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Building System Efficiency Modeling—Improving the Accuracy of Building Energy Modeling

A Study of the Relative Strengths and Weaknesses of Building Energy Modeling Tools and Recommendations for Improvements

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CONTENTS

Executive Summary

Building energy modeling (BEM) tools are used to document compliance with energy codes, in green building certification, for incentive programs, to help optimize new designs, and to inform project retrofits. Organizations like ASHRAE and AIA advocate for the wider use of energy modeling, viewing it as essential for achieving low-energy and net-zero energy buildings. However, discrepancies between modeled and actual building performance have been widely reported, reducing credibility and bringing into question the feasibility of relying on energy models for decision-making.

This paper explores reasons for disagreements between the actual and modeled energy use for several building systems, including lighting, motors, and controls. It highlights substantial uncertainty in the impactful modeling inputs for these systems related to occupant behavior, building operation, and actual versus ideal performance. It also reviews the selected capabilities of the simulation tools, including eQUEST, Trane TRACE, IESVE, EnergyPlus, and OpenStudio based on the input from tool vendors, developers, and users.

- eQUEST offers a user-friendly interface, mature simulation capabilities, and transparent reporting. It enjoys a large and loyal user base ranging from beginner to advanced modelers and is used on the majority of commercial modeling projects, based on most sources cited in this paper.
- TRACE 700 has a good balance between usability and simulation features. It is favored by design engineers who can use it for both energy analysis and equipment selection. It is transitioning to using EnergyPlus as the calculation engine, which will enhance its simulation capabilities.
- IESVE is a comprehensive design tool that fully integrates an advanced daylighting simulation with energy simulation, and automated code compliance following several protocols, including ASHRAE 90.1 Section 11 and Appendix G, IECC, AIA 2030, and Title 24 in California.
- EnergyPlus is widely used on research projects, offering flexibility for modeling nonstandard systems and controls. However, it has a steep learning curve and is best suited for advanced users.
- OpenStudio offers the promise of combining the simulation capabilities of the EnergyPlus calculation engine with usable custom interfaces. The tool works best for intermediate users who can access features beyond those supported by the native graphical user interface or through custom (proprietary) interfaces.

A BEM tool capabilities matrix is included in Appendix A. In addition, the relevant existing and emerging industry Standards and guidelines are discussed, such as ASHRAE Standards 90.1, 140, 205, 209, and Guideline 14. The key reasons of misalignment identified in this paper include the uncertainty of the simulation inputs, differences between the modeled versus actual system operation, modeler errors, and the limitations of BEM tools.

In conclusion, recommendations for improving the credibility of energy modeling are provided, including the following:

- Enhance the BEM tool features important for commercial models, including the following:
  - User-friendly graphical user interface
  - Transparent reporting to help with model troubleshooting
  - Explicit support of common systems, designs, and operation, including common operational faults
  - Automated quality control to flag possible modeling mistakes
  - Rapid integration of new systems and components
  - Integrating energy analysis with other tasks commonly performed as part of commercial energy modeling, such as modeling-based code compliance, daylighting analysis, and evaluation of design alternatives and energy conservation measures
  - Integrated capabilities to compare modeled energy use to measured consumption (e.g., utility bills)

- Updating simulation rules of the relevant Standards, including the following:
  - Standard 90.1: Develop and prescribe detailed operating conditions for use in compliance modeling
  - Standard 140: Prescribe the acceptance ranges for software tools being tested
  - Standard 205: Engage with equipment manufacturers to develop methodologies for better capturing impactful aspects of building systems and components in the energy models to help differentiate and encourage the use of efficient technologies
  - Standard 209: Develop methodology for establishing modeling uncertainty so that the simulation results of design support models are reported as the ranges of likely outcomes as opposed to a fixed value
- Improve consistency in energy modeling–related policies:
  - Align the BEM tool policies of incentive programs, jurisdictions (for energy code compliance), and other adopters of energy modeling (e.g., LEED) with the relevant industry Standards to foster competition between BEM tools and allow users to pick the tools that work best for them while meeting the industry-standard requirements
  - Develop an infrastructure for peer-reviewed, unbiased comprehensive comparison of the simulation tools based on their support of systems and components found in real buildings and interface features important on commercial modeling projects
  - Establish modeler certification requirements to minimize human error, and require post-occupancy model calibration and measurement and verification (M&V)

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Background

Buildings are complex systems composed of numerous interacting components that are influenced by external factors such as weather and occupant behavior. Whole building energy modeling (BEM) tools use physics equations to evaluate building performance. BEM inputs include building geometry; thermal and solar properties of construction materials; lighting fixtures and controls; and type, efficiency, and controls of HVAC, refrigeration, and water heating systems. In addition, information about a building's use and operation such as occupancy, lighting and plug load operating hours, mechanical ventilation rates, and thermostat setpoints are provided. A BEM program combines these inputs with local weather to calculate thermal loads, system response to those loads, and resulting energy use and cost. BEM programs perform a full year of calculations on an hourly or shorter time step accounting for system interactions, such as the impact of internal heat gains from lighting and space heating and cooling needs.

The ASHRAE Advanced Energy Design Guide (AEDG) for K-12 schools on achieving zero-energy buildings (the first one in the series) has a chapter dedicated to building performance simulations. Further, ANSI/ASHRAE/IES Standard 90.1 recently adopted a second path for documenting code compliance through energy modeling (ASHRAE 90.1 Appendix G). The American Institute of Architects (AIA) repeatedly emphasizes the importance of energy modeling for achieving carbon-neutral buildings by 2030:

- "A standout finding from 2015 is the critical role of energy modeling in improving building design." (*AIA 2030 Commitment: 2014 Progress Report*)
- "Our numbers continue to demonstrate that energy modeling is an essential component of success." (AIA's *2030 by the Numbers* – 2016 summary)

As a result, BEM tools are increasingly used to inform the design of new buildings, identify the optimal package of energy conservation measures on retrofit projects, document code compliance, obtain green building certifications such as LEED, and qualify projects for tax deductions and utility incentives. The premise in all these applications is that BEM tools provide a reasonably accurate prediction of performance of the individual building systems and the building as a whole.

However, studies have shown that energy use projected by energy models often significantly deviates from measured consumption. For example, in a sample of LEED-certified buildings, the measured energy use deviated by more than 25 percent from the design projections for over half of the projects, with 30 percent performing significantly better and 25 percent significantly worse (Figure 1[1]).

[1] Cathy Turner and Mark Frankel, *Energy Performance of LEED® for New Construction Buildings*, New Buildings Institute, March 4, 2018, https://newbuildings.org/sites/default/files/Energy_Performance_of_LEED-NC_Buildings-Final_3-4-08b.pdf.

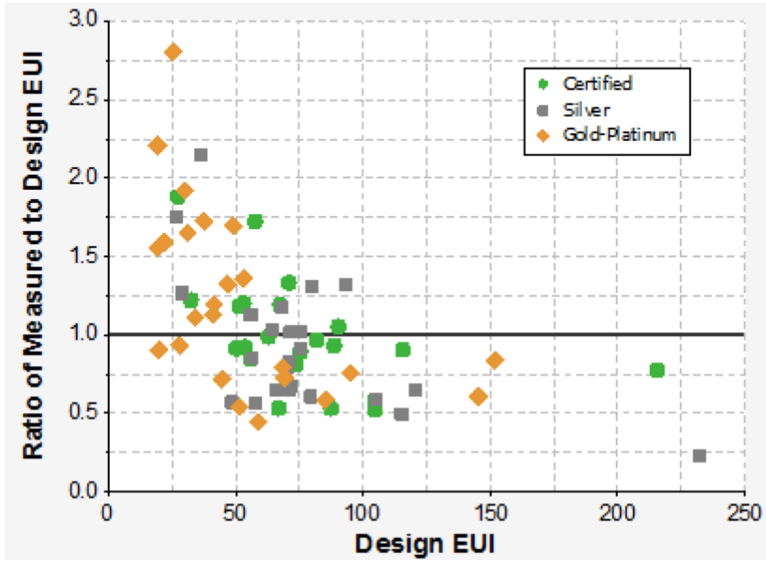

Figure 1
Design (Simulated) Versus Measured EUI[2] for LEED Buildings

A study of 171 projects[3] that have completed comprehensive retrofits and participated in a modeling-based incentive program found that projected savings were within 25 percent of the actual realized savings for only 39 percent of projects, with the remaining projects having a greater discrepancy (Figure 2).

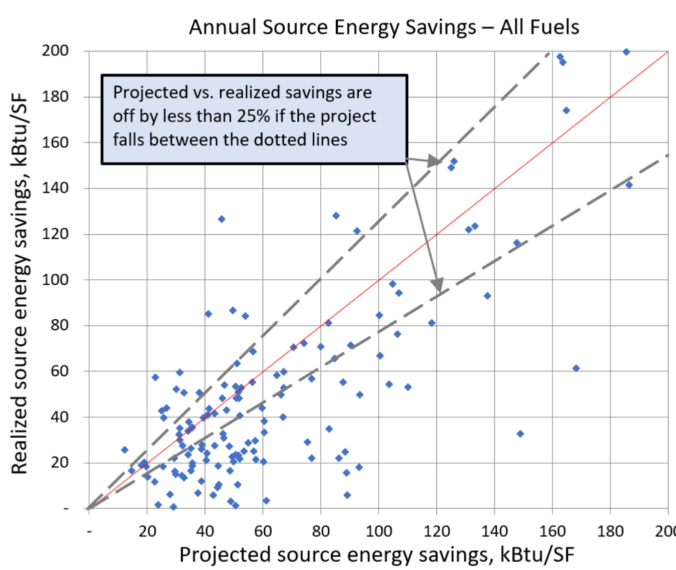

Figure 2
Simulated Savings Projection Error for Retrofit Projects

[2] Energy use intensity (EUI) is a ratio of annual energy use in kBtu/year to the building floor area.
[3] Chris DeAlmagro and Maria Karpman, "Comparison of Projected to Realized Savings for Projects that Participated in a Modeling-Based Incentive Program" (presentation, 2017 ASHRAE Building Performance Analysis Conference, Atlanta, GA, September 27-29, 2017), http://karpmanconsulting.net/TRC_EnergyServices_ASHRAE_Presentation_20170928_Final.pdf.

Standards Related to Energy Modeling

Several existing and emerging Standards and guidelines described below address the use of energy modeling and capabilities of BEM tools.

ANSI/ASHRAE/IES Standard 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings (ASHRAE 90.1)

The Standard establishes the minimum energy-efficiency requirements for the design and construction of buildings other than low-rise residential buildings. It covers new construction, additions, and renovations and is the basis of energy codes in the majority of the states. The adopted editions of ASHRAE 90.1 vary from state to state, with some state codes exceeding ANSI/ASHRAE/IES Standard 90.1-2013 while other codes are less stringent than ANSI/ASHRAE/IESNA Standard 90.1-2007 (Figure 3).[4]

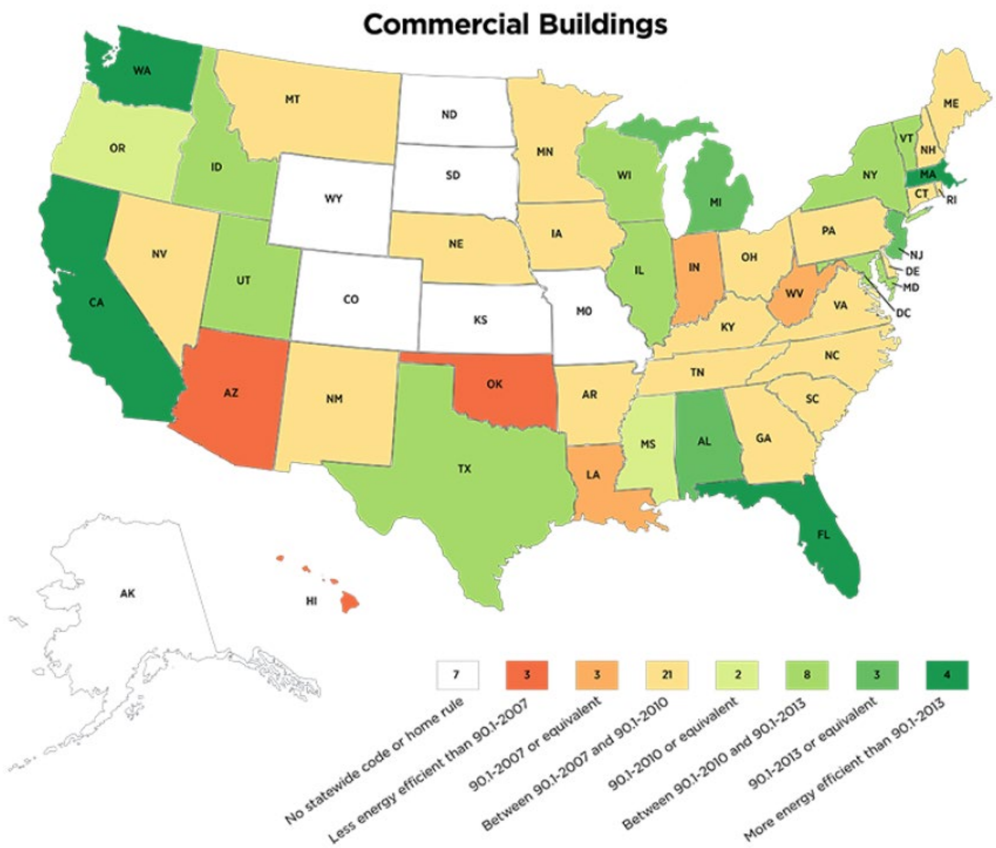

Figure 3
State-by-State Commercial Buildings Energy Codes

Section 11 and Appendix G of the Standard include the modeling protocols that may be used to document compliance with the Standard. These protocols involve developing two energy models—the first model reflects the proposed design; the second model is of a virtual building (the baseline or budget design) configured as described in the respective modeling protocol and representing a version of the proposed design minimally compliant with a given edition of ASHRAE 90.1. Compliance is achieved when the energy use of the proposed design does not exceed the energy use of the virtual baseline (ASHRAE 90.1 Section 11) or is below the baseline energy cost by a certain margin (ASHRAE 90.1 Appendix G).

[4] "Status of State Energy Code Adoption," U.S. Department of Energy, https://www.energycodes.gov/status-state-energy-code-adoption.

ASHRAE 90.1 provides details on how each model must be developed and lists the minimum capabilities of the simulation tools that may be used to document compliance.

ANSI/ASHRAE Standard 140 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (ASHRAE 140)

The Standard specifies test procedures for evaluating the technical capabilities and ranges of applicability of BEM tools that calculate the thermal performance of buildings and their HVAC systems. While these standard test procedures do not test all algorithms within a building energy computer program, they can be used to indicate major flaws or limitations in capabilities. The current set of tests focuses on building thermal envelope and air-side HVAC systems and includes comparative tests, in which a program's results may be compared to the results of other programs, and analytical verification tests, in which a program's results may be compared to known solutions. Test cases involve permutations of one- or two-zone buildings (Figure 4). The sample results for the test cases from several tools are included in an informative appendix. However, no formal acceptance criteria are provided, and thus BEM tools cannot “fail” ASHRAE 140—testing alone is required.

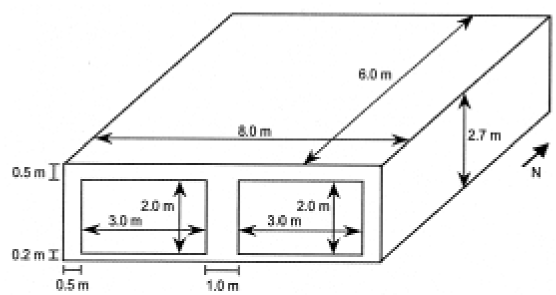

Figure 4
ASHRAE 140 Base Case for Building Envelope and Fabric Load Tests

ASHRAE Standard 205, Standard Representation of Performance Simulation Data for HVAC&R and Other Facility Equipment (ASHRAE 205)

The goal of this proposed Standard (which is still in development) is to work with equipment manufacturers and software developers to create standard formats for the performance data of systems and equipment to make it easier to capture characteristics of the actual equipment in the BEM tools. This will offer the modelers access to the performance data of equipment that they wish to simulate. The current work focuses primarily on the performance of HVAC systems such as unitary air-conditioning equipment and chillers.

ASHRAE Standard 209 Energy Simulation Aided Design for Buildings except Low-Rise Residential Buildings (ASHRAE 209)

The Standard defines minimum requirements for providing energy design assistance using building energy simulation and analysis. It discusses the use of energy modeling at different stages of building design, from pre-schematic to construction documents to post-occupancy modeling. The first version of the Standard was published in 2018. The Standard requires using BEM tools compliant with the minimum requirements of ASHRAE 90.1 Appendix G.

ASHRAE Guideline 14 Measurement of Energy, Demand, and Water Savings

The purpose of the guideline is to provide procedures for measuring the energy, demand, and water savings achieved in conservation projects. The guideline may be used in various contexts, such as documenting energy savings for credit programs (e.g., emission reduction credits associated with energy-efficiency activities). One of the measurement and verification (M&V) approaches covered in ASHRAE Guideline 14 is a whole building calibrated simulation, which involves developing an energy model representative of the existing conditions and using it to calculate savings from building retrofit. The guideline prescribes the calibration tolerances, which determine how closely the calibrated model must be aligned with the measured energy use. The minimum BEM tool capabilities required by ASHRAE Guideline 14 largely echo the requirements of ASHRAE 90.1.

Applications of Energy Modeling

Energy modeling may be used for research or in commercial settings. For example, ASHRAE 1651-RP *Development of Maximum Technically Achievable Energy Targets for Commercial Buildings* used energy modeling to evaluate a wide range of potential improvements to building systems, components, and controls that would lead to ultra-low energy use buildings. Another research example is *Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction* (PNNL-25985) from the Pacific Northwest National Laboratory. This study identified the most promising control-related improvements in existing buildings and used energy modeling to rank the improvements based on their impact. Research-grade modeling is performed by experts—and extensively peer-reviewed and documented—and typically enjoys generous budgets and schedules.

Common commercial applications include optimizing building design, documenting compliance with energy codes, participation in above-code programs, estimating future energy use of new buildings, and estimating the impact of building retrofits on utility bills. Commercial-grade energy models are typically developed by design engineers or energy consultants (57 percent and 29 percent, respectively, according to an AIA study[5]); the modelers typically have no specialized training and often acquire the skills while working on projects. Modeling budgets are often tight, and quality control and peer review of the completed models are minimal. Different types of commercial energy modeling are discussed below.

Design Support Modeling

Design support modeling involves using BEM tools to identify the optimal building shape and orientation, minimize heating and cooling loads through efficient envelope and lighting design, evaluate alternative HVAC system designs, etc. The analysis is performed throughout the design process and aims to establish the relative performance of the evaluated options. This type of modeling is addressed in ASHRAE 209-2018. It is impossible to conclusively validate the accuracy of the provided recommendations because post-construction performance is available only for the final design and not for any of the alternatives that have been evaluated.

Compliance Modeling

Compliance modeling involves using energy simulation to document compliance with energy codes, incentive programs, green building rating programs such as LEED, IRS tax deductions, and various local laws. It is most commonly done for new construction and major renovation projects and follows the modeling protocols of ASHRAE 90.1. Just as with design support modeling, the focus of compliance modeling is on the relative performance of the two models (the proposed design and the baseline/budget design) and not predicting post-construction performance. This is stressed in the following informative note that is included in both ASHRAE 90.1 Section 11 and Appendix G:

> "… calculations are applicable only for determining compliance with this standard. They are not predictions of actual energy consumption or costs of the proposed design after construction. Actual experience will differ from these calculations due to variations such as occupancy, building operation and maintenance, weather, energy use not covered by this standard, changes in energy rates between design of the building and occupancy, and precision of the calculation tool."

Predictive Modeling

Predictive modeling may be performed for both new construction and retrofit projects. On new construction projects, the goal is to estimate the future energy use. For example, a college may commit to having all new buildings on campus designed to have annual energy use intensity (EUI) no greater than 25 kBtu/SF. Various alternatives would be modeled during design development to identify the configurations that meet this goal. After the building is put into operation and fully occupied for a year, the actual EUI may be determined based on the utility bills to confirm that the performance target was achieved.

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[5] *2015 Progress Report,* The American Institute of Architects, http://aiad8.prod.acquia-sites.com/sites/default/files/2016-11/AIA%202030%20Commitment_2015%20Progress%20Report-v4.pdf.

On retrofit projects, predictive modeling may be used to estimate the impact of energy conservation measures on energy costs. The analysis involves developing a model of an existing building (the baseline model) based on site data collected during an energy audit and using the baseline model to estimate savings from a variety of energy conservation measures to identify the most cost-effective retrofit package. To improve precision, the baseline model is trued up (calibrated) to utility bills by adjusting simulation inputs that were estimated, such as infiltration rates in the absence of a blower door test. The calibration methodology and the necessary degree of alignment between the model and utility bills are described in ASHRAE Guideline 14.

Predictive modeling may also be used in conjunction with the EPA ENERGY STAR® Target Finder,[6] which is similar to the EPA ENERGY STAR Portfolio Manager® (ESPM) but relies on the estimated building performance in lieu of actual utility bills. The Target Finder may be used to estimate the future ENERGY STAR score for new construction projects that don't yet have billing data or for an existing building that is undergoing a retrofit. The Target Finder does not specify how the future building performance may be estimated; however, energy modeling is often used.

Building Energy Modeling Tools

Market Share

The Building Energy Software Tools directory[7] maintained by the International Building Performance Simulation Association-USA (IBPSA-USA) lists over 50 different BEM tools; however, a handful of tools are used on most modeling projects. Figure 5A shows BEM tool use based on 2015 and 2017 AIA 2030 Progress Reports. eQUEST is the most used tool based on the sources, with IESVE and TRACE in the second tier.

It is noteworthy that tool popularity varies from state to state and depending on who does the modeling, so an unbalanced sample may introduce bias. For example, in California, software must be certified in order to be used for energy code compliance. IESVE and EnergyPro are certified, whereas eQUEST, EnergyPlus, TRACE, and OpenStudio are not. Thus, samples with a large percentage of California projects (which is the case in the AIA Progress Reports) will show an increased use of EnergyPro and IESVE. On the other hand, eQUEST and Trane TRACE are more popular in the Northeast samples (Figure 5B). For example, an incentive program for high performance buildings in Massachusetts, which is one of a handful of states (along with California) that has an energy code more stringent than ASHRAE 90.1-2013 (Figure 3), requires projects to use eQUEST; EnergyPlus may be used subject to special approval.[8] Based on the *AIA 2030 Commitment: 2015 Progress Report* sample, 24 percent of the models developed by design engineers used IESVE, 21 percent used Trane TRACE, and 18 percent used eQUEST, while energy consultants overwhelmingly favor eQUEST (53 percent).

Based on the evaluated samples, eQUEST, Trane TRACE, and IESVE are used most widely on commercial models and were included in this paper. EnergyPlus is widely used on research projects and was also included. OpenStudio is a relatively new tool that offers a framework for combining the advanced capabilities of EnergyPlus with custom user interfaces. Recognizing its potential, it was also included in spite of its current low market share.

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[6] "EPA's Target Finder calculator," ENERGY STAR, https://www.energystar.gov/buildings/service-providers/design/step-step-process/evaluate-target/epa%E2%80%99s-target-finder-calculator.
[7] Building Energy Software Tools, www.buildingenergysoftwaretools.com.
[8] *Hourly Simulation Guidelines: Version 2.2*, Mass Save, August 2017, https://www.masssave.com/-/media/Files/PDFs/Business/MA-PA-Simulation-Guidelines-v22.pdf?la=en&hash=C8AE342C6E058B301659FABE59A098C0C0F43CF8.

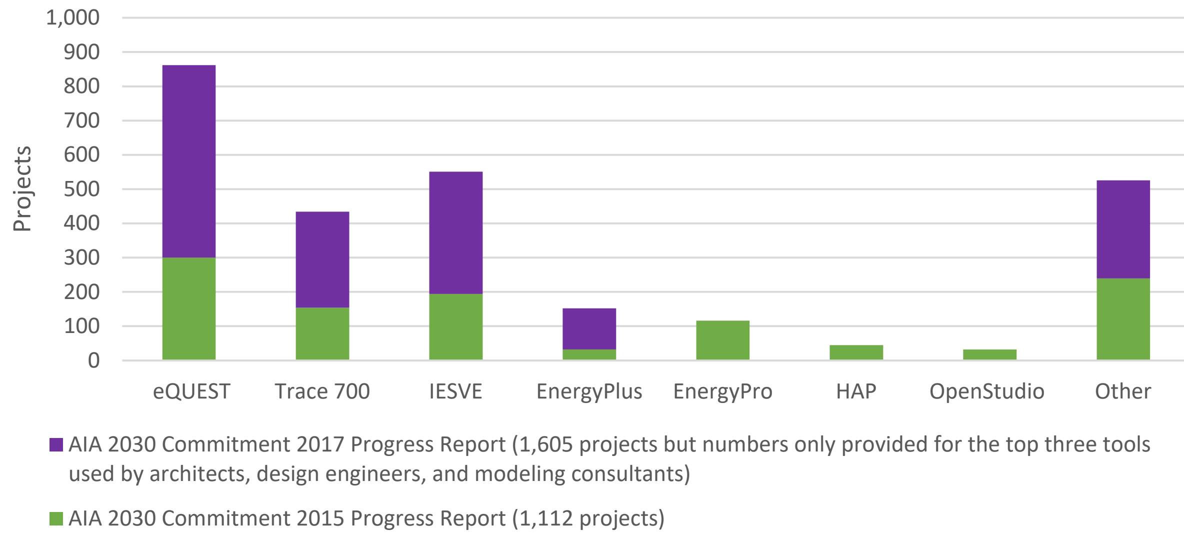


Figure 5A
BEM Tool Use—National Sample

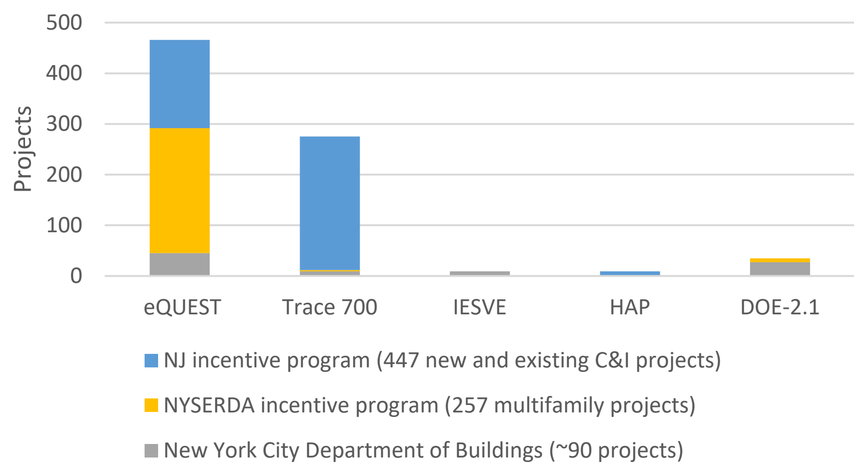


Figure 5B
BEM Tool Use—Northeast Sample

Overview of the Selected BEM Tools

eQUEST[9] is a user interface to the DOE-2.2 calculation engine developed by James J. Hirsch and Associates. DOE-2.2 is an advanced derivation of the DOE-2.1 engine that was originally funded by the U.S. Department of Energy (DOE). In addition to the various enhancements to the calculation engine, the software includes utilities to streamline initial data entry (Schematic Design Wizard, Design Development Wizard) and to analyze design alternatives (Energy Efficiency Measure Wizard, Parametric Runs). It has powerful reporting capabilities and an automated Quality Control module. The version of eQUEST released in November 2018 incorporates a substantially updated version of the calculation engine (DOE-2.3) and many new capabilities. There is no cost for software licenses.

[9] "eQuest," DOE2.com, www.doe2.com/equest.

Trane TRACE 700[10] is developed by Trane, an HVAC systems manufacturer and service provider. The tool initially focused on informing HVAC system design but evolved into a design and analysis software. It supports a wide range of systems and designs, such as waterside economizers, advanced chiller plant configurations, water-source and central and distributed ground-source systems, variable refrigerant flow (VRF) and underfloor air distribution (UFAD) systems, dedicated outdoor-air systems, and optimized control strategies, among others. TRACE 700 uses a proprietary simulation engine. A version released in 2017 (TRACE 3D Plus) transitioned to the EnergyPlus simulation engine. TRACE 700's license cost is available from the vendor.

IESVE[11] is developed by Integrated Environmental Solutions (IES) Ltd. and offers a whole-building integrated interface to Apache for energy/carbon simulation, RadianceIES for daylight simulation, SunCast for solar simulation, and other simulation engines. The IESVE (Virtual Environment) software allows users to evaluate different design options, identify the best passive solutions, compare low-carbon technologies, and draw conclusions on energy use, CO_2 emissions, occupant comfort, light levels, and airflow. Automated code-compliance examples include ASHRAE 90.1 Section 11 and Appendix G and Title 24 in California, among others. IESVE includes advanced electric lighting design, HVAC design, and daylighting analysis. All analysis applications share a central integrated data model, saving time and facilitating an integrated design approach. The software license cost is available from the vendor.

EnergyPlus™[12] is a simulation engine for modeling energy consumption and water use in buildings funded by the U.S. Department of Energy. It is a console-based program that reads input and writes output to text files. It ships with a number of utilities, including the IDF Editor for creating input files using a simple spreadsheet-like interface, EP-Launch for managing input and output files and performing batch simulations, and EP-Compare for graphically comparing the results of two or more simulations. It has advanced analysis capabilities, including flexibility for modeling nonstandard systems, controls (via the use of EMS scripting), and operational faults (via fault models). It has a steep learning curve and works best for advanced users.

OpenStudio®[13] is a collection of software tools that supports energy modeling using EnergyPlus and daylight analysis using Radiance. The open-source graphical applications include the OpenStudio Application and Parametric Analysis Tool. The OpenStudio Application is an interface to OpenStudio models, including envelope, loads, schedules, HVAC, SHW, renewable integration, and controls. The HVAC system editor allows users to drag and drop HVAC components to create custom HVAC configurations. The Parametric Analysis Tool allows studying the impact of applying multiple combinations of OpenStudio Measures to a base model to support parametric or optimization studies, and simulating OpenStudio models using the OpenStudio Server running on Amazon Web Services.

BEM Tool Comparison Methodology and Challenges

An objective comparison of BEM tools is a challenging endeavor. A common method is to create a list of features and indicate BEM tool support of each feature with a binary (yes/no) answer. This approach was used to develop the tables in Appendix A. Limitations of the method are discussed below and must be recognized when interpreting the information provided in the appendix.

- It is difficult to develop an unbiased list of features for a comparison of BEM tools. If the list is based on the capabilities of any given tool, other tools are not able to demonstrate their advantages. If it is based on an individual's perception of which features are more important, it is affected by that individual's professional experience and bias.

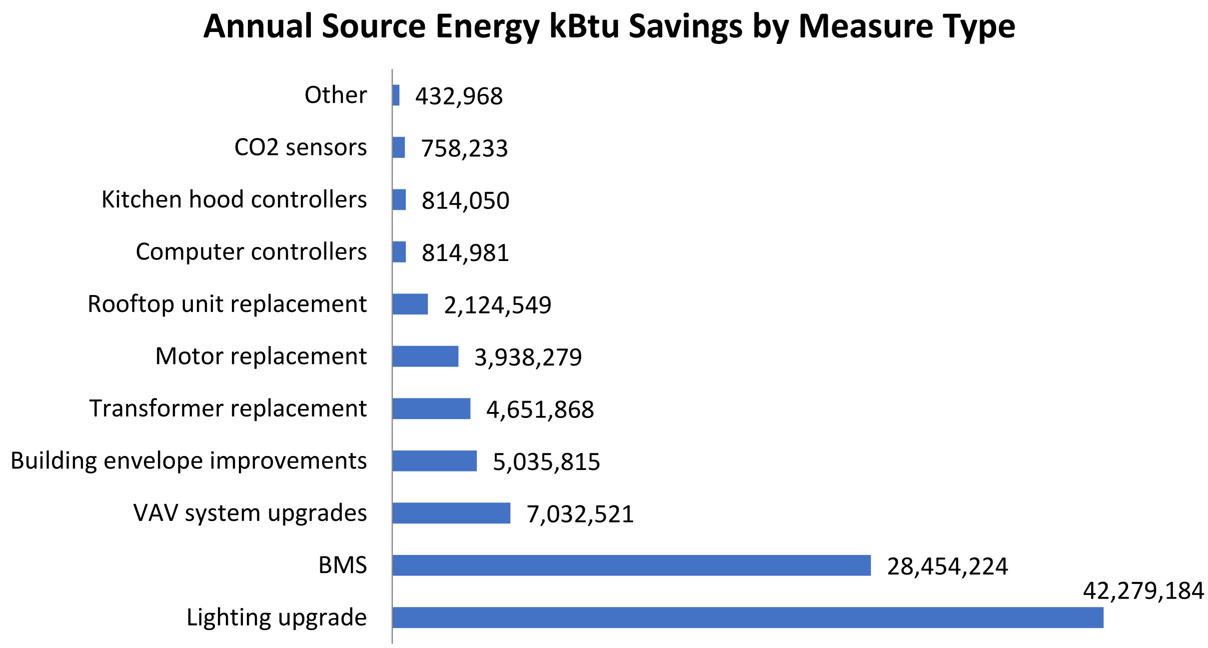
[10] "TRACE™ 700," Trane, https://www.trane.com/commercial/north-america/us/en/products-systems/design-and-analysis-tools/analysis-tools/TRACE-700.html.
[11] "VE for Engineers," Integrated Environmental Solutions, https://www.iesve.com/software/ve-for-engineers.
[12] EnergyPlus, https://energyplus.net.
[13] OpenStudio, https://www.openstudio.net.

- All tools are periodically updated, and thus a snapshot of capabilities at any given time is bound to become outdated. For example, Trane TRACE is transitioning to the EnergyPlus calculation engine; a new version of eQUEST was released in November 2018 (as this paper was being written), incorporating substantial updates to the DOE-2 calculation engine.
- The binary yes/no answers do not recognize the extent of support of a given feature. For example, BEM tools typically do not explicitly link the function of lighting occupancy sensors with the occupancy schedule; instead, modelers adjust the lighting schedule to reflect the expected reduction in lighting fixture runtime. Should BEM tools that require this workaround (which is industry standard) be treated as not capable of modeling lighting occupancy sensors? Appendix A lists the feature as supported (with a "Yes") if it can be explicitly modeled in the tool or if there is an industry-standard workaround that the tool supports. The feature is marked with "No" if the workaround requires external calculations (e.g., exporting hourly results into a spreadsheet for additional processing) or was developed by a vendor or users to overcome the tool's inherent shortcomings.
- The information in Appendix A was provided by tool vendors, software developers, and tool users. To mitigate possible bias, the responses were shared with all contributors, and multiple adjustments were made based on the peer review.
- There are many peer-reviewed reports, papers, and presentations discussing the strengths and weaknesses of EnergyPlus and eQUEST. Fewer resources are available for other tools. Thus, when the shortcomings of EnergyPlus or eQUEST are discussed in the following sections, it should not be assumed that other tools are superior in these areas. They may or may not be; they were simply not included in the source reference.

Modeling of Common Building Systems and Components

The following sections review selected building systems of interest to NEMA Members, the simulation requirements of the applicable Standards, relevant capabilities of BEM tools, and reasons for disagreement between the modeled and actual energy use of these systems. Some of these systems are among the most impactful and commonly evaluated on energy modeling projects. For example, in a large-scale modeling-based incentive program for existing buildings in New Jersey,[14] energy conservation measures involving lighting and building management systems (BMS) were most common and were projected to have a higher contribution toward the overall savings compared to other modeled measures (Figure 6).

[14] Maria Karpman and Chris DeAlmagro, "Model Projections versus Measured Energy Savings in a Large Scale Incentive Program" (presentation, 2014 ASHRAE/IBPSA-USA Conference, Atlanta, GA, September 10-12, 2014), http://karpmanconsulting.net/IBPSA_0910a.pdf.



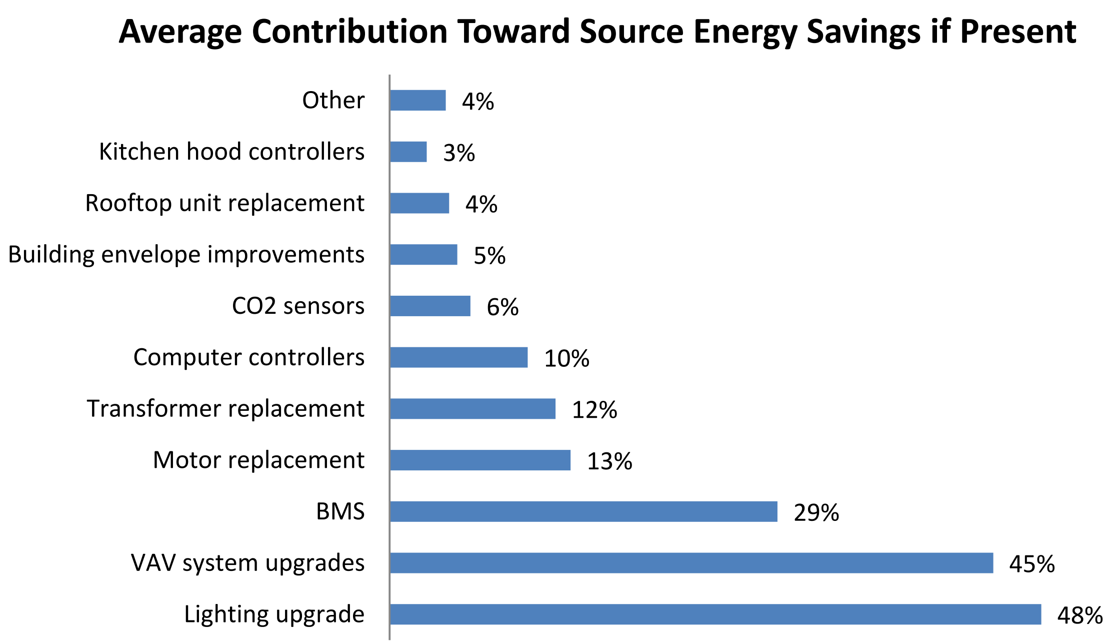


Figure 6
Modeled Savings for Projects Participating in a Modeling-Based Incentive Program

Lighting Fixtures and Controls

Background

According to the *Commercial Buildings Energy Consumption Survey* (CBECS),[15] lighting accounted for 17 percent of electricity consumption in commercial buildings in 2012, down from 38 percent in 2003. The

[15] "Trends in Lighting in Commercial Buildings," U.S. Energy Information Administration, https://www.eia.gov/consumption/commercial/reports/2012/lighting.

savings are due to the wide adoption of technologies such as LED fixtures, occupancy sensors, and daylighting controls, which are being increasingly integrated into energy codes. ASHRAE's research project on ultra-low energy buildings (ASHRAE RP-1651) identified thirty measures (out of the initial pool of almost 400) which, if applied together, were estimated to cut the energy use of new construction projects in half compared to designs minimally compliant with ASHRAE 90.1-2013. Of the thirty finalists, six involved improvements to lighting fixtures and controls, including high-efficacy exterior and interior lighting, a shift from general to task illumination in offices, optimal daylighting controls, external light shelves, and daylighting control by fixture.

Lighting fixtures affect building performance directly (by using electricity) and indirectly (through the internal heat gains that impact heating and cooling energy use). The simulation inputs may include a geometric model, lighting fixture placement, lighting fixture wattage (the lighting power), lighting controls, and the number of hours per year the lighting is on (the lighting schedule). The lighting power is the peak connected wattage of the installed lighting system, including lamp, ballast, and controls. The lighting schedule defines how lighting fixtures are used (i.e., turned on and off) by allowing a user to assign a fraction of peak lighting power that is on during each hour of the year (Figure 7).

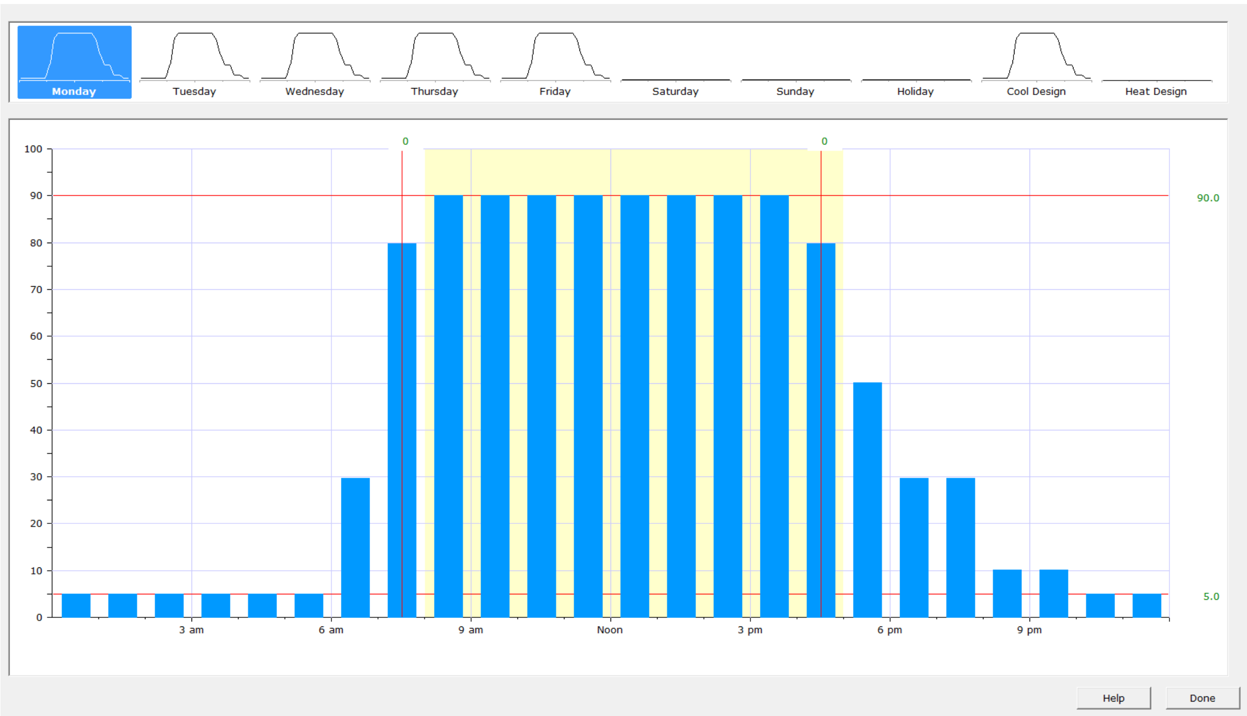


Figure 7
Lighting Schedule Example (eQUEST)[16]

Occupancy sensors are typically modeled by adjusting the lighting schedule fractions. For example, Figure 8 illustrates the change in the office lighting schedule included in ASHRAE Standard 90.1 User's Manual to capture the change in lighting runtime due to the new occupancy sensor requirements of ASHRAE 90.1.

[16] Screenshot from an eQUEST wizard.

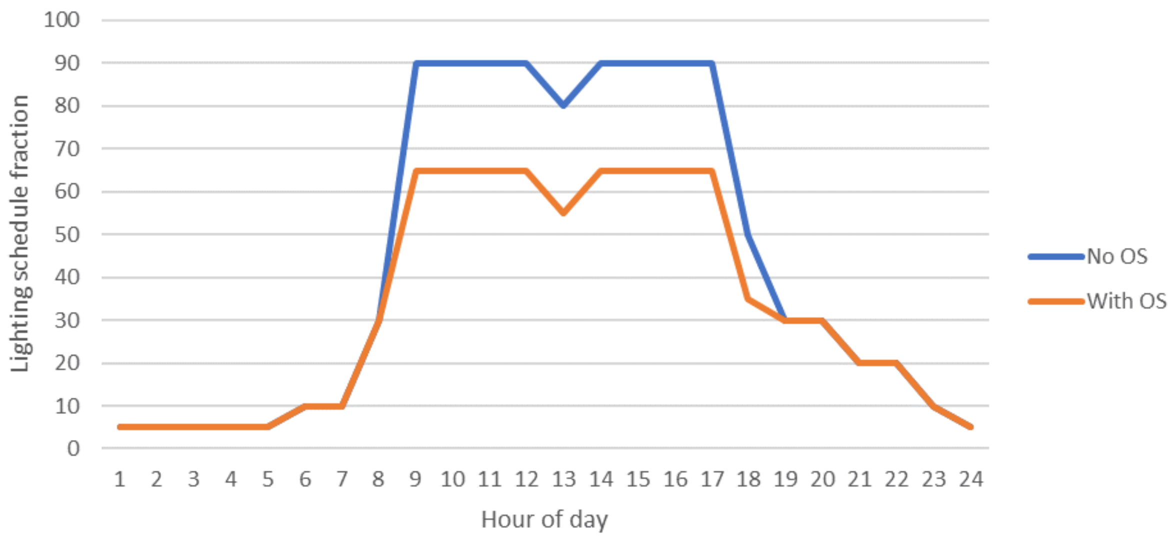


Figure 8
ASHRAE 90.1 User's Manual Office Lighting Schedules With and Without Lighting Occupancy Sensors

Figure 9 is an example of a lighting simulation analysis calculating the electric (artificial) lighting power in watts and W/ft^2, luminous efficacy (lm/W), and visual performance of lighting on the working plane of a room with individual luminaire photometric polar webs.

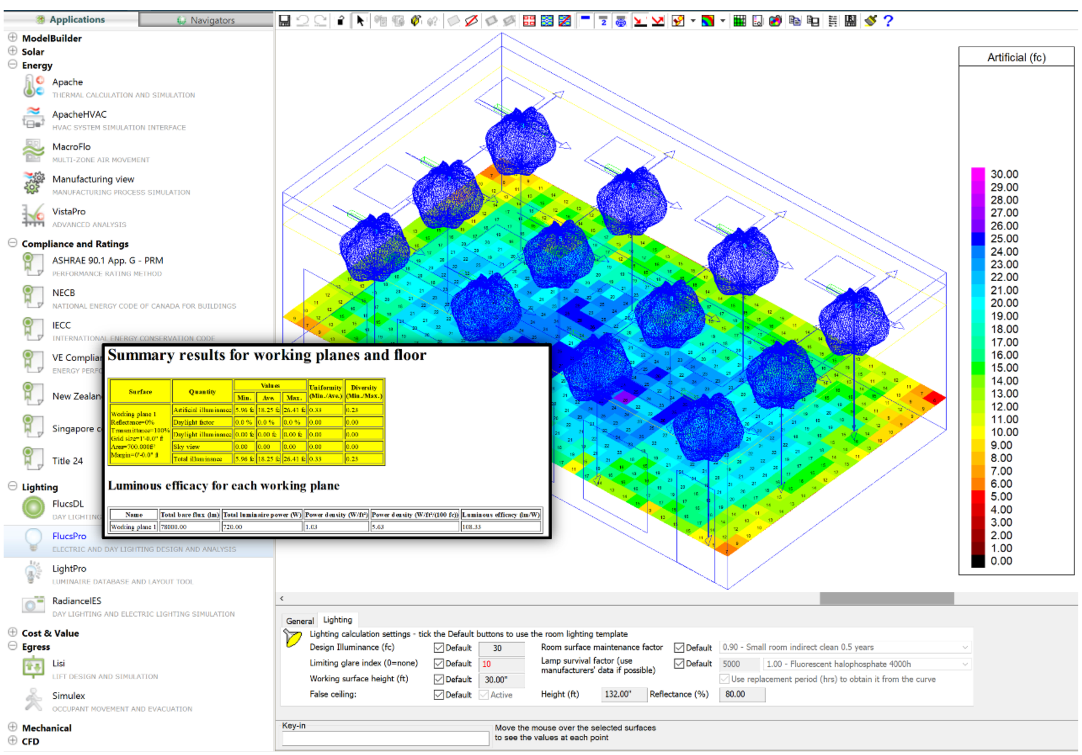


Figure 9
Lighting Fixture Layout and Calculation Example (IESVE)

Some BEM tools have integrated capability for the lighting analysis that may be performed as a precursor to the energy simulation in the same model (Figure 10).

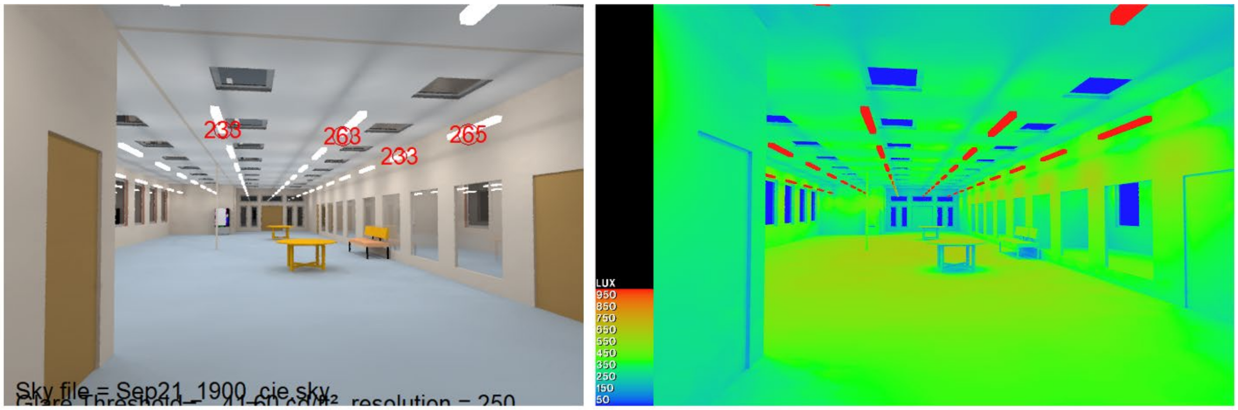


Figure 10
Lighting Luminance and Illuminance Simulation Example (IESVE)

ASHRAE 90.1 has the following requirements for simulating lighting fixtures and controls:

- The modeled lighting power must be based on the fixture manufacturer's maximum rated wattage and include all power used by the luminaires, including lamps, ballasts/drivers, transformers, and control devices.
- The runtime of the lighting fixtures must be typical for the modeled building type and the same in proposed design and the baseline/budget model, except when capturing certain lighting controls.
- Most types of spaces require occupancy sensors. Appendix G prescribes reduction in lighting runtime that must be modeled to capture occupancy sensor savings for different types of spaces (e.g., 45 percent reduction in storage rooms, 10 percent reduction in hospital patient rooms). For manual-ON or partial-auto-ON occupancy sensors, lighting runtime may be further reduced by a prescribed fraction.
- Most types of spaces with windows or skylights must have automatic daylighting controls capable of reducing lighting in response to available daylight using continuous dimming or stepped controls. The automatic daylighting controls may be either modeled directly in the BEM tool or through a schedule adjustment based on the detailed daylighting analysis.

ASHRAE Guideline 14 recommends collecting the following site data in support of the calibrated simulation:

- fixture counts, fixture types, and nameplate data from lamps and ballasts;
- 24-hour weekday, weekend, and holiday schedule of indoor-outdoor lighting use, for a sample of fixtures;
- characteristics of fixtures for estimating radiative and convective heat flows;
- thermal zone assignments;
- illuminance measurements; and
- diversity of operation.

Lighting use profiles can be sampled with lighting loggers or measured at the electrical distribution panel. The profiles may be predictable, such as in office buildings that operate in a consistent fashion on weekdays and weekends/holidays throughout the year, or variable, such as in conference centers and hotels/motels with variable vacancy rates.

Reasons for Mismatch in Simulated Versus Actual Energy Use

- **The actual lighting power differs from the modeled lighting wattage.**

ASHRAE 90.1 requires modeling lighting fixtures based on the manufacturer's labeled maximum fixture wattage. For example, incandescent or tungsten-halogen luminaires without permanently installed ballasts that are labeled for 150 W must be modeled as 150 W even if fitted with a lower-wattage bulb (e.g., 13 W screw-in CFL). Similarly, luminaires with permanently installed or remote ballasts must use the maximum input watts of any permitted lamp/ballast combination shown on the fixture label. This requirement ensures that compliance is established based on the worst-case scenario, e.g., if a less efficient bulb is used as a replacement, but leads to exaggerated modeled lighting wattage compared to what is actually installed.

In residential spaces such as multifamily apartments, dormitories, and hotel guest rooms, hard-wired lighting shown on drawings is commonly supplemented by plug-in fixtures provided by a tenant. It is not uncommon for such lighting to be omitted from the models—for example, if hardwired lighting is specified for kitchens and bathrooms but not for living rooms and bedrooms, then kitchen and bathroom lighting would be modeled as serving the entire apartment, underestimating the actual lighting load. The same issue may occur if drawings include only temporary or partial lighting.

On retrofit projects, the wattage of existing lighting fixtures is often estimated based on data collected in a sample of spaces, as allowed by ASHRAE Guideline 14, and thus has sampling error. The lighting wattage of the unlabeled existing fixtures is often estimated using a crude rule of thumb.

- **Modeled schedules do not reflect the actual fixture runtime.**

Building operating hours are the predominant driver of lighting energy use in buildings where the majority of spaces have no windows, such as in large offices; however, the hours are rarely known in advance for new construction projects. In addition, the industry-standard modeling references provide conflicting guidance on typical lighting use during unoccupied hours. The lighting schedules in ASHRAE Standard 90.1 User's Manual suggest that only 5 percent of lights (i.e., emergency lighting) are on during unoccupied hours, compared to 18 percent in the models developed in support of ASHRAE's Advanced Energy Design Guide (AEDG) for medium office buildings. Most commercial buildings are unoccupied far longer than occupied (Figure 11). Modeling 18 percent versus 5 percent of the lighting fixtures lit during unoccupied hours translates into an approximately 12 percent increase in the annual lighting energy use. Field studies suggest significant variations in lighting energy use during unoccupied hours from project to project (20 percent to 35 percent based on studies of office buildings[17, 18]), which means that modeling only 5 percent of lights on during unoccupied hours, as prescribed by ASHRAE Standard 90.1 User's Manual, significantly underestimates lighting annual use for many projects.

[17] *C&I Lighting Load Shape Project FINAL Report*, KEMA, July 20, 2011, https://neep.org/sites/default/files/resources/NEEP_CI_Lighting_LS_FINAL_Report_ver_5_7-19-11_0.pdf.
[18] Xin Zhou, Da Yan, Xiaoxin Ren, and Tianzhen Hong, "Data Analysis and Modeling of Lighting Energy Use in Large Office Buildings," https://cercbee.lbl.gov/sites/all/files/attachments/BRI%20-%20A2%20-%20Data%20analysis%20and%20modeling%20of%20lighting%20energy%20use%20in%20large%20office%20buildings.pdf.

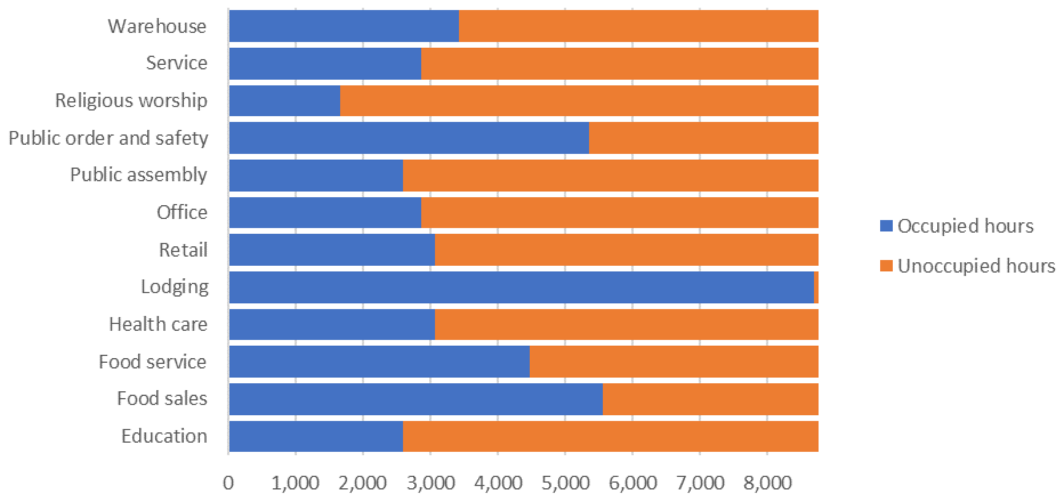


Figure 11
Mean Annual Occupied Versus Unoccupied Hours by Building Type (EIA[19, 20])

Another impactful issue with the lighting schedules in ASHRAE Standard 90.1 User's Manual and other industry-standard modeling references such as the COMNET modeling guidelines is that they are defined on the building level, ignoring differences in lighting runtime in different types of spaces. For example, COMNET prescribes modeling 3,276 hours per year for lighting runtime for all spaces in multifamily buildings. However, lighting fixtures inside apartments are typically lit only 2-3 hours a day, versus 24/7 in common spaces such as corridors and stairwells.

For existing buildings, lighting runtime may be established in a sample of spaces, introducing sampling error. On some projects, the measurements are not performed because of budget constraints, and typical runtime is modeled based on ASHRAE Standard 90.1 User's Manual or software defaults.

- **The actual settings of lighting controls are not captured in the model.**

The realized occupancy sensor (OS) savings depend on the settings, such as motion sensor field of view, delay between the time when the last occupancy is detected and the time when the luminaire is turned off or dimmed, and the number of luminaires that turn on and off together in groups. In one study,[21] the scenario leading to the least lighting energy use in an open office (narrow field of view, 1-minute delay period, ungrouped, turn off when unoccupied) used 35 percent of energy compared to the manual switches, while the scenario leading to the most energy use (wide field of view, 20-minute delay period, nominal groups of 8, turning off during vacancy) used 75 percent of the energy compared to manual switching, more than double the lowest energy use case. The OS settings are typically not accounted for in the models, and in compliance models the prescribed schedule reduction due to OS must be used irrespective of the setting. To complicate matters, more aggressive initial settings (e.g., 1-minute delay period) may be changed because of occupant dissatisfaction.

[19] "Table B1. Summary Table: Total and Means of Floorspace, Number of Workers, and Hours of Operation for Non-Mall Buildings, 2003," U.S. Energy Information Administration, December 2006, https://www.eia.gov/consumption/commercial/data/2003/pdf/set1.pdf.
[20] Reid Hart, Steve Mangan, and Will Price, *Who Left the Lights On? Typical Load Profiles in the 21st Century*, Eugene Water & Electric Board, 2004, https://aceee.org/files/proceedings/2004/data/papers/SS04_Panel7_Paper08.pdf.
[21] Jeremy Snyder, *Energy-saving strategies for luminaire level lighting controls*, Lighting Research Center, January 10, 2018, https://www.lrc.rpi.edu/programs/energy/pdf/ZoneSizeFinalReport.pdf.

- **Performance of the specified dimming controls is not captured in the model.**

For dimming controls, energy use is directly related to light output level, and thus the relationship of light output versus power input is the key factor affecting savings; however, characteristics of the specified control are commonly not captured in the energy models. Dimming reduces an incandescent bulb's lumen output more than its wattage, which makes the bulbs less efficient as they are dimmed.[22] For fluorescent systems, not all ballasts are as efficient during dimming or respond to the control signal in the same way. Efficacy may also change at different levels of dimming, as illustrated in Figure 12[23]—for example, at 50 percent of initial lumens, the input power is at 45 percent of its initial value. Part load performance of the specified dimming controls is often not captured in the energy models.

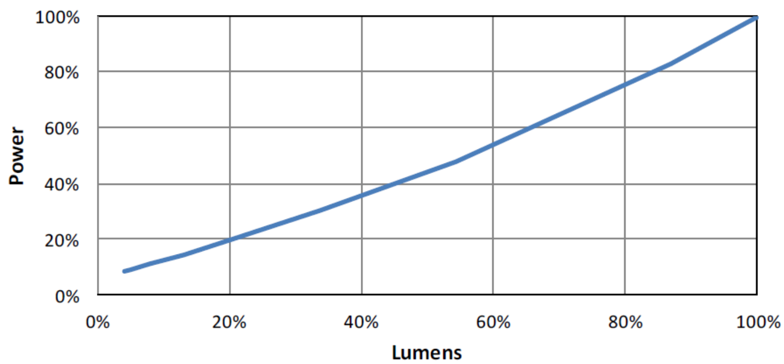


Figure 12
LED Luminaire Dimming Efficiency and Lighting Output

- **BEM tools have varying support for daylighting modeling.**

Capabilities of the simulation tools related to lighting and lighting controls are described in Appendix A. Most BEM tools can perform daylighting analysis; however, the precision of the algorithms used to derive interior space daylight levels differs between the tools. For example, the native daylighting algorithms of EnergyPlus and eQUEST do not account for factors such as ever-changing sky conditions that occur in the real world or complex space and fenestration system geometries that may be captured in the specialized daylighting tools. Typical building energy simulation models have infinitely thin walls and other geometric simplifications that mischaracterize the true relationship of the building form and the electric lighting and photosensors to the available daylight. In addition, some new daylighting strategies rely on advanced methods for delivering and redirecting daylight into spaces to improve the performance of a daylighting design. These so-called complex fenestration systems (CFS) promise the delivery of glare-free daylight to spaces for greater periods of the year, and to spaces that otherwise would never receive daylight, such as core spaces far from the building perimeter. The challenge of simulating these systems in BEM tools remains significant, even when an advanced lighting simulation engine such as Radiance is used.[24]

The methods within eQUEST and EnergyPlus are reasonably accurate for modeling simple daylighting designs—e.g., the ones that rely on windows and not CFS. For example, one study found that the daylighting savings modeled in eQUEST were about 10 percent off compared to the savings calculated in

[22] "Lighting Controls," U.S. Department of Energy, https://www.energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/lighting-controls.
[23] NEMA LSD 73-2015 *Energy Savings with Fluorescent and LED Dimming*, NEMA, July 14, 2015, https://www.nema.org/Standards/Pages/Energy-Savings-with-Fluorescent-and-LED-Dimming-.aspx.
[24] Rob Guglielmetti, Shanti Pless, and Paul Torcellini, *On the Use of Integrated Daylighting and Energy Simulations To Drive the Design of a Large Net-Zero Energy Office Building*, National Renewable Energy Laboratory, NREL/CP-550-47522, August 2010, https://www.nrel.gov/docs/fy10osti/47522.pdf.

a specialized daylighting tool for a simple space.[25] However, in another study, the daylighting energy savings were 21 percent to 32 percent lower (depending on space exposure) when modeled in eQUEST compared to a specialized tool.[26]

The daylighting analysis performed in the specialized tool can be integrated into the energy model by adjusting the lighting schedule to reflect the detailed analysis. This method is allowed by ASHRAE 90.1, and the steps are documented in several papers, including the one by NREL that described applying the method to the design of a large net-zero energy office building.[27] Some tools, like OpenStudio and IESVE, support a more detailed daylighting analysis, eliminating the need to create two separate geometric models for energy and daylighting analysis and having to update both as the design evolves.[28] On the other hand, using a separate tool for daylighting may allow simplifying the energy model (for example, the exact window shape and position within the space do not have to be captured) and reducing the simulation runtime. It is also not uncommon for the energy and daylighting analysis to be completed by different members of the team or even different companies (e.g., mechanical engineer versus lighting designer) working on the same project.

- **Input simplifications and errors affect modeling results.**

Some common input simplifications may have significant impacts on daylighting. For example, windows are often entered as a percentage of gross exterior wall area, with the location and dimensions of individual windows left at default. This does not affect heating and cooling loads as long as the overall window area is correctly captured but may have a dramatic impact on daylighting. Visible transmittance of the fenestration may also be left at default or entered based on glass properties, ignoring the window frame. Interior obstructions such as bookcases and cubicles are commonly not captured. In addition, individual spaces in the energy models are typically aggregated into HVAC zones, so the interior walls that separate spaces within one HVAC zone are not modeled. Shading from exterior structures such as adjacent buildings in urban settings may also be excluded from the model, exaggerating modeled daylighting savings.

- **Interior shades deployed by occupants interfere with daylighting.**

While simulation tools may be capable of detecting excessive glare, the deployment of shades in response to the glare index is typically modeled only if the building has automatic shades. However, the manual shades will likely be pulled down by occupants if the glare is excessive and may be kept down longer than necessary, interfering with daylighting.

Motors and Variable Speed Drives

Background

Motor-driven systems and components account for almost one-third of electricity use in commercial buildings.[29] A majority of systems are HVAC-related, such as packaged and unitary air conditioners,

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[25] Scott Schuetter, "Daylight and energy modeling: a developing relationship," *Enlighten* 4, no. 1 (January 2011), https://www.seventhwave.org/sites/default/files/enlighten_Jan11.pdf.
[26] John An and Sam Mason, *Integrating Advanced Daylight Analysis Into Building Energy Analysis*, Atelier Ten, August 2010, http://ibpsa-usa.org/index.php/ibpusa/article/view/303/292.
[27] Rob Guglielmetti, Shanti Pless, and Paul Torcellini, *On the Use of Integrated Daylighting and Energy Simulations To Drive the Design of a Large Net-Zero Energy Office Building*, National Renewable Energy Laboratory, NREL/CP-550-47522, August 2010, https://www.nrel.gov/docs/fy10osti/47522.pdf.
[28] Ladan Ghobad, *Daylighting and Energy Simulation Workflow in Performance-Based Building Simulation Tools*, September 2018, https://www.ashrae.org/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C053.pdf.
[29] *Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment*, U.S. Department of Energy, December 2013,

chillers, air and water distribution systems, and heat rejection systems. Elevators are an example of a common non-HVAC motor-driven building system (Figure 13).

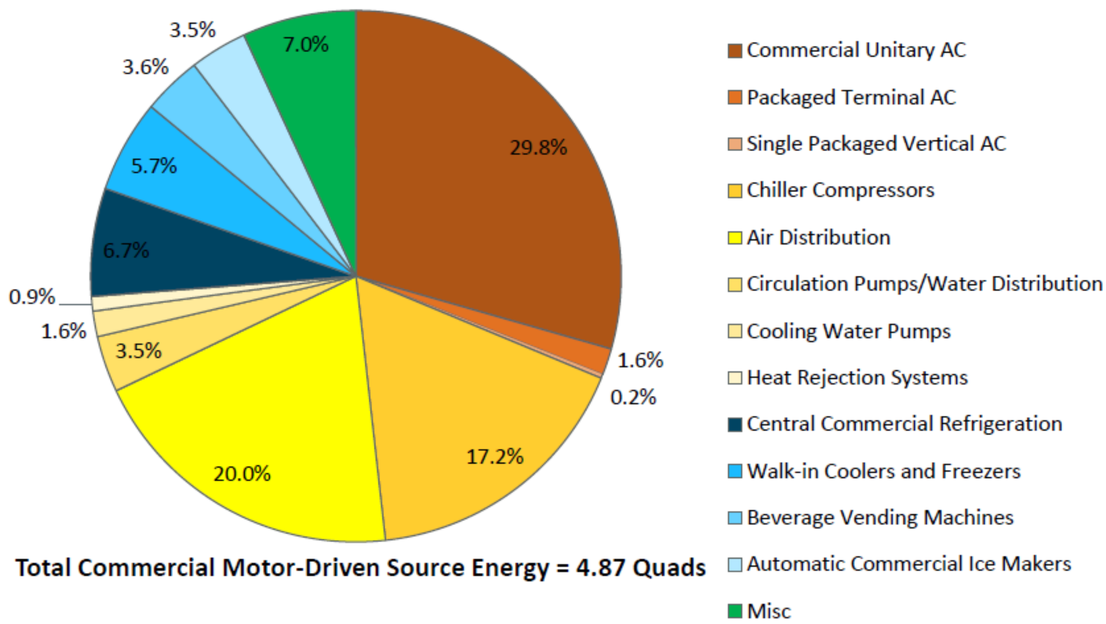

Figure 13
Commercial Motor-Driven Systems Energy Use

Some motor-driven HVAC components, such as compressors and condenser fans, are not modeled explicitly in BEM tools; instead, their performance is reflected in the overall unit efficiency rating. Others, such as supply and return fans in the air-handling units, exhaust fans, room fan coils, and chilled water pumps, are explicitly modeled, and their efficiency and variable speed capabilities are directly captured.

The energy use of motor-driven equipment depends on the system load, control, and operation as well as the inherent motor system performance, including motor efficiency and use of variable frequency drives (VFD). Motor efficiency improvements may yield a 1 percent to 5 percent reduction in operating costs; improvements that address how the motor, controls, and driven system work together—and how they influence other building systems—may provide savings of 50 percent or more.[30]

BEM tools' support of the motor-driven systems differs depending on the system type—e.g., whether it's a supply fan in a central air-handling unit (AHU), chilled or hot water loop circulation pump, zone exhaust fan, or non-HVAC system. The modeling of HVAC supply fans and elevators is discussed in more detail below as examples of HVAC and non-HVAC motor-driven systems.

- **Modeling of HVAC supply fans**

Software commonly models fans in three ways. The simple method is for the user to enter the electric power per unit of air flow (W/cfm). Alternatively, the static pressure, fan efficiency, and motor efficiency at design conditions may be specified. A third method is to specify brake horsepower at design conditions instead of fan efficiency and static pressure.

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https://www.energy.gov/sites/prod/files/2014/02/f8/Motor%20Energy%20Savings%20Potential%20Report%202013-12-4.pdf.

[30] *EDR Design Brief: Drivepower*, Energy Design Resources, https://energydesignresources.com/media/1726/EDR_DesignBriefs_drivepower.pdf.

Fan control may be specified as constant volume, multispeed, cycling, or variable flow. Fan energy use at reduced flows for the variable flow applications (i.e., fan part load performance) may be left at the software default for the selected flow control method (Figure 14). Alternatively, modelers may specify a custom fan performance curve that determines the percentage of full load power draw of the supply fan as a function of the percentage of the full load airflow. A minimum fan flow ratio is also specified (20 percent in Figure 14).

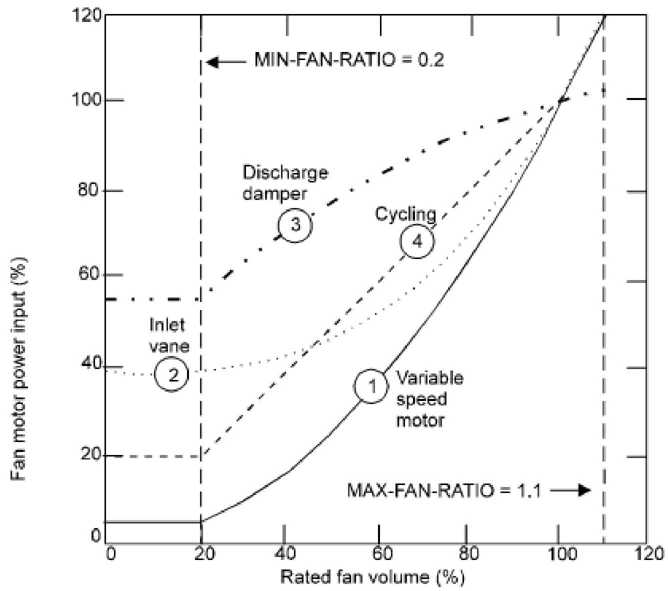

Figure 14
eQUEST Default Fan Part Load Performance Curves

Other inputs include fan mechanical efficiency at design conditions excluding motor losses and fan motor efficiency at full load. The overall fan efficiency is a product of its mechanical and electrical efficiency. Internal gains from a fan motor are modeled by specifying the fan position relative to the cooling coil such as draw through (the fan is downstream of the coil) or blow through (the fan is upstream of the coil); the fan motor position may be specified as either in or out of the air stream.

- **Modeling of elevators**

The elevator components that use energy include the motors and controls as well as lighting and ventilation systems for the cabs. Different sources give varying estimates of elevator energy use. One reference suggests 5 percent to 14 percent of the overall energy cost in buildings that have them,[31] another says 3 percent to 5 percent of electricity energy use in buildings,[32] and yet another says 1 percent to 7 percent of the total building energy load. Opportunities for energy savings include advanced controls that optimize the position of cars for minimum travel and regeneration motors that become generators when a loaded car descends or an empty car rises. These technologies can result in 35 percent to 40 percent savings.[33]

[31] "2013 End Use Tables," Pacific Northwest National Laboratory, http://www.energycodes.gov/sites/default/files/documents/2013EndUseTables.zip.
[32] S. Goel, M. Rosenberg, and C. Eley, ANSI/ASHRAE/IES Standard 90.1-2016 *Performance Rating Method Reference Manual*, Pacific Northwest National Laboratory, PNNL-26917, September 2017, https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26917.pdf.
[33] Harvey Sachs, *Opportunities for Elevator Energy Efficiency Improvements*, American Council for an Energy-Efficient Economy, April 2005, https://aceee.org/white-paper/opportunities-elevator-energy-efficiency-improvements.

With the exception of IESVE, elevators are not explicitly modeled in BEM tools. Instead, the associated energy use is typically captured by specifying the elevator peak power demand (kW) and an hourly schedule that determines the annual use profile. The schedule depends on the elevator's energy use in different modes (e.g., standby versus travel) and use patterns (e.g., number of trips per day).

ASHRAE 90.1 has the following relevant simulation requirements:

- Supply, return, exhaust, and relief fans must be explicitly captured in the simulation. The part load performance curve is provided for the variable air volume (VAV) system to define the fraction of design system power as the fraction of flow for a fan system that minimally complies with code.
- All components within and associated with the building must be modeled. Examples of motor-driven systems that may be subject to this requirement include parking garage ventilation fans, swimming pool pumps, elevators, and escalators. Where the simulation program does not specifically model the functionality of the installed system, spreadsheets or other documentation of the assumptions must be used to generate the power demand and operating schedule of the systems.
- The energy use associated with the non-HVAC motor and process loads included in the model must be estimated based on the building or space type.
- The elevator motor, ventilation fan, and lighting load must be modeled. The cab ventilation fan and lights must be modeled with the same schedule as the elevator motor. A calculation is provided in the Standard for determining the baseline elevator motor power as a function of the weight of the car, rated load, counterweight and speed of the car, mechanical efficiency of the elevator, and motor efficiency. The baseline elevator is assumed to be hydraulic for buildings four stories or fewer and traction for taller buildings. The proposed elevator may be modeled to demonstrate savings relative to this baseline.
- Simulation tools must have the ability to explicitly model the part load performance curves for mechanical equipment.

Reasons for Mismatch in Simulated Versus Actual Energy Use

- **The motor runtime hours are uncertain or unknown.**

The annual energy use of motor systems depends on the number of hours per year the motor is running. For example, in a constant volume dedicated outdoor air system, a fan runs continuously, supplying ventilation air to spaces when the building is occupied and is shut off during unoccupied hours. However, building operating hours for new construction projects are not known with certainty when the models for new construction projects are developed, or may change after retrofit.

Uncertainty in runtime hours is greater for non-HVAC systems, such as elevators. The European energy-efficiency label for elevators (VDI 4707) provides average elevator travel times ranging from 0.2 hours per day for small offices to 6 hours per day for high-rise office buildings, compared to the 4.2-hour elevator schedule in ASHRAE Standard 90.1 User's Manual for office buildings of any size. And while the schedules in ASHRAE Standard 90.1 User's Manual are meant to be used only when the actual schedules are unknown, their use in commercial models is overwhelmingly common, and they are also often the basis of the software defaults.

- **HVAC loads are modeled incorrectly, skewing modeled energy use of motor-driven HVAC components.**

The energy use of motor-driven HVAC components (e.g., AHU supply fans) depends on the modeled heating, cooling, and ventilation loads and controls. Heating and cooling loads in turn depend on the performance of the envelope, internal gains from lighting and equipment and their change over time, building occupancy, and occupant behavior (such as heating and cooling thermostat setpoints). Uncertainty or error in any of these inputs will affect the accuracy of modeled fan energy use. The load is also impacted by input simplification. For example, ASHRAE 90.1 requires excluding ductwork and piping losses from the compliance models. And while the loss of precision may be small for new construction projects that comply with the current codes, distribution losses are often similarly ignored in the models of existing buildings where the associated energy penalty may be high. For example, one study[34] found that eliminating half of the total thermal loss due to ductwork air leakage would lead to a 33 percent reduction in overall fan energy consumption. The study dates back to 1990; however, duct air sealing is rarely done on commercial retrofit projects participating in incentive programs, so the analysis likely still applies to many existing buildings.

- **Controls malfunction or are overridden.**

The operation of HVAC motor-driven components strongly depends on how they are controlled. More complex controls are prone to malfunction or may be disabled by building staff. For example, operators are known to override VFD controls because of a lack of training, such that energy consumption is not actually reduced after installing VFD.[35]

- **The performance of motors and drives at part load conditions is not accurately captured.**

VFDs have 95 percent to 97 percent efficiency at full load, which leads to a slight increase in energy use at full load compared to the same motor without VFD. VFD efficiency goes down with the load, especially below 25 percent of the rated power output, and is lower for smaller motors (Figure 15).

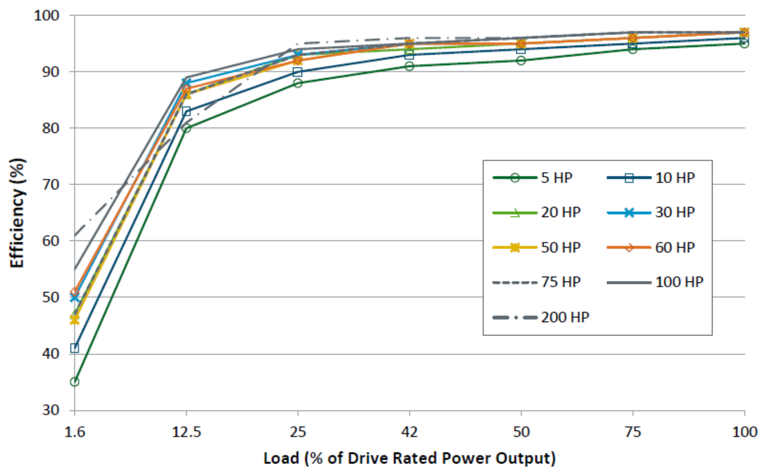

Figure 15
VFD Efficiency at Part Load[36, 37]

Electric motors are generally most efficient when operating from 75 percent to 100 percent of full load. Performance at part load is different for different models, as illustrated in Figure 16.[38] Permanent magnet motors tend to have a more constant efficiency over a range of speeds and may be more efficient than

[34] Mark Modera, Tengfang Xu, Helmut Feustel, Nance Matson, Charlie Huizenga, Fred Bauman, Edward Arens, and Tom Borgers, *Efficient Thermal Energy Distribution in Commercial Buildings*, May 1994, https://eetd.lbl.gov/sites/all/files/publications/lbnl-41365.pdf.

[35] *Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment*, U.S. Department of Energy, December 2013, https://www.energy.gov/sites/prod/files/2014/02/f8/Motor%20Energy%20Savings%20Potential%20Report%202013-12-4.pdf.

[36] Ibid.

[37] "Adjustable Speed Drive Part-Load Efficiency," U.S. Department of Energy, November 2012, https://www.energy.gov/sites/prod/files/2014/04/f15/motor_tip_sheet11.pdf.

[38] Charles M. Burt, Xianshu Piao, Franklin Gaudi, Bryan Busch, and N. F. N. Taufik, *Electric Motor Efficiency under Variable Frequencies and Loads*, April 2008, https://pdfs.semanticscholar.org/eaec/15862ffadddf88cb90126c48e44ecc70690f.pdf.

induction motors during part load operation. The part load efficiency is worse for small motors.[39] While simulation tools compliant with ASHRAE 90.1 must have an ability to explicitly model part load performance curves of mechanical equipment, the generic or default curves are commonly used for motors and drives irrespective of the performance characteristics of the specified equipment. Motor oversizing is also typically not captured.

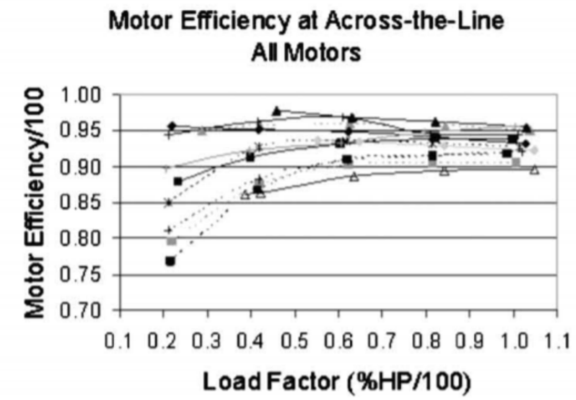

Figure 16
Part Load Efficiency of Different Motors

- **Simulation tool capability affects estimated savings.**

Assumptions and simplifications built into simulation tools may skew results. For example, one study found that EnergyPlus and eQUEST overstate savings from rooftop unit (RTU) fan speed reduction, as illustrated in Figure 17.[40]

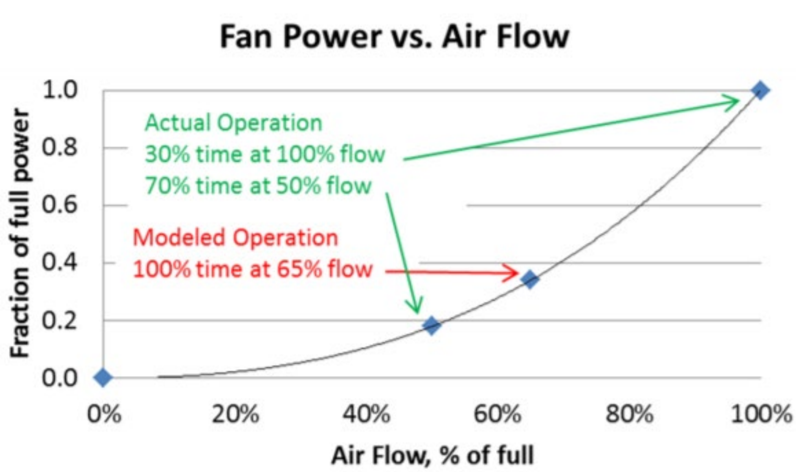

Figure 17
RTU Fan Speed Control—Actual Versus Simulated Performance

[39] *EDR Design Brief: Drivepower*, Energy Design Resources, https://energydesignresources.com/media/1726/EDR_DesignBriefs_drivepower.pdf.
[40] Reid Hart, "Use EMS to Improve Simulation of Outside Air Economizer and Fan Control for Unitary Air Conditioners" (presentation, Building Energy Simulation Forum, January 2014), https://www.energytrust.org/wp-content/uploads/2017/02/Hart_EconoFanSimulation_BESF_141501.pdf.

Building Energy Management Systems and Controls

Background

As performance of mechanical equipment approaches theoretical limits, controls that ensure optimal operation of multiple building components as a system, eliminate energy waste during unoccupied hours, and help detect and troubleshoot operational faults are increasingly coming into focus. Thus, many new requirements in ASHRAE 90.1 are related to metering and controls, including advanced and expanded lighting control requirements, chilled water plant metering, requiring large electric-driven chilled water plants to be monitored for electrical energy use and efficiency, economizer fault detection and diagnostics, monitoring requirements for air-cooled DX cooling units with economizers, and others. ASHRAE RP-1651, which investigated the maximum technically achievable energy targets for commercial buildings, included five control measures among the thirty finalists.

In a sample of 142 projects that participated in a modeling-based incentive program for commercial and industrial buildings, control-related measures were included in 90 percent of the projects. Based on the submitted models, measures involving installation and upgrades of the building management system (BMS) were projected to have the second highest savings after lighting retrofits. PNNL's study on *Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction* estimated that as much as 30 percent of energy consumption in existing buildings can be eliminated through more accurate sensing, more effective use of existing controls, and deployment of advanced controls.[41] In the study, 34 different control measures were simulated using EnergyPlus. Several measures that were identified as more widely applicable and/or showing the highest savings potential are summarized below, along with the discussion of challenges in capturing savings from these measures on actual projects that participated in the modeling-based incentive program. An advanced plug load control measure is also included as an example of a non-HVAC control.

- **Shorten HVAC operation schedules**

The measure involved adjusting faulty or neglected controls that keep the HVAC systems running in the occupied mode longer than necessary. In the PNNL study, it was modeled by extending the occupied mode of operation for HVAC fan schedules, heating and cooling thermostat setpoint schedules, and infiltration schedules by four hours each day.

This measure was common on projects participating in the incentive program. However, establishing pre-retrofit schedules has proven to be challenging, as buildings commonly have multiple systems and no records of past operation except for the recollection of maintenance staff or short-term measurements. There was a tendency to exaggerate inefficiency of existing conditions (e.g., assume that all systems operated in occupied mode 24/7). Some projects had existing BMS, but schedules were reportedly not set correctly.

- **Supply air temperature (SAT) reset in variable air volume (VAV) systems**

In the PNNL study, the savings were evaluated relative to constant SAT setpoints of 55°F. Warmer SAT setpoints, when applied appropriately, reduce simultaneous heating (at the VAV box reheat coils) and cooling (at the AHU's cooling coil). Automatic SAT is required by ASHRAE 90.1. The PNNL study evaluated three alternative control strategies:

  - Manual control (in buildings without building automation systems), with the building operator setting SAT setpoints depending on the season.
  - Automatic outdoor air temperature–based reset.

[41] N. Fernandez, Y. Xie, S. Katipamula, M. Zhao, W. Wang, and C. Corbin, *Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction*, Pacific Northwest National Laboratory, PNNL-25985, May 2017, https://buildingretuning.pnnl.gov/publications/PNNL-25985.pdf.

- Night-cycle mode SAT reset control, raising the SAT during unoccupied hours so that air is heated only if there is a heating load. Night-cycle mode SAT reset control was modeled in addition to the automatic outdoor air temperature–based reset.

The measure was common in the incentive program for projects with VAV systems. Again, it was challenging to establish the actual existing conditions, as the long-term SAT measurements or records of the manual changeovers were never available. In addition, the proposed new controls were often misrepresented in the model. For example, controls would be modeled as having a capability to set SAT hourly to adequately cool the zone with the highest temperature, while the actually specified control would support only the outdoor temperature-based reset.

- **Widened thermostat deadbands and night setback**

Many buildings have a thermostat control that uses a central zone setpoint with a deadband or a range of temperatures where no heating or cooling is required. This range helps to keep from switching from heating to cooling mode too frequently and also saves energy by lowering the effective heating and raising the effective cooling setpoint. The baseline control was modeled with effective heating setpoints of 71°F and effective cooling setpoints of 73°F during occupied hours (equivalent to a central setpoint of 72°F with a ±1°F deadband). The measure widened the deadband to ±3°F, for an effective heating setpoint of 69°F and an effective cooling setpoint of 75°F. In addition, the heating night setbacks were changed from 65°F to 60°F.

This measure was among the most common on projects participating in the incentive program. Spaces were often reported as overheated and with no night setback; the proposed new controls were modeled by reducing the heating setpoint and an aggressive night setback (e.g., down to 55°F). It was unclear whether the modeled temperature settings will persist, so the maximum modeled temperature change was capped in the program's simulation guidelines to avoid exaggerated savings.

- **Demand control ventilation (DCV)**

Two different strategies were modeled in the PNNL study depending on building type:

- **Zone Sum Procedure** simulated multizone VAV systems that dynamically comply with the ventilation requirements of ANSI/ASHRAE Standard 62.1 *Ventilation for Acceptable Indoor Air Quality*. For each AHU using this demand control ventilation measure, the ventilation requirement was the sum of the ventilation requirements in each zone (5 cfm per person plus 0.06 cfm/ft^2 of floor area for office spaces). As the occupancy changes, so does the minimum ventilation.
- **Indoor Air Quality Procedure** was used for buildings with single-zone packaged equipment. This demand control ventilation strategy uses an estimation of zone carbon dioxide (CO_2) concentration to drive the minimum outdoor air requirements, maintaining the levels of indoor air CO_2 at or below 1,000 ppm.

The PNNL report cited the following issues with capturing savings for this measure:

- Zone Sum Procedure control simulates a perfect scenario and is very difficult to implement in reality.
- The measure's effectiveness is limited by leaking economizer dampers, which limit the outdoor air fraction to a minimum of 10 percent.

On projects participating in the incentive program, the modeled savings tracked occupancy, which was unknown. On some projects, the measure was modeled by reducing the design ventilation rate instead of the change in ventilation control.

The DCV measure was also included in ASHRAE 1651-RP. The report noted that "the actual implementation of demand-controlled ventilation using EnergyPlus is somewhat complicated."

- **Advanced plug load control**

The measure simulates the control devices that can turn off plug loads when they are not in use, such as smart power strips for task lighting and office equipment, special occupancy-based sensors for vending machines, and time switches for water coolers. In the PNNL study, it was modeled by adjusting the fraction of plug loads as illustrated in Figure 18.

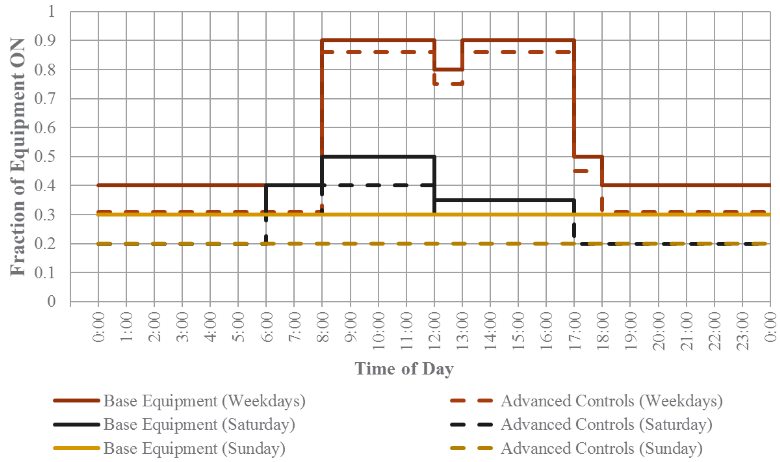

Figure 18
Schedule Changes to Model Advanced Plug Load Control

The change in schedules that was modeled is clearly approximate. It is also impossible to establish with certainty the equipment loads to which the new schedule should be applied. The recent editions of ASHRAE 90.1 require that at least 50 percent of receptacles in private offices, classrooms, and several other common types of spaces have automatic receptacle controls; however, on some designs, the number of specified receptacles is increased (e.g., doubled) so that occupants do not have to use the controlled outlets. In this case, there are no savings from the controls. Based on the most recent *Commercial Buildings Energy Consumption Survey* (CBECS),[42] office and computing equipment account for approximately 24 percent of the total electricity use in office buildings, and thus uncertainty in the energy savings with this control may have a significant impact on the overall model accuracy.

Reasons for Mismatch in Simulated Versus Actual Energy Use

- **The actual operation of controls differs compared to the modeled "ideal" operation.**

The PNNL study stressed that significant savings can be achieved by addressing improper operation of the existing controls (e.g., recalibrating faulty sensors). Models often emphasize the existing issues but assume the ideal, correct operation of new controls. However, the newly installed controls can similarly malfunction, leading to higher actual energy use compared to what was modeled. For example, economizers can save 9 percent to 32 percent of cooling energy use depending on project location, but they do not properly function in over 70 percent of the installations.[43] Thus, models reflecting correct economizer operation substantially underestimate cooling energy use on many actual projects.

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[42] "Table E5. Electricity consumption (kWh) by end use, 2012," *Commercial Buildings Energy Consumption Survey*, U.S. Energy Information Administration, May 2016, https://www.eia.gov/consumption/commercial/data/2012/c&e/cfm/e5.php.
[43] *HVAC Economizers 101*, Battelle, https://buildingretuning.pnnl.gov/training/economizers/PNWD-SA-8511%20HVAC%20Economizers%20101-Section%203.pdf.

- **Uncertainty exists in the simulation inputs for modeling control malfunction.**

The PNNL study noted that modeling assumptions related to faulty controls are guesses at best, and savings from their correction could use significant refinement, aided by additional research. A similar uncertainty exists for projects participating in incentive programs for existing buildings.

- **Operating conditions are difficult to establish.**

Savings from control measures must typically rely on assumptions about operating conditions such as heating and cooling thermostat setpoints, changes in occupant density of spaces throughout the day (for DCV measures), etc. These conditions are rarely known for existing buildings and may change when new controls are installed.

- **A variety of modeling mistakes affect estimates.**

Experience has shown that control measures are prone to modeling mistakes and oversimplifications. For example, it was not uncommon for projects participating in the incentive program to attempt modeling a complex BMS installation as one measure, without explicitly capturing the individual controls that will be implemented. Instead, the HVAC operating schedules and heating/cooling thermostat setpoints were arbitrarily adjusted to match the preconceived level of savings. As a result of frequent and impactful modeling mistakes and the uncertainty of the existing conditions and future control settings, the incentive program modeling rules had to be changed to cap the contribution of savings from a BMS system and controls to no more than 50 percent of the total savings from the proposed package of measures.

- **Simulation tools' capabilities are limited.**

An energy management system (EMS) is a dedicated computer that can be programmed to control all of a building's energy-related systems, including heating, cooling, ventilation, hot water, interior lighting, exterior lighting, on-site power generation, and mechanized systems for shading devices, window actuators, and double facade elements. It is challenging to compare simulation tool capabilities with respect to controls because of a wide variety of control applications, a lack of established comparison frameworks, and subjectivity in determining whether a feature is supported. For example, in the PNNL study, fixing/replacing leaking hot water coil valves was modeled assuming an average impact of 2°C of heating. Since this measure could not be modeled explicitly (as replacing a leaking valve), should it be marked as not being supported by EnergyPlus? Thus, a binary yes/no capabilities matrix is an oversimplification and does not communicate well BEM tool support of controls.

Advanced users of EnergyPlus may take advantage of its EMS feature, which allows using a simple programming language to specify the control algorithms to simulate novel control strategies or savings from fixing faulty controls.[44] Advanced OpenStudio users also have access to this functionality.

Reasons for Disagreements Between Modeled and Actual Performance

Uncertainty of the Simulation Inputs

- **Building operation depends on occupant behavior and demographics.**

Energy consumption strongly depends on occupant behavior and demographics. For example, energy use of two schools with identical designs will be significantly different if one is occupied only when school is in session and the other is also used for afterschool activities. Service hot water use of two identical

[44] P.G. Ellis, P.A. Torcellini, and D.B. Crawley, *Simulation of Energy Management Systems in EnergyPlus*, January 2008, https://www.nrel.gov/docs/fy08osti/41482.pdf.

apartments may differ by a factor of four or more[45] if one apartment is occupied by seniors and another by a family with small children. The modeled operating conditions for new construction projects are just the best guesses. For retrofit projects, the existing operating conditions can be established during an energy audit, but site measurements on commercial projects are often limited, and operating hours may change after retrofit.

- **Systems and equipment installed by building occupants are not shown on drawings; their energy use is difficult to establish.**

All buildings have systems and equipment that are installed by occupants or are part of commercial or industrial processes. Depending on the building type, these may include computers, servers, printers, consumer electronics, kitchen appliances, task lighting, and industrial equipment. These systems account for approximately 35 percent of the total energy cost of new buildings compliant with ASHRAE 90.1-2013,[46] but their energy use on specific projects is difficult to establish even if the nameplate data is available. In one study, office equipment with a 3.5 W/SF load based on the nameplate rating consumed around 0.75 W/SF based on field measurements.[47] These systems affect energy use both directly (by consuming electricity) and indirectly (by contributing to the internal heat gains that impact HVAC energy use)—for example, heat gains from typical desktop computers may differ by a factor of three depending on the manufacturer, processor speed, and RAM.[48]

- **Necessary equipment performance data is not available from equipment manufacturers.**

A significant amount of translating and pre-processing is often required to bridge the gap between information available in the design documents and energy model inputs. For example, the performance of cooling systems at part load is expressed as the Integrated Energy Efficiency Ratio (IEER) or Integrated Part Load Value (IPLV) in the manufacturer's catalogs; however, these metrics cannot adequately support the analysis performed by BEM tools. Modelers must develop the performance curves that define variation in system efficiency and capacity at different indoor and outdoor conditions to capture the performance of a given system. On commercial models, the generic software default performance is often used to curtail the effort.

ASHRAE 205 aims to address this gap. However, its development is progressing slowly, in part because of difficulties with obtaining the necessary data from equipment manufacturers.

- **Modeled weather conditions do not match actual weather conditions.**

Models commonly use typical meteorological year (TMY) weather representative of the conditions during the past five to thirty years. However, weather during any given year differs from the typical. Variations in weather were found to be one of the leading reasons for discrepancies between modeled and realized savings from envelope, heating, and cooling system improvements in multifamily and school projects participating in a modeling-based incentive program.

Systems Operation and Maintenance

Control sequences specified in the design documents often are not fully implemented, are not implemented correctly, or malfunction. For example, all buildings compliant with the recent editions of energy codes must have controls capable of shutting off non-emergency lighting when a building is unoccupied. However, it is not uncommon to see buildings with predominantly daytime occupancy, such

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[45] The amount of service hot water used in an apartment building varies from 12 to 44 gallons/day per person depending on the occupant demographics based on the ASHRAE Applications Handbook.
[46] M. Rosenberg, J. Zhang, R. Hart, and R. Athalye, *Roadmap for the Future of Commercial Energy Codes* (Figure 2.6), Pacific Northwest National Laboratory, January 2015, https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24009.pdf.
[47] *2017 ASHRAE Handbook—Fundamentals* (p.18.13, Figure 4).
[48] *2017 ASHRAE Handbook—Fundamentals* (p.18.12, Table 8A).

as offices, brightly lit during nighttime. A simulation will grossly underestimate lighting energy use in such buildings if it assumes that the specified controls are enabled. Many projects undergoing retrofits have existing controls that are not programmed correctly or that malfunction.

Modeler Errors

The Building Energy Modeling Innovation Summit[49] cited the difference in the simulation results obtained by different modelers simulating the same building in the same simulation tool (i.e., the lack of reproducibility of the results) as one of the top issues affecting BEM credibility. The U.S. Department of Energy's Roadmap for Building Energy Modeling[50] identified better training of energy modelers as the highest-priority task for improving BEM accuracy. A study comparing projected to realized savings for 108 projects that participated in a modeling-based incentive program showed clear patterns in projection accuracy between different companies (Figure 19).[51] For example, projected savings significantly exceeded realized savings on projects completed by Company I, while Company A underestimated savings on most projects. (In the figure, percent error is calculated as the difference between projected and realized savings divided by the realized savings. For example, a project with projected savings that are twice greater than realized is shown as having 100 percent error.)

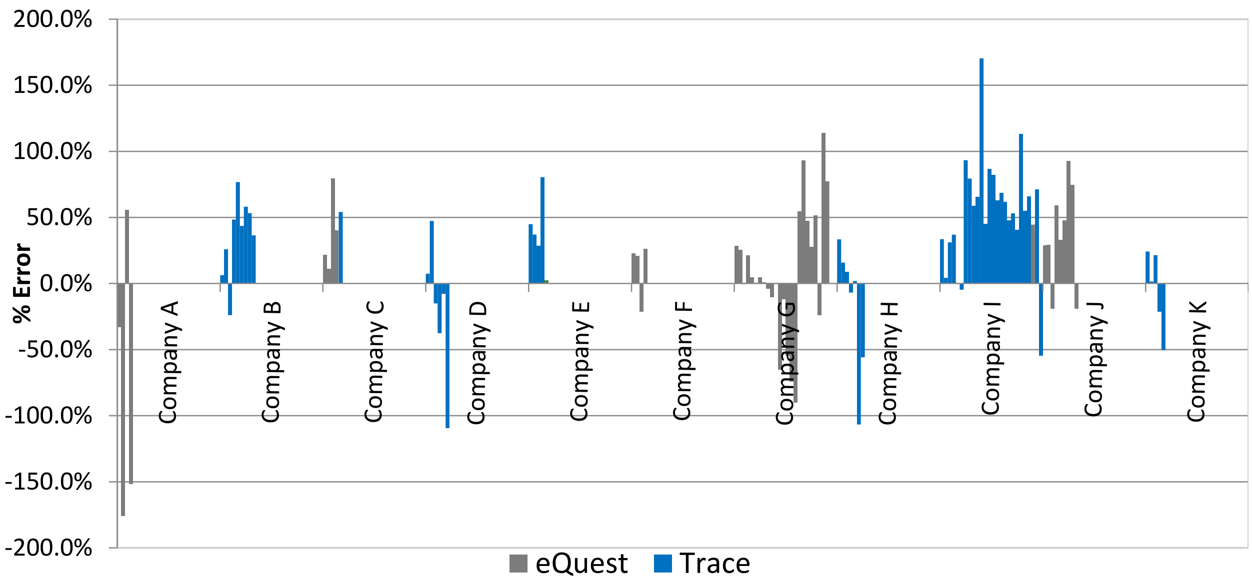

Figure 19
Retrofit Savings Projection Error by Company and BEM Tool

On the other hand, projects had similar accuracy irrespective of whether they were modeled in eQUEST or TRACE, with around 20 percent of projects modeled in either tool having projected savings within 10 percent of the actual.

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49 Building Energy Modeling Innovation Summit, Rocky Mountain Institute.
50 C.E. Barbour, R. Zogg, E. Cross, and D. Clark, *Research & Development Roadmap for Building Energy Modeling—Draft—for Review Only*, Navigant Consulting, February 2016, https://www.energy.gov/sites/prod/files/2016/02/f29/DOE-BTO-BEM-Roadmap-DRAFT-2-1-2016.pdf.
51 Chris DeAlmagro and Maria Karpman, "Comparison of Projected to Realized Savings for Projects that Participated in a Modeling-Based Incentive Program" (presentation, 2017 ASHRAE Building Performance Analysis Conference, Atlanta, GA, September 27-29, 2017), http://karpmanconsulting.net/TRC_EnergyServices_ASHRAE_Presentation_20170928_Final.pdf.

BEM Tool Limitations

- **Peer-reviewed comparative testing of BEM tools is limited.**

There are case studies documenting variations in energy use projected by different tools[52]; however, there is no established framework for determining which result should be considered more accurate. ASHRAE 140 specifies test procedures for evaluating the technical capabilities and ranges of the applicability of BEM tools. However, the currently included tests address a very small subset of common building systems and components. Furthermore, the Standard provides no formal criteria for when results agree or disagree. In other words, testing alone is all that is required, and there is no established output range that the results of the BEM tool must fall within in order to be considered correct.

- **There is a lack of validation using actual performance data.**

ASHRAE 140 includes analytical verification (comparing the output from a simulation program to a known analytical solution) and comparative testing (e.g., comparing results of different tools to each other). It does not include the empirical validation, which would compare simulation results to the real building or laboratory experiment. According to the informative annex of the Standard, the empirical validation is excluded because it is affected by experimental uncertainties (e.g., imperfect knowledge/specification of the building being simulated), the complexities and expense of obtaining detailed measurements, and the difficulties in diagnosing misalignment between the actual and simulated performance. The same challenges are faced by modelers working on commercial models, except the actual projects are incomparably more complex than ASHRAE 140 test cases.

- **Tools lack support for modeled systems and components.**

BEM tools may not explicitly support systems and technologies included in the project being modeled. For example, until recently, dedicated outdoor air systems (DOAS) and variable refrigerant flow (VRF) heat pumps could not be modeled in eQUEST despite becoming increasingly common. (This was addressed in the November 2018 version.) When the needed features are not explicitly implemented, workarounds are commonly used to overcome these limitations. And while some workarounds may be as rigorous as the native BEM tool algorithms and performed at the same time step (e.g., by exporting hourly simulation results into spreadsheets for further processing), the accuracy varies widely from user to user. Thus, an integrated support of common systems and technologies is of significant value for improving accuracy.

- **Models are developed to meet the minimum requirements of the applicable Standards.**

On commercial projects where budgets and schedules are tight, the level of design details captured in the model will gravitate toward the minimum required by the applicable Standards (e.g., ASHRAE 90.1 for compliance models). Thus, the advanced features (such as flexibility in modeling controls with EnergyPlus EMS, or integration of detailed daylighting such as in IESVE) may be underused, as they may increase modeling effort compared to the simplified methods that are allowed. As long as the bar is not raised in the Standards, and clients who pay the modeling fees do not recognize the value of the more detailed analysis by increasing the modeling budgets, the simpler tools and methods will likely be favored, limiting the accuracy.

Recommendations

BEM Tools Features

Buildings modeled for LEED, code compliance, and energy audit and incentive program participation typically involve large and complex projects with 50+ thermal zones served by diverse HVAC systems with advanced controls. Models of existing buildings commonly rely on the limited data collected during site visits; as-built drawings are often not available or do not reflect all renovations. Energy modeling budgets on commercial projects are often tight because of competitive pressure, and energy modelers often lack the necessary qualifications and experience. The existing Standards, guidelines, and research papers[53] on the subject largely focus on the accuracy of BEM tool algorithms. However, on real-life projects, usability of the graphical user interface (GUI), smart built-in defaults, and transparent reporting that facilitates model troubleshooting and quality control are as important or arguably more important. Even when alternative, more accurate simulation methods for the given system and technology are available within the tool, the simplest method is likely to be used in commercial models to speed up data entry and minimize simulation time.

The following BEM tool features mitigate the typical reasons for disagreement between actual building performance and energy use projected by commercial models, and thus should be emphasized:

- User-friendly interface with the key features included as an integrated package
- Transparent and flexible reports covering a wide range of simulation inputs and outputs to facilitate model quality control and troubleshooting
- Explicit support of common systems and designs
- Explicit support or documentation on modeling common malfunctions of systems and controls
- Rapid integration of support for new technologies
- Integrated quality control to flag simulation inputs and outputs outside of the expected ranges
- Robust integration of energy analysis with other tasks that are commonly performed on commercial models such as daylighting analysis, compliance analysis (e.g., following ASHRAE 90.1), and streamlined evaluation of design alternatives and energy conservation measures
- Extensive on-screen help and reference materials on modeling common systems and designs
- Availability of software trainings
- Simulation algorithms validated through ASHRAE 140 testing
- Integrated support of model calibration to allow direct comparison of the simulation results to the measured energy use; the comparison may be on the building level, between the modeled monthly energy use and actual utility bills, or component level, e.g., between the modeled chiller energy use and measured chiller performance

Standards and Guidelines

ANSI/ASHRAE/IES Standard 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings

- Prescribe the standard operating conditions to be used in compliance models.

Compliance models for new construction projects rely on numerous assumptions, such as building operating hours, occupant demographics, lighting and equipment use schedules, and weather. They capture the ideal operation of building systems and components assuming no control malfunction, no air and water distribution losses, etc. Thus, in most cases, the modeled performance will inevitably deviate from the actual post-construction energy use. Using the standard operating conditions in the compliance models would eliminate unrealistic expectations of the match between the model and utility bills, and allow for a fair apples-to-apples comparison of different building designs based on their performance at the standardized conditions (e.g., same operating hours, same thermostat setpoints). This approach is conceptually similar to the ones already used in the marketplace to compare the efficiency of products such as HVAC systems (e.g., system efficiencies at rating conditions from the Air Conditioning, Heating, and Refrigeration Institute), appliances, and cars. The Department of Energy's Fuel Economy website has a "Your Mileage Will Vary" disclaimer; there is a similar disclaimer on the EnergyGuide label for consumer appliances (Figure 20).

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[53] Dandan Zhu, Tianzhen Hong, and Da Yan, *A Detailed Comparison of Three Building Energy Modeling Programs: EnergyPlus, DeST, and DOE-2.1E*, September 2013, https://cercbee.lbl.gov/sites/all/files/attachments/a%20detailed%20comparison%20of%20three%20buidling%20energy%20modeling%20programs.pdf.

Figure 20
Efficiency Ratings and Difference Between Rated and Actual Performance

- Establish sufficiently detailed standard operating conditions for use in compliance models, such as operating hours, occupancy, thermostat and lighting schedules, miscellaneous equipment loads, etc. The currently available defaults are often too crude (e.g., the schedules included in ASHRAE Standard 90.1 User's Manual do not differentiate between different types of spaces within a building).
- ASHRAE 90.1 already requires that simulation programs are able to explicitly model part load performance curves for mechanical equipment. However, part load performance is commonly captured in detail only for heating and cooling systems. Requirements may be expanded to include other components where part load performance is impactful, such as dimmers or VFDs.

ANSI/ASHRAE Standard 140 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs

- Prescribe the acceptance ranges for the software tools being tested.
- Expand testcases to include a wider range of common systems and components

ASHRAE Standard 205 Standard Representation of Performance Simulation Data for HVAC&R and Other Facility Equipment [In Development]

Modelers often develop custom performance curves to demonstrate energy savings from chillers or DX units that have superior performance at part loads. However, systems such as motors, VFDs, transformers, and lighting dimmers are typically modeled without accounting for the impact of part load on efficiency or by using generic performance curves that do not differentiate between models.

- Identify the impactful efficiency characteristics for different types of systems and components that may be currently overlooked in the energy models.
- Develop methodologies for use in the simulation tools to capture the identified efficiency characteristics.
- Engage with equipment manufacturers to get the necessary performance data to help effectively model their systems. (Some HVAC equipment manufacturers have funded development of the methodologies to help capture performance of their products in the simulation tools, such as the Daikin VRV system modeling in eQUEST.)
- Establish a validation framework to confirm that the performance data provided by manufacturers reflects the product's performance and is derived in a consistent way across product classes.

ASHRAE Standard 209 Energy Simulation Aided Design for Buildings except Low-Rise Residential Buildings

Even if BEM tool algorithms are absolutely accurate and the modeler is an expert in the field, the actual performance is affected by a slew of factors that are impossible to foresee, such as occupant behavior and poor operation and maintenance. Simulation results are currently reported as the set values (e.g., the annual electricity and gas use), and a deviation between these values and the actual measured performance is perceived as an inaccuracy that may be remedied by improving BEM tools or having a more experienced modeler. To avoid creating unrealistic expectations, modeling results should be expressed as a range of likely performance outcomes. A wider range would be appropriate for early design models that rely on the multitude of assumptions to supplement yet undefined design parameters, compared to the models developed based on the completed construction documents. The range may be further narrowed for the models of existing buildings if the inputs related to operating conditions and controls are based on site measurements. While some related tools and methods have been developed,[54] BEM tools do not currently perform such uncertainty analysis.

- Develop methodology for establishing uncertainty of model results.
- For predictive models, require reporting simulation results as a range of possible outcomes as opposed to a single value, to avoid setting unrealistic expectations of alignment between simulated versus actual building performance, which undermines the credibility of energy modeling.

Building Energy Modeling Policies and Infrastructure

- Align software policies with the relevant industry standards.

Some administrators of the modeling-based incentive programs and jurisdictions involved with state and local energy codes enact policies that restrict the use of BEM tools to a subset of those allowed by ASHRAE 90.1. For example, a statewide Massachusetts incentive program for new high performance buildings (Mass Save) requires the use of eQUEST, while in California, EnergyPro and IESVE are the only two commercial tools allowed for documenting compliance with the energy code. Both states are at the forefront of building energy efficiency, with state energy codes that are among the most stringent in the nation. Massachusetts is ranked #1 and California is ranked #2 in ACEE's *2018 State Energy Efficiency Scorecard*.[55] The best way to raise the bar for BEM tool qualities is through tightening the relevant standard, such as the software requirements of ASHRAE 90.1, allowing the tools to compete and letting users pick the tools that work best for them, depending on their professional focus. For example, the AIA 2030 Commitment progress reports clearly show that design engineers have different preferences compared to energy consultants. For some users, the tool's ability to support design optimization or detailed daylighting analysis will be more important, while others may look for the best support of existing building analysis.

- Develop an infrastructure for peer-reviewed comparisons of the simulation tools based on their support of systems and components found in real buildings and interface features important on commercial projects.

There is currently no framework for developing and maintaining an objective peer-reviewed comparison of BEM tools that would encompass the simulation capabilities and usability of the graphical user interface. ASHRAE 140 focuses only on the simulation capabilities, and its development is progressing slowly in part because of a very high rigor that may be excessive for commercial modeling projects. The comparison should be developed with input from a wide range of industry stakeholders to ensure that it is

[54] Occupancy Simulator, http://occupancysimulator.lbl.gov/pages/intro.
[55] Weston Berg, Seth Nowak, Grace Relf, Shruti Vaidyanathan, Eric Junga, Marianne DiMascio, and Emma Cooper, *The 2018 State Energy Efficiency Scorecard*, American Council for an Energy-Efficient Economy, October 2018, https://aceee.org/sites/default/files/publications/researchreports/u1808.pdf.

unbiased, and regularly updated to reflect new versions of BEM tools. The work may be spearheaded by organizations such as IBPSA.

- Establish modeler certification requirements to minimize human error, and require post-occupancy model calibration and M&V.

Currently, modelers working on compliance projects almost never get an opportunity to see the actual post-construction utility bills for projects that they have modeled. Thus, they are unaware of whether the model was representative of the actual performance. This lack of feedback keeps both modelers and building owners in the dark regarding the quality of the analysis, hindering improvement in the accuracy.

Appendix A: BEM Tool Feature Matrix

Table A1 compares user interfaces of the BEM tools based on their support of selected features that are important for commercial-grade energy modeling. Each category is described in more detail below.

- **Building a prototype library to speed up project creation**

This feature allows using one of the built-in templates as the starting point for the project instead of having to enter all project information from scratch.

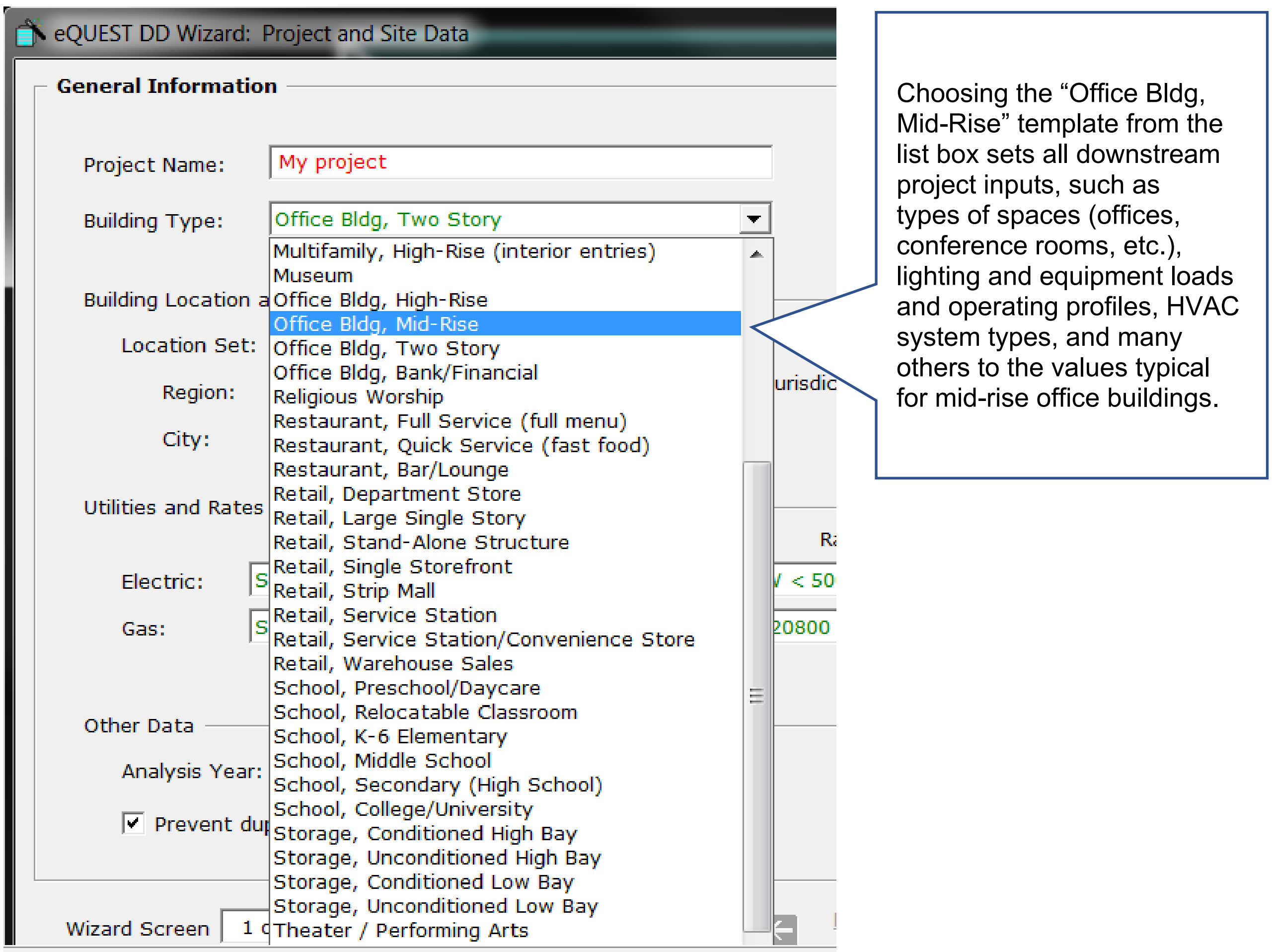

Figure A1
Building Template Selection in eQUEST Design Development Wizard

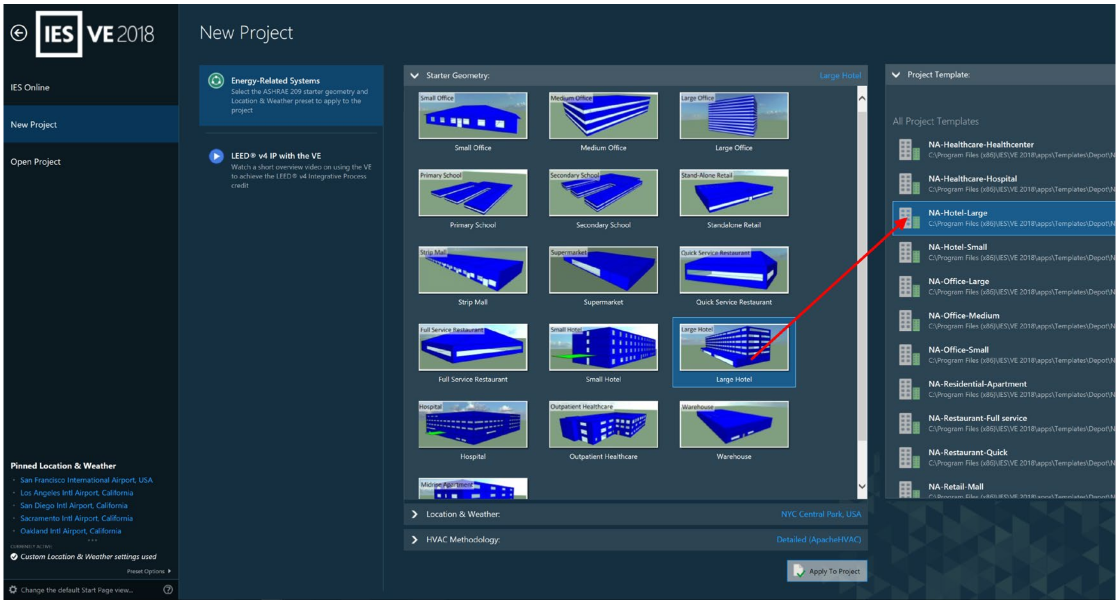

Figure A2
Using IESVE Project Templates for Early-Stage Energy Simulation

Pre-configured reference models (DOE Prototype Buildings) can be created using the OpenStudio “Create Prototype Building” measure. The building can be subsequently scaled in size using the “scale building” measure.

TRACE 700 provides global and local template capabilities that allow users to group room type information. This simplifies building creation and makes mass changes easy.

- **Expression inputs**

With this feature, inputs may be specified using numerical or logical expressions instead of the fixed values, similar to entering formulas into spreadsheet programs. The functionality speeds up data input and updating. For example, an expression may be used to assign occupant density to spaces based on the space type (Figure A3).

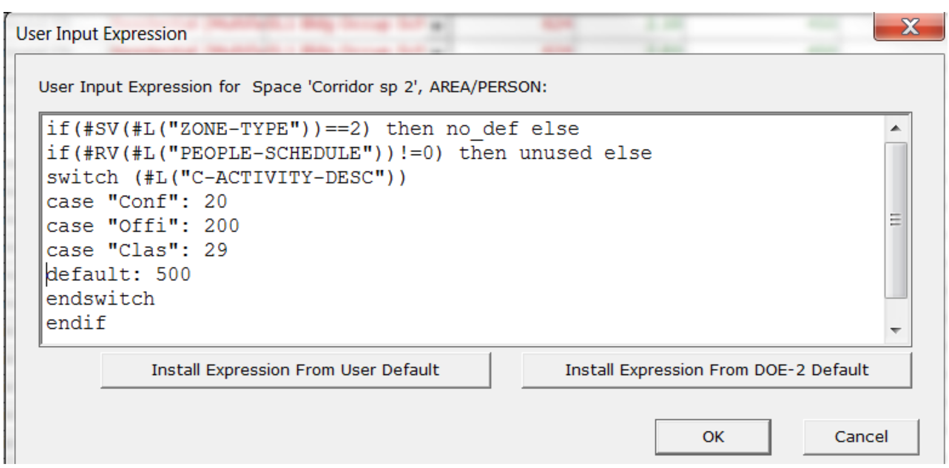

Figure A3
eQUEST User Expression Example

- **Graphic results presentation**

This feature allows visualizing results through the tool's GUI.

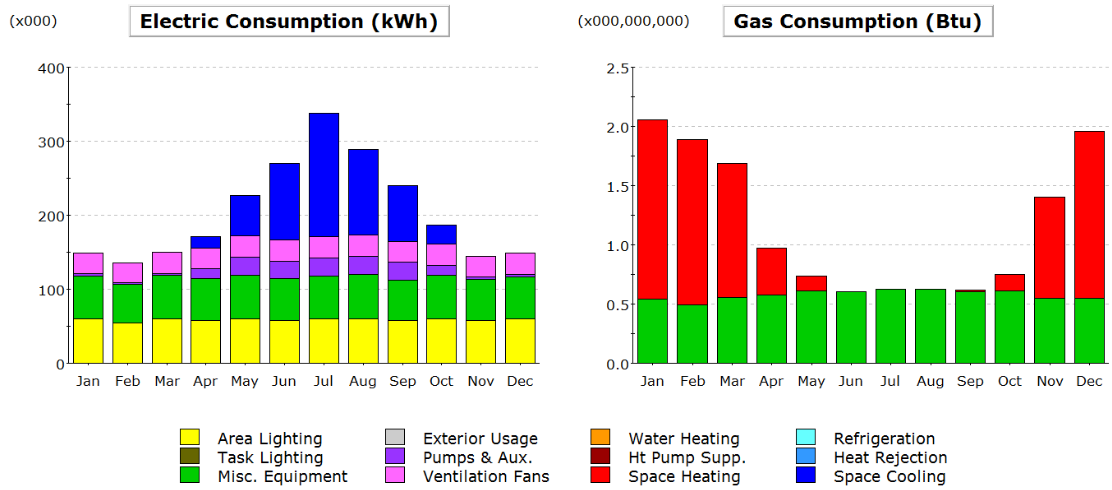

Figure A4
eQUEST Summary Reports

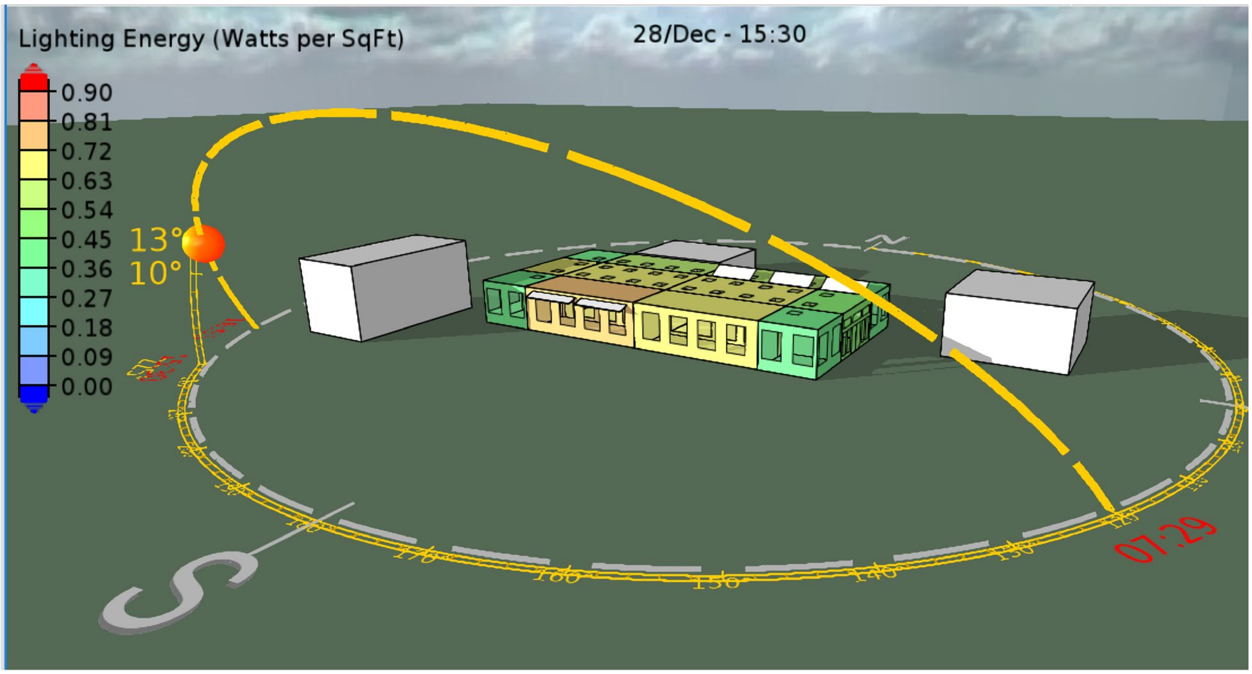

Figure A5
Color-Coded Energy Use Intensity by End Uses Overlaid on the 3D View (IESVE)

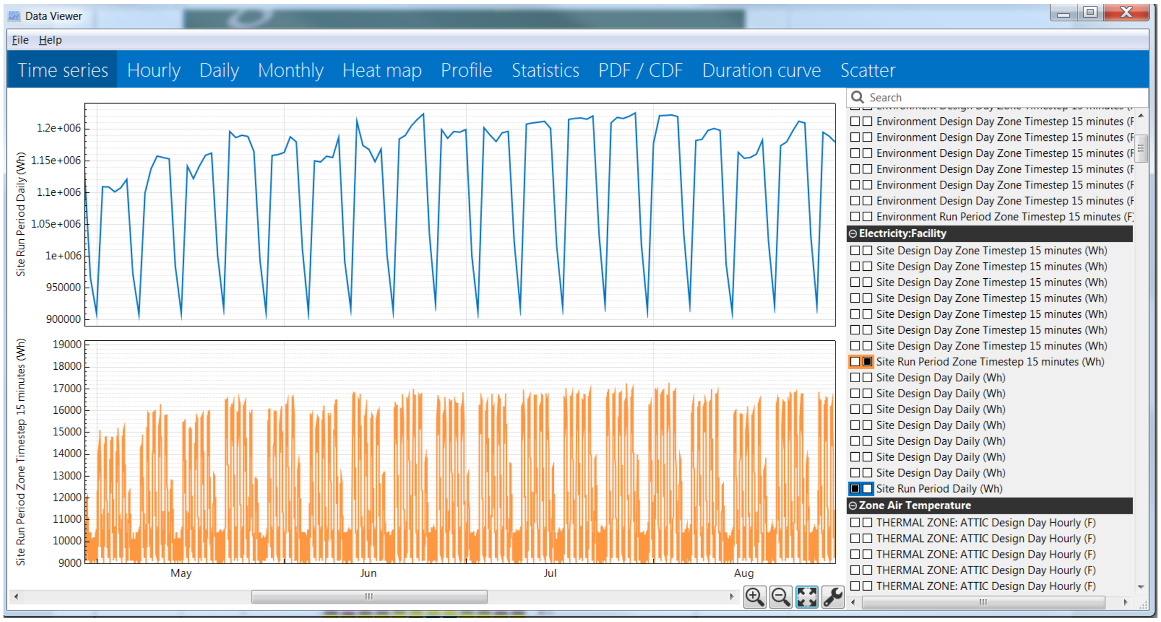

Figure A6
Interactive Visual Results Generated Using "OpenStudio Results" Measure

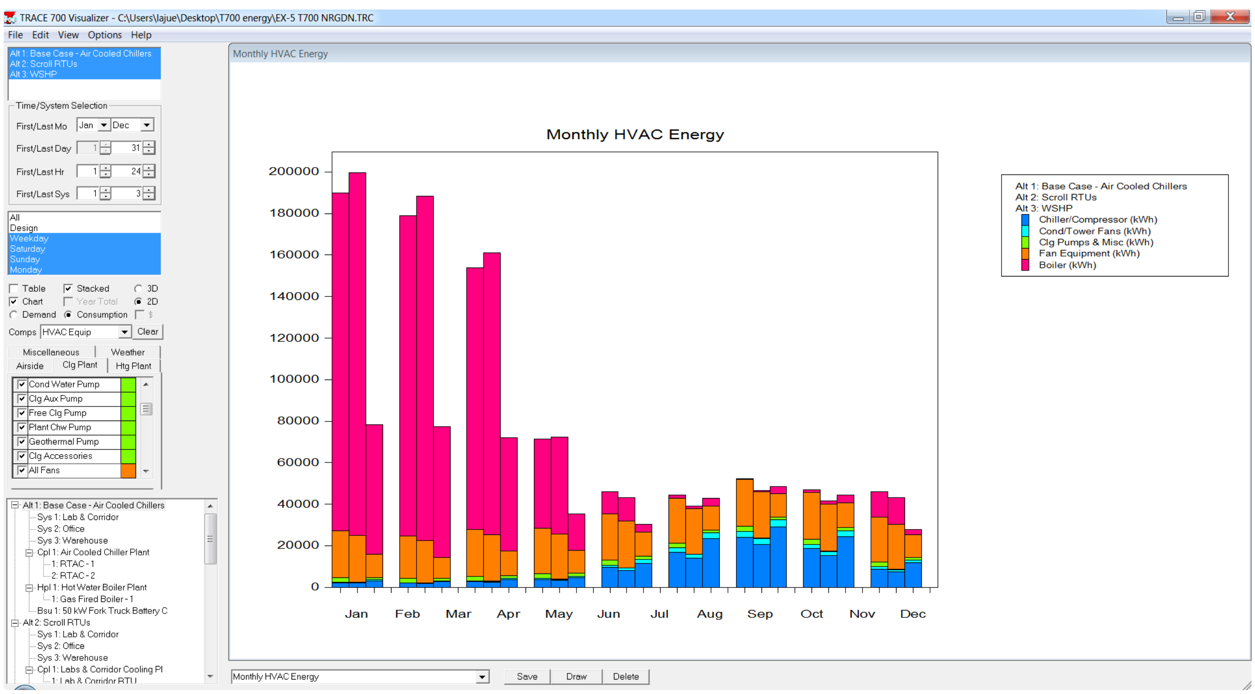

Figure A7
TRACE 700 Visualizer

TRACE 700's visualizer allows users to customize graphs by selecting the alternatives, time, system and components to be included.

- **Integrated quality control**

Quality control functionality flags inputs that are outside of the expected range to alert modelers and reviewers of possible mistakes.

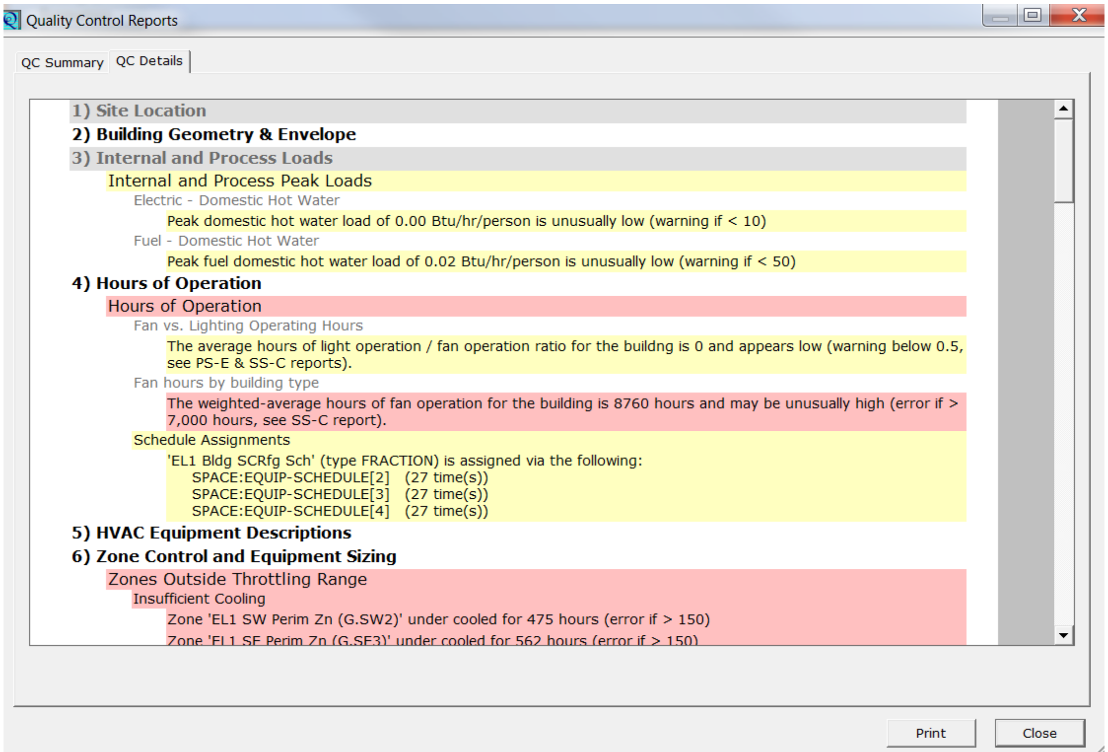

Figure A8
eQUEST Quality Control Reports Module

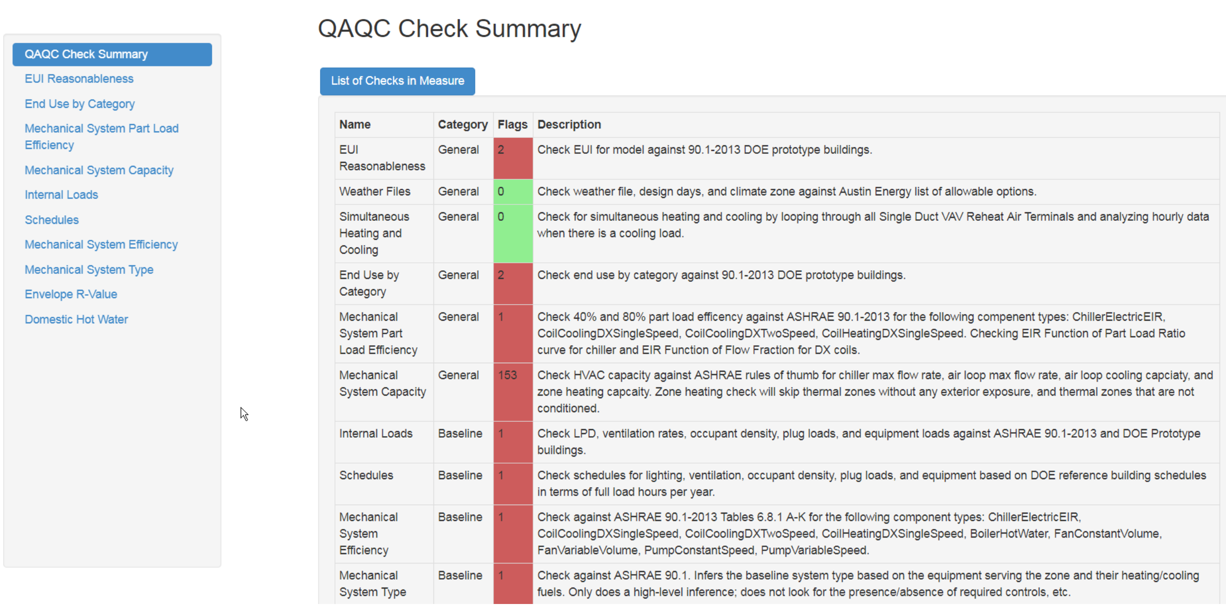

Figure A9
Quality Control Reports Generated by Applying the “Generic QAQC” OpenStudio Measure

- **Automated support for parametric analysis**

Energy modeling projects commonly involve comparing many alternatives, such as varying levels of wall insulation, different lighting design options, or pump energy use with and without variable speed drives.

The parametric analysis capability allows creating and managing multiple alternatives through the BEM tool interface.

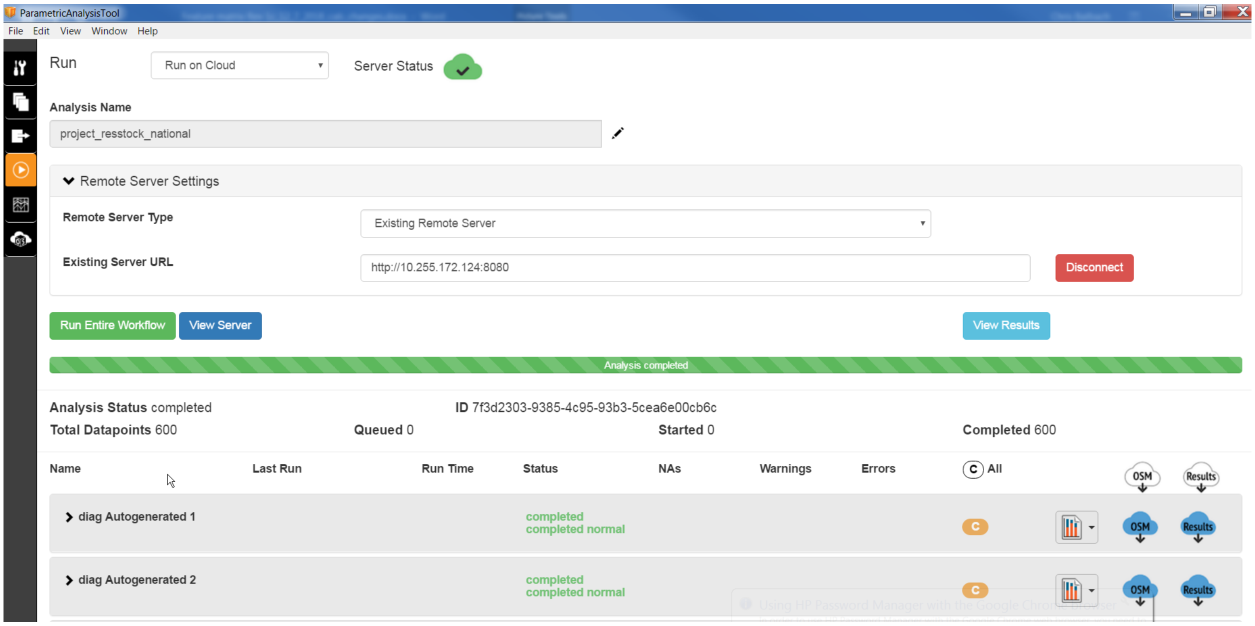

Figure A10
OpenStudio Parametric Analysis Tool

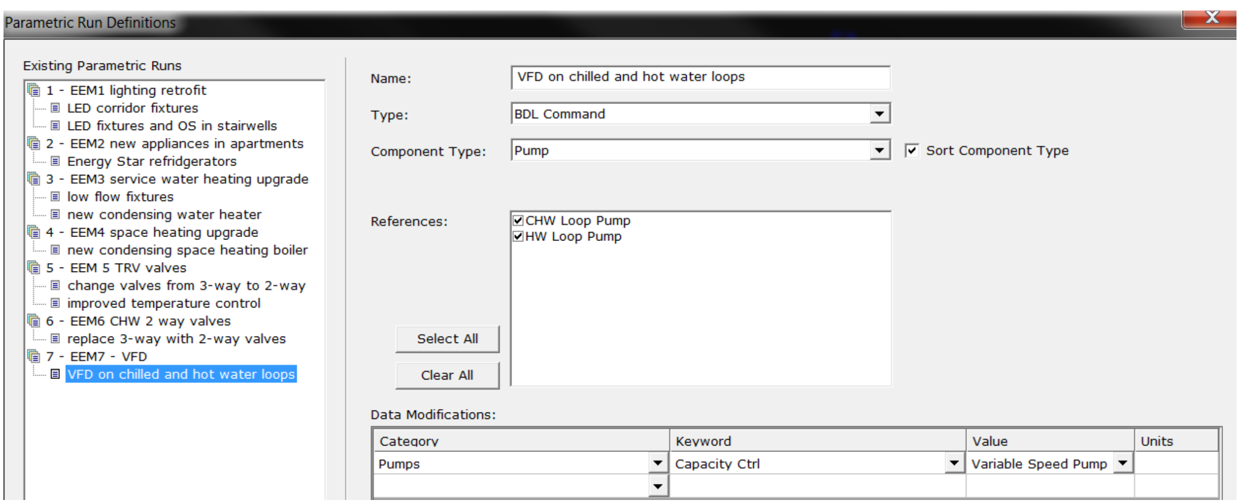

Figure A11
Entering Energy Conservation Measures Using eQUEST Parametric Runs

- **Component libraries**

Component libraries may include properties of the common construction materials (e.g., conductivity, density, and specific heat of batt insulation), typical wall assemblies, lighting and equipment load profiles for different types of spaces (e.g., private offices and multifamily apartments), typical performance characteristics of heating and cooling systems at part load conditions, and many others.

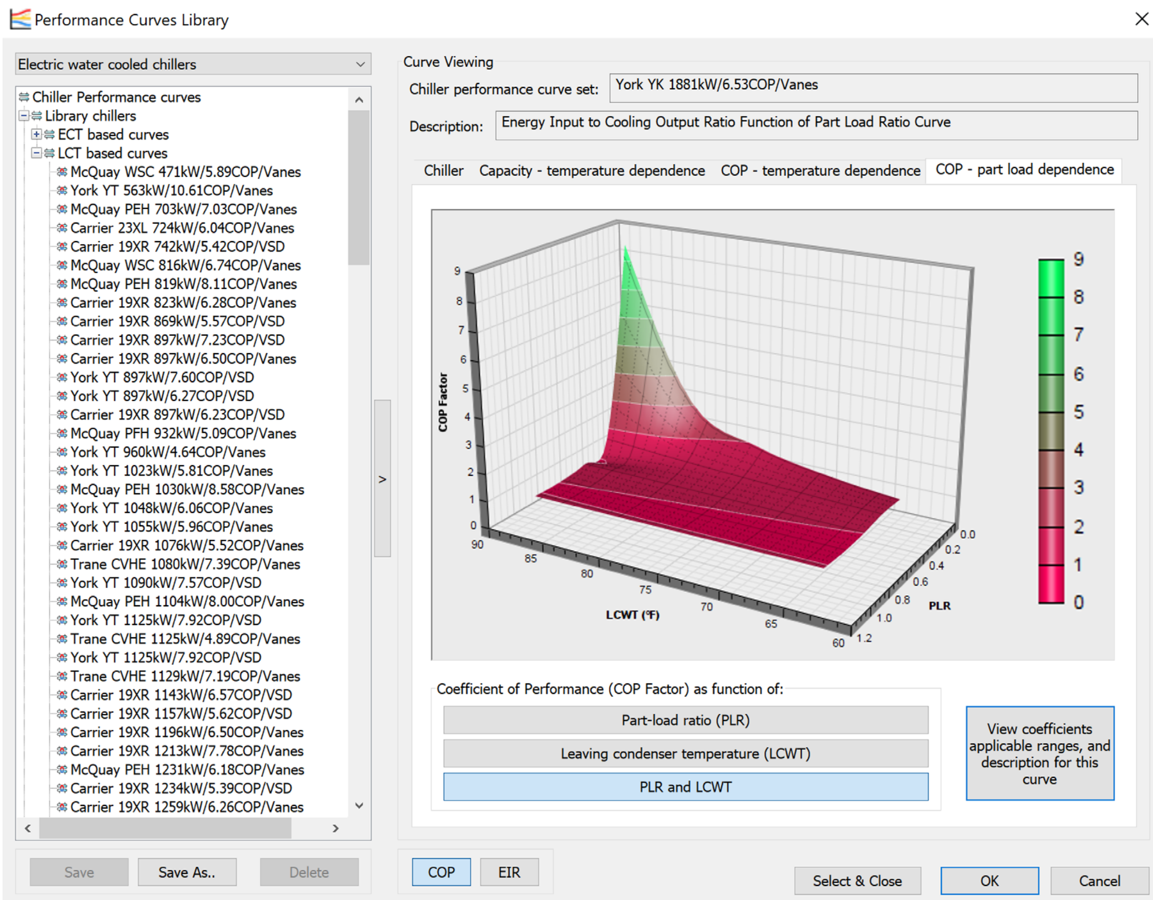

Figure A12
IESVE Chiller Library Performance Curves

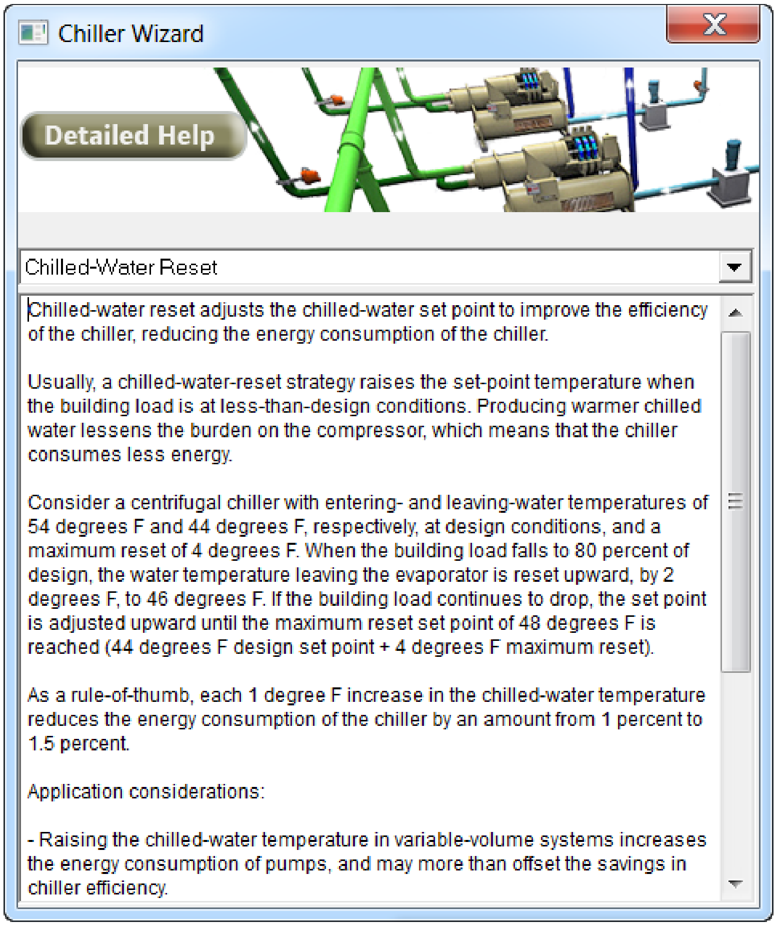

Figure A13
TRACE 700 Chiller Wizard

- **User Acceptance**

The binary yes/no format of the Feature Matrix does not capture the degree to which a given feature is supported by different BEM tools. For example, while most tools support parametric analysis, some implementations may be more comprehensive and user-friendly than others. In addition, features may have different relative importance to users. Thus, the popularity of a BEM tool among users may be used to gauge the quality of the user interface and the balance between usability and simulation capabilities.

The user acceptance category ranks BEM tools from 1 (highest) to 3 (lowest) based on market share in the two nationwide samples in Figure 5A. eQUEST has the highest use and is thus ranked #1 in terms of reported usage. To recognize that the sample has a high percentage of projects in California, a state where IESVE is more popular than TRACE 700, and that TRACE 700 is more popular than IESVE in the Northeast (Figure 5B), IESVE and TRACE are both ranked #2 in terms of reported usage. Even though OpenStudio is used less than EnergyPlus based on Figure 5A, both are ranked #3 in terms of reported usage to account for the difference in presentation of results in the *AIA 2030 Commitment: 2015 Progress Report* versus 2017 reports. OpenStudio was excluded from the 2017 report because it wasn't among the top three tools used by any of the following three trades: architects, design engineers, and energy consultants.

Table A1
User Interface Features

	EnergyPlus	eQUEST	IESVE	OpenStudio/ PAT	TRACE 700
Building prototype library to simplify project creation	No	Yes	Yes	Yes (Note D1, D8)	Yes
Expression inputs	Yes	Yes	Graphical & numerical	Yes (Note D2, D8)	No (Note E1)
Graphic results summary	No (Note A1)	Yes	Yes	Yes (Note D3, D8)	Yes
User-selectable hourly outputs	Yes	Yes	Yes	Yes	Yes
Automated quality control	No (Note A2)	Yes	Yes	Yes (Note D4, D8)	Yes
Automated support for parametric analysis	No	Yes	Yes	Yes (Note D5)	Yes
On-screen help	No	Yes	Yes	No	Yes
Materials/assemblies and schedules library	Yes	Yes	Yes	Yes (Note D6)	Yes
Performance curve library	Yes (Note D7)	Yes	Yes	Yes (Note D7)	Yes
User acceptance (1: highest, 4: lowest)	3	1	2	3	2

Notes:

EnergyPlus

- A1: Third-party tools may be used, such as xEsoView and SVG viewer.
- A2: There are warning and error messages in the simulation output reports.

OpenStudio

- D1: OpenStudio measures for generating the DOE Prototype (https://bcl.nrel.gov/node/83591) and DEER Prototype models (https://bcl.nrel.gov/node/84449) can be downloaded from the Building Component Library, or BCL (https://bcl.nrel.gov). Extension and customization of these prototypes' definitions are supported via the OpenStudio-Standards gem (documentation available at https://github.com/NREL/openstudio-standards).
- D2: Examples of customizable "expression input" available for users to apply via the OpenStudio GUI are available for download from the BCL. This includes access to EnergyPlus EMS functionality available through the OpenStudio API/SDK.
- D3: Multiple OpenStudio Results reports are available from the BCL (https://bcl.nrel.gov/search/site?f%5B0%5D=im_field_measure_tags%3A959) and can be applied using the OpenStudio Application GUI. Users can customize these new reports using the OpenStudio API/SDK. Reports are designed to be dynamic and utilize charting libraries such as D3.js (https://d3js.org). Customized reports can be shared among public and private communities as OpenStudio Reporting measures by publishing them to the BCL.
- D4: An "OpenStudio QAQC" report is available from the BCL (https://bcl.nrel.gov/node/83673). Users can apply this measure to their model using the OpenStudio Application GUI. Users can also create customized QAQC reports (modifying the criteria of existing QAQC checks or adding new QAQC checks) by using the OpenStudio API/SDK. QAQC measures can be shared with other users (via public or private groups) by publishing the QAQC measure to the BCL.

- D5: OpenStudio provides a companion user-facing application (Parametric Analysis Tool) that serves as a scenario management tool. This tool provides capabilities for users to connect to remote OpenStudio servers (via the Amazon cloud) to speed up calculations.
- D6: OpenStudio provides component libraries based on ASHRAE 90.1, California DEER, and California Title 24.
- D7: Equipment-specific libraries (including manufacturer-generated performance curves) are available for download on the public areas of the BCL. The libraries currently contain VRF equipment curves and can be easily extended to include other HVAC equipment types. The OpenStudio-Standard's gem also contains libraries of “standard” performance curves that can be easily retrieved and assigned to HVAC equipment via the use of OpenStudio measures.
- D8: The feature is not included in the OpenStudio/PAT core functionality and is accessible to users only through downloading measures and components that are hosted on the BCL.

TRACE 700

- E1: TRACE 700 allows scalable units in the room inputs for people density, lighting heat gain and miscellaneous loads inputs. It is also available in the systems and plants sections for equipment like fans and pumps.

Table A2
Compliance with ANSI/ASHRAE/IES Standard 90.1-2016 Appendix G Software Requirements

	EnergyPlus	**eQUEST**	**IESVE**	**OpenStudio**	**TRACE 700**
Tested according to ASHRAE 140	Yes	Yes	Yes	Yes	Yes
8,760 hours per year*	Yes	Yes	Yes	Yes	Yes
Hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat setpoints, HVAC system operation*	Yes	Yes	Yes	Yes	Yes
Thermal mass effects*	Yes	Yes	Yes	Yes	Yes
Ten or more thermal zones*	Yes	Yes	Yes	Yes	Yes
Part-load performance curves for mechanical equipment*	Yes	Yes	Yes	Yes	Yes
Capacity and efficiency correction curves for mechanical heating and mechanical cooling equipment*	Yes	Yes	Yes	Yes	Yes
Air-side economizer with integrated control*	Yes	Yes	Yes	Yes	Yes
Design load calculations to determine required HVAC equipment capacities and air and water flow rates	Yes	Yes	Yes	Yes	Yes

*Must be modeled explicitly in the simulation tool

Table A3
Lighting Fixtures

Inputs	EnergyPlus	eQUEST	IESVE	OpenStudio /PAT	TRACE 700
Maximum number of lighting systems per space	Unlimited	5	Unlimited (Note C1)	Unlimited	1
Lighting power	Yes	Yes	Yes	Yes	Yes
Photometric visualization	No	No	Yes (Note C2)	No	No
Internal gains	Yes	Yes (Note B1)	Yes (Note C3)	Yes	Yes
Lighting schedules	Yes	Yes	Yes (Note C4)	Yes	Yes
Component libraries	Yes	Yes (Note B2)	Yes (Note C5)	Yes	Yes
Simulation Reports					
Entered lighting wattage	Yes	Yes	Yes	Yes	Yes
Detailed illuminance reports	No	No	Yes (Note C6)	No	No
kWh building yr/month/hr	Y/Y/Y	Y/Y/Y	Y/Y/Y	Y/Y/Y	Y/Y/Y
kWh thermal block yr/month/hr	Y/Y/Y	Y/Y/Y	Y/Y/Y	Y/Y/Y	N/N/N
Lighting internal heat gains	Yes	Yes	Yes	Yes	Yes

Notes:
eQUEST

- B1: Heat gain may be allocated between radiative and convective, and between the space where lighting is located, return air stream, or adjacent unconditioned space or plenum.
- B2: Building-level and a limited number of space-level (e.g., auditorium, apartment) schedules can be selected from the library. Advanced users may create custom schedule libraries and import them into the model.

IESVE

- C1: The following additional features are supported:
  - Lamp(s) and luminaire(s) selection and layout per room
  - Lighting design calculation
  - Ballast driver fraction
- C2: Photometric visualization features include the following:
  - Lamp photometric visualization
  - Electric lighting illuminance plots on working plane
  - Electric lighting illuminance plots on all room bounding surfaces (horizontal and vertical)
- C3: Includes lighting radiant fraction and convective gain percentage allowance to ceiling plenum for recessed luminaires.
- C4: Lighting schedules include optional dimming schedule and optional diversity factors.
- C5: The following libraries are available:
  - Lamp and luminaire fixture database
  - Import of manufacturers' fixture data (.IES files)
  - Furniture libraries
- C6: The following reports are available:
  - Luminous efficacy for each working plane
  - Detailed illuminance reports

- Electric lighting illuminance (min/max/average/uniformity/diversity) for each working plane and floor
- Total luminous flux (lumens)
- Recommended luminaire layout (rows and columns)
- Light output ratios, correction factors, and maintenance factors
- Luminance view glare images

Table A4
Daylighting

	EnergyPlus	**eQUEST**	**IESVE**	**Open Studio**	**TRACE 700**
Simulation method	Simplified (split-flux or daylight factor)	Simplified (split-flux)	Detailed (Note C-1)	Same as EnergyPlus plus Radiance	Simplified (split-flux)
Number of daylighting sensors per space	2	2	Unlimited (Note C0)	2 (Note D1)	2
Daylighting sensor location within the space	Yes	Yes	Yes (Note C1)	Yes	Yes
Target illuminance levels at the sensor location	Yes	Yes	Yes	Yes	Yes
Continuous dimming control	Yes	Yes	Yes	Yes	Yes
Continuous dimming control input	Allowed	Yes (Note B1)	Yes (Note C2)	Yes	Yes
Step control	Yes	Yes	Yes	Yes	Yes
Maximum number of steps	Not sure	10	Unlimited	10	30
Inputs available for each step	No (Note A1)	Yes (Note B2)	Fraction of input power & lighting output	Same as EnergyPlus	No
Automatic shades for glare control	Yes	Yes (Note B3)	Yes	Yes	No
Daylight obstructions (e.g., furniture, cubicle partitions)	No	Yes	Yes	Yes, if using Radiance	No

Notes:

EnergyPlus

- A1: The reduction in fraction is equally split between steps.

eQUEST

- B1: The inputs include minimum input power and minimum lighting output.
- B2: Fraction of input power and lighting output.
- B3: Based on entered max glare and direction of occupant view.

IESVE

- C-1: Supports point-by-point plus radiosity method, daylight coefficient method, ray-tracing method, fixed sky condition (e.g., standard CIE overcast sky), dynamic sky conditions (e.g., uses cloud cover variables from a weather file), hourly co-simulation link to RadianceIES.
- C0: Unlimited sensors for RadianceIES simulation. Co-simulation link from RadianceIES to energy simulation engine (Apache) uses a maximum of two sensors per room.
- C1: Also includes daylighting sensor direction within the space; accounts for the reflectance of opaque surfaces in addition to the transmittance and reflectance of glazing.

- C2: Min Input Power / Min Lighting Output / Illuminance Target / Formula Control.

Open Studio
- D1: Radiance simulation will use one primary daylight control sensor per space.

Table A5
Energy Storage, On-Site Distributed Generation, Power Distribution, and Elevators

	EnergyPlus	**eQUEST**	**IESVE**	**Open Studio**	**TRACE 700**
Energy Storage					
Hot water storage	Yes	Yes	Yes	Yes	Yes
Chilled water storage	Yes	Yes	Yes	Yes	Yes
Ice or eutectic thermal storage	Yes	Yes	Yes	Yes	Yes
On-Site Distributed Energy Generation					
Photovoltaic	Yes	Yes	Yes (Note C1)	Yes	No
Fuel cell	Yes	No	Yes	Yes	No
Diesel engine w/heat recovery option	Yes	Yes	Yes	Yes	Yes
Steam or gas turbine w/heat recovery option	Yes	Yes	Yes	Yes	Yes
Gas turbine w/heat recovery option	Yes	No	Yes	Yes	Yes
Wind turbine	Yes	No	Yes	Yes	No
Power Distribution					
Stepdown transformers explicitly modeled, including performance at part load	Yes	Yes	No	Yes	No
Power distribution line losses and savings from rightsizing feeders to minimize voltage drop	No	No	No	No	No
Elevators					
Elevators explicitly modeled (hydraulic/traction, mechanical efficiency, motor size and efficiency, etc.)	No	No	Yes	No	No

Note:
IESVE
- C1: Site- and building-specific photovoltaic panel layouts may be specified.

§