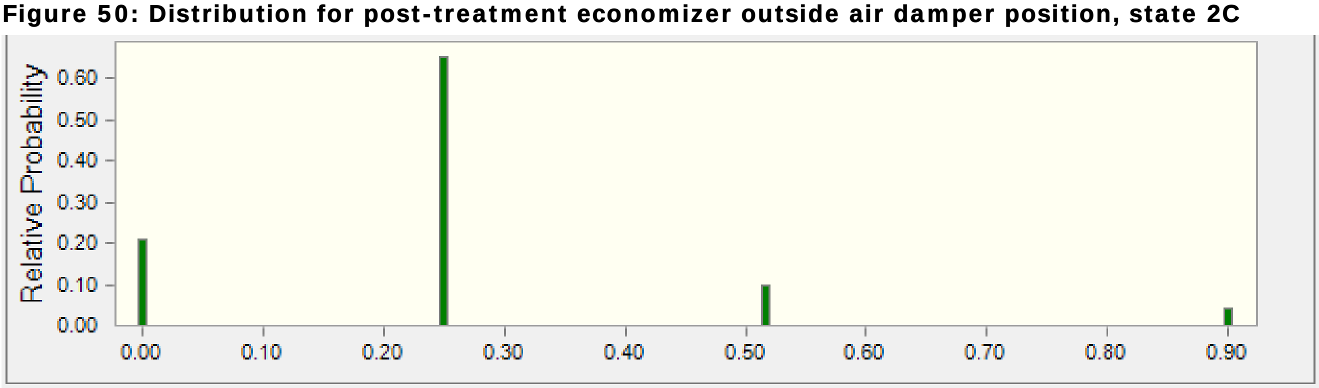


For the post-treatment scenario, a weighted installation rate (for economizer repair) of approximately 61% and the assumed "repaired" minimum economizer position of "minimum" (which converts to 25% open) were used as inputs to adjust the pre-treatment distribution for use as a post-treatment distribution. Table 61 and Figure 50 show the economizer position descriptors, corresponding input parameter values, and the discrete distribution for the post-treatment scenario.[67]

Table 61: Distribution for post-treatment economizer outside air damper position, state 2C

OA Damper Position	Input Parameter Value	Distribution (%)
Closed	0.000	21%
Minimum	0.250	65%
Partial	0.516	10%
Open	0.900	4%

Figure 50: Distribution for post-treatment economizer outside air damper position, state 2C



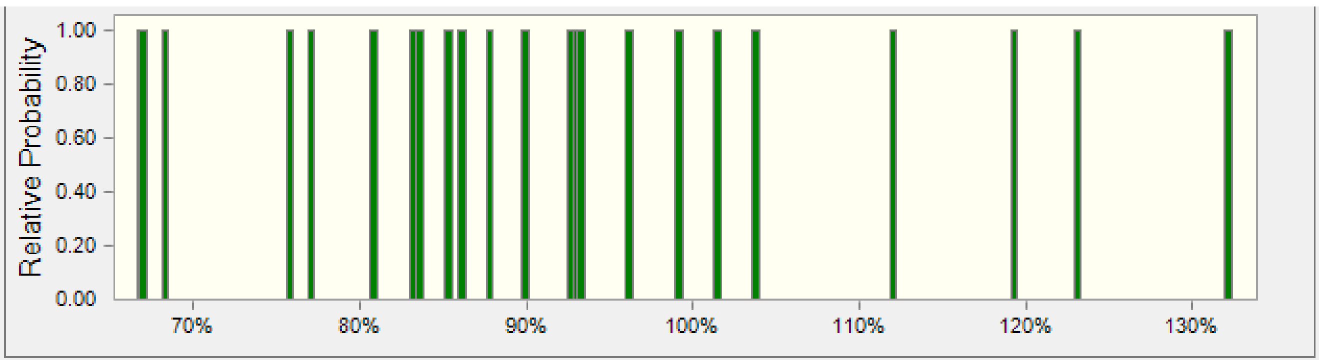
[67] Installation rate is a weighted rate from HVAC3 evaluation which used PY2013-15 participant field data. Correlation between the regression's damper position value (between 0 and 1), the qualitative damper position descriptors, and the estimated outdoor air fraction were based on total and outside air flow tests performed on a representative unit while modulating the damper position through its range (from 2.0 to 10.0V damper actuation voltage).

Supply fan airflow percentage

The supply fan airflow percentage input parameter represents the supply fan airflow rate relative to the nominal flowrate of 400 cfm/ton. Due to limited test data involving airflow faults, this input parameter was only selected for RTU2 (TXV, multi-stage). The main intent of the airflow fault tests was to determine the efficacy of refrigerant charge protocol tests.

DNV GL used limited HVAC3 field data to determine the distribution of this input parameter. The distribution is custom and is based on 24 individual air flow tests conducted on representative units[68]. The custom, discrete distribution can be seen in Figure 51. This distribution was used for the all treatment scenarios in experiments 1AB and 3AB. For experiment 2AB, 2BC, and 2AC, states 2B and 2C are assumed to have a fan airflow of 100% (of 400 cfm/ton).

Figure 51: Distribution for supply fan airflow percentage input



Regression model coefficients

The regression model coefficients for the parameters predicting RTU5 and RTU2 capacity and efficiency are provided in Table 62.

Table 62: Regression model coefficients for RCA

Coeff-icient	RTU5			RTU2		
	Values for net total cooling	Values for net sensible cooling	Values for EER	Values for net total cooling	Values for net sensible cooling	Values for EER
a_0	0.9443	0.9667	0.9127	1.4236	0.6590	1.6837
a_1	0.2751	0.2402	0.1670	0.2843	0.1170	0.2010
a_2	-0.2132	-0.1643	-0.5462	0.3160	0.2524	-0.1780
a_3	-0.6401	-0.4859	-0.8105	-0.6858	0.3287	-0.7903
a_4	0.0633	0.0889	0.1092	-0.2527	-0.2319	-0.7335
a_5	n/a	n/a	n/a	-0.0269	-0.1711	-0.0180
a_{11}	-0.8013	-0.6290	-0.5883	-0.8387	-0.5357	-0.8057

68 The 24 air flow testing points were selected based on economizer repair verification. The test points collected economizer status and then measured total and outdoor air flowrates

Coeff-icient	RTU5			RTU2		
	Values for net total cooling	Values for net sensible cooling	Values for EER	Values for net total cooling	Values for net sensible cooling	Values for EER
a_{12}	-0.3923	-0.0287	-0.4811	-0.2398	-0.2158	-0.4833
a_{13}	-0.6342	-0.8568	-0.2179	0.1496	0.1568	0.1306
a_{14}	0.0685	0.0922	0.0208	0.0000	0.0000	0.0000
a_{15}	n/a	n/a	n/a	0.0000	0.0000	0.0000
a_{22}	0.0351	0.0819	0.2167	-0.1956	-0.1082	-0.1427
a_{23}	0.2346	0.2943	0.8840	-0.3834	-0.2855	-0.1308
a_{24}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
a_{25}	n/a	n/a	n/a	0.0000	0.0000	0.0000
a_{33}	0.8324	0.3905	1.1545	0.2790	0.0377	0.1116
a_{34}	0.0000	0.0000	0.0000	-0.1654	-0.0071	0.3027
a_{35}	n/a	n/a	n/a	0.0000	0.0000	0.0000
a_{44}	0.0833	0.0121	0.0687	0.6572	0.4425	0.6887
a_{45}	n/a	n/a	n/a	0.0000	0.0000	0.0000
a_{55}	n/a	n/a	n/a	-0.2733	0.0020	-0.4254

Figure 52, Figure 53, and Figure 54 show the plots of measured (i.e., lab tests) versus predicted normalized values for net cooling capacity, net sensible capacity, and EER for RTU5. Similar regression models were also generated for RTU2.

Figure 52: Predicted vs measured normalized net cooling capacity for RTU5

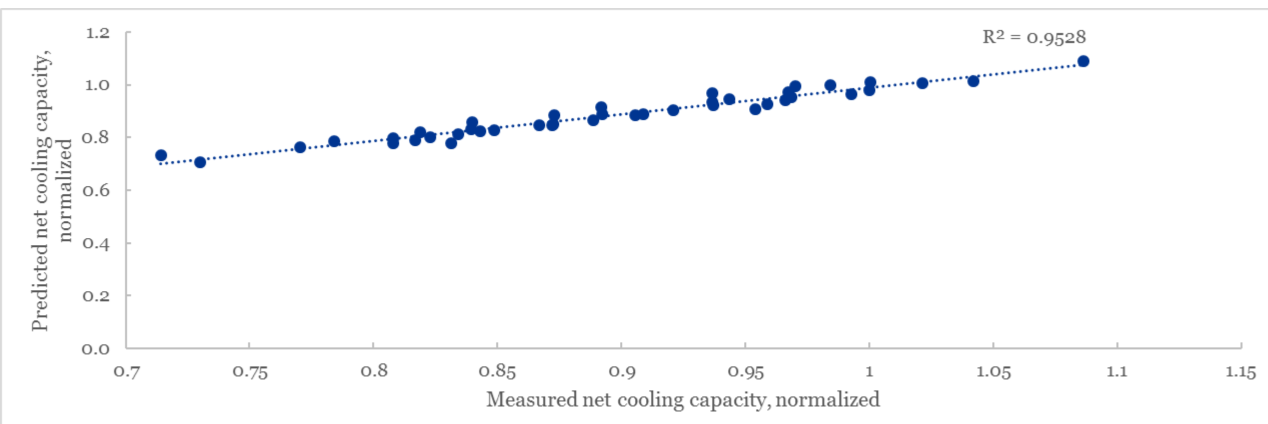


Figure 53: Predicted vs measured normalized net sensible capacity for RTU5

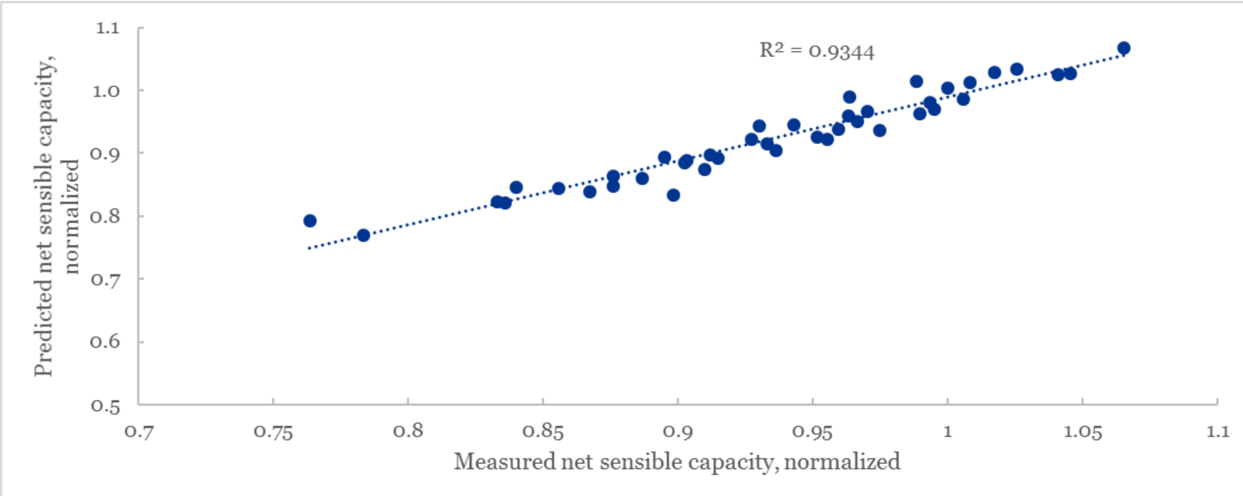
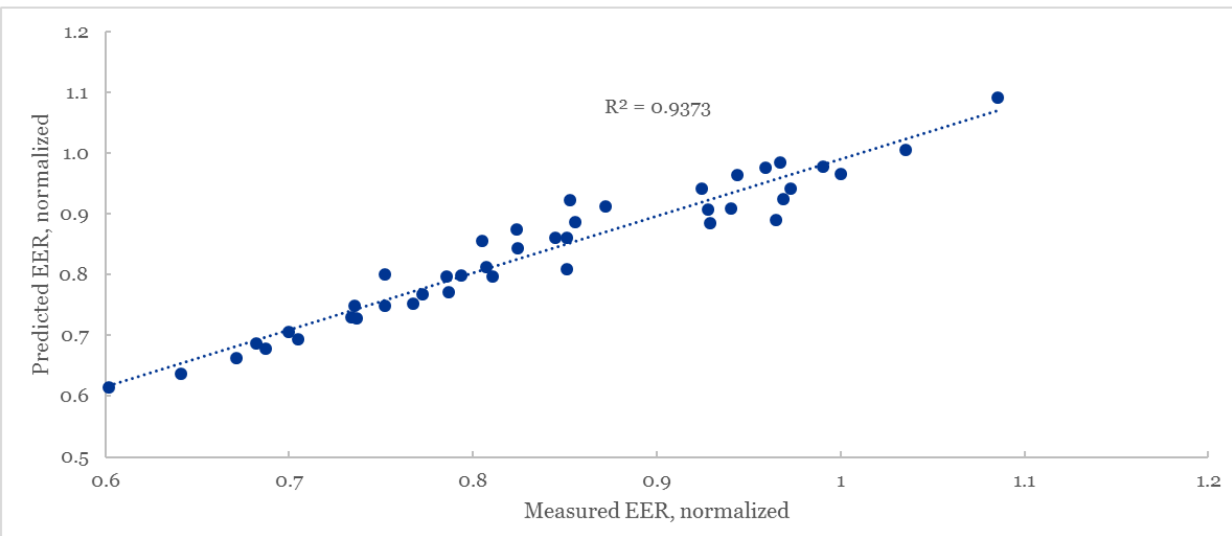


Figure 54: Predicted vs measured normalized EER for RTU5



The figures show that the regression models fit well with the HVAC5 data. The average deviation between measured and predicted net cooling capacity, sensible capacity, and EER for RTU5 are -1.2%, -1.3%, and 0.1%, respectively. Like all regression models generated for HVAC4, they introduce error when used to predict values and uncertainty in Crystal Ball. This error cannot be quantified within the Monte Carlo analysis.

Cooling capacity results across all experiments

As was provided for EER in Figure 28, the percent differences between the net total cooling capacity and the net sensible cooling capacity across all experiments are provided in Figure 55 and Figure 56.

Figure 55. Mean Percent Difference of Net Total Cooling Capacity for All Experiments

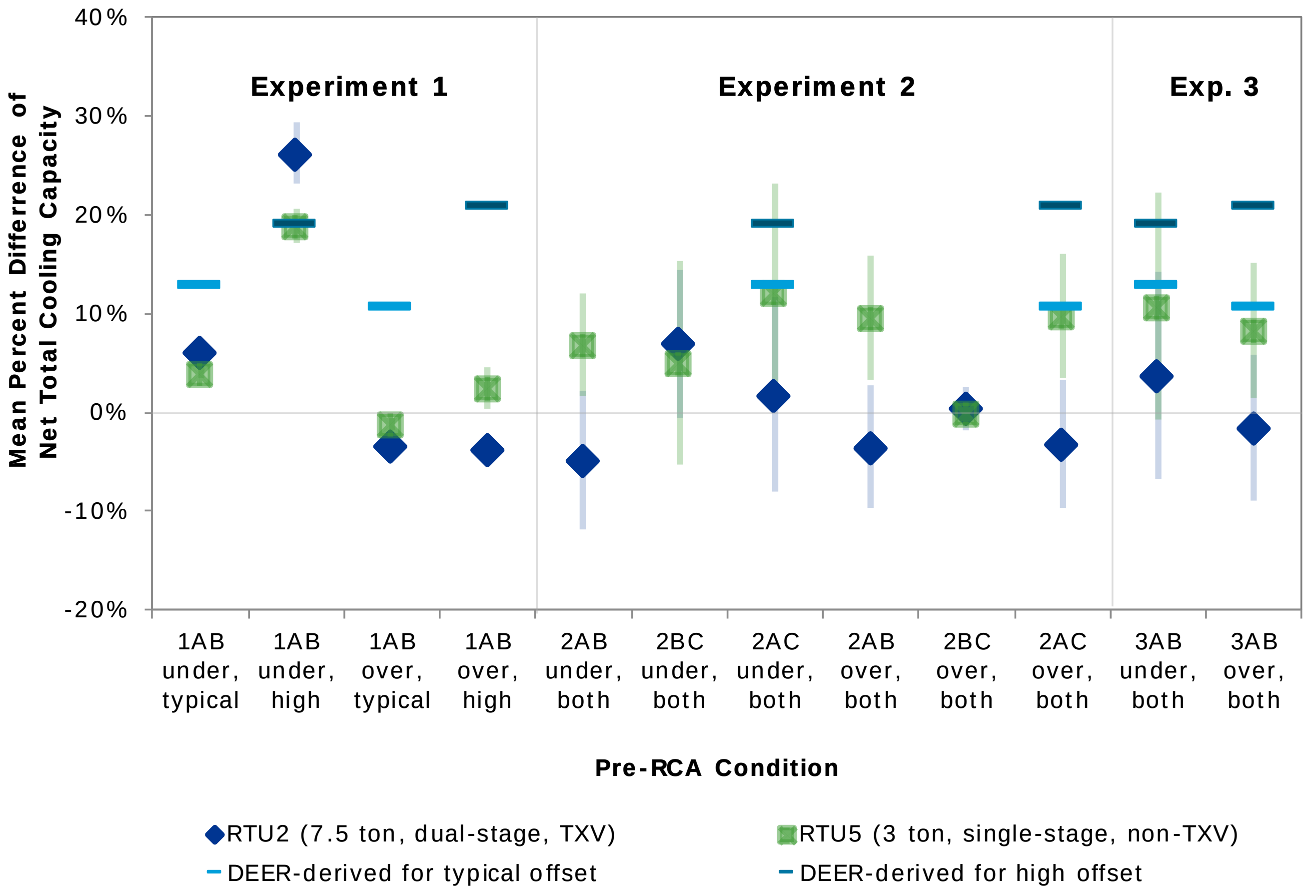
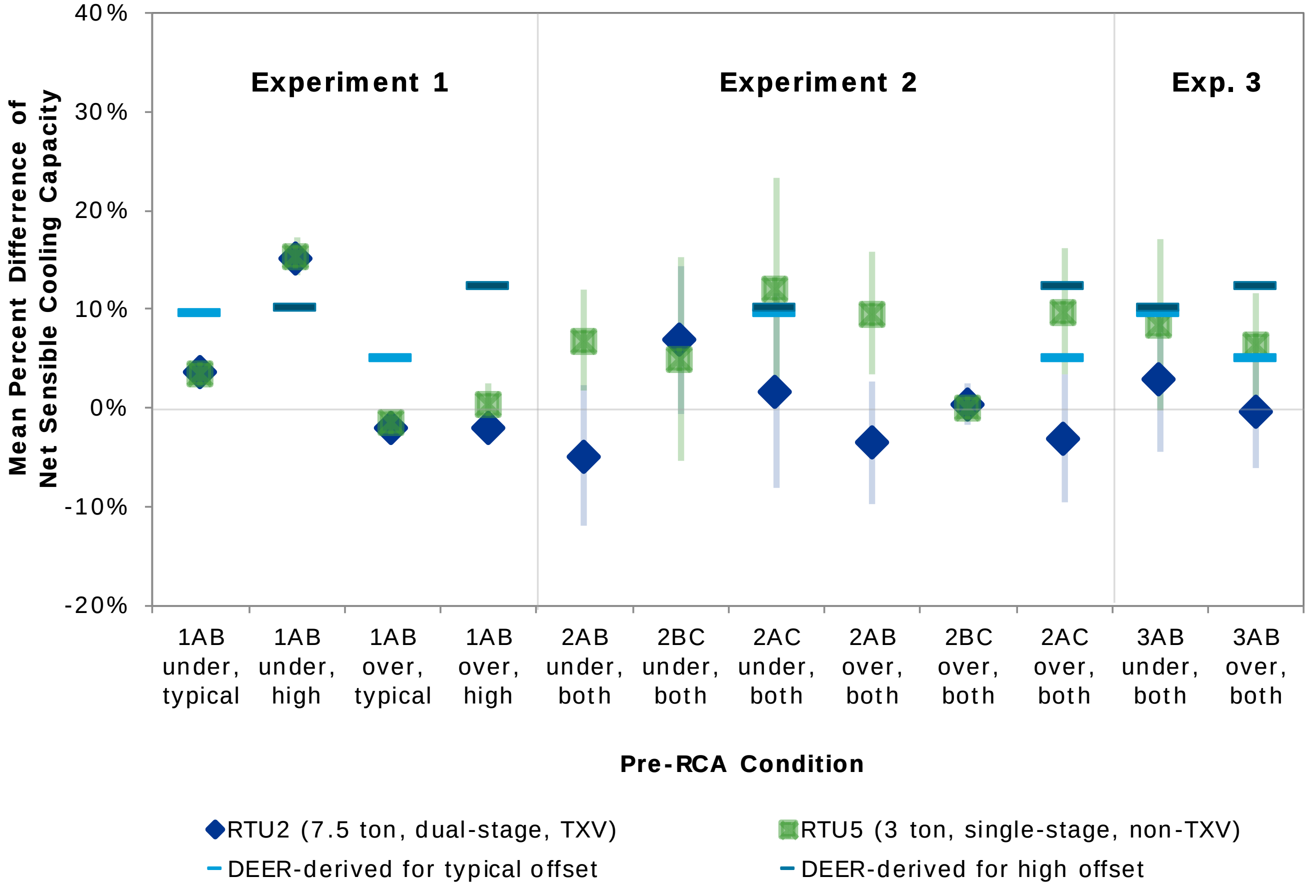


Figure 56. Mean Percent Difference of Net Sensible Cooling Capacity for All Experiments



APPENDIX D. PUBLIC-REVIEW PERIOD COMMENT AND RESPONSE

One comment was received as provided in Table 63. DNV GL response is also provided therein.

Table 63: Draft Report Comments from Members of the Public and DNV GL Responses

No.	Commenter	Organization	Report Section	Comment	DNV GL Response
1	Carol Yin, Ph.D.	Yinsight, Inc.	Overall Findings and Recommendations	IESR: Would it be possible for the evaluation team to include an appendix with recommendations presented using the table from the CPUC Energy Division Impact Evaluation Standard Reporting Guidelines? Thank you! https://pda.energydataweb.com/api/downloads/1399/IESR_Guidelines_Memo_FINAL_11_30_2015.pdf	Yes—see appendix that follows.

APPENDIX E. APPENDIX AC – IESR STANDARDIZED RECOMMENDATIONS

Study ID	Study Type	Study Title	Study Manager
CPU0145.03	Impact Evaluation	Study of Deemed HVAC Measures Uncertainty Year 3 Report (HVAC4)	Rachel Murray

Recommendation	Program or Database	Summary of Findings	Additional Supporting Information	Best Practice / Recommendations	Recommendation Recipient	Affected Workpaper or DEER
1	Nonresidential Upstream HVAC Distributor Rebate Program	For Tier-2 unitary systems under 55 kBtu/h, the mean annual savings in CZ08 for the small office building prototype were 218.2 kWh/ton, with a standard deviation of ± 29.4 kWh/ton (compared to 2015 DEER savings of 327.8 kWh/ton). The savings uncertainty was most sensitive to whether systems have 1- or 2-speed fans, the fan power index, and the cooling setpoint.		Assumptions used to estimate DEER savings should be reviewed. Additional data collection for factors contributing to savings uncertainty is warranted.	IOUs and ED	PGECOHVC128, SCE13HC012, & SCE13HC035

Recommendation	Program or Database	Summary of Findings	Additional Supporting Information	Best Practice / Recommendations	Recommendation Recipient	Affected Workpaper or DEER
2	Nonresidential Upstream HVAC Distributor Rebate Program	For Tier-2 unitary systems under 55 kBtu/h, the mean annual savings in CZ12 for the small office building prototype were 178.0 kWh/ton, with a standard deviation of ± 29.2 kWh/ton (compared to 2015 DEER savings of 322.2 kWh/ton). The savings uncertainty was most sensitive to whether systems have 1- or 2-speed fans, whether systems have an economizer, the fan power index (W/cfm), and the cooling-sizing ratio.		Assumptions used to estimate DEER savings should be reviewed. Additional data collection for factors contributing to savings uncertainty is warranted.	IOUs and ED	PGECOHVC128, SCE13HC012, & SCE13HC035
3	Nonresidential Upstream HVAC Distributor Rebate Program	For Tier-2 unitary systems between 65 and 134 kBtu/h, the mean annual savings in CZ08 for the small office building prototype were 69.8 kWh/ton, with a standard deviation of ± 12.7 kWh/ton (compared to 2015 DEER savings of 61.3 kWh/ton). The savings uncertainty was most sensitive to the cooling-sizing ratio, the cooling setpoint, and the fan power index.		Additional data collection for factors contributing to savings uncertainty is warranted.	IOUs and ED	PGECOHVC128, SCE13HC012, & SCE13HC035

Recommendation	Program or Database	Summary of Findings	Additional Supporting Information	Best Practice / Recommendations	Recommendation Recipient	Affected Workpaper or DEER
4	Nonresidential Upstream HVAC Distributor Rebate Program	For Tier-2 unitary systems between 65 and 134 kBtu/h, the mean annual savings in CZ12 for the small office building prototype were 59.8 kWh/ton, with a standard deviation of ± 10.1 kWh/ton (compared to 2015 DEER savings of 53.0 kWh/ton). The savings uncertainty was most sensitive to the cooling-sizing ratio, the cooling setpoint, and the fan power index.		Additional data collection for factors contributing to savings uncertainty is warranted.	IOUs and ED	PGECOHVC128, SCE13HC012, & SCE13HC035
5	Nonresidential Upstream HVAC Distributor Rebate Program	For Tier-2 air-cooled chillers, the mean annual savings in CZ03 for the large office building prototype were 35.6 kWh/ton, with a standard deviation of ± 21.6 kWh/ton (compared to 2014 DEER savings of 84.4 kWh/ton). The savings uncertainty was most sensitive to the full-load cooling efficiency, the cooling temperature schedule, and the minimum condenser temperature.		Assumptions used to estimate DEER savings should be reviewed. Additional data collection for factors contributing to savings uncertainty is warranted.	IOUs and ED	PGECOHVC120 & SCE13HC030

Recommendation	Program or Database	Summary of Findings	Additional Supporting Information	Best Practice / Recommendations	Recommendation Recipient	Affected Workpaper or DEER
6	Nonresidential Upstream HVAC Distributor Rebate Program	For Tier-2 air-cooled chillers, the mean annual savings in CZ08 for the small office building prototype were 36.8 kWh/ton, with a standard deviation of ± 23.4 kWh/ton (compared to 2014 DEER savings of 176.7 kWh/ton). The savings uncertainty was most sensitive to the full-load cooling efficiency, the cooling-temperature schedule, and the minimum condenser temperature.		Assumptions used to estimate DEER savings should be reviewed. Additional data collection for factors contributing to savings uncertainty is warranted.	IOUs and ED	PGECOHVC120 & SCE13HC030
7	Nonresidential Upstream HVAC Distributor Rebate Program	The part-load efficiency (IPLV) qualification pathway results in some qualifying air-cooled chillers with full-load efficiency that is below the Title-24 code requirement; this results in negative savings during full-load periods of operation. Since eQUEST does not support efficiency performance curves that deviate significantly from the default curve, exaggerated mean annual savings are predicted.		Full- and part-load efficiency metrics (EER and IPLV) should be gathered and recorded in the program tracking data.	IOUs and ED	PGECOHVC120 & SCE13HC030
8	Nonresidential Upstream HVAC Distributor Rebate Program	Given the influence of the cooling temperature schedule and the minimum condenser temperature on the annual savings uncertainty for air-cooled chillers, a retro-commissioning measure opportunity exists.		Consider establishing a retro-commissioning measure for air-cooled chillers to influence the practices of building equipment managers.	IOUs	PGECOHVC120 & SCE13HC030

Recommendation	Program or Database	Summary of Findings	Additional Supporting Information	Best Practice / Recommendations	Recommendation Recipient	Affected Workpaper or DEER
9	Nonresidential Upstream HVAC Distributor Rebate Program	The part-load efficiency (IPLV) qualification pathway for air-cooled chillers results in some qualifying chillers with full-load efficiencies that are below the Title-24 code requirement; this results in negative savings during full-load periods of operation.		Consider adding the full-load efficiency rating (EER) and the part-load efficiency rating (IPLV) to list of required fields in the tracking data for air-cooled chillers.	IOUs	PGECOHVC120 & SCE13HC031
10	Nonresidential HVAC Quality Maintenance Rebate Program	For both system types studied--single-stage without TXV and multi-stage with TXV--results suggest that, even with other faults present, correctly diagnosing and addressing undercharged refrigeration circuits will nearly always have positive performance impacts. This is particularly true for highly undercharged units.		Continue to offer the RCA measure where refrigerant charge is very low.	IOUs and ED	PGE3PHVC160, PGECOHVC138, & SCE13HC037
11	Nonresidential HVAC Quality Maintenance Rebate Program	For multi-stage units with TXV, results suggest that, on average, correctly diagnosing and addressing overcharged refrigeration circuits diminishes system performance.		Consider discontinuing correcting the refrigerant charge for systems that are typically overcharged.	IOUs and ED	PGE3PHVC160, PGECOHVC138, & SCE13HC038
12	Nonresidential HVAC Quality Maintenance Rebate Program	For single-stage units without TXV, results suggest that correctly diagnosing and addressing typically overcharged units will result in diminished performance. On the other hand, treating highly overcharged units results in improved system performance.		Continue correcting the refrigerant charge for systems that are highly overcharged.	IOUs and ED	PGE3PHVC160, PGECOHVC138, & SCE13HC039

Recommendation	Program or Database	Summary of Findings	Additional Supporting Information	Best Practice / Recommendations	Recommendation Recipient	Affected Workpaper or DEER
13	Nonresidential HVAC Quality Maintenance Rebate Program	The performance-metrics effects on multi-stage units with TXV due to non-RCA treatments are smaller than (and in some cases, negative) those for single-stage units without TXV.		Consider expanding services to repair refrigerant lines or targeting replacement of units that have an established track record of low refrigerant charge.	IOUs and ED	PGE3PHVC160, PGECOHVC138, & SCE13HC040
14	Nonresidential HVAC Quality Maintenance Rebate Program	For units where non-RCA faults are treated first, undercharged units experience greater performance improvements from RCA-treatments than overcharged units.		With the exception of very low refrigerant charge levels, consider focusing efforts on addressing non-RCA faults before refrigerant offsets.	IOUs and ED	PGE3PHVC160, PGECOHVC138, & SCE13HC041
15	Nonresidential HVAC Quality Maintenance Rebate Program	HVAC4 results corroborated the HVAC3 finding that greater performance benefits are realized by non-RCA fault treatments than the RCA treatments, themselves. This is especially true for multi-stage units with TXV.		With the exception of very low refrigerant charge levels, consider focusing efforts on addressing non-RCA faults before refrigerant offsets.	IOUs and ED	PGE3PHVC160, PGECOHVC138, & SCE13HC042
16	Nonresidential HVAC Quality Maintenance Rebate Program	Economizer malfunctioning impacts continue to be a large source of savings uncertainty.		Continued investigation and training regarding economizer functionality, reasons for failure, and unintentional operation is warranted.	IOUs and ED	PGE3PHVC160, PGECOHVC138, & SCE13HC043
17	P4 Database	To leverage the HVAC4 findings, relative standard deviation better characterizes the annual savings uncertainty than relative precision.		Consider creating a "All Things Simulated (ATS)" table--modeled after the "All Things Reported (ATR)" tables--to leverage the HVAC4 findings.	ED	

Recommendation	Program or Database	Summary of Findings	Additional Supporting Information	Best Practice / Recommendations	Recommendation Recipient	Affected Workpaper or DEER
18	P4 Database	HVAC4 simulations of mean annual savings and associated standard deviations are best determined for each climate zone and for each building type of the available DEER prototypes.		Consider expanding the resolution of the P4 database to include building types and climate zones.	ED	

About DNV GL

Driven by our purpose of safeguarding life, property, and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter, and greener.