Standardized HVAC Control Sequence Savings Estimation Calculator

Final Report

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Disclaimer

Executive Summary

HVAC control sequences of operation standardized by ASHRAE Guideline 36 (G36) have demonstrated, through field validation, the potential to reduce energy use by 12–60% in nonresidential buildings compared to typical practice (Taylor Engineering, TRC, Integral Group, 2022). An underutilized opportunity exists for energy savings in building retrofits and retro-commissioning using optimized sequences of operation. The project team developed a calculator to estimate savings from implementing G36 sequences of operation in existing buildings. This web-hosted calculator is based on an energy modeling database that includes variations of climate zone, building size and HVAC system configuration.

The ASHRAE G36 savings estimation calculator is freely available for use at the following location: dataanalysis.capturesportal.com/ASHRAE/Guideline36_Savings_Calculator/.

The project team developed the calculator based on stakeholder outreach, which identified the absence of an offering in efficiency programs that is flexible enough to account for building and system characteristics but simpler than a custom energy modeling approach. The team did extensive testing of energy modeling parameters to determine the 13 parameters with the greatest impact on measure performance. Based on feedback from stakeholders, most of the inputs are optional, allowing for greater accessibility and ease of use. The calculator includes an uncertainty analysis that accounts for the added uncertainty from unknown building parameters and returns a dynamically calculated uncertainty range.

This report details the process the project team completed to select the measures for analysis, refine the input parameters and complete two rounds of parametric energy model simulations of 48,000 and 64,000 simulations respectively. It describes the statistical methods used to create the back end of the calculator and the team's uncertainty analysis at each stage in calculator development. The report also includes documentation of the automated calibration performed by the calculator to reduce error. Furthermore, the report demonstrates the use of the calculator with six example buildings that underwent G36 sequence of operations measure implementation.

The project team recommends that the framework developed here be refined for use by individual energy efficiency programs. The approach is scalable to different building types, climate zones, efficiency measures and levels of accuracy. The Recommendations section outlines lessons learned and proposed next steps in the process of tailoring the savings estimation calculator to specific markets and goals of programs administrators.

Abbreviations and Acronyms

Acronym	Meaning
ASHRAE	American Society of Heating and Refrigeration Engineers
ATU	Air Terminal Unit
CV(RMSE)	Coefficient of Variation of the Root Mean Squared Error
G36	ASHRAE Guideline 36
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air Conditioning
kWh	Kilowatt-hour
NMBE	Normalized Mean Bias Error
PG&E	Pacific Gas & Electric
RCx	Retro Commissioning
TSP	Total Static Pressure

Table of Contents

List of Tables

List of Figures

Introduction

An underutilized opportunity for energy savings in building retrofits and retro-commissioning (RCx) is optimized heating, ventilation and air conditioning (HVAC) system sequences of operations (SOO). The project team developed a calculator to estimate energy savings from implementing standardized and optimized HVAC SOOs developed by the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) under Guideline 36 (G36) (ASHRAE, 2021) for a variety of existing building and HVAC system types in California based on energy model simulation results.

SOOs developed by ASHRAE have proven their energy-saving capabilities through field validation in new construction projects and major control upgrades. A recent Electric Program Investment Charge Best-In-Class research project (EPIC - BiC) (Taylor Engineering, TRC, Integral Group, 2022) funded by the California Energy Commission (CEC) showed that implementation of standardized SOOs in building automation systems (BAS) reduced HVAC energy use by 12–60% in six nonresidential buildings compared to typical practice. The EPIC - BiC project and other related research have shown that G36 is most easily applied to new construction and major controls upgrades and revealed a variety of compatibility barriers when applied in existing control system hardware. These barriers can be addressed while capturing a large portion of the savings potential with a subset of key measures in G36.

For example, one specific SOO measure (reducing variable air volume (VAV) minimum airflows) has large energy savings potential and is relatively easy to implement. California Building Energy Efficiency Standards Title 24-2005 introduced dual maximum VAV box logic and limited VAV box minimum airflow to ≤ 30%. Title 24-2008 lowered the maximum to 20%. Title 24-2022 further lowered the maximum permitted ventilation airflow. In all cases, however, Title 24 permits higher airflow rates if required for ventilation. As part of a proposed measure for Title 24-2025, the Statewide CASE Team found through literature review, stakeholder interviews and drawing review, that current industry practice for new construction does not meet current Title 24 regulations, and has a wide range of VAV box minimums, with a minimum airflow of 30% being common (Rupam Singla, 2023). High minimums are even more common in existing buildings. Multiple studies have found that reducing VAV box minimum airflow saves energy and improves occupant thermal comfort (Edward Arens, 2015; Paliaga, 2019). VAV boxes are typically at their minimum the majority of the time and reducing the minimum airflow to the G36-recommended levels saves fan energy, cooling energy and reheat energy. One study found that this single measure saves 10–30% HVAC energy (Edward Arens, 2015). Implementing the measure requires adjusting a single setpoint for each VAV box and requires no programming, making the measure highly achievable.

Despite the potential to achieve significant energy savings through control retrofits in existing buildings to standardize SOOs, it is difficult and costly to accurately estimate the savings. Barriers to identifying viable retrofit sites will be greatly reduced if an energy savings and incentive-estimating calculator exists that can quickly assess the value of a potential retrofit before embarking on engineering studies and project design.

Utility program services and incentives play a pivotal role in driving the adoption of standardized HVAC SOOs. While custom programs offer retrofit incentives and require a high level of investment into documentation, prescriptive programs simplify the process with pre-approved savings algorithms and data inputs. Feedback provided by efficiency stakeholders indicated that there is a gap between prescriptive and custom measures. G36 measures are too complex to be addressed using a prescriptive path. However, a custom incentive application requires a very high level of documentation and rigor which inhibits the use of this pathway. This project can potentially be approved as a hybrid approach that reduces the burden of a custom application or serves as a preliminary savings estimation tool that complies with the California Normalized Meter Energy Consumption (NMEC) rulebook.

This report presents the project background, goals, methodology and approach for the development of the savings estimation calculator. An analysis of results, including energy savings for default prototypes, sensitivity of calculated savings, uncertainty analysis and results validation is also included in this report.

Background

ASHRAE Guideline 36 (G36) titled High-Performance Sequences of Operation for HVAC Systems (ASHRAE, 2021) establishes standardized SOOs for HVAC systems. Its initial release in 2018 focused on airside sequences of operations for air handler units (AHUs) and terminal boxes. The 2021 update for the guideline added chilled water and hot water plant sequences. The guideline's core focus is to maximize the energy efficiency and overall performance of HVAC systems. By providing uniform sequences of operation that include reset strategies based on real-time building HVAC parameters, G36 helps in achieving substantial energy savings. In addition, G36 can save time for designers by reducing the need for custom design work and for contractors by reducing project timelines for programming and commissioning phases. Other key features include control stability, real-time fault detection and diagnostics and improved indoor air quality (IAQ).

To estimate the achievable energy savings by implementing the standardized SOOs of G36, three methods that are commonly used by utility programs can be considered: building simulation, pre-approved calculators and engineering calculations. Developing accurate models to conduct building simulations requires substantial time and effort to gather comprehensive data on the building and oftentimes require making assumptions that can affect accuracy. This resource-intensive approach is commonly reserved for scenarios where seasonal controls are prominent, and project scale justifies the investment. Pre-approved calculators require less investment from implementers, but a substantial amount of coordination between stakeholders. Additionally, their limited capabilities may lead to abbreviated or simplified project scopes submitted to programs. Engineering calculations emerge as the most adaptable and potentially straightforward solutions within the implementation community. This is why numerous derivatives exist for any given measure. However, the quality of engineering calculation methods can vary considerably based on factors such as the intended audience, level of engineer expertise and level of investment in the analysis.

Each of these methods have distinct advantages and disadvantages, and the calculator developed in this project incorporates aspects of each method into a single framework, as illustrated in Figure 1.

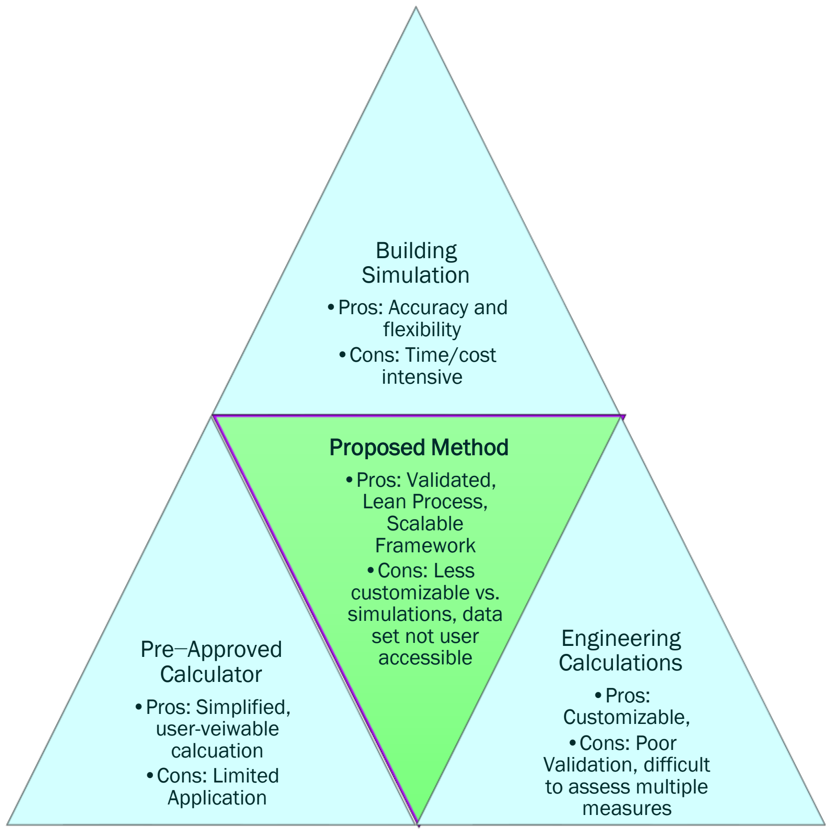

Figure 1: Savings Estimation Methods Comparison

Incumbent Technology

Within the California energy efficiency industry, there have been multiple attempts at creating a simple pre-approved calculator. One specific tool that is actively being used in programs throughout California is the PG&E HVAC Calculator Tool v2.2.03, which was released in 2023 (available through (California Technical Forum, 2023)).

An example input form for airside system analysis in the PG&E HVAC Calculator Tool is shown in Figure 2. The tool also includes chilled water side and hot water side analysis forms.

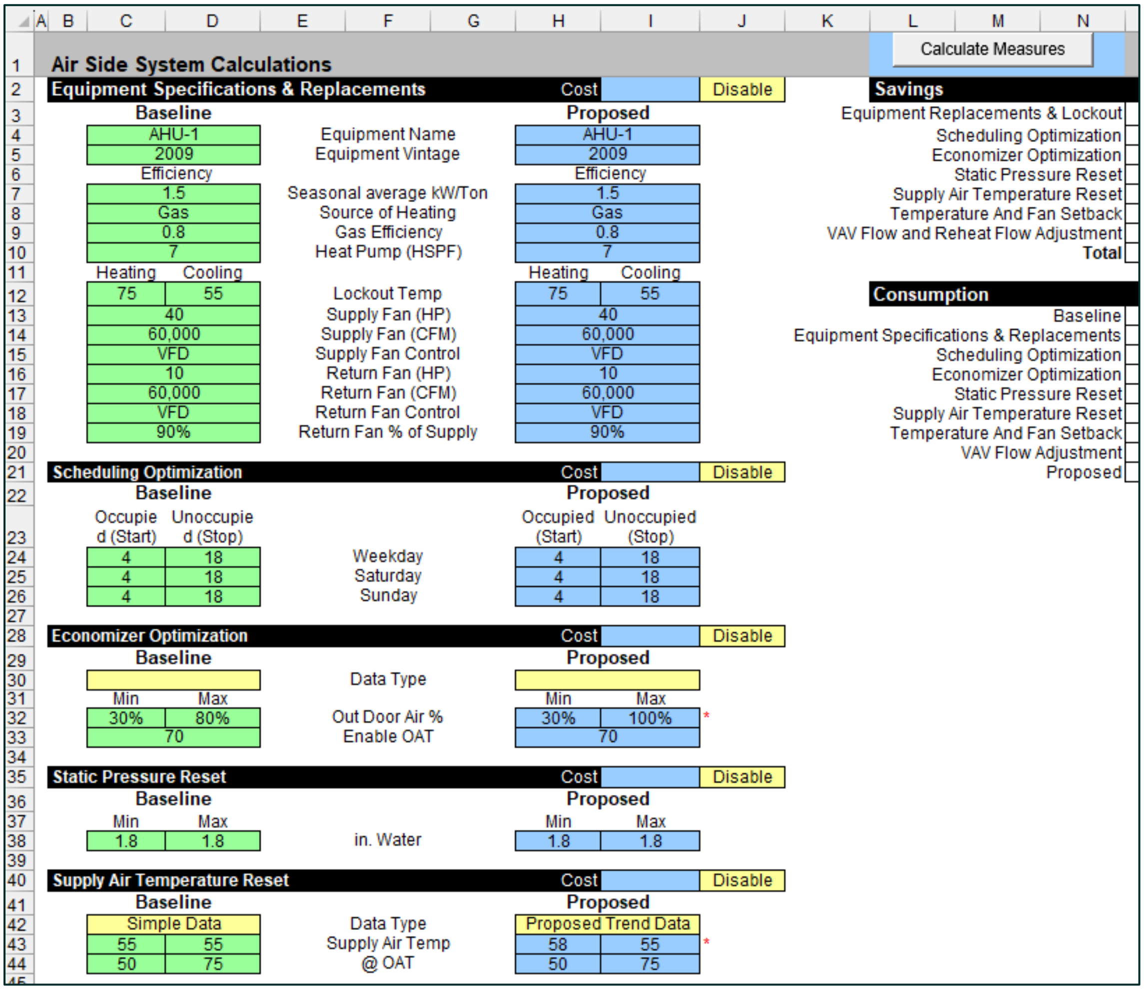

Figure 2: Form of PG&E HVAC Calculator Tool – Airside System Input Form

To use the PG&E tool, the user needs to input required HVAC system information such as the capacities, efficiencies and schedules. In this way it is similar to the process of using building simulation, but the overall process is much simpler because the tool's functions don't need to be calibrated to match building information as opposed to building simulation. The PG&E tool uses a bin analysis and engineering calculations in the back end, and these are based on assumptions that can potentially lead to a mismatch between the real building characteristics and the baseline characteristics used by the calculator to estimate savings, thus reducing the accuracy of results. The benefit of the PG&E tool is that it provides savings at the end use which can be verified pre- and post-installation with trend data, a CPUC programs requirement for custom measures.

Another recently developed calculator that shares the concept of the calculator developed under this project came out of an EPIC - BiC research project (Kun Zhang, 2022; Blum, 2021). A partial screen capture of the EPIC - BiC calculator's interface is shown in Figure 3. User inputs of building details are used to calculate savings based on a database of building simulation results. For the EPIC - BiC calculator, data from 243 EnergyPlus building simulations were used, in combination with Modelica simulations of the underlying controls sequences. In contrast, the calculator developed in this project uses EnergyPlus's controls algorithms but uses 64,000 simulations and more user input categories, thus, providing the ability to match the baseline building conditions far more accurately resulting in more accurate savings estimates.

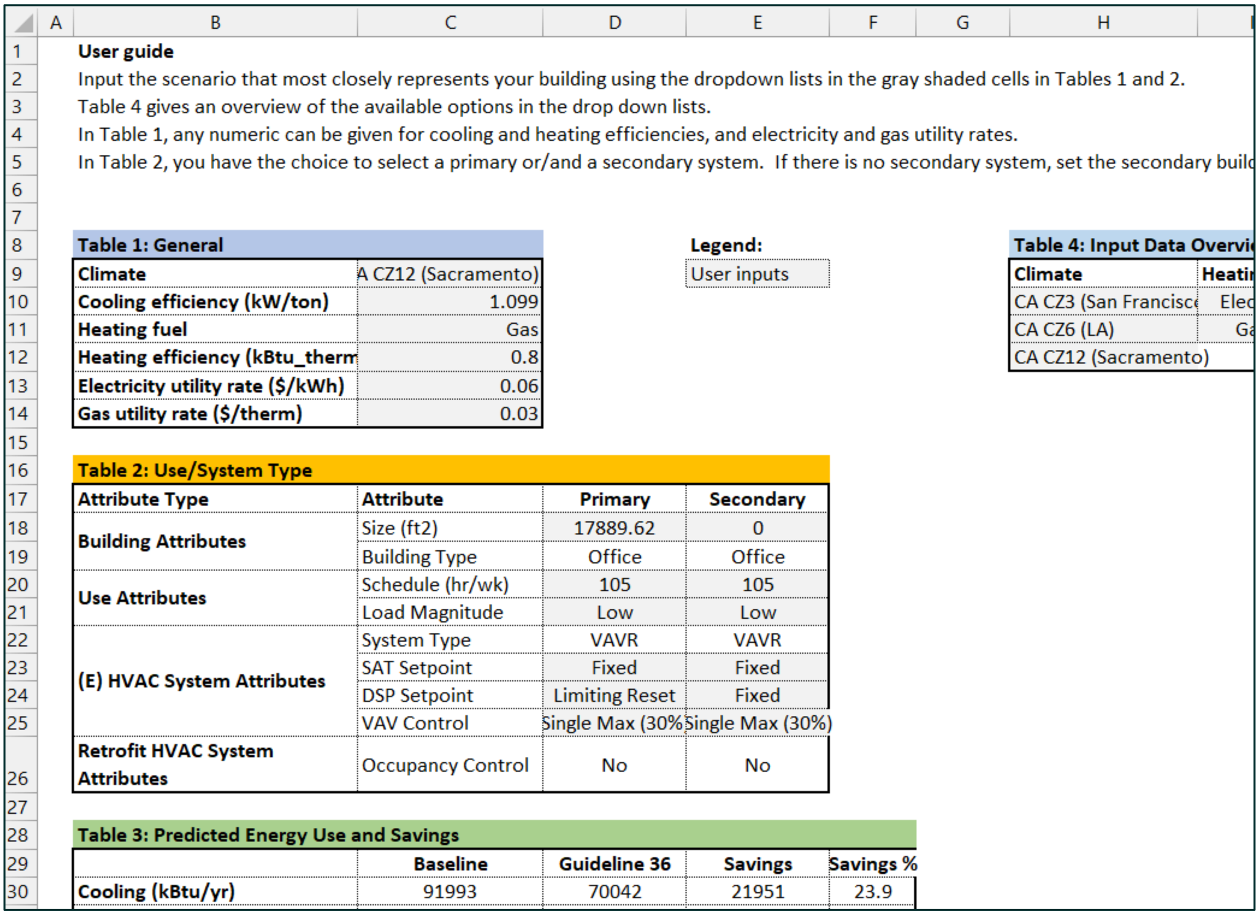

Figure 3: Interface of the G36 Savings Calculator from EPIC Best-in-Class Project

Objectives

The ASHRAE G36 savings estimation calculator estimates the potential energy and cost savings of retrofit activities when provided with minimal case information. The resulting estimates are based on pre-run simulations of permutations of G36 retrofits across specific climates, building types and building parameters. The project team conducted a sensitivity analysis to ensure the calculator balances required inputs with accuracy to produce deep energy and greenhouse gas emissions savings estimates.

This calculator reduces the burden building owners and utility programs face when assessing how beneficial a retrofit project would be by providing quick access to reliable savings estimates. When used, the calculator will accelerate the adoption of G36 measures by communicating how HVAC systems can achieve maximized energy efficiency through advanced control technology.

Utility incentive programs could see increased participation by using the calculator to streamline operations. There is also the possibility of making new RCx and other custom program offerings simpler through the calculator. By quantifying uncertainty, the calculator can help utility incentive programs invest in measures with less risk.

The calculator's straightforward approach to calculating energy savings does not require significant investment from users and can be viewed as an asset that proves the value of efforts to improve energy efficiency. The calculator has a large degree of flexibility with respect to building characteristics and modeling assumptions that allow users to customize the level of detail that goes into the calculation.

Methods & Approach

Energy and cost savings associated with full implementation of G36 measures are difficult to predict without complex modeling and significant investment. The ASHRAE G36 savings estimation calculator makes envisioning the impact of changes to commercial buildings much easier for screening and to kick-start a controls retrofit study.

This calculator is a streamlined, data-driven program offering scalable control retrofits and provides a large database of simulation data that can be used to assess uncertainty. During development, the calculator has the capability to leverage Database for Energy Efficiency Resources (DEER) prototype models. The DEER models are maintained by the California Public Utilities Commission to provide data on the costs and benefits of energy saving technologies. The DEER prototypes include 25 building types, 16 climate zones and several vintage eras, and are calibrated to California building stock and utility energy consumption data.

Utility program managers have total control over savings calculations. The amount of detail that users must input to be used in calculations can scale, as can the scope of applicability (i.e., building types, vintage, measures, etc.).

While the calculator's level of flexibility is scalable, it can never fully approximate a custom simulation. Because the calculator involves multiple moving parts on the development side, users cannot easily replicate savings calculations.

As with any tool, the calculator requires field validation. In addition, as the scope and detail of inputs grow, so does the amount of effort required for field validation. Increased scope and detail of inputs requires additional computational resources for initial development.

That said, the calculator is user-friendly. Users can enter the minimal amount of required data about their building and produce useful information. The calculator can be accessed in any web browser.

Figure 4 below shows how energy modeling and statistical modeling build on one another to produce the calculator's savings estimates. The basis of the energy modeling is the prototype buildings. The prototypes can be based on databases such as the DEER database or the DOE building prototypes, which include energy models that represent the building stock. In calculator development, the energy efficiency program administrator (PA) defines the scope of the study, the measures and the risk and uncertainty limits. After the parametric simulations are run and the statistical model is developed, the calculator goes live, hosted on a website. The user conducts a low-level facility audit if needed and interacts with the front end of the calculator to input data and receive savings and uncertainty estimates. The back end, hidden from the user, processes the building inputs and runs the statistical model in order to produce these estimates.

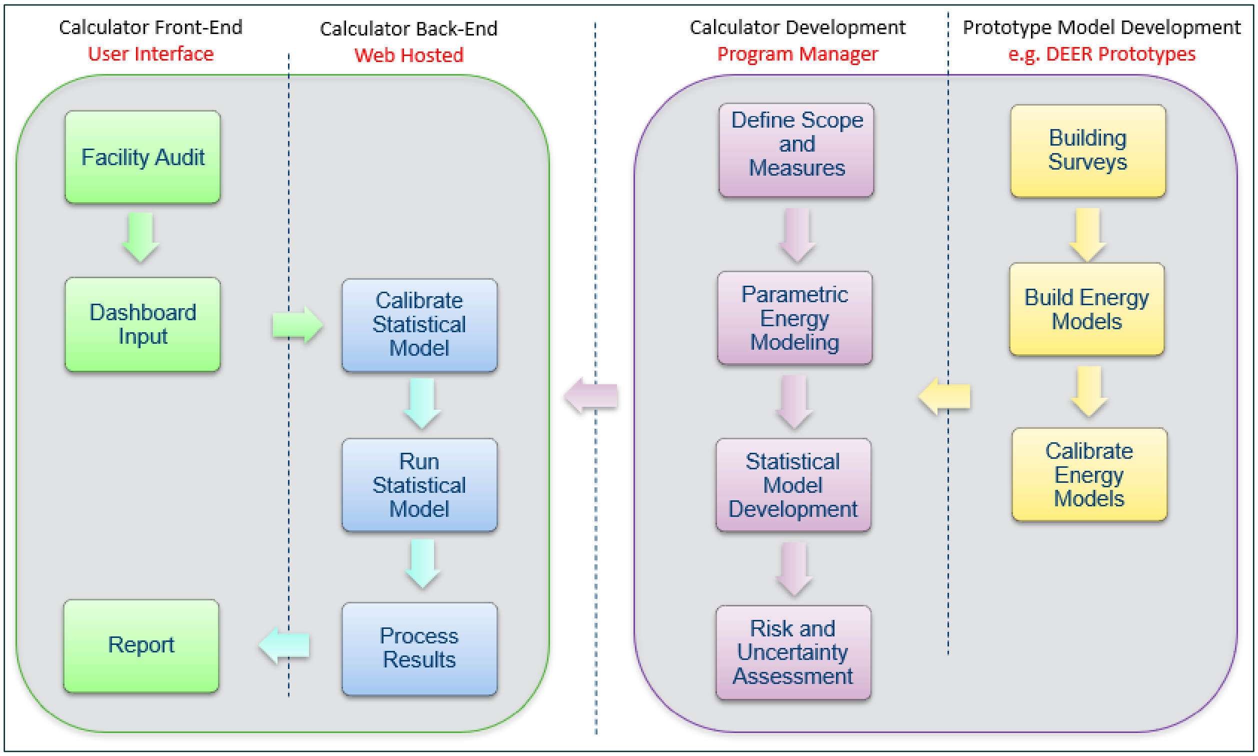

Figure 4: Information Flow in Calculator Development and Use

Building Energy Modeling

The building energy simulation process used detailed models developed using EnergyPlus, which is an open-source whole building energy simulation program developed and maintained by the U.S. Department of Energy's Building Technology Office and the National Renewable Energy Laboratory. This program is combined with Modelkit framework to conduct parametric simulations and generate energy consumption results for the calculator's back end.

Prototype Models

The project team selected buildings to model based on those that would have system types covered by G36 (primarily VAV reheat systems) and have the widest applicability to the California existing building stock. The project team reviewed the building types in the California eTRM and determined that the following building types would be likely to have VAV reheat systems serving at least part of the building: Education – Community College, Education – Secondary School, Education – University, Lodging – Hotel, Office – Large, Retail – Multistory Large. Note that this does not include Health/Medical – Hospital and Health/Medical – Nursing Home, which Office of Statewide Health Planning and Development (OSHPD) regulates, and therefore would not be a good application of the savings calculator. This version of the savings calculator would only be applicable to those buildings if the office portion is separately metered, or the building is determined to have similar internal gains and schedules as a typical office building.

The project team selected two prototype office buildings: (1) medium office and (1) large office building based on California Title 24-2022 by the CEC, and representing the Office – Large eTRM building type. These two types of office buildings represent the majority of the current office building stock by floor area in California. The Education, Lodging, and Retail building types have spaces that are similar to Office building types and could therefore potentially be represented by the medium office and large office prototypes. To represent the variations present within these two types of buildings, such as the vintage, operating conditions and HVAC control strategies, 16 major parameters (reduced to 13 in the final calculator) in the building model were varied. This is further discussed in the Parameters section. The medium office prototype has about 50,000 ft^2 floor area within three floors and five zones in each floor. The large office prototype has about 500,000 ft^2 floor area within five floors including a conditioned basement. While the basement is a single large zone, each of the other floors have five zones and are identical between floors. A three-dimensional rendering of the large office building is shown in Figure 5.

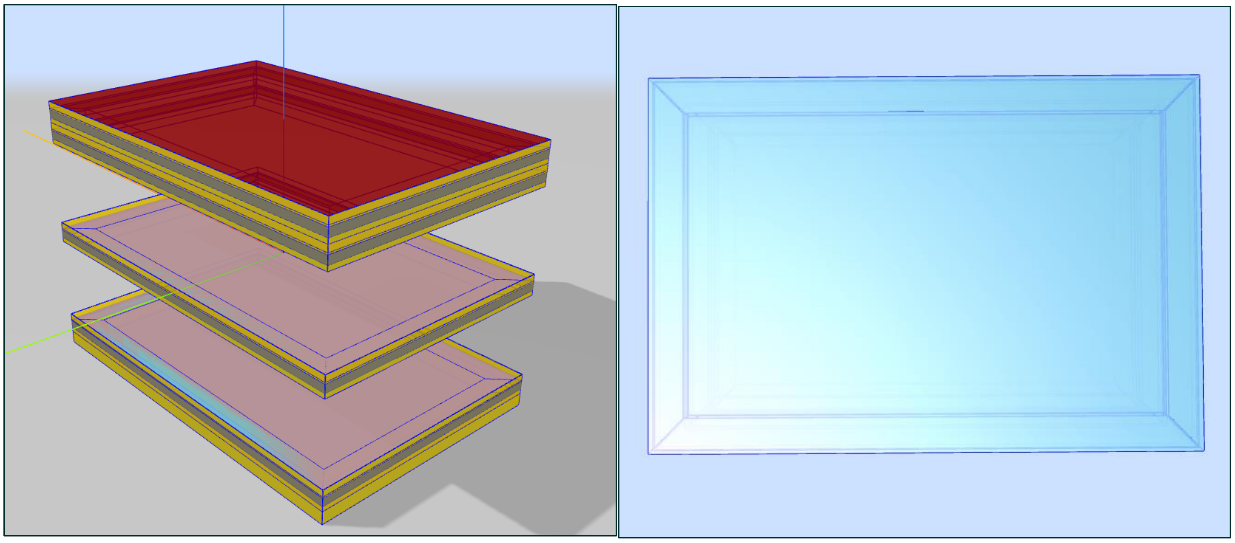

Figure 5: Three-dimensional View and Floor Zoning of the Large Office Prototype Building. Each of the Top Four Floors Have Five Zones Each (One Core Zone, Four Perimeter Zones)

The medium office prototype has a similar zoning structure with four perimeter zones and one core zone. Table 1 includes key features of the two prototypes.

Table 1: Comparison of Modeled Prototype Buildings

System Component	Medium Office Prototype	Large Office Prototype
Number of Floors	3	13 including basement
Area	53,633 ft^2	498,637 ft^2
HVAC Type	VAV reheat	VAV reheat
Cooling Type	Direct Expansion Air	Chilled Water
Heating Type	Condensing Boiler	Condensing Boiler

The two selected prototypes are much simpler than real world buildings in terms of zoning, and this makes the modeling process much simpler compared to calibrating a single model for a single real building. The simplicity of either prototype also makes them more flexible in their ability to represent more complicated building types by changing characteristics of select zones. Each prototype building has two types of zones. The first space type represents regular office spaces that stay the same across all simulations. The second space type has three levels of occupancy and equipment energy use density. The second space type is determined by user selection between a building with only office spaces, a building with separately zoned conference/meeting rooms and a building with large meeting rooms or assembly spaces. The ventilation requirement for these variable density zones also changes, depending on the space type option selected by the user, to account for higher occupant density.

Real-World to Model Uncertainty

Of the physics-based methods for predicting building energy consumption, full building energy modeling is generally considered to be the most detailed and accurate. However, there remain significant sources of uncertainty in energy model predictions. A calibrated model is often used to document energy savings due to the adoption of complex HVAC measures, such as the methods laid out in ASHRAE Guideline 14.

Uncertainty is introduced by the simplifications and assumptions made in the energy modeling process. The calculator calibrates model parameters to reduce this source of uncertainty and calculates the Normalized Mean Bias Error (NMBE) and coefficient of variation of the root mean square error [CV(RMSE)] to quantify it. Because the savings estimation calculator builds on energy model results, the project team mitigated the uncertainty from the energy modeling process by building automated calibration into the calculator framework. In addition, the project team tested measured data from six real world applications of ASHRAE G36 measures in office buildings against the savings estimation calculator. For a detailed explanation of model calibration and uncertainty calculations refer to the Back End section.

Controls Sequences

Uncertainty can also be introduced through the representation of the controls measures in the models. The project team used EnergyPlus's built-in control algorithms, which in some cases simplify the controls algorithms outlined in G36. For example, to calculate the fan power with static pressure reset EnergyPlus uses a fan curve developed from test data instead of calculating the actual static pressure setpoint at each timestep based on zone feedback. In another example, the supply temperature reset algorithm used by EnergyPlus does rely on feedback from individual zones, but doesn't include a portion of the G36 algorithm that ties in outdoor air temperatures. The project team decided to rely on EnergyPlus's controls algorithms because they can be directly integrated into the DEER Prototypes, making the results usable for DEEM Measure Package Development.

Parameters

For the preliminary parametric simulations of different building conditions, the project team initially considered 17 building parameters that represent key variations in real world buildings. Descriptions of these parameters are given in the Calculator Development section. Out of the original 17 parameters, the team selected 13 parameters with the largest energy savings impact for the final version of the savings estimation calculator to improve usability and data processing speed. Additionally, the number of variations simulated for each selected parameter was reduced in the final parametric simulation set to optimize the list for use with a design of experiments algorithm. The Preliminary Simulation Results section includes further discussion of this process. Table 2 lists the parameters used for parametric simulations for both preliminary and final phases of the calculator as well as the corresponding default values.

Table 2: Simulation Parameters

Parameter	Preliminary Tool Parameters	Final Tool Parameters	Default Value
Building Type	Ofc-medium, Ofc-large	Ofc-medium, Ofc-large	-
Climate Zone+	CA CZ1 to CZ16	CA CZ3, CZ4, CZ9, CZ12	-
Orientation (Degrees to North)*	0, 45, 90, 135	0	0
Zone Air Terminal Unit (ATU) Average Minimum Airflow (Minimum Flow Fraction)+	0.01, 0.1, 0.2, 0.3, 0.4, 0.5	0.01, 0.2, 0.3, 0.5	0.3

Parameter	Preliminary Tool Parameters	Final Tool Parameters	Default Value
Supply Air Temperature Control Strategy+	Fixed, Warmest Reset (5°F), Warmest Reset (10°F), Outdoor Air Reset (5°F), Outdoor Air Reset (10°F)	Fixed, Warmest Reset (5°F)	Fixed
Supply Air Temperature Setpoint – Low °F+	50, 55, 60	50, 55	55
Total Static Pressure (in w.c.)+	1, 3, 5, 7, 9	1, 5, 9	3
Fan Control Strategy	VAV with VSD, VAV with VSD and Static Pressure Reset	VAV with VSD, VAV with VSD and Static Pressure Reset	VAV with VSD
Economizer Control Strategy+	None, Fixed Drybulb, Differential Drybulb, Differential Enthalpy	None, Fixed Drybulb	None
Ventilation – Minimum OA+	0.1, 0.15, 0.2, 0.3	0.1, 0.15, 0.25	0.15
Building Schedule (Occupied Hours)	14, 12, 10	14, 12, 10	14

Parameter	Preliminary Tool Parameters	Final Tool Parameters	Default Value
Space Type	General office, Office with separately zoned conference/meeting rooms, Office with large meeting rooms or assembly spaces	General office, Office with separately zoned conference/meeting rooms, Office with large meeting rooms or assembly spaces	Office with separately zoned conference/meeting rooms
[Equipment Gains (W/sf), Occupant Density (sf/person)]+	[0,300], [0.5,250], [1,200], [1.5,150], [2,100], [2.5,50]	[0,300], [1,200], [2,100]	[1.5,150]
Infiltration (CFM/sf at 75 Pa)	0, 0.25, 0.5, 1, 2	0, 1, 2	1
Cooling Efficiency (COP)*	Med – 2.44, 3.42, 4.89; Lg – 3.69, 5.17, 7.39	Med – 3.42, Lg – 5.17	Med – 3.42, Lg – 5.17
Heating Efficiency*	0.65, 0.84, 0.99	0.84	0.84
Building Vintage*	Title 24-2022 Compliant	Title 24-2022 Compliant	Title 24-2022 Compliant
*Not varied for final tool database +Reduced number of parameters used for final tool database			

See the Front End Inputs section for a detailed description of each parameter. The project team chose these parameters to represent a wide range of office buildings in California as well as the design and operational characteristics of buildings that have the most significant influence on SOO energy savings. As mentioned previously, the Modelkit framework reads the parameters from an input list file and uses them to develop EnergyPlus IDF files where each building model will have said parameter value. Therefore, simulation of these building models results in the total and monthly energy consumption and breakdown by end uses as well as fuel source, which were used in developing back-end numerical models for the calculator. The Calculator Development section includes further discussion.

Note that numerical inputs such as Zone ATU Min Flow Fraction, Supply Air Temperature Setpoint, Static Pressure, Ventilation, Infiltration and Gains have a limited number of input parameters in the simulation database, but the statistical model allows interpolation from any value within the range.

Measures

The project team considered four ASHRAE G36 measures for the savings estimation calculator, as well as the associated baseline existing conditions.

1. **VAV dual max logic minimum flow fraction:** Under ASHRAE G36, zone air terminal unit variable air volume systems are controlled based on a dual maximum logic and the calculator compares the existing zone air terminal unit minimum airflow (minimum air flow fraction) averaged for all zones in the building, with a proposed minimum VAV flow fraction of the required ventilation rate. This ensures that at minimum demand level, each VAV box can provide the ventilation requirement for the zone and not supply excess air to the zone when not needed, thus saving cooling, heating and fan energy.
2. **Supply air temperature control strategy:** Supply air control type for the prototype buildings is set at a fixed level of 55°F by default. In the proposed measure, the supply air setpoint is adjusted to the warmest setpoint that can meet all zones' cooling demands at maximum airflow, up to 5°F above the minimum setpoint. For the default case, this means that the temperature is varied between 55°F and 60°F depending on the heating/cooling demand from zones. This allows for reducing conditioning energy but leads to an increase in fan energy. The Preliminary Simulation Results section includes further discussion.
3. **Fan control strategy:** Supply airflow fan control is set, by default, to variable air volume method using variable frequency drive (VAV-VFD) but without any duct static pressure reset. Under the ASHRAE G36 proposed measure, this is modified to also include static pressure reset, thus saving fan electrical energy.
4. **Economizer control:** The default prototype buildings used as the models have no economizing in central air handler units. Economizing allows for using cool outside air to reduce initial cooling requirement of mixed air at the building level air handler units. Under the proposed measure, this is changed to an economizer with fixed dry bulb control. The fixed dry bulb upper temperature limit for economizing is set using California Title 24 requirement for each climate zone and ranges between 69–75°F.

Estimated energy savings produced by this calculator equal the difference between the current energy consumption of the building, from user inputs, and the predicted energy consumption with the above measures implemented, from the calculator. Some buildings can have some of these measures already implemented in which case, the calculator will show zero savings for implementing those measures.

Parametric Simulation

For parametric simulations, the team used EnergyPlus in conjunction with the Modelkit parametric simulation framework developed by Big Ladder Software. Modelkit automates the modeling and simulation process by reading through a large number of cases from an inputs list file with different input parameters that define building model characteristics (e.g., climate zone, building type, system type, etc.). Modelkit then iteratively generates EnergyPlus input files (IDF files) used for simulation and runs EnergyPlus simulations for each of the input cases. The Modelkit framework also processes results for each simulation where it captures key results related to energy consumption from EnergyPlus results files. These key results are consolidated to comma separated value (.csv) files, which then undergo post processing to rearrange the data into the desired format for use in the results database for the calculator's back end. Figure 6 illustrates the simulation process.

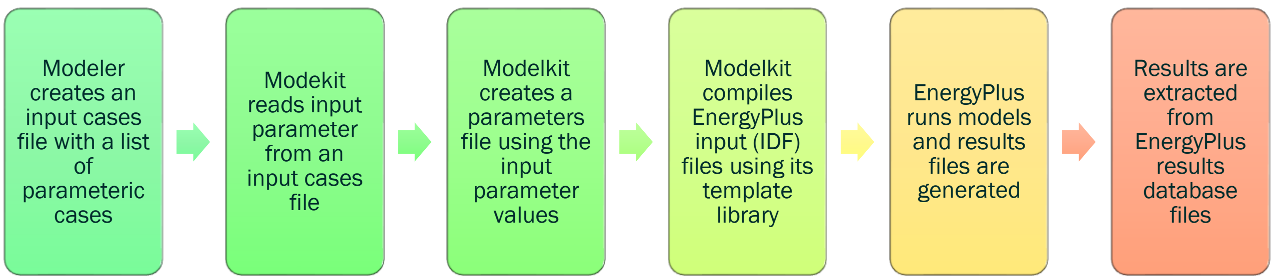

Figure 6: Modelkit EnergyPlus Parametric Simulation Process

The input cases file contains all simulation cases used for the back-end database and for the final calculator, totaling 64,000 cases. All parametric values included in Table 2 can be combined to generate about 1.2 billion unique combinations. The team used the Federov algorithm (Fedorov, 2010) to construct an optimal list of cases to be simulated so that the number of simulations is practical in terms of simulation time and resources, as well as to ensure that enough variations of each parameter are present to ensure model fit robustness. For the preliminary calculator's development, this subset was 3,000 cases (about 1,500 each for the two buildings), which were simulated for all climate zones leading to total 48,000 simulations.

Preliminary results analysis showed that additional data was desired for a better statistical model, and the energy consumption variation was small for some of the parameters that had been included. This led the team to separate out the parameters directly related to ASHRAE G36 measures, building type and climate zones, leaving 1,458 unique combinations. The team used the same optimal list selection algorithm to select 250 cases, representing a sample set of building configurations that span the space created by the building descriptor parameters. Each of the 250 cases were simulated for all combinations of parameters related to G36 measures in order to get a direct comparison that included interactive effects of measures. This led to 8,000 unique simulations per climate zone per building, or a total of 64,000 simulations. Further information on this process is provided in the Final Simulation Input Parameters Section.

Figure 7 shows a screenshot of the input cases file (step 1 of Figure 6) that identifies each simulation case by a unique ID (e.g., 1001, 1002, etc.) and lists the parameters used. Figure 8 and Figure 9 show annual and monthly results for these simulation cases.

case_name	:main_atu_flow_min_frac	:main_fan_curve	:main_fan_rise	:main_fan_return_rise	:main_sat_reset_type	:main_sat_temp_min	:main_sat_temp_max	:main_oa_econ_type
base_00								
Office-Large_1001_1	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1002_2	0.01	VAV-VSD	3.3333333333333	1.66666666666667['in H.	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1003_3	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1004_4	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1005_5	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1006_6	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1007_7	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1008_8	0.01	VAV-VSD	3.3333333333333	1.66666666666667['in H.	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1009_9	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1010_10	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1011_11	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1012_12	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1013_13	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1014_14	0.01	VAV-VSD	3.3333333333333	1.66666666666667['in H.	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1015_15	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1016_16	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1017_17	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1018_18	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	55['F']	55['F']	NONE
Office-Large_1019_19	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1020_20	0.01	VAV-VSD	6['in H2O']	3['in H2O']	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1021_21	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	50['F']	50['F']	NONE
Office-Large_1022_22	0.01	VAV-VSD	0.6666666666666	0.333333333333333['in H	WARMEST-ZONE	55['F']	55['F']	NONE

Figure 7: Screenshot of Input Cases File Used for Parametric Simulations

Results Schema

Energy consumption results from the above simulations are extracted from the EnergyPlus output database file and written into comma separated value (.csv) files for further processing (final step of Figure 6). Figure 8 shows a screenshot of the annual results .csv file. In addition to total energy, other values were extracted, including electricity and natural gas energy use, end-use energy breakdown (heating, cooling, fans, lighting etc.), long-term system-wide cost, CO_2 emissions, boiler and chiller design capacity and fan design capacity that are not used in the current version of the calculator but could be used in the future to provide more information to the user.

File Name	Total (kBtu)	Elec Energy (kBtu)	NG Energy (kBtu)
runs/CZ03/office-large/base_00/instance-out.sql	11138592.34	9186593.3	1951999.04
runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	3751456.22	3081518.72	669937.5
runs/CZ03/office-large/Office-Large_1002_2/instance-out.sql	4135506.99	3551546.07	583960.92
runs/CZ03/office-large/Office-Large_1003_3/instance-out.sql	4415353.07	3927396.61	487956.46
runs/CZ03/office-large/Office-Large_1004_4/instance-out.sql	4344253.37	3792581.35	551672.02
runs/CZ03/office-large/Office-Large_1005_5/instance-out.sql	12464633.83	12440195.18	24438.65
runs/CZ03/office-large/Office-Large_1006_6/instance-out.sql	16612613.64	16589302.37	23311.27
runs/CZ03/office-large/Office-Large_1007_7/instance-out.sql	16215855.57	16190508.16	25347.41
runs/CZ03/office-large/Office-Large_1008_8/instance-out.sql	5674665.1	3436109.42	2238555.68
runs/CZ03/office-large/Office-Large_1009_9/instance-out.sql	5852527.26	3775250.09	2077277.17
runs/CZ03/office-large/Office-Large_1010_10/instance-out.sql	7799233.66	7203856.31	595377.35
runs/CZ03/office-large/Office-Large_1011_11/instance-out.sql	8752908.02	8178244.7	574663.32
runs/CZ03/office-large/Office-Large_1012_12/instance-out.sql	12248814.27	11968737.52	280076.75
runs/CZ03/office-large/Office-Large_1013_13/instance-out.sql	12306901.39	12022858.24	284043.15
runs/CZ03/office-large/Office-Large_1014_14/instance-out.sql	13218232.7	12910473.29	307759.41

Figure 8: Simulation Results for Annual Energy Consumption

In addition to annual results used for calculating estimated annual energy savings from implementing ASHRAE G36 measures, monthly energy consumption results were also extracted. Figure 9 shows a screenshot of monthly energy consumption simulation results. Monthly results are used to test the calibration of the model against the user-input monthly energy consumption data. The Calculator Development section includes further discussion.

1	File Name	month	Electricity (kWh)	Natural gas (therms)
2	runs/CZ03/office-large/base_00/instance-out.sql	1	215611.14	3965.1
3	runs/CZ03/office-large/base_00/instance-out.sql	2	195257.95	2715.54
4	runs/CZ03/office-large/base_00/instance-out.sql	3	225200.11	2388.57
5	runs/CZ03/office-large/base_00/instance-out.sql	4	224362.04	1523.61
6	runs/CZ03/office-large/base_00/instance-out.sql	5	220029.26	921.93
7	runs/CZ03/office-large/base_00/instance-out.sql	6	237990.94	558.65
8	runs/CZ03/office-large/base_00/instance-out.sql	7	240183.02	591.89
9	runs/CZ03/office-large/base_00/instance-out.sql	8	229968.73	700.61
10	runs/CZ03/office-large/base_00/instance-out.sql	9	236618.86	452
11	runs/CZ03/office-large/base_00/instance-out.sql	10	236189.66	772.8
12	runs/CZ03/office-large/base_00/instance-out.sql	11	203164.95	1545.12
13	runs/CZ03/office-large/base_00/instance-out.sql	12	225953.71	3384.15
14	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	1	71031.94	2434.58
15	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	2	64230.11	1280.52
16	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	3	73501.94	721.38
17	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	4	73195.89	143.38
18	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	5	75246.36	7.44
19	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	6	82201.59	0.19
20	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	7	81660.82	1.25
21	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	8	78145.07	1.37
22	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	9	81066.08	0.2
23	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	10	80118.78	27.45
24	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	11	68062.21	387.99
25	runs/CZ03/office-large/Office-Large_1001_1/instance-out.sql	12	74041.29	1693.65

Figure 9: Simulation Results for Monthly Energy Consumption

Calculator Development

The motivation for developing a predictive model comes from the need for quick, efficient energy consumption estimates without relying on the extensive simulations performed in EnergyPlus. The goal is to create a streamlined solution that can provide reasonably accurate predictions with minimal computational resources and minimal user burden.

The model uses the outputs of EnergyPlus simulations as the training dataset. This dataset includes a variety of inputs. The predictive model is built using different algorithms, namely linear regression, decision tree, neural networks, ensemble models and XGBoost. The final model selection depended on the accuracy and time required to estimate energy savings. We observed that most algorithms did not meet the desired performance criteria in terms of accuracy or computational efficiency. While the ensemble model demonstrated favorable predictive performance, the time required to obtain results was impractical. The project team ultimately chose XGBoost (eXtreme Gradient Boosting) as the preferred algorithm. XGBoost combines the strengths of decision trees and ensemble learning, providing a robust solution for predictive modeling. XGBoost can handle complex relationships in data and provide accurate predictions. Figure 10 depicts this process.

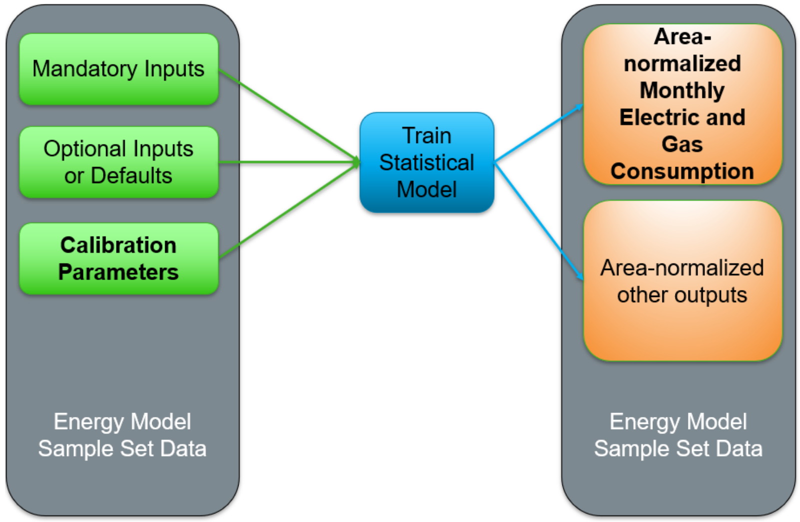

Figure 10: Energy Consumption Estimation Process

The model trains on EnergyPlus's outputs, where the model inputs correspond to the inputs used in the energy EnergyPlus run and the target output variable is the corresponding energy consumption.

The model's performance is evaluated using various metrics such as Mean Absolute Error (MAE), Root Mean Squared Error (RMSE) and R-squared. These metrics provide insights into how well the model generalizes unseen data.

Front End

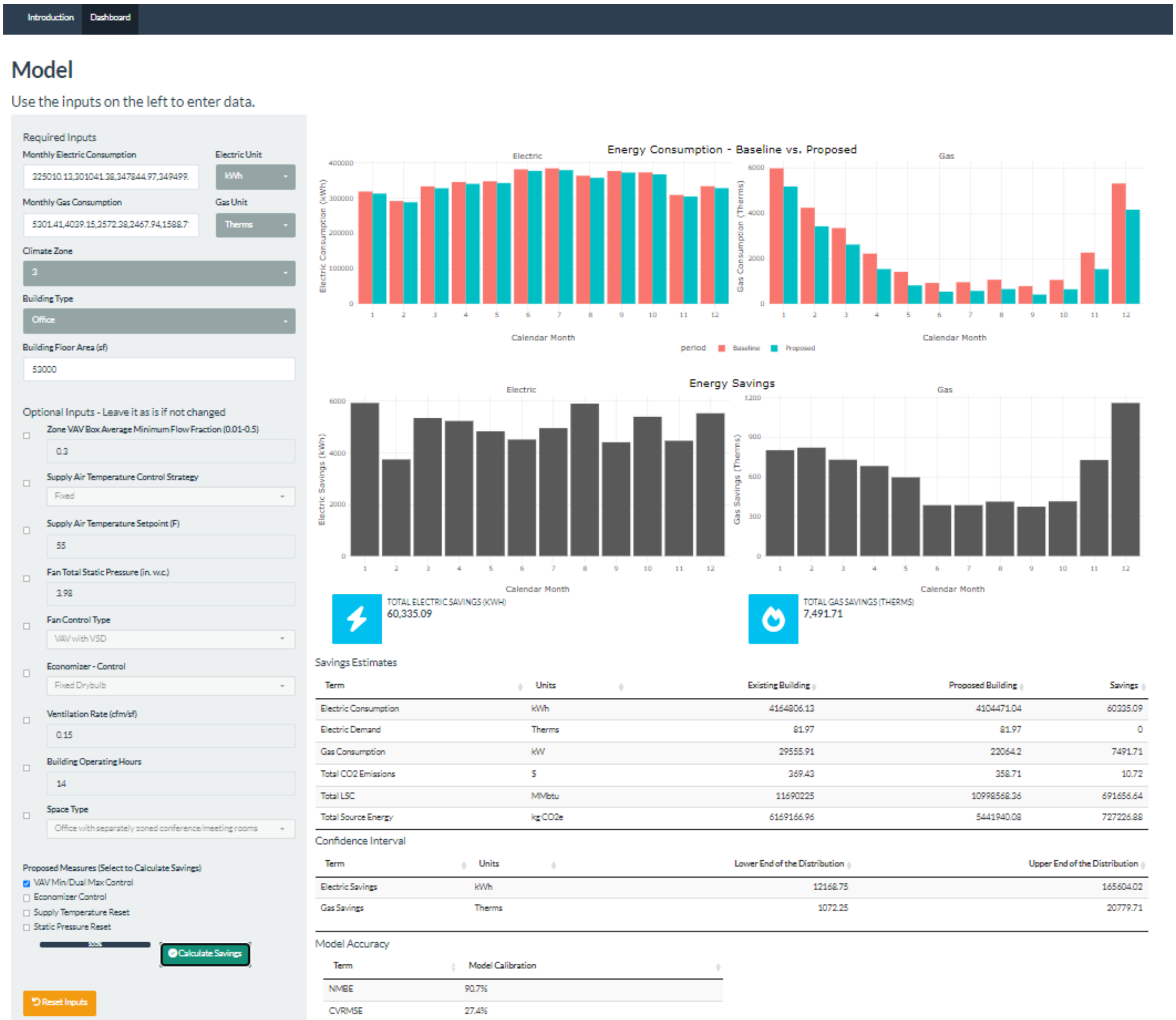

Figure 11: Dashboard Front End

The front-end interface (dashboard) of the savings estimation calculator is designed to facilitate user-friendly interaction with the model. Using the Shiny framework, the dashboard provides required and optional inputs for users to input information about their existing systems and explore the potential impact of proposed measures on energy consumption.

INPUTS

On the left-hand side of the dashboard, users are presented with a set of input fields to describe their existing building systems. The required inputs include:

1. Monthly Energy Consumption: Users are required to input monthly energy consumption, distinguishing between electric and gas services. At least one of these services must be entered. If users have both electric and gas services, they can input consumption values for each of the 12 months, representing the annual energy usage. This detailed monthly breakdown ensures a comprehensive understanding of energy consumption patterns, enhancing the accuracy of the modeling process.
2. Climate Zone: Users can select the climate zone corresponding to their geographical location.
3. Building Type: The type of building. Currently the only option is Office building.
4. Building Size: Size of the building in square feet.

Additionally, users have the option to provide more detailed information about existing building conditions through optional inputs:

1. VAV Average Min Flow Fraction: The fraction of the minimum airflow setpoint (minimum airflow rate setpoint divided by the maximum cooling airflow rate setpoint) for Variable Air Volume (VAV) systems.
2. SAT Control Type: The type of control strategy employed for Supply Air Temperature (SAT) in HVAC systems. This includes fixed supply air temperature and variable supply air temperature based on the warmest zone. In the latter case, SAT will be increased up to 5°F from the SAT design temperature. For the preliminary tool, warmest zone-based control with 5°F and 10°F were considered as well as outdoor air temperature (OAT) based control with 5°F and 10°F. OAT based control increases the SAT up to the high limit when outdoor air temperature decreases below 70°F and reaches the max SAT when OAT becomes 60°F.
3. SAT Design Temperature: The design temperature set for the Supply Air Temperature in the HVAC system. For the warmest zone-based control, this is the minimum SAT setpoint.
4. Fan Control Type: The control strategy implemented for the fans in the HVAC system. This includes variable air volume with variable speed drive (VAV with VSD) and Variable air volume with variable speed drive and static pressure control (VAV with VSD and Static Pressure Control).
5. Fan Total Static Pressure: The TSP in the air handlers, influencing the performance of the HVAC system. This ranges from 1 to 9 in. w.c.
6. Economizer Control Type: The type of control used for the economizer in the HVAC system. This includes No-economizer and Fixed Drybulb economizer. In the latter, economizing begins below a fixed dry bulb temperature between 69-75°F depending on the climate zone.
7. Building Schedule – Hours Per Day: The number of hours per day the building is typically occupied, affecting energy consumption patterns. This includes 10-, 12- and 14-hour occupancy periods.

8. Secondary Space Types: Detail about additional space types within the building that may have different occupancy characteristics. This includes General office, Office with separately zoned conference/meeting rooms, and Office with large meeting rooms or assembly spaces.
9. Ventilation – Building Average CFM/sqft: The average cubic feet per minute (CFM) of ventilation per square foot. This includes values between 0.1 to 0.25 CFM/ft^2 of floor area.

These optional inputs allow users to provide more specific details about their building systems, contributing to more granular and tailored energy consumption estimates.

At the bottom of the input selection, users have the option to select up to four proposed ASHRAE G36 measures.

- VAV Min/Dual Max Control
- Economizer Control
- Supply Temperature Reset
- Static Pressure Reset

These measures represent potential changes or improvements to the existing system. The goal is to model the energy consumption both with and without these proposed measures, allowing users to estimate the theoretical energy savings.

Back End

After users input the necessary information through the front-end interface, they can click the designated calculate button to begin the energy savings estimation process. This calculation involves multiple steps to ensure accurate and reliable energy consumption predictions by calibrating the models to the user data and calculating uncertainties.

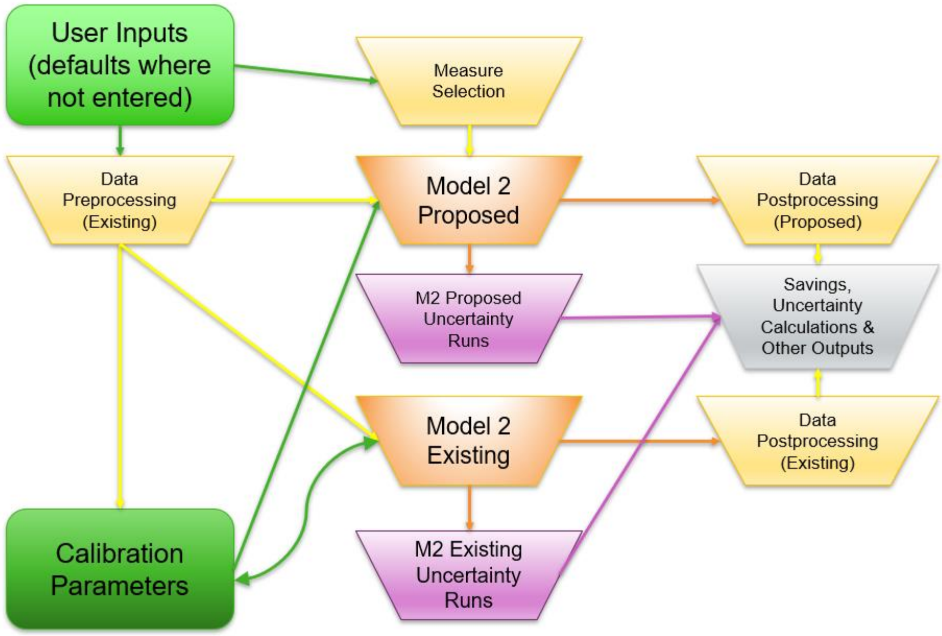

Figure 12: Calculator Back End Process

Figure 12 depicts the back-end process. Each of the steps is described below:

1. Pre-processing
   The back end pre-processes the user utility data by normalizing it by conditioned building area for better comparison to the prototype buildings.

2. Model Calibration
   The calculator executes a separate calibration model to estimate two crucial calibration parameters: gains density and infiltration. This model utilizes the user's actual annual electric and gas consumption values to fine-tune the calibration parameters. We integrate the calibrated gains density and infiltration parameters obtained from this step into the energy savings model. If, after calibration, there is still a difference between the user-entered energy consumption and the modeled energy consumption, the calculator determines a fixed factor with which to scale the model's energy consumption outputs. The fixed factor is applied after the model calibration metrics are calculated, so the user can see whether the model was successfully calibrated using model inputs.

3. Energy Savings Model
   The baseline energy consumption represents the energy consumption of the existing system. This baseline value captures the current energy usage pattern based on the user-provided inputs and building characteristics.
   The energy consumption with the proposed measures reflects the estimated energy consumption if the proposed measures are implemented. This is calculated using the statistical model with parameters adjusted to account for the selected measures.

4. Uncertainty Analysis
   We integrate a Monte Carlo simulation approach to address uncertainties arising from optional inputs. If users do not provide values for certain optional parameters, we randomly sample potential values for unspecified optional inputs from predefined ranges. We repeat this sampling 1,000 times. We then execute our savings model to generate a distribution of possible outcomes.
5. Post-processing
   The calculator reverts the area-normalized output values to absolute units of energy consumption, cost and greenhouse gas emissions. In addition, the calibration metrics of NMBE and CV(RMSE) are calculated to quantify the fit of the model to the monthly data provided by the user.

CALIBRATION

The savings estimation calculator incorporates a two-step modeling approach to enhance the accuracy of energy consumption estimates. The first step involves a calibration model designed to derive two crucial calibration parameters: receptacle gains density and infiltration. These parameters play a crucial role in refining energy consumption predictions.

The project team considered several parameters for use in model calibration, including receptacle gains density, infiltration rate, heating efficiency and cooling efficiency. Testing by the team determined that the limited data provided by the user was not sufficient to calibrate more than two parameters reliably. Two calibration parameters were chosen to address variations in internal and envelope gains.

We chose receptacle gains density and infiltration rate as the most useful calibration parameters. Receptacle gains density represents the peak equipment energy consumption and heat gain during a typical day. It is a critical factor in determining the internal heat gain within the building, affecting both heating and cooling loads. It has a direct correlation to the overall electricity use of a building and variation in receptacle power density is a primary cause of variation in energy use intensity (EUI) between office buildings. In addition, the occupant density was assumed to be proportional to the receptacle gains density because the largest source of receptacle usage in office space is personal computer and other personal appliances tied to individual occupants. Furthermore, the receptacle gains density can act as a proxy for other internal gains such as lighting power density.

Infiltration is the uncontrolled air leakage into the building, measured in CFM per square foot of envelope area at 75 Pascals (Pa) of pressure. Estimating infiltration is essential for understanding the impact of outdoor air temperature and wind speed on the building's heat load. Infiltration rate is generally correlated with natural gas consumption for space heating. Infiltration is one component of envelope loads, which also include walls, windows and roofs. Due to infiltration heat loss's correlation to outdoor air temperature, using infiltration as a calibration parameter provided a proxy to tune the model for envelope heat loss. This provided additional flexibility for the calculator to represent buildings of older vintages with less efficient envelopes.

The calibration process begins with the user providing their actual annual electric and gas consumption values. The project team took a two-step approach to calibration. In the first step the calibration model focuses solely on estimating gains density and infiltration. By using the user's actual consumption values, the model fine-tunes these parameters to align the predicted baseline energy consumption with the observed values. The second model calculates the energy consumption estimates by using user entered inputs and the calibration parameters determined in the first step.

The metrics for determining the success of the calibration, NMBE and CV(RMSE), are then calculated.

Normalized Mean Bias Error and CV(RMSE) are defined in ASHRAE Guideline 14 (ASHRAE, 2023) and are used to assessing an energy model's level of calibration and the accuracy of savings predictions. The standard refers to a limit of 5% for NMBE and 15% for CV(RMSE) when using monthly data. The metrics are defined as follows:

$$NMBE = \frac{\sum_{i-1}^{n}(y_i - \hat{y}_i)}{(n-1) * \bar{y}}$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{(n-1)}}}{\bar{y}}$$

Where y is the user-entered energy consumption, $\bar{y}$ is the arithmetic mean energy consumption, $\hat{y}$ is the predicted energy consumption, n is the number of months (12), and i is the month.

Calibrating the model ensures that the predicted baseline energy consumption aligns closely with the metered utility consumption provided by the user. This approach prevents the model from generating estimates that deviate significantly from real-world energy consumption patterns.

UNCERTAINTY DUE TO MODEL ASSUMPTIONS

The savings estimation calculator incorporates an uncertainty analysis to account for the variability introduced when users do not provide optional inputs. This uncertainty arises because default values are assigned to these inputs when they are left unspecified, causing a loss of accuracy in energy consumption estimates. The analysis also addresses the uncertainty introduced by the assumptions for building type and zoning. Other sources of uncertainty include calibration and model fit, which are addressed in the Calibration and Statistical Analysis sections, respectively.

From the user's perspective, this measure of uncertainty is highly dependent on the variation in system design and configuration within the building stock. To assess the uncertainty, conservative assumptions were made about the range and distribution of each characteristic across the building stock. With better data on the building stock that the calculator will be used within, the uncertainty of the calculator due to using default parameters could be significantly reduced.

To quantify the uncertainty due to default parameters, the project team used a Monte Carlo simulation approach. This method involves randomly sampling potential values for each unspecified optional input from their respective predefined ranges. The simulation is repeated to generate a distribution of possible outcomes for the energy consumption predictions.

For each optional input without user-provided values, a uniform distribution is assumed within the predefined range. The simulation involves running the savings model with the sample's optional input values. In addition, while the building type (medium or large office) is determined by the calculator based on user-entered floor area, the uncertainty calculation varies the building type randomly to capture the variation in results introduced by two very different building and zoning geometries. The assumption of a uniform distribution may be a source of error, because to get a true confidence interval the distribution of each parameter in the building stock and the correlation between parameters must be known. However, it is the project team's assessment that our approach likely gives a more conservative uncertainty range.

We execute the simulation 1,000 times to capture a diverse set of potential outcomes. Each simulation produces an energy consumption estimate based on the sampled input values. After the simulations, we take the 20% and 80% quantiles, representing the lower and upper bounds of the distribution. These quantiles serve as the minimum and maximum uncertainty values for the energy savings predictions.

When users do not input optional parameters, the uncertainty analysis informs them about the potential range of energy savings outcomes. If more optional parameters are defined by the user, the uncertainty range will narrow around the savings estimate. The dashboard presents not only a single point estimate but also a plausible spread of the simulated data. The 20% quantile represents the lower bound, below which only 20% of the simulated values are located. Similarly, the 80% quantile serves as the upper bound, below which 80% of the simulated values are located.

Results

Stakeholder Outreach

The project team identified several research questions at the outset of the project, with the objective of driving the development of the savings estimation calculator in the direction of maximum impact to energy efficiency practitioners and program managers.

We conducted interviews, workshops and a literature review to address several foundational research questions, the first being what support material to build from. The consensus was that the best support for the simulations to build off was the DEER prototypes due to their adoption throughout the energy efficiency ecosystem in California. However, because the non-residential EnergyPlus prototypes were still in development at the time of calculator development, prototypes were based on the CBECC medium and large office prototypes. Both sets of prototypes are used in ModelKit, which simplifies the process of switching to the DEER prototypes for future development of the savings estimation calculator.

This initial research also addressed the questions of whether the savings estimation calculator should be a stand-alone tool or should be integrated with an incumbent tool. The professionals the project team interviewed indicated that a stand-alone tool would provide a more meaningful contribution because this approach would allow greater flexibility in the design of the user interface.

To determine which G36 measures are the most impactful, the project team interviewed controls and energy efficiency professionals at TRC and referenced the EPIC Best-in-Class (EPIC – BiC) study. The interviews and the EPIC – BiC study emphasized that combinations of measures should be studied to account for interactive effects. The most impactful measures depend on the context. The project team used the preliminary simulations to gain more insight into which measures were most impactful.

The project team considered several potential target users for the savings estimation calculator, including mechanical, electrical and plumbing (MEP) firms; HVAC system researchers; codes and standards developers and energy efficiency program stakeholders. The primary opportunity identified was for energy efficiency stakeholders, providing a solution to fill the gap between prescriptive and custom measures. The project team found that G36 measures are too complex to be addressed using a prescriptive path. However, a custom incentive application requires a very high level of documentation and rigor which inhibits the use of this pathway. This project can potentially be approved as a hybrid approach that reduces the burden of a custom application or serve as a preliminary savings estimation tool that complies with the California Normalized Meter Energy Consumption (NMEC) rulebook. The NMEC rulebook does not require baseline savings calculations backed up by trend data, because the actual savings are verified at the meter.

Energy efficiency program stakeholders stated that the savings estimation calculator would provide a useful tool to efficiency programs but emphasized that quantifying uncertainty was of critical importance in gaining approval for documenting incentives.

Preliminary Simulation Results

Table 2 above lists parameters used for preliminary simulations. To determine the impact of each of the varied parameters on energy savings and the sensitivity of total energy consumption to each of the parameters, the project team considered two types of analysis. These analyses, as well as other practical considerations, resulted in refinement of the input parameters for the final simulations.

Sensitivity Analysis

The project team evaluated the variation of energy use between the base case, with default values for parameters, and parametric simulations, with different parameter values. This gave valuable insights into what parameters impact the total energy consumption most and led to the modified set of parameters used in the final simulation runs.

Figure 13 shows Zone VAV minimum flow fraction and total energy use for the medium office building type, and the large office analysis showed a similar trend. Energy Plus determines each zone minimum airflow setpoint as the larger of the minimum flow fraction and the required ventilation rate. Because the ventilation rate prevents the minimum setpoint from being reduced below a “floor” value, the results show a significant change between 0.5 and 0.3. The “floor” is typically reached somewhere between 0.3 and 0.1 so there is a somewhat smaller but still significant change between those values, and there is no change below 0.1. At this point the actual VAV minimum fraction is determined by the outside air ventilation requirement.

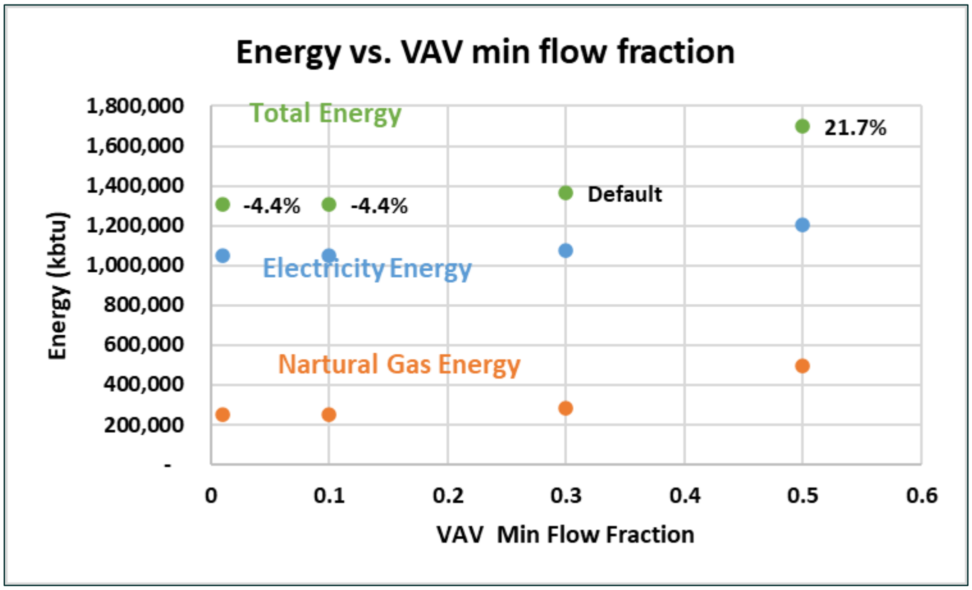

Figure 13: Simulation Results – Medium Office: Energy Use for Different VAV Minimum Fractions. Percentage Value Indicates the Difference with Default Building Consumption

Evaluation of energy consumption for different economizer control strategies for the medium office building shown in Figure 14 revealed that the results are similar between the three control strategies. Analysis showed a similar trend for the large office building type. This led to the removal of different economizer control strategies in the final simulations, retaining only no-economizer and fixed dry bulb cases.

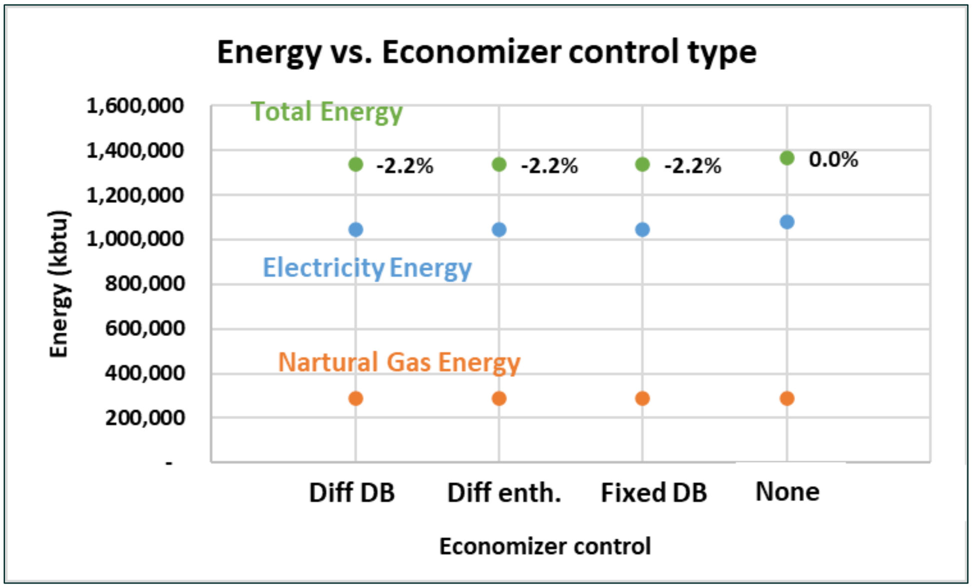

Figure 14: Simulation Results – Medium Office: Energy Use for Different Economizer Control Strategies. Percentage Value Indicates the Difference with Default Building Consumption

Figure 15 shows energy consumption's relationship to a rise in fan pressure for the medium office prototype, which shows a linear relationship. Analysis showed a similar relationship for the large office building type. This led to the reduction of the number of different values from five to three in the final simulation runs.

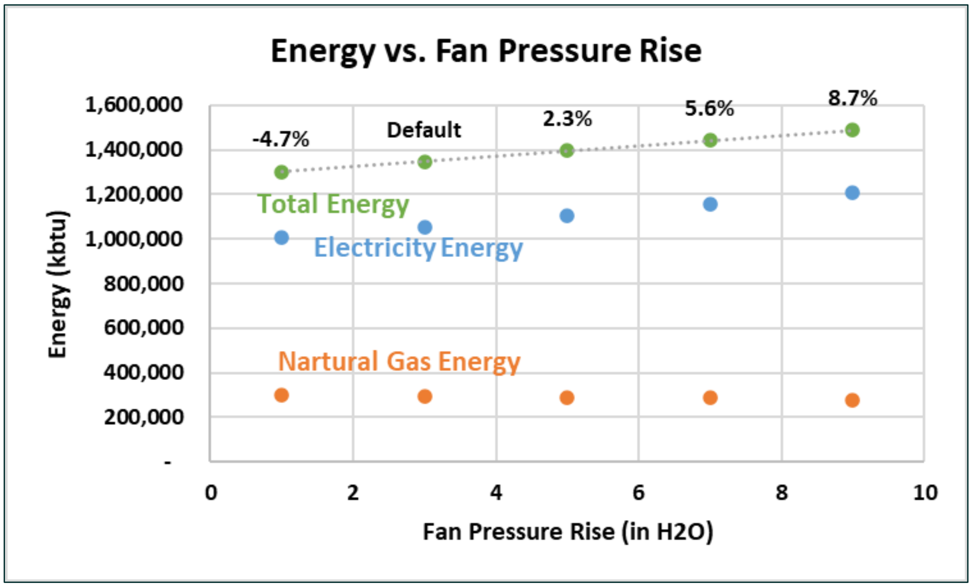

Figure 15: Simulation Results – Medium Office: Energy Use for Different Fan Pressure Rises. Percentage Value Indicate the Difference with Default Building Consumption

Overall, this analysis helped the team to significantly reduce the number of parameters used for simulations, which reduced the computational burden of simulations. This also allowed for the development of a simulation database that provides a direct comparison between building scenarios with and without the ASHRAE G36 measures implemented. This is expected to improve the accuracy of savings results calculated by the calculator.

Energy Savings for the Default Case

The project team evaluated energy savings resulting from each G36 measure, both individually and collectively, for all 16 California climate zones. Figure 16 shows the total energy savings percentage of implementing G36 measures from default conditions listed in Table 2. When G36 measures are implemented:

- Zone ATU average minimum airflow fraction is set to 0.01 from the default value of 0.3,
- Supply air temperature control strategy is set to Warmest Reset (5 °F) from the default Fixed strategy,
- Fan control strategy is changed to VAV with VSD and Static Pressure Reset from the default VAV with VSD, and
- Economizer control strategy is changed to Fixed Drybulb from None.

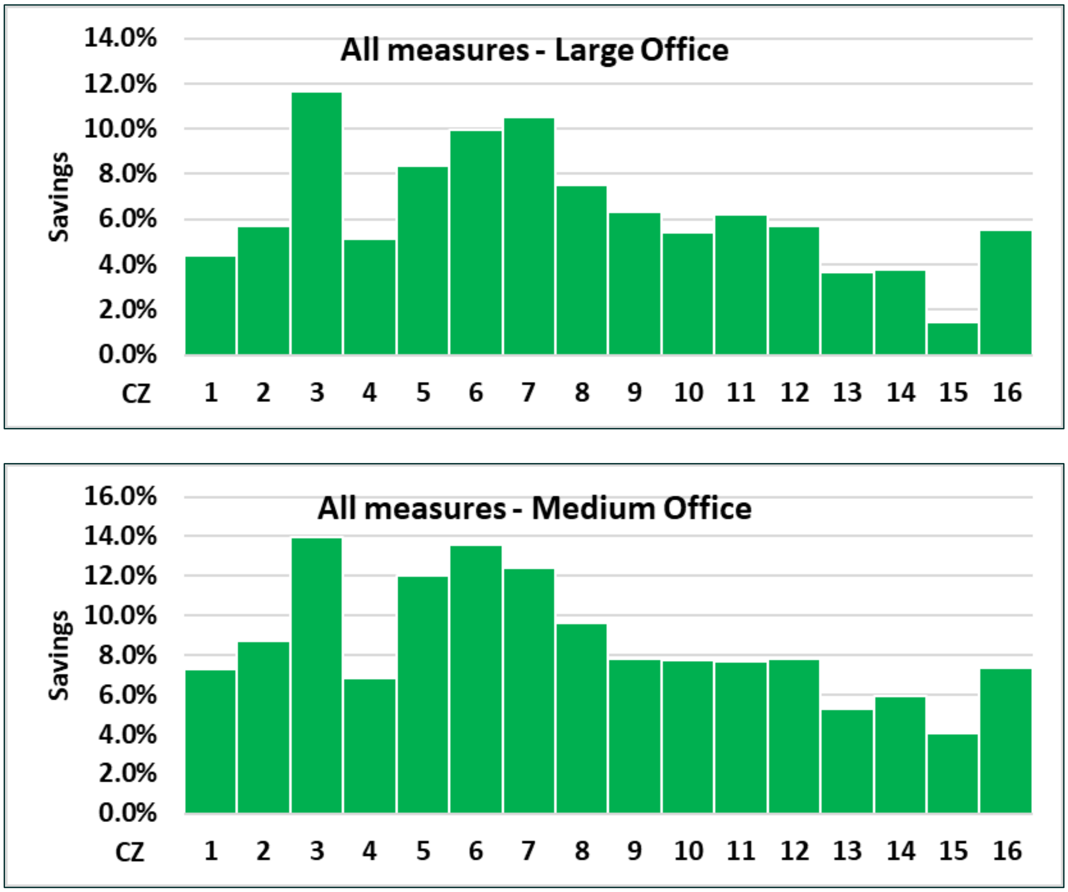

Figure 16: Whole Building Energy Savings Percentage of G36 Measures

Figure 17 and Figure 18 show a breakdown of percentage savings for each individual measure.

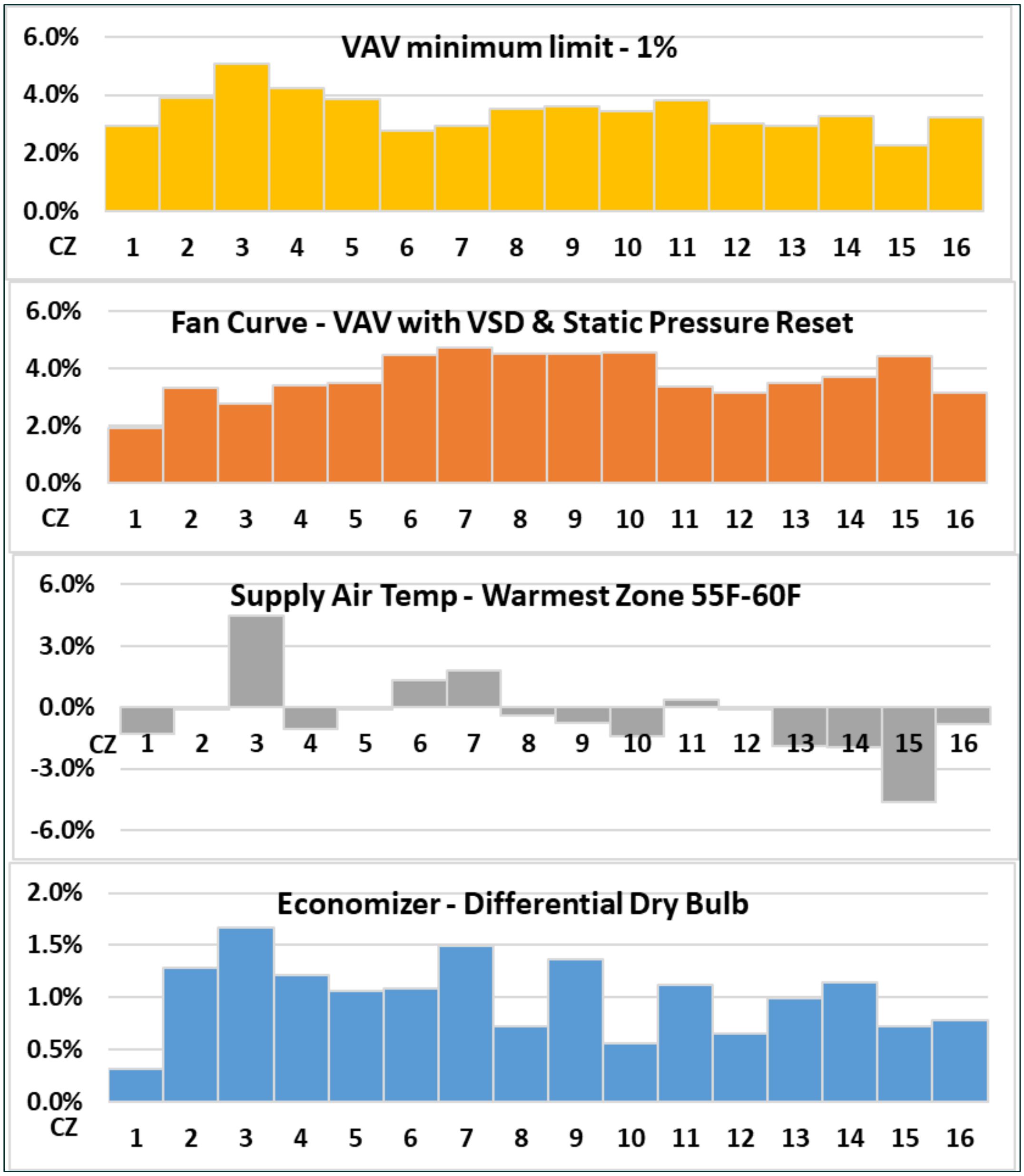

Figure 17: Large Office – Percentage of Energy Savings from Each G36 Measure

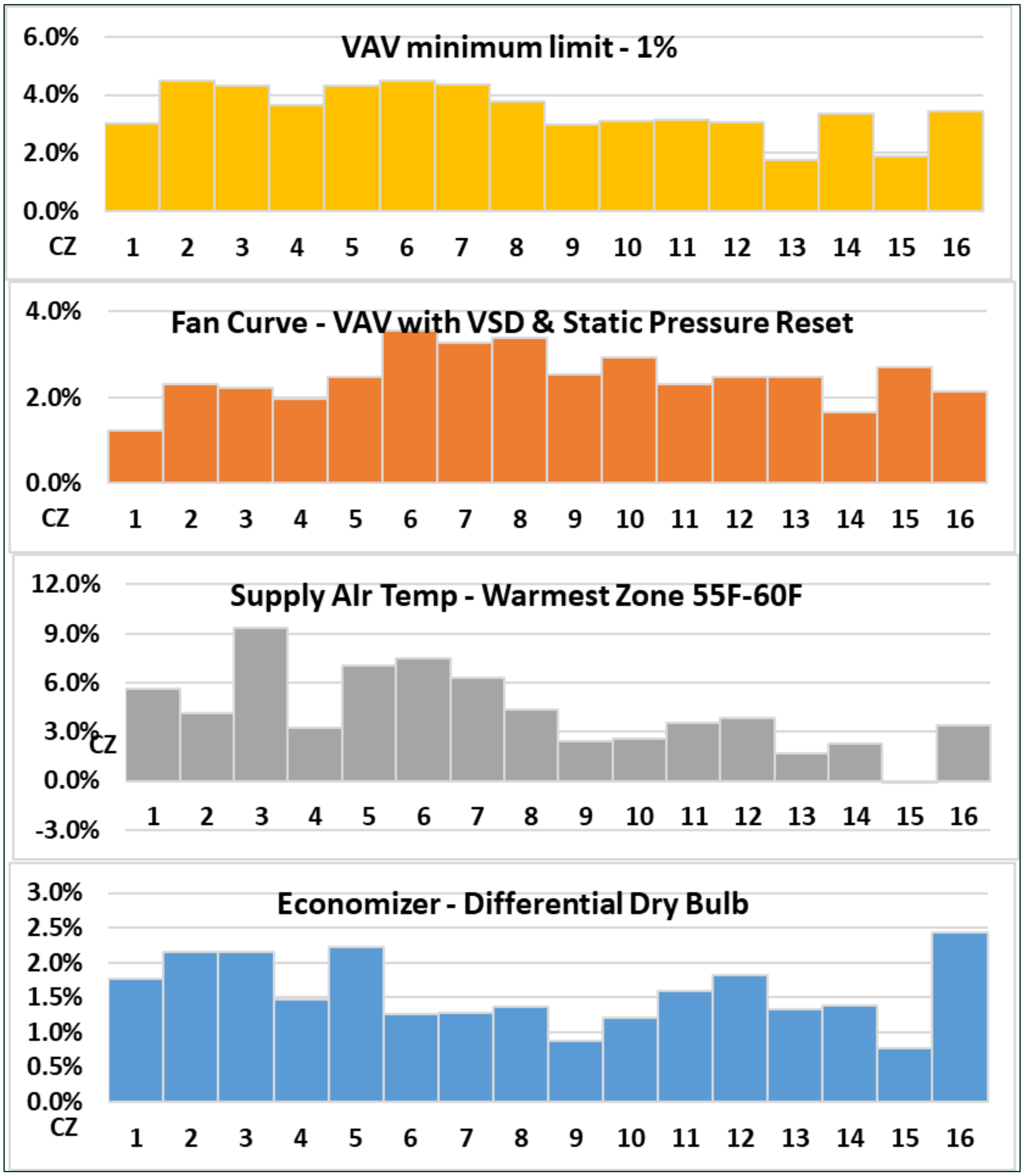

Figure 18: Medium Office – Percentage of Whole Building Energy Savings from Each G36 Measure

This analysis shows that energy savings depend on the climate zone (CZ) where some climate zones have higher savings, and some have lower savings. For the final simulation runs, only four climate zones were used (3, 4, 9, 12) with the potential to expand to other CZs in the future. This analysis provides insights into what can be expected when the other climate zones are simulated (e.g., for energy savings from all measures, expect CZ 11 to be similar to CZ 9 and CZ 16 to be similar to CZ 12).

For the large office prototype, implementation of the supply air temperature reset strategy results in negative energy savings for some climate zones. This could be due to the large office prototype having large core zones that predominantly require cooling even during the heating season due to heat transfer from surrounding zones. Allowing the supply air temperature setpoint to increase based on the warmest zone would require more airflow to achieve the core zones' temperature setpoints, requiring more fan and conditioning energy. This needs further evaluation in conjunction with real world building results.

Final Simulation Input Parameters

After the initial simulation set was completed, the parameters being varied and the options for each parameter were reassessed for the final simulation set. The final set excluded parameters and options that had a limited effect on the results, narrowing the focus onto the parameters directly affecting the measure performance in order to get better energy savings data.

We removed several parameters and options from the study. This allowed us to use the feasible number of simulations more effectively. These included:

- **Climate zones:** The project team determined that, based on data provided from the CEC, it could reduce the number of climate zones from 16 to 4 while still including the majority of existing office space in the state and all five validation sites.
- **Building orientation:** The results showed that orientation had less than 1% impact on the energy consumption of the building, and an even smaller impact on the savings for each measure. Building orientation was removed as a parameter.
- **Supply air temperature control strategy:** The preliminary results showed that the outdoor air reset (5°F) strategy showed similar savings to the warmest 5°F strategy within 1%, so the outdoor air reset strategy was removed as the less common measure. In addition, the preliminary results showed that both the outdoor air reset 10°F and warmest 10°F strategies showed lower savings than the warmest 5°F strategies, and so were determined not to be effective measures.
- **Supply air temperature setpoint – low °F:** The project team removed the setpoint of 60°F in order to reduce the complexity of the models. We determined that this option was lower priority due to being an uncommonly used setpoint in office buildings.
- **Economizer high limit control strategy:** The preliminary results showed that Fixed Drybulb, Differential Drybulb and Differential Enthalpy economizer control showed results within 1% of each other, and there was no strategy that consistently performed better than the others. As a result, the project team chose to move forward with only the simplest strategy: Fixed Drybulb.

- **Heating and cooling efficiency:** The preliminary results showed that the statistical model was not able to consistently calibrate all four calibration parameters in a way that reduced NMBE and CV(RMSE). The heating and cooling efficiency parameters had fewer interactive effects and a smaller impact on the whole building energy use, so the project team removed them from the simulation set. It is noted that they could be used for calibration through post processing the heating and cooling end use due to their very minor interactive effects.

For some continuous variables such as equipment gains density, infiltration rate, fan TSP and zone ATU average minimum flow fraction, the number of variations included in the simulation set was reduced between the preliminary and final simulation runs. The team determined that three variations was sufficient to interpolate the trends within the range of values under consideration. Reducing the number of discrete variations in these parameters reduced the complexity to the level needed in order to successfully run the Federov design of experiments algorithm as described in the Parametric Simulation section.

Statistical Analysis

The project team relied on several statistical metrics to assess the performance of the XGBoost model. The team focused on three crucial performance measures: R-squared (R^2) value, Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE).

R-squared Value (R^2)

The R-squared value provides an indication of how well the model explains the variance in the observed data. It is a unitless measure that ranges from 0 to 1, with higher values indicating a better fit. It indicates the proportion of the total sum of squared errors (sum of the squared differences between each data point and the overall mean) that remains unexplained after controlling for other information through the model.

Mean Absolute Error (MAE)

The Mean Absolute Error represents the average absolute difference between the predicted and actual values. It provides insights into the average magnitude of errors, regardless of their direction. A lower MAE indicates the model's predictions are closer to the actual values.

Root Mean Squared Error (RMSE)

The Root Mean Squared Error is a variation of the Mean Squared Error. Similar to MAE, a lower RMSE suggests that the model's predictions are closer to the actual values. The term *root mean squared* indicates that the errors are squared, averaged and then the square root is taken. RMSE penalizes larger errors more significantly than smaller errors, making it sensitive to outliers.

In examining the performance of the XGBoost model, the project team observed specific metrics: an R-squared value of 0.99 (both electric and gas), a MAE-Electric of 0.0067 kWh/sqft MAE-Gas of 0.00025 Therms/sqft and a RMSE-Electric of 0.0093 kWh/sqft, and a RMSE-Gas of 0.000389 Therms/sqft.

EnergyPlus is a deterministic model where inputs determine outcomes without randomness or variability in the calculations. EnergyPlus's lack of uncertainty contributes XGBoost's capacity to capture nearly all the variance observed in the data. The model replicates observed outcomes, resulting in a high R-squared value.

Data Validation

To validate the results of the savings estimation calculator, the team developed an additional 10 cases for the two prototype buildings (Office-Large and Office-Medium) and four climate zones (CZ3, CZ4, CZ9 and CZ12). These 10 cases are different from the 64,000 cases used for the tool back-end database. EnergyPlus simulations were conducted for the 10 cases and their corresponding proposed cases with G36 measures implemented to calculate energy savings based on model simulations.

The information of the 10 cases were separately used in the calculator to generate estimated energy savings, and this was compared with the model-based savings. Figure 19 and Figure 20 below compares the model-based savings and calculator estimated savings for electrical energy and natural gas energy consumption for Large office prototype building in Climate Zone 3.

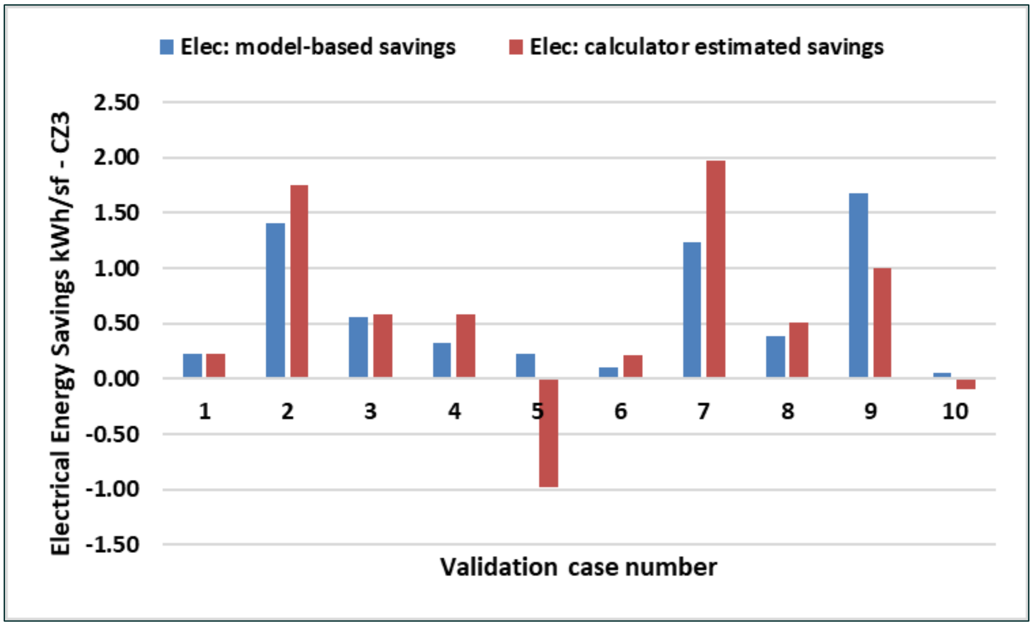

Figure 19: Comparison of Model-Based Electricity Savings and Calculator Estimated Savings for 10 Validation Cases for Climate Zone 3 for Large-Office Prototype

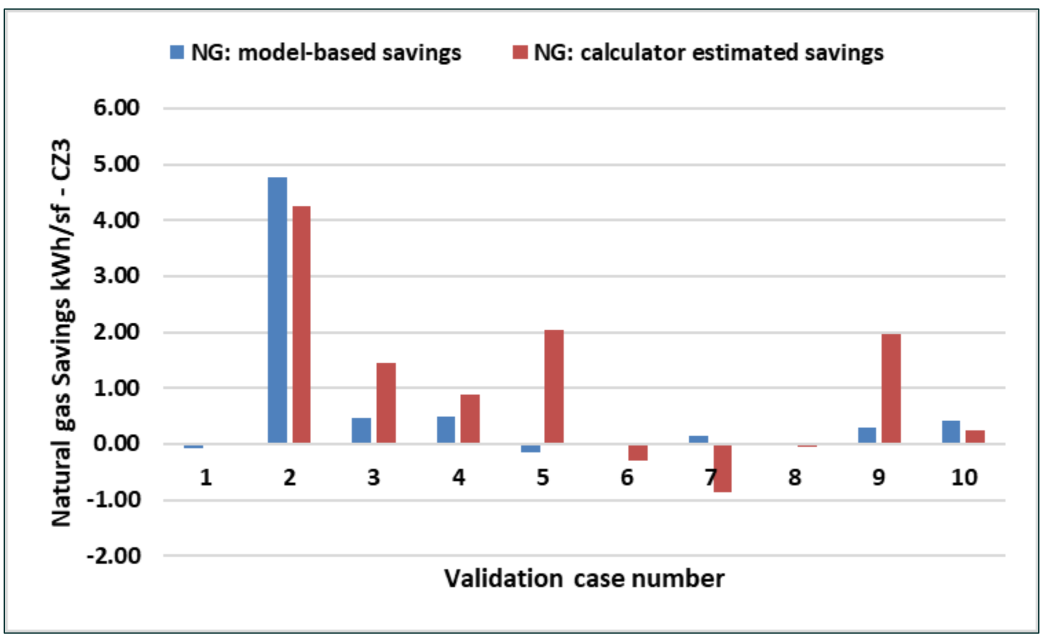

Figure 20: Comparison of Model-Based Natural Gas Savings and Calculator Estimated Savings for 10 Validation Cases for Climate Zone 3 for Large-Office Prototype

This shows significant differences in the estimated energy savings from the tool against the model-based savings. Office medium prototype and climate zones 4, 9 and 12 also show significant difference between the two savings estimates.

For all validation cases, results show a mean absolute error of 0.73 kBtu/sf over all test cases. However, the test cases include a random selection of buildings some of which already include the G36 measures. When only test cases with a predicted energy savings of at least 2 kBtu/sf per year, the target buildings for these measures, are included, the mean absolute error reduces to 0.07 kBtu/sf or 15% of predicted savings.

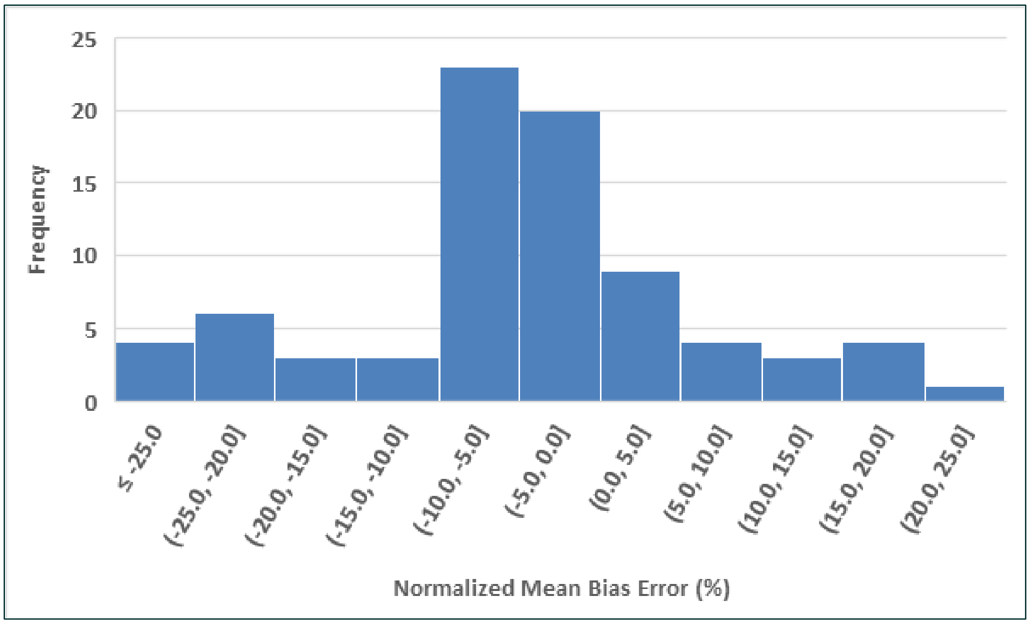

Figure 21: Frequency of Normalized Mean Bias Error after Calibration for 80 Validation Cases

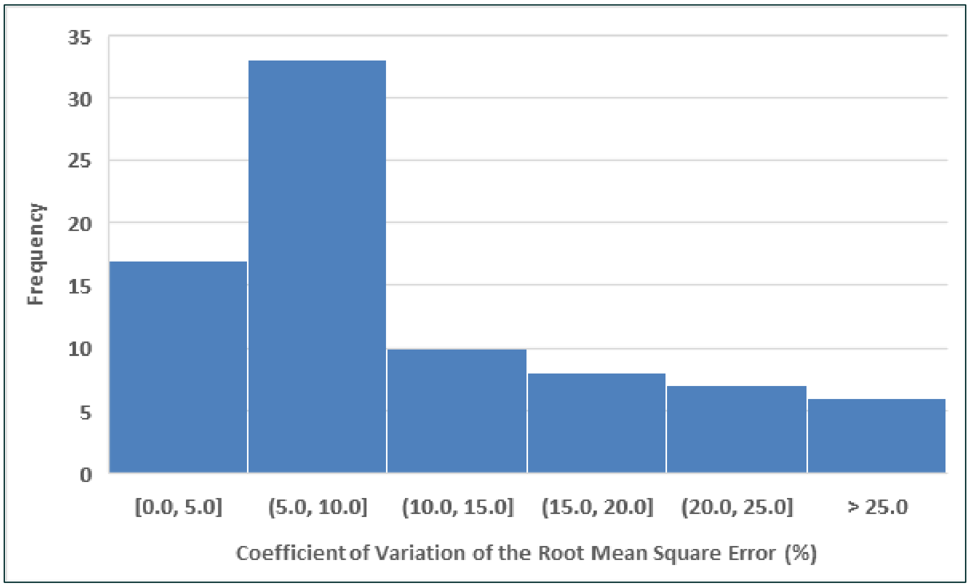

Figure 22: Frequency of the Coefficient of Variation of the Root Mean Square Error after Calibration for 80 Validation Cases

Figure 21 and Figure 22 show the distribution of NMBE and CV(RMSE) after model calibration. The results show that only 36% of the cases meet the ASHRAE Guideline 14 limit of 5% NMBE, while 74% of the cases meet the limit of 15% for CV(RMSE).

It should be noted that the uncertainty range for the savings estimate accounts for the calibration fit. However, these test results indicate that further work could be completed to improve the statistical model fit. Preliminary testing of other statistical models showed that the fit can be improved, at the expense of increased calculation time for the back-end. See the Recommendations section for further discussion.

Example Analysis of Uncertainty due to Model Input Assumptions

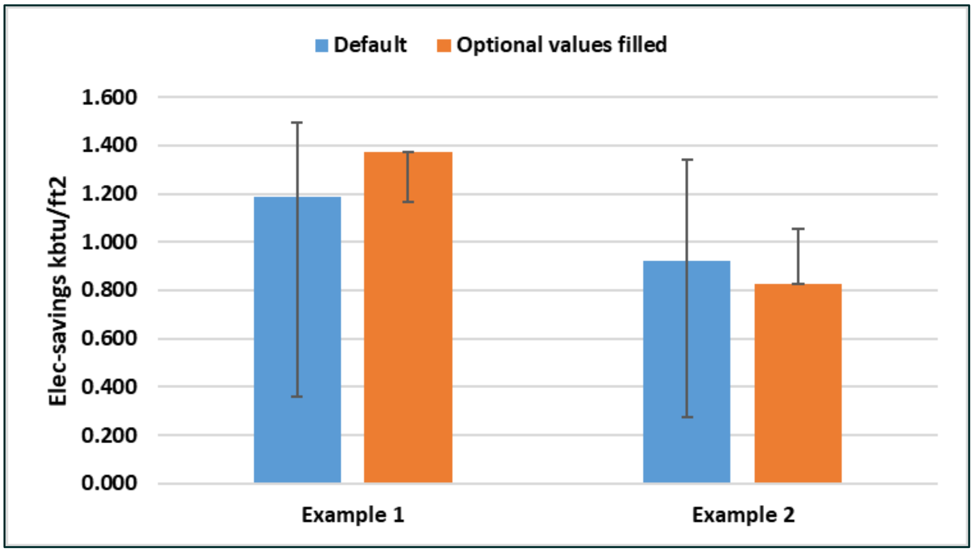

Figure 23 and Figure 24 show the comparison between electricity and natural gas energy savings for two example cases. For both cases, the blue bars show the energy savings estimate from the calculator if none of the optional inputs are filled in, i.e., assuming default values from Table 2. The orange bars represent energy savings estimate when all of the optional inputs are filled in. Error bars representing uncertainty due to model input assumptions of the calculation are smaller for the latter case reflecting the availability of more information for the building, which reduces uncertainty.

Figure 25 shows the model fit metrics NMBE and CVRMSE. Example 1 NMBE value and both CVRMSE values are within the ASHRAE Guideline 14 limits suggesting acceptable model fit accuracy.

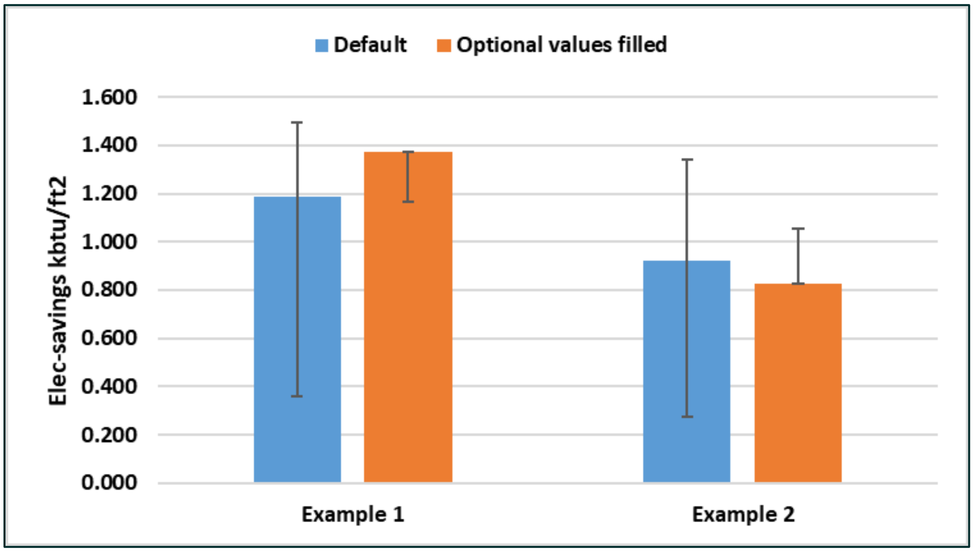

Figure 23: Comparison of Electricity Energy Savings Uncertainty due to Model Input Assumptions Showing the impact of Entering Optional Inputs

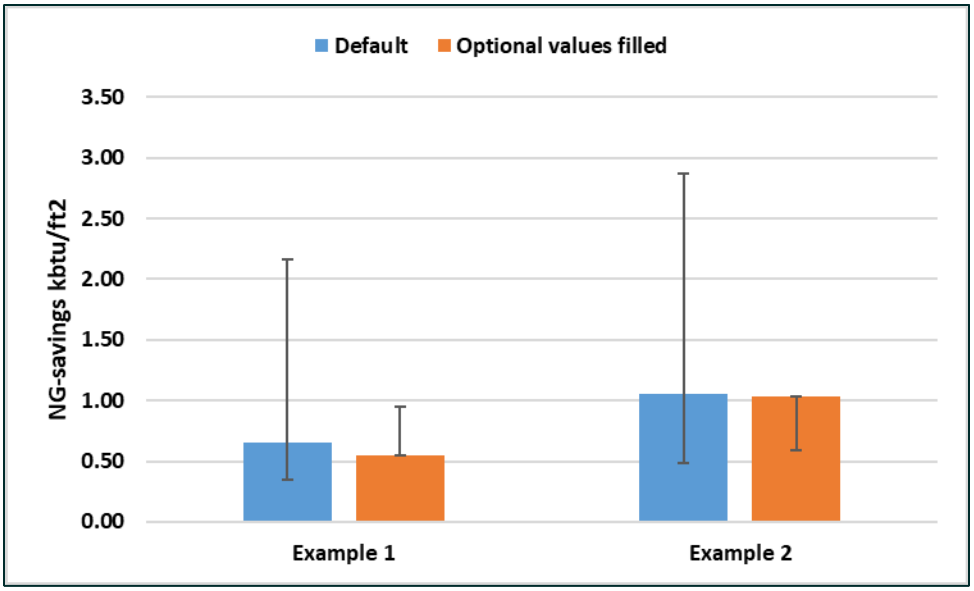

Figure 24: Comparison of Natural Gas Energy Savings for Two Examples Showing the impact of Entering Optional Inputs

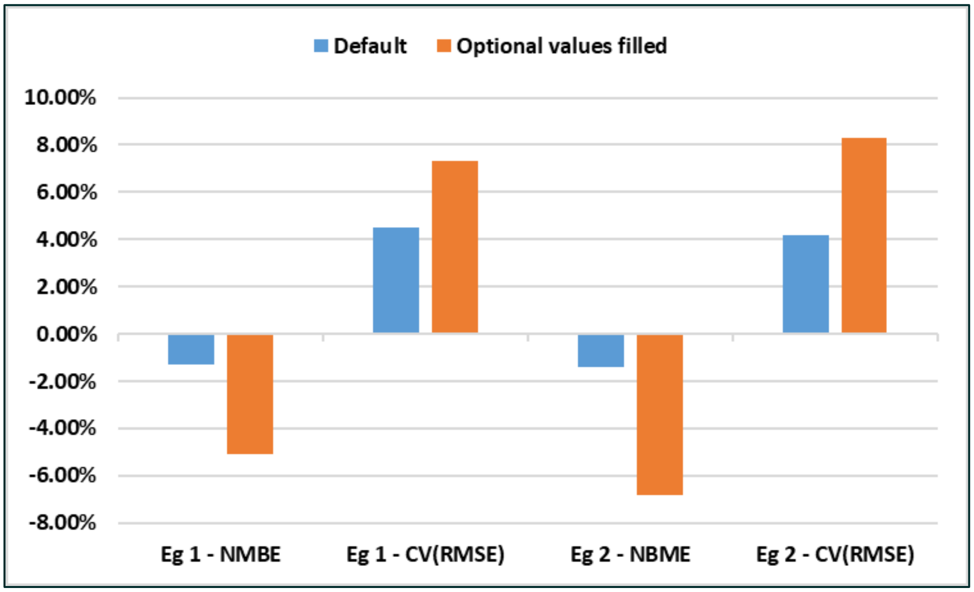

Figure 25: Comparison of NMBE and CV(RMSE) metrics for the two examples

Example Site Analysis

The team also analyzed results from two previous projects where ASHRAE G36 measures have been implemented in real buildings and where energy consumption was measured before and after implementation. Data was used from two buildings from CEC EPIC-BiC project (CCC SAB and KPPDC buildings) (Cheng, Singla, & Paliaga, 2022) and three buildings from ASHRAE RP-1515 project (Yahoo! Buildings A, B and E) (Edward Arens, 2015). The team used project reports, building plans and mechanical drawings to capture building information needed for estimation calculator inputs. Monthly electricity and natural as energy consumption were extracted from a normalized metered energy consumption (NMEC) analysis for each building. For the Yahoo! buildings, monthly gas energy consumption data were not available. The team used the annual gas energy consumption data and calculated monthly breakdown using the usage ratio of the CCC SAB building. This is not expected to affect savings results since monthly consumptions are only used for uncertainty analysis of the model fit. Default values were used for all inputs other than the VAV minimum fractions in Yahoo! buildings. Table 3 shows the summary of building information for the five example sites.

Table 3: Baseline Conditions of Example Sites Used for Tool Validation

	CCC SAB	KPPDC	Yahoo! A	Yahoo! B	Yahoo! E
Retrofit Type	All measures	All measures	VAV control	VAV control	VAV control
CZ	3	12	4	4	4
Building Area (ft2)	41,000	23,700	180,700	180,700	212,600
Avg VAV Min Flow Fraction	0.357	0.3	0.3	0.3	0.3
Supply Air Temp Control	Warmest reset (5°F)*	Warmest reset (5°F)	Default	Default	Default
SAT Setpoint (F)	55	55	Default	Default	Default
Static Pressure Design Factor (in w.c.)	5.35	3.25	Default	Default	Default
Fan Control Strategy	VAV with VSD	VAV with VSD	Default	Default	Default
Economizer Control	Fixed Drybulb	Fixed Drybulb	Default	Default	Default
Ventilation - Min OA (cfm/ft2)	0.18792	Default	Default	Default	Default

	CCC SAB	KPPDC	Yahoo! A	Yahoo! B	Yahoo! E
Building Schedule	Default	Default	Default	Default	Default
Space Type	General-office	General-office	Default	Default	Default
Pre-Annual Energy - NG - Therms	7,717	18,883	34,060	19,310	36,950
Pre-Annual Energy - Elec - kWh	272,155	465,670	1,428,737	1,130,426	1,941,318
Post-Annual Energy - NG - Therms	7,417	16,008	28,450	15,580	33,590
Post-Annual Energy - Elec - kWh	243,333	386,444	1,384,337	1,046,826	1,816,038
Annual Savings - NG - Therms/sf	**0.007**	**0.121**	**0.031**	**0.021**	**0.016**
Annual Savings- Elec - kWh/sf	**0.703**	**3.343**	**0.246**	**0.463**	**0.589**

**The actual building supply air temperature was 63.25F, but the closest available option was chosen for calculator input.*

Building information and monthly energy use data for the five sites were used in the estimation calculator to produce estimated energy savings. This was compared with the measured energy savings reported for each site in the EPIC-BiC and ASHRAE RP-1515 projects (summarized in Table 3). Figure 26 and Figure 27 show the comparison of annual savings for electricity and natural gas consumption calculated using the savings estimation calculator and the reported savings from measured data. The percentage difference is shown above each pair of bars.

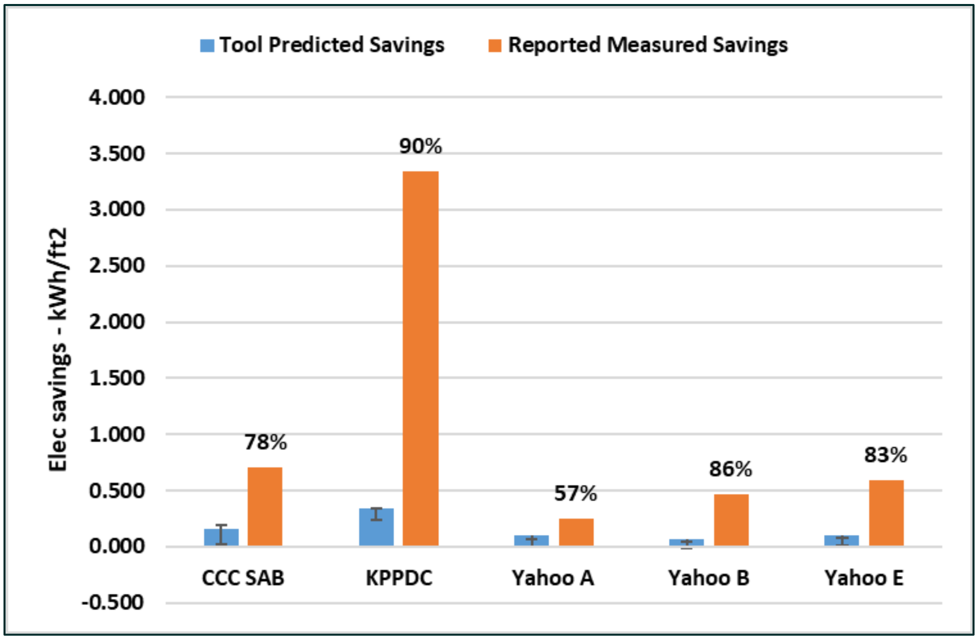

Figure 26: Comparison of Tool Predicted Electricity Savings and Reported Measured Savings for Five Example Sites from EPIC-BiC Project and ASHRAE RP-1515 Project

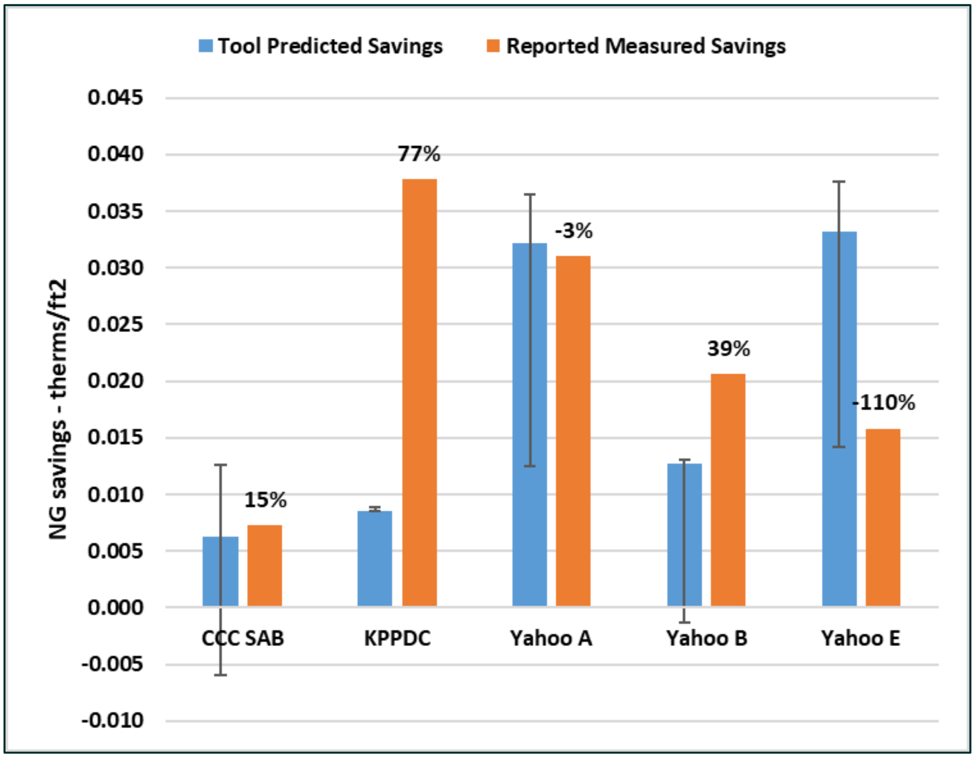

Figure 27: Comparison of Tool Predicted Natural Gas Savings and Reported Measured Savings for Five Example Sites from EPIC-BiC Project and ASHRAE RP-1515 Project

Figure 26 and Figure 27 above show that the savings estimation calculator appears to underestimate the savings compared to the real-world implementation of G36 measures in existing office buildings, especially with regards to electricity. However during the implementation of G36 measures as part of retro commissioning, there are often HVAC system faults such as malfunctioning sensors or dampers, controls over-rides or disabled energy saving sequences of operations which are fixed as part of the retro commissioning process. The savings estimation calculator's baseline energy models assume that all building components are functioning as intended, while in reality the existing conditions may be less efficient than the baseline models. This is likely part of the reason for the difference between real-world and predicted savings.

The calculator may underestimate the savings by only including controls measures while some RCx may be necessary in order to implement the controls measures in older buildings. However, stakeholder outreach indicated that while RCx savings are impossible to predict without a detailed investigation, the savings from controls measures alone is often high enough to make a combined controls and RCx project cost effective. Furthermore, G36 controls measures should only be implemented after implementation of RCx.

In three of the five buildings, the calculator underestimated the natural gas savings. One possible cause for this is that the EnergyPlus prototype buildings do not include hot water distribution losses. A recent study by Raftery et al demonstrated that in a sample of five buildings the reheat hot water distribution loss ranged from 6% to 60% of the HVAC energy, and in another detailed study of a single office building distribution losses were 44% of HVAC energy consumption (Raftery P. V., 2023), (Raftery P. A., 2018). By assuming perfect distribution, the energy models may underestimate the gas consumption and the gas savings. In the case of Yahoo E, the calculator over-estimates the natural gas savings. The measured savings vary widely between the Yahoo buildings, while based on the available data the three Yahoo buildings appear to be similar. Due to lack of data many of the inputs were left as "default" for these buildings. This resulted in both increased uncertainty ranges and decreased accuracy for those buildings.

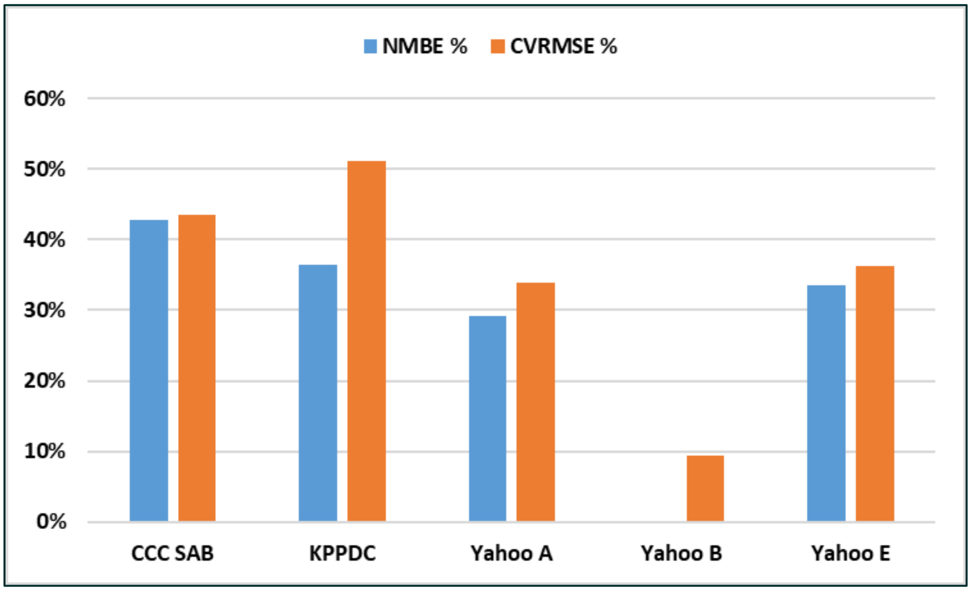

Figure 28: Comparison of Total Energy NMBE and CV(RMSE) Metrics to Test Model Calibration

Furthermore, Figure 28 shows that the statistical model was unable to use the calibration metrics to fit the predicted monthly results to the monthly data within the limits recommended by ASHRAE Guideline 14. This could be in part due to the reasons discussed in the previous paragraph. In addition, more work is needed to reduce the statistical model's error and study is needed to determine whether additional parameters must be included in the savings estimation calculator. The Recommendations section includes further discussion.

Stakeholder Feedback

The Draft Final Report was distributed for feedback to 16 stakeholders, including energy efficiency program stakeholders, codes and standards developers, MEP designers and HVAC system researchers. Responses were received from seven stakeholders. Below is a summary from stakeholder feedback:

- Energy efficiency program stakeholders provided generally encouraging feedback, for example, "We need this to improve and accelerate program deployment, better and more quickly implement measures, and increase customer satisfaction so RCx programs and offerings become more influential in promoting RCx projects in CA."
- The flexibility of the framework was appreciated, and stakeholders expressed interest in expanding the climates, building types, and HVAC system types covered by the calculator.
- There were conflicting views on the results of the example site analysis.

  - An HVAC system researcher noted that the algorithms used by EnergyPlus for static pressure reset and supply temperature reset may not adequately represent the controls logic outlined in G36, and this could be a cause for the error.
  - An energy efficiency program stakeholder noted that existing buildings usually have controls inefficiencies and deficiencies that are not accounted for in the baseline energy models, so they do not feel the results should be held against the study.
  - Another energy efficiency program stakeholder noted that the results will raise red flags with the CPUC and although they are conservative, we need to do a better job of demonstrating why.
- A stakeholder from CalTF coordinated with the project team to include the tool in the CalTF Custom Tool Library, in draft form.
- Stakeholders provided specific feedback on the characterization of the efficiency programs landscape, the clarity of the report and the discussion of referenced studies and tools which was incorporated into the Final Report.

Recommendations

This project demonstrated the feasibility of packaging highly complex controls measures into a simplified calculator while retaining both a degree of flexibility for different buildings and a quantifiable level of accuracy.

Based on conversations with stakeholders, the project team recommends that the calculator framework is used to improve program deployment, streamline measure implementation and increase customer satisfaction so controls and RCx measures become more widely adopted. These conversations resulted in recommendations that the framework be further developed to match the specific needs of energy efficiency programs trying to cost-effectively comply with the CPUC's NMEC rulebook and the Energy Trust of Oregon's coordinated research process. This project provides a customizable framework for future implementations to build from. As the calculator becomes specialized for program use, important considerations include the implementation of utility rate structures, agreement on the uncertainty limits, and defining the scope of the building parameters and measures to be considered.

In coordination with efficiency programs, the scope of the calculator can be both narrowed to target building type(s) and measures and expanded to include a wider range of existing building conditions. This will allow for more robust automated calibration, and applicability to buildings of different vintages in different states of repair. It will allow PAs to target buildings that present the greatest opportunity in their portfolio.

Based on the results of the research project, several next steps were determined for general development of the dashboard. During the development process, the team chose to run a lightweight machine learning algorithm, allowing extensive dynamic uncertainty calculations in the back end but at the expense of reduced accuracy in the algorithm's results. Further research can reduce the level of uncertainty by adjusting the machine learning approach as well as the number of parametric simulations used. This will improve the results of the data validation, reducing CV(RMSE), NMBE and the error in the savings calculations. In addition, developing custom controls algorithms in EnergyPlus could improve the energy savings estimates for the measures by aligning more closely with G36.

Finally, several methods for calculating uncertainty were assessed through the development of this project. In order to reduce the uncertainty range created by default inputs, more data is needed to define the distribution of each optional parameter in the existing building stock. An approach to uncertainty that dynamically combines each source of error can then be used, reducing risk for the calculator's adopters.

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