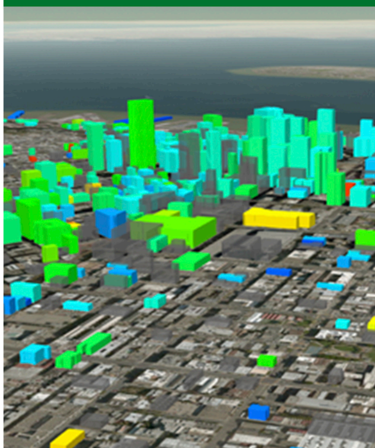
U.S. DEPARTMENT OF ENERGY

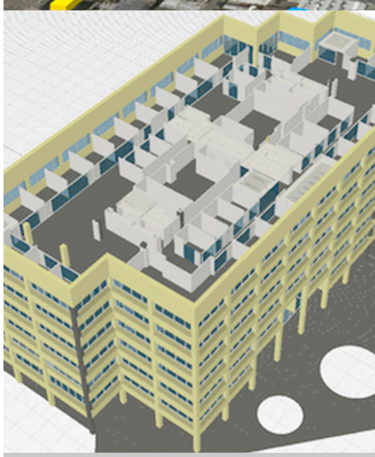
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

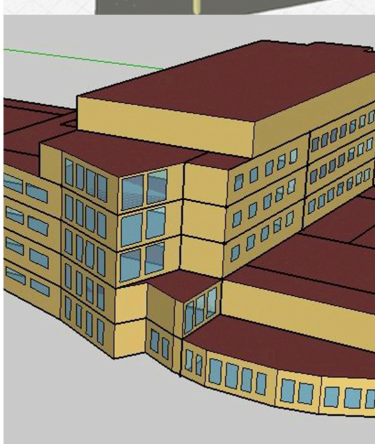
Innovations in Building Energy Modeling

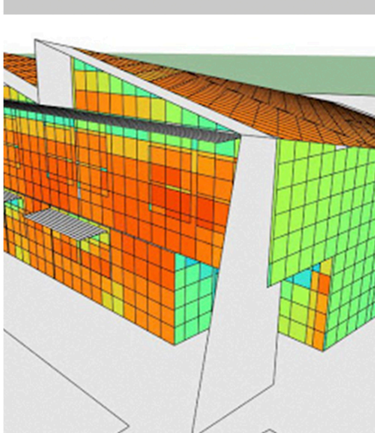
Research and Development Opportunities Report for Emerging Technologies

November 2020









Disclaimer

Acknowledgments

Prepared by Amir Roth, Ph.D.

Special thanks to the following individuals and groups.

Robert Zogg and Emily Cross of Guidehouse (then Navigant Consulting) conducted the interviews, organized the stakeholder workshops, and wrote the first DRAFT BEM Roadmap.

Janet Reyna of NREL (then an ORISE Fellow at BTO) provided extensive feedback on the initial DRAFT BEM Roadmap and helped create the organization for the subsequent DRAFT BEM Research and Development Opportunities (RDO) document.

The IBPSA-USA Advocacy Committee and its leadership collected feedback on the DRAFT BEM RDO document and for continued dialogue with BTO to help address industry and community concerns.

Michael Deru of NREL (then on detail to BTO) helped review, organize, and prioritize the feedback on the DRAFT BEM RDO document.

A final thanks to the many organizations and individuals who provided valuable feedback on both DRAFT documents.

List of Acronyms

AEE	Association of Energy Engineers
AEO	Annual Energy Outlook
AHJ	authority having jurisdiction
AIA	American Institute of Architects
API	application programming interface
BAU	business as usual
BCL	Building Component Library
BCVTB	Building Controls Virtual Test Bed
BDE	Building Data Exchange
BEM	building energy modeling
BEMP	ASHRAE's Building Energy Modeling Professional credential
BESA	AEE's Building Energy Simulation Analyst credential
BIM	building information modeling
BOMA	Building Owners and Managers Association
BPI	Building Performance Institute
BTO	U.S. Department of Energy's Building Technologies Office
CBEA	Commercial Building Energy Association
CBECS	EIA's Commercial Building Energy Consumption Survey
CCx	continuous commissioning
CEC	California Energy Commission
CGDB	Complex Glazing Database
CLI	OpenStudio Command Line Interface
DDx	AIA's Design Data Exchange
DOE	U.S. Department of Energy
DOD	U.S. Department of Defense
EIA	U.S. Energy Information Administration
EE	energy efficiency
EEM	energy efficiency measure

EERE	DOE's Office of Energy Efficiency and Renewable Energy
EMS	energy management system
EPA	U.S. Environmental Protection Agency
ERDA	Energy Research and Development Administration
ESPC	energy savings performance contract
EUI	energy use intensity
FDD	fault detection and diagnosis
FMI	Functional Mockup Interface
FRP	Oak Ridge National Laboratory's Flexible Research Platform
GEB	Grid-interactive Efficient Buildings
GHG	greenhouse gas
GSA	General Services Administration
GSF	gross square footage
HERS	RESNET's Home Energy Rating System
HVAC	heating, ventilation, and air conditioning
IBPSA	International Building Performance Simulation Association
IBPSA-USA	The USA chapter of IBPSA
ICC	International Code Council
IDF	EnergyPlus's Input Data Format
IECC	International Energy Conservation Code
IGDB	International Glazing Database
LEED	U.S. Green Business Council's Leadership in Energy and Environmental Design credential
LBNL	Lawrence Berkeley National Laboratory
MHEA	Mobile Home Energy Audit
MPC	model predictive control
MulTEA	Multifamily Tool for Energy Auditing
MYPP	BTO's Multi-Year Program Plan
M&V	measurement and verification
NEAT	National Energy Audit Tool

NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
NZERTF	net-zero energy research test facility
ORNL	Oak Ridge National Laboratory
OSM	OpenStudio Model
OSW	OpenStudio Workflow
PAT	OpenStudio’s Parametric Analysis Tool
QA	quality assurance
R&D	research and development
RECS	U.S. Energy Information Administration’s Residential Energy Consumption Survey
RESNET	Residential Energy Services Network
RMI	Rocky Mountain Institute
SDK	software development kit
SEED	Standard Energy Efficiency Data Platform
SEER	Seasonal Energy Efficiency Rating
TPEX	BTO’s Technology Performance Exchange
TRACE	Trane Air-Conditioning Economics
USGBC	U.S. Green Buildings Council
VRF	variable refrigerant flow

Report Purpose, Scope, and Approach

Building energy modeling (BEM) is a multipurpose tool for building energy efficiency (EE). The U.S. Department of Energy Building Technologies Office (BTO) seeks to expand the use and effectiveness of BEM in the design and operation of commercial and residential buildings with the goal of achieving lasting reductions in total and peak energy use. This report identifies gaps and outlines recommended initiatives to achieve this goal, based on a combination of technical analysis and stakeholder input. In addition to BTO, this report can benefit BEM professionals (architects, mechanical engineers, energy consultants, building auditors, equipment manufacturers, and BEM software vendors) and BEM clients (building owners and operators, EE program administrators, EE service providers, policymakers, and policy and code jurisdictions such as states and cities).

This report was developed in two phases. In the first, BTO worked with a team from Navigant Consulting (now Guidehouse) to characterize objectives, opportunities, and current activities; identify gaps and barriers; and define initiatives. To collect input, Navigant conducted telephone interviews and workshops with industry experts. The initial phase produced a draft report, which was released for public review in 2016 and yielded over 400 comments.

Based on these comments, BTO compiled a second draft report that addressed many of those comments while acknowledging changes that had occurred both at BTO and in the industry. Unlike the first draft report, the second focused much more heavily on BTO's own role, portfolio, and activities. BTO is a direct player in the BEM field—it funds the development of several significant software packages that are embedded in commercial products—and transparency about its goals and future plans is requisite. BTO recognizes that a great number of other public and private organizations contribute to the BEM enterprise. With the second draft report, BTO did not attempt to produce a blueprint for the industry as a whole, but rather a working document BTO can use to iteratively solicit stakeholder input and synthesize it into a program.

BTO released the second draft report for public review in 2019. The second round of review generated 83 pages of feedback and comments—almost exactly the length of the draft report itself—a significant portion of which was collected and synthesized by IBPSA-USA Advocacy Committee. This final report incorporates this feedback.

This report does not address the use of BEM in support of building-based grid services, a recent BTO initiative called Grid-interactive Efficient Buildings (GEB). In 2019, BTO published a report that specifically addresses the role of BEM—and other "integration" technologies—in GEB (Roth and Reyna 2019).

Executive Summary

The U.S. Department of Energy (DOE) Building Technologies Office (BTO) seeks to achieve significant and lasting reductions in energy use in U.S. commercial and residential buildings. Deep and sustained savings reduce consumer costs, help mitigate grid stress and improve reliability, and support building and system resiliency.

As one of the means to achieve this larger goal, BTO seeks to increase the use of building energy modeling (BEM) both in the design and operation of individual buildings, but also in activities that support building EE, including EE code development, EE program management, product design, research, and education. BTO has pursued this goal and invested in BEM since before DOE rose to the status of a cabinet-level department. Currently, BTO develops the open-source BEM engine EnergyPlus®, the open-source BEM software development kit (SDK) OpenStudio®, and funds and directs a number of other initiatives. A complete listing of BTO's current activities in BEM is available on BTO's BEM subprogram webpage.[1]

Despite progress in recent years, use of BEM is still far from saturated, especially in individual building applications. Stakeholders estimate that BEM is used to design only about 20% of new commercial and residential floor area.

This report identifies barriers to increased effective use of BEM in building EE applications, and suggests BTO initiatives to address them. These were developed using both technical analysis and input from stakeholders, including BEM practitioners such as architects, mechanical engineers, sustainability consultants, energy auditors, and code and rating officials; BEM clients such as building owners, EE program administrators, and policymakers; BEM software developers; heating, ventilation, and air-conditioning (HVAC) equipment manufacturers; researchers; and educators.

This report organizes barriers and initiatives into six aspects:

- Predictive accuracy and consistency
- Core modeling capabilities
- Interoperability and workflow automation
- Data ecosystem
- Education and professional support
- Market and value proposition.

Table ES-1 follows this structure and lists some of the barriers and initiatives. These are explored in more detail in Sections 3 through 8.

[1] For more information, please see https://energy.gov/eere/buildings/building-energy-modeling/.

Table ES-1. Barriers to Increased BEM Use and BTO Initiatives Designed to Address Them

Topic	Barriers	BTO Initiatives
Predictive Accuracy and Consistency	Predictive BEM is challenging. At the same time, the inherent error of BEM engines is not quantified and separated from input uncertainty, creating the perception that the BEM enterprise is built on shaky tools. BEM engines are currently tested against one another and analytical results rather than validated against ground truth, which reinforces this perception.	Support empirical validation of BEM engines using well-characterized and instrumented test facilities such as Lawrence Berkeley National Laboratory's (LBNL's) FLEXLAB and Oak Ridge National Laboratory's (ORNL's) Flexible Research Platform (FRP).
		Support the expansion of ASHRAE Standards 140 and 229P for testing and validation of BEM engines and rulesets.
		Support development and use of methods for model input calibration.
Core Modeling Capabilities	Incomplete support for co-simulation and inflexibility in some key inputs make it difficult to incorporate EnergyPlus into larger analyses (e.g., neighborhood- and urban-scale BEM).	BTO should continue to emphasize support for co-simulation and input and output flexibility and give preference to these approaches over adding functionality to EnergyPlus proper.
	EnergyPlus's monolithic structure makes it difficult to reuse its component models as building blocks in other tools and analyses.	Emphasize making selected EnergyPlus modules available as libraries and on increasing the use of libraries within EnergyPlus.
Interoperability and Automation	Building information modeling (BIM)-to-BEM geometry translation is not robust, requiring modelers to fix up geometry in the BEM tool or recreate it from scratch.	Support research to develop fundamentally sound methods and rules for translating 3D BIM geometry to 2.5D BEM geometry. Develop standard test suites to test translation and export. Collaborate with design model authoring tool vendors to improve BIM-to-BEM translation and export to help designers create analyzable models.
	Many BEM procedures that surround and complement the basic physics simulation can be automated. Although automation is proliferating, testing and certification of this subset of BEM software is lagging, leading to inconsistencies and suppressing use, especially in regulatory or financial use cases.	Leverage standard output and reporting exchanges, and to the degree possible, input exchanges to develop testing and certification frameworks for BEM rulesets.
		Promote use of open scripting frameworks for automation of BEM rulesets and general workflow integration.
	Multiple vendors have invested in direct integration with EnergyPlus, bypassing OpenStudio.	Improve EnergyPlus application integration features to assist vendors who access EnergyPlus directly.

Data Ecosystem	The Residential Energy Consumption Survey (RECS) and Commercial Building Energy Construction Survey (CBECS) data sets that are used as the basis for determining default values and assumptions for building asset and operation inputs and benchmarks for energy use are not updated and analyzed quickly enough and have insufficient detail and granularity.	Leverage BTO building energy data projects such as SEED™ (the Standard Energy Efficiency Data platform), BuildingSync®, Home Energy Score/Asset Score, and ResStock™/ComStock™ to complement RECS and CBECS with more detailed asset, operational, and energy use data that can be used to develop more current and granular default assumptions and values for BEM projects.
	Outdated detailed performance data for fans, coils, chillers, and other HVAC equipment.	Support ASHRAE in expanding Standard 205P.
	TMYx weather data is not representative of weather likely to be encountered by buildings throughout their service lifetimes.	Evaluate methodologies for creating future weather data from climate projection models. Promote the use of future weather data in design and retrofit BEM applications.
Education and Professional Support	Educational offerings are sparse. Few architecture or engineering programs offer BEM as part of an architecture or engineering curriculum.	Continue collaboration with IBPSA to support participation of students and young professionals in BEM conferences, technical meetings, and design competitions.
		Consider awarding graduate fellowships for BEM research.
		Work with ASHRAE and IBPSA to develop tool-agnostic training content for building physics and HVAC.
	The Building Energy Modeling Professional (BEMP) certificate is under-subscribed with only 370 certified professionals in the United States. BEMP is not required by any program or procurement.	Support ASHRAE in developing and administering the BEMP credential. Use stakeholder networks to promote BEMP requirements in projects and procurements.
Market and Value Proposition	Lack of evidence and analysis that shows how much energy savings should be attributed to BEM as opposed to factors such as engineering judgement or simpler calculations.	Leverage the American Institute of Architects' AIA 2030 DDx (Design Data Exchange) to establish longitudinal correlations between BEM and project performance and cost.
		Conduct a rigorous classical performance attribution for BEM in integrated design and perhaps other use cases.
	ASHRAE Standard 209 is new and not widely referenced or required.	Promote an ASHRAE Standard 209 requirement in federal projects and more generally via BTO's network of stakeholders including Better Buildings.

	Common BEM use cases like code-compliance and even conventional building design do not place inherent value on BEM.	Use stakeholder networks to promote use cases that place inherent value on BEM, including energy savings performance contracts (ESPCs), outcome-based codes, and net-zero design.

In addition to these, we recommend that BTO implement the following programmatic initiatives:

Table ES-2. Recommended BTO BEM Subprogram-Level Initiatives

Programmatic Initiatives
Perform public program-level reviews of BTO's BEM portfolio at regular intervals, e.g., every three years.
Refresh this report at regular intervals, perhaps aligning with BTO BEM program review, and solicit public comment.
Continue dialog and collaboration with IBPSA-USA Advocacy Committee to gather higher frequency feedback.

Table of Contents

List of Figures

List of Tables

1 Building Energy Modeling and Its Use Cases

Buildings use 39% of energy consumed in the United States and 70% of the electricity (EIA 2020). To reduce building energy use, building industry professionals use building performance analysis tools to evaluate individual energy efficiency measures (EEMs) and entire designs. Building energy modeling (BEM) is the most sophisticated of these analytical tools. For this report, BEM is defined as a physics-based simulation that, at a minimum:

- Accounts for thermal loads based on climate, envelope characteristics, lighting, occupancy, other internal processes such as cooking or computing, infiltration, and ventilation rates
- Uses these loads and system constraints and rules to deduce the actions of the heating, ventilation, and air-conditioning (HVAC) system and calculate net impact on interior thermal conditions
- Accounts for energy use of all common major building systems including HVAC, lighting, service water heating, refrigeration, plug and process loads, and on-site generation and storage
- Accounts for thermal interactions among building systems
- Performs calculations at an hourly (or finer) time step
- Tabulates and reports energy consumption by end-use and fuel type.

BEM plays a variety of roles in building energy efficiency (EE). BEM provides insight about whole-building energy performance that is not readily attainable by metering and measurement, e.g., interactive effects of EEMs. It also supports modes of comparison that are difficult to set up in the physical world, e.g., comparison under identical weather and operating conditions. Quantitative estimates of relative efficiencies of different design alternatives, energy and cost savings associated with particular EEMs, and calculation of annual and peak energy requirements provided by BEM are essential to actors such as architects, engineers, building owners, utilities, manufacturers, and policy makers.

BEM supports a diverse set of applications and use cases that we divide into two categories. Use cases—including new construction and retrofit design, code compliance, green certification, measurement and verification (M&V), and model predictive control—apply to specific buildings. Use cases like code development, EE program development, the development of prescriptive guidelines, and product development apply to building stocks and typically use prototype models. Of course, specific and prototypical buildings represent a continuum, which an emerging set of applications leverages; an application may start with a prototypical model and slowly morph or calibrate into a specific model as more information about the specific building is acquired. However, for the purposes of this discussion, the specific-prototypical distinction is helpful.

1.1 Specific Building Use Cases

Performance documentation. The most intuitive BEM use case is building design, but the most common one is performance documentation, sometimes called "compliance" or "LEED"[2] modeling. Performance documentation uses BEM to isolate the inherent performance of a building from the effects of occupancy, operation, and weather by using standard typical values for these inputs. This methodology—which has the added benefit of working even before the building is built—is used to demonstrate compliance with code and to demonstrate "above-code" performance levels for certificates like LEED or for EE incentives from utilities and states.

Building EE codes include a checklist-based prescriptive compliance path. Many also include a BEM-based "performance" compliance path that provides more design-tradeoff flexibility than the prescriptive path. The performance-path compliance procedure typically involves comparing simulation results from two models: (1) the proposed (or actual) building, and (2) a minimally compliant "baseline" version of the proposed (or actual) building that is derived from the latter by the mechanistic application of prescriptive rules. Both versions are simulated under the same operational and weather assumptions. ASHRAE Standard 90.1, "Energy Standard for Buildings Except Low-Rise Residential Buildings," has two performance paths: "Energy Cost Budget" for compliance and the "Performance Rating Method," commonly known as Appendix G, for both compliance and above-code performance calculations. Historically, each version of the code has tightened the prescriptive rules, e.g., required higher levels of insulation or greater equipment efficiencies. Starting with the 2016 update, the prescriptive baseline remains fixed at 2004 levels and updates raise the required percent improvements over this fixed baseline.[3] This new setup effectively mandates performance-path compliance. Other EE standards with performance-based compliance paths include ASHRAE 189.1 "Design of High-Performance Green Buildings," the International Code Council's (ICC) International Energy Conservation Code (IECC) and International Green Construction Code (IgCC), the California Energy Commission's (CEC) Title 24, and the codes of states and local jurisdictions.

Rating, certificate, and incentive programs use this two-simulation self-comparison method to calculate performance relative to code, and determine certificate and incentive levels. The U.S. Green Buildings Council's (USGBC) LEED-NC[4] Energy and Atmosphere Credit 1 is based on ASHRAE 90.1 Appendix G. The Residential Energy Services Network's (RESNET's) Home Energy Rating System (HERS) is based on IECC's Energy Rating Index (ERI)[5] self-comparison procedure. Note that not all rating systems are based on self-comparison procedures. ASHRAE's Building Energy Quotient (bEQ), the U.S. Department of Energy's (DOE's) Home Energy

---

[2] LEED is the U.S. Green Business Council's Leadership in Energy and Environmental Design certificate.
[3] ASHRAE 90.1-2016 Addendum BM unifies the performance paths by allowing Appendix G to be used for code compliance.
[4] Note that NC stands for New Construction.
[5] https://www.energycodes.gov/resource-center/training-courses/2015-iecc-energy-rating-index-eri-compliance-alternative

Score,[6] and the Commercial Energy Asset Score[7] use a single-model approach, simulating the building under standard operation and weather assumptions and mapping the simulated energy use intensity (EUI) to a predetermined scale.

Because they typically take place at the end of a design project, compliance and LEED modeling do not inform design or improve building EE. However, they have been primary drivers for increased use of BEM.

Integrated design. BEM impacts building EE most directly when it is used to actively inform design of new buildings and major renovations. Integrated design uses BEM to evaluate multiple design strategies for reducing loads, achieving EE, maintaining comfort, and minimizing capital costs.[8] To do so effectively, BEM must be used early in the design process and regularly thereafter as the design evolves. ASHRAE Standard 209, "Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings," attempts to codify this process.[9] Integrated design is not required to achieve high levels of EE. Note that an EE building can be designed in a serial way and without BEM by using highly insulating constructions, small and efficient windows, minimal and efficient lighting, and minimally sized and maximally efficient HVAC equipment. The resulting building will be EE, but also expensive to build and potentially uncomfortable to occupy. BEM-driven integrated design is needed to quantify EE and occupant comfort and balance these against cost and other constraints. Unfortunately, integrated design is not commonplace and has not been a driver for BEM.

Common practice likely falls somewhere on the spectrum between no BEM or end-of-project BEM for compliance documentation and full-blown integrated design, with models created at several points throughout the project to track performance against a target.

Integrated operation. Even less common than integrated design is BEM-aided operation. There are several ways in which BEM can also help buildings operate more efficiently. Building performance degrades over time. Equipment wears out or breaks. Ducts and envelope components crack and leak. Insulation settles. Sensors drift. Occupants and operators override or counteract design intent. BEM can be used to maintain design performance via a process called continuous commissioning (CCx), in which actual building performance is compared to simulated building performance in real time and discrepancies are investigated. BEM can also help improve building performance beyond original design levels by dynamically optimizing building operations—and operating costs—in response to occupancy changes, weather forecasts, and grid conditions in an application called model predictive control (MPC).

[6] https://betterbuildingssolutioncenter.energy.gov/home-energy-score/
[7] https://buildingenergyscore.energy.gov/
[8] Case studies from USGBC/Green Building Certification Institute with scorecard credit for LEED EAc1 (see http://www.usgbc.org/projects) provide examples of projects where BEM tools were integrated into the design process to help produce low-energy design options.
[9] https://www.ashrae.org/about/news/2018/ashrae-publishes-energy-simulation-aided-design-standard

BEM applications in building operations, like fault detection and diagnosis (FDD) and CCx, benefit from calibrated models, i.e., models whose inputs have been aligned to the extent possible with actual conditions in the building. The increasing availability of granular energy use data—e.g., interval meter and submeter data as well as data from thermostats and other sensors—aids model input calibration.

Measurement and verification (M&V). BEM also supports EE by helping to document and value it. Calibrated BEM is an accepted method for M&V of the realized energy savings of various EEMs. M&V protocols and guidelines include ASHRAE Guideline 14, "Measurement of Energy and Demand Savings,"[10] Energy Valuation Organization's International Performance Measurement and Verification Protocol (IPMVP),[11] the National Renewable Energy Laboratory's (NREL's) Uniform Methods Project (UMP),[12] and DOE's Federal Energy Management Program's (FEMP) M&V Guidelines.[13]

1.2 Prototypical Building Use Cases

Prescriptive codes and guidelines. Behind any program that uses BEM to document performance for specific buildings, extensive BEM on prototype models was first used to establish the target performance levels. BTO has created prototype models for commercial[14] and residential[15] buildings and these—weighted with floor area multipliers—are used to represent entire building stocks. EE codes like ASHRAE Standard 90.1 are updated by analyzing the results of prototypical BEM experiments to identify prescriptive requirements and performance levels that can be implemented cost-effectively.

Above-code prescriptive guidelines and performance levels are established in similar ways. One example is ASHRAE's Advanced Energy Design and Retrofit Guides,[16] which provide building type and climate zone specific design recommendations for achieving 30% and 50% savings over ASHRAE Standard 90.1-2004. Other examples include "deemed" ("average" or "expected") savings for EEMs in utility EE programs, the LEED EAc1 point scale and the Home Energy Score and Commercial Building Energy Asset Score scales.

Prototypical, prescriptive BEM applications like standards, design guides, and deemed savings calculations provide less insight and precision than specific-building BEM because they rely on prototypical, generic assumptions for inputs such as space planning, occupancy, plug loads, and even geometry rather than on information specific to the project. However, they ensure a minimal level of performance while saving the designer the effort and cost of creating a model (or maybe several models).

---

10 http://webstore.ansi.org/RecordDetail.aspx?sku=ASHRAE+Guideline+14-2014
11 http://www.evo-world.org/index.php?option=com_rsform&formId=113&lang=en
12 http://www.nrel.gov/extranet/ump/draft_protocols.html
13 http://www.energy.gov/sites/prod/files/2016/01/f28/mv_guide_4_0.pdf
14 https://www.energycodes.gov/development/commercial/prototype_models
15 https://www.energycodes.gov/development/residential/iecc_models
16 http://www.ashrae.org/standards-research-technology/advanced-energy-design-guides

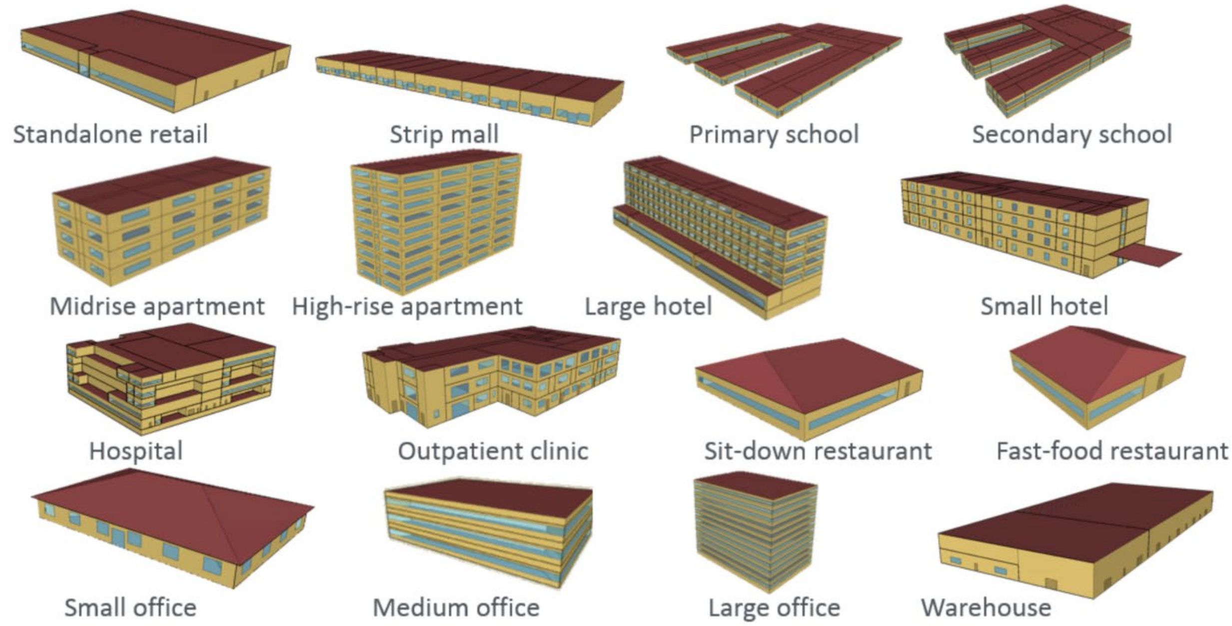


Figure 1. DOE commercial prototype building models

Program and product design. Utilities use BEM to develop deemed savings values to incentivize simple EEMs. But more so than calculating individual savings values, utilities use prototypical BEM to develop entire EE programs covering multiple EEMs, EEM packages, and even custom projects. Utility EE programs are often regulated, required to procure a certain quantity of EE for a certain sum of money. BEM is used to optimize the program portfolio by helping to estimate how much individual EEMs will save and what incentive levels are required to make them cost-effective and attractive to customers. Utilities also use BEM as part of the evaluation, measurement, and verification (EM&V) to demonstrate these savings to regulators.

Companies design products and services in a similar way, using BEM to establish product performance targets, calculate energy savings for typical buildings, and derive cost premiums that would make high-performance products cost competitive.

Finally, BTO itself uses prototypical BEM to inform its portfolio of technologies and programs, which is aimed at cost-effectively meeting its congressionally mandated EE targets. Prototypical BEM is used to characterize the energy savings associated with existing, emerging, and future technologies at the building-type, climate zone, and end-use level. A tool called Scout[17] combines these with cost, lifetime, year-of-market-introduction, and adoption assumptions in a stock-and-flow simulation to identify high-impact technologies and desired performance, cost, and time-to-market characteristics.

[17] https://scout.energy.gov/

1.3 Relationship Between Specific and Prototypical Use Cases

Table 1 summarizes the specific-building BEM use cases and corresponding prototypical building use cases.

Table 1. Specific-Building BEM Use Cases and Corresponding Prototypical Building Use Cases

Specific Building Use Cases	Prototypical Building Use Cases
Performance path code compliance	Development of prescriptive and performance code requirements
Integrated design	Development of prescriptive design guides
Performance documentation for asset ratings and green certificates	Determination of asset rating and green certificate performance levels
Performance documentation for EE program incentives	Deemed savings calculations and EE program design
Measurement and verification (M&V)	
MPC, FDD, and CCx	Design and testing of high-performance control sequences and MPC, FDD, and CCx algorithms
	Product design
	Research
	Education

The EUI "waterfall" diagram in Figure 2 shows how some of these use cases conceptually relate to each other and contribute to overall building EE. The EUI axis is intentionally left unscaled because impacts vary greatly by building type, climate zone, project delivery method, and many other factors, and are generally not well quantified. The percentages in parentheses under each use case represent the contribution of BEM to those use cases and are guesses. Finally, the location of the operational BEM applications is also somewhat arbitrary relative to the design BEM applications. FDD, CCx, and MPC can be applied to buildings of any performance level.

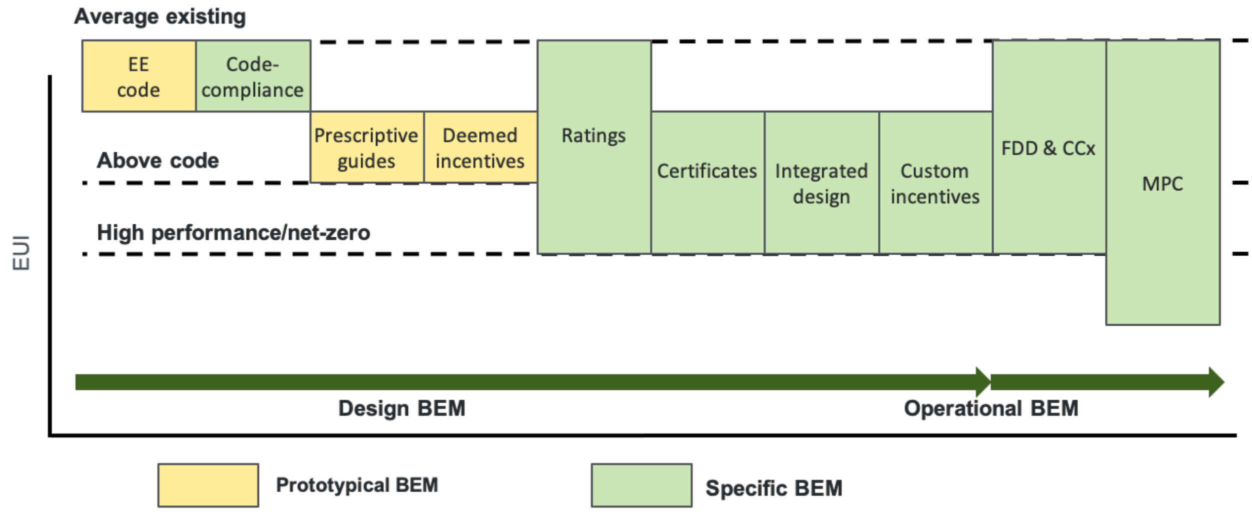


Figure 2. Performance attribution of BEM use cases

For a new construction project, standard practice in the absence of a prevailing EE code would result in a certain EUI represented by the "average existing" dashed line. An EE code would result in somewhat lower EUI represented by the "code level" dashed line. BEM gets some of the credit for the development of the EE code—50% is a guess—and some for code-compliance—50% is the guess here too because BEM gets 100% of the credit for performance path compliance and 0% for prescriptive path compliance. Additional EUI reductions can be achieved by using prescriptive guides; again, BEM gets some credit for its role in developing this guidance. Even greater reductions are possible when BEM is used in a project-specific capacity to inform integrated design; BEM gets most of the credit here, 90%, because it is a necessary component in this process. BEM is also a significant component of green certification, although green certification on its own does not reduce EUI.

Building performance naturally degrades over time as insulation settles, seals leak, equipment wears out, sensors drift, and actuators stick—this performance level is shown by the dashed line "degraded performance." BEM applications like FDD and CCx can help restore building performance to design levels by identifying failures and quantifying their energy and financial costs. BEM can improve building performance beyond design level by dynamically optimizing control in response to actual occupancy and use conditions along with short-term weather predictions. Where used, BEM is a critical piece of these applications. Again, the placement of these BEM applications in the performance waterfall relative to design applications is arbitrary; they can be applied to buildings of any performance level, not just high-performance buildings.

One point of note from the waterfall is that prototypical BEM use cases are concentrated in the design stages and are generally associated with higher EUI targets, i.e., lower performance levels.

Differences between specific and prototypical use cases. One meaningful difference between these categories is the number and type of professionals that perform them. Specific BEM is done by a relatively large number of professionals in professions such as architecture, mechanical engineering, energy consulting, and building energy auditing, and spanning a range of skill and experience levels. Prototypical BEM is performed by a smaller number of typically more experienced professionals. To use a BTO-relevant example, national laboratory researchers only do prototypical BEM—they analyze code updates and develop control algorithms, but do not design new buildings.

Different use cases and different kinds of users place different requirements on BEM software. BEM software targeted at specific-building use cases and a broader range of users needs to be fast, user-friendly and well-integrated with other software tools and workflows those professions use. User-friendliness is less important to expert users performing large-scale prototypical BEM analysis. Large-scale prototypical BEM analysis is also not integrated with other workflows and requires high computing bandwidth but is less sensitive to speed of individual runs. At the same time, prototypical BEM use cases like code development, program design, and research require transparency, advanced capabilities, and often the ability to develop experimental new functionality. These are less important for BEM software that targets specific buildings.

As with everything, prototypical and specific BEM represent a continuum. Some use cases and workflows may hybridize the two, e.g., start with a prototype model and then evolve it incrementally to represent a specific building as relevant information is acquired.

2 BTO's BEM Program

BTO's Multi-Year Program Plan (MYPP) sets goals for the use of BEM in integrated design, the use case that leads to deepest energy savings (BTO 2016). BTO also seeks to establish BEM in applications such as control design, while continuing to support traditional prototypical BEM use cases like code and EE program development, product design, and research.

2.1 Role of Government and Software Development Philosophy

BTO's current strategy for achieving its BEM goals includes the development, maintenance, and support of an open-source, state-of-the-art BEM platform consisting of the EnergyPlus engine, the Spawn engine, and the OpenStudio™ software development kit (SDK). These packages directly support prototypical BEM applications like code development, program design, product design, and research. They also indirectly support specific BEM use cases like integrated design, code compliance, and LEED. To support the latter, BTO relies on third-party vendors to incorporate its BEM platform, in part or as a whole, into use-case-specific tools, and to train and support the respective end-user communities.

BTO's status as a direct player in the BEM marketplace is unusual. It is enabled by the economies of scale of software production, specifically that the cost of software development is largely fixed and independent of the number of copies of the software that are subsequently distributed. It is motivated by prototypical BEM use cases like code development and deemed savings calculations where transparency, impartiality, and advanced (sometimes experimental) functionality are important. There are also significant historical and inertial components. The positioning of BTO BEM tools as shared public goods—reinforced by the 2012 re-release of those tools as open-source software—has influenced the evolution of the BEM industry, pushing some third-party vendors away from engine development and toward application integration, simulation services, and user support. At this point, no single actor seems prepared to step in and replace BTO's annual investment in BEM engine development—around $4.5 million per year since 2012, initially devoted entirely to EnergyPlus but more recently split between EnergyPlus and Spawn—much less while keeping that engine open-source. Although reduced diversity in the BEM engine space is a negative consequence, benefits include greater consistency, improved capabilities for a larger number of users, and greater investment in integration and deployment resulting in overall growth in the BEM market. To clarify its position and minimize competition with commercial BEM vendors, BTO has developed the following strategy:

- **Shared, core, state-of-the-art capabilities.** BTO software provides advanced capabilities that support existing and new use cases.
- **Minimal end-user applications and relationships.** BTO leaves end-user application and service development and end-user support to market actors. BTO has historically not followed this position, most notably by developing and distributing the graphical OpenStudio Application. In August 2018, BTO announced that it will cease funding the

OpenStudio Application in April 2020.[18] OpenStudio 3.0.0[19] does not include the OpenStudio Application. The application now exists in its own repository[20] and can be cloned and carried forward by interested third parties.

- **Commercial-friendly open-source licensing.** BTO software can be embedded into other software in part or as a whole, modified in proprietary ways, and relicensed with no “downstream” obligations, supporting a variety of business models.
- **Commercial-grade development and support.** Commercial vendors do not pay to use EnergyPlus and the OpenStudio SDK and do not receive formal quality and service guarantees, but need commercial-grade robustness and support. BTO uses state-of-the-art development and testing methods and tools to provide the reliability necessary to support derivative commercial products and services.
- **Long-term commitment.** BTO is committed to supporting its software portfolio for the long-term to enable existing and prospective client vendors to conduct long-term business planning.

2.2 Project Portfolio

Current and (recent) past projects funded by BTO’s BEM subprogram are listed at: https://energy.gov/eere/buildings/building-energy-modeling-project-portfolio.

History: DOE-2 and EnergyPlus. DOE’s support of BEM predates its status as a cabinet-level agency. In 1971, the U.S. Postal Service developed the “Post Office Program” to analyze energy use in post offices. In 1977, the national Energy Research and Development Administration (ERDA), along with the CEC, developed the first government-funded whole-building energy modeling tool called CAL-ERDA. CAL-ERDA was based on the Post Office Program and included multiple new sections, including a building description language to simplify input. Shortly thereafter, ERDA was merged with the Federal Energy Administration and Federal Power Commission to become the modern DOE, and the CAL-ERDA program was renamed DOE-1. DOE continued developing DOE-1 and its successor DOE-2 for the next 15 years.

In the early 1990s, the Electric Power Research Institute (EPRI) and J. J. Hirsch and Associates began development of DOE-2.2 and secured the rights to distribute it. Rather than continuing with overlapping development of DOE-2.1, DOE rebooted its BEM program around the Department of Defense’s (DoD) Building Loads Analysis and System Thermodynamics (BLAST) program, looking to develop a modular engine based on physical first principles that would be easier to update and maintain and would include many new features. The rights to this new engine, named EnergyPlus, would be held jointly by the Regents of the University of California, (the operators of Lawrence Berkeley National Laboratory [LBNL] and the rights

[18] https://www.openstudio.net/new-future-for-openstudio-application
[19] https://github.com/NREL/OpenStudio/releases/tag/v3.0.0
[20] https://github.com/NREL/OpenStudioApplication/

holders to DOE-2.1E) and by the Regents of the University of Illinois (holders of the rights to BLAST). BTO began EnergyPlus development in 1996 and released the first version in 2001. BTO has continued to develop EnergyPlus, releasing updates every six months.[21]

In January 2012, BTO re-released EnergyPlus (then v7.0) under a permissive open-source license, allowing companies greater freedom to modify the code and incorporate it into products. Enabled by this license, in 2013 Autodesk Corporation led work to translate EnergyPlus source-code from FORTRAN to C++, donating the translated code back to BTO. BTO released the first C++-based EnergyPlus version (v8.2) in September 2014, and has since worked with this code-base exclusively.

Historically, EnergyPlus had been missing several capabilities key to modeling residential buildings. In 2014, BTO began shoring up these areas with the expectation of unifying its own BEM portfolio around EnergyPlus and OpenStudio, and establishing EnergyPlus as a credible tool for residential BEM applications. In March 2017, BTO transitioned its BEopt™ residential modeling software to EnergyPlus v8.7 and currently plans to transition its Home Energy Score software to EnergyPlus as well.

OpenStudio. Computer systems tend to follow a three-layer organization. The bottom layer is an engine that provides basic computing capabilities. The top layer consists of applications that provide use-case-specific functionality and interact with end users or one another. The middle layer, appropriately called "middleware," provides abstractions and services on top of the engine and facilitates application development and maintenance. The three layers are separated by stable application programming interfaces (APIs) that allow layer implementations to evolve separately. An operating system like Microsoft Windows is an example of successful middleware. Windows provided useful programming abstractions, allowing application developers to read and write files and insulating them from the particulars of disk management, for instance. In doing so, Windows ushered in a wave of new applications and fostered competition among engine (i.e., PC) manufacturers.

For many years, the BEM industry evolved without middleware. Vendors developed applications that were tightly coupled to engines (e.g., eQuest for DOE-2.2). This "stove-pipe" model likely contributed to the slow rate of evolution of BEM in comparison to other software technologies. More significantly, the tight coupling precluded the reuse of engines in other applications, e.g., the TRACE engine could not be pulled out of the TRACE application and embedded into an auditing tool. In this environment, BTO focused on engine development and relied on third parties to develop applications around them. This strategy was slow to materialize because of a combination of factors, including low demand for EnergyPlus's advanced modeling capabilities,

[21] Early history based on LBNL website information (http://eetd.lbl.gov/newsletter/cbs_nl/nl18/cbs-nl18-energyplus.html) and the Building Energy Modeling Body of Knowledge (BEMBook) website (http://www.bembook.ibpsa.us/index.php?title=History_of_Building_Energy_Modeling)

EnergyPlus's low level of technical maturity and stability relative to more established engines, its slow execution speed, and the high cost of developing applications for it.

In recent years, several of these factors have changed. As energy codes have become more stringent, green certificates like LEED have gained adoption, and programs like the American Institute of Architects' AIA 2030 have expanded, demand for modeling in general and for advanced modeling features more specifically has grown. EnergyPlus itself matured and stabilized. And BTO began investing in the OpenStudio SDK to reduce effort and improve the value proposition of EnergyPlus application development. OpenStudio was originally developed by NREL as an EnergyPlus geometry plug-in for the SketchUp 3D drawing program. Beginning in 2009, NREL re-architected OpenStudio into an open-source SDK and turned the SketchUp plug-in into an SDK client application.

EnergyPlus uses files for input and output. The OpenStudio SDK wraps EnergyPlus inputs and outputs with a dynamic, object-oriented data model that allows developers to incrementally access EnergyPlus inputs and outputs by calling functions—this is often referred to as an API. Programmatic access is faster and more convenient than file-based access. It also improves compatibility—a well-designed API can remain unchanged while the underlying file interface evolves. Most importantly, the right API can significantly improve development productivity. In addition to access to basic inputs and outputs, the OpenStudio API provides higher-level abstractions that do not exist within EnergyPlus. For instance, EnergyPlus does not have internal concepts of "space" and "space type," which are important in many applications, including standards.[22] OpenStudio has internal space and space type representations, and allows applications and users to work in those terms before translating that information to zone-level concepts EnergyPlus expects. In addition to access to individual objects and attributes, OpenStudio also includes high-level functions that manipulate multiple objects together in a consistent way, further enhancing development productivity. It also provides features model import and merging from schema such as Green Building XML (gbXML)[23] and Home Performance XML (HPXML)[24] and export to other engines, including ESP-r and CEN/ISO 13790.

The three-layer architecture created by the OpenStudio SDK has accelerated the pace of EnergyPlus application development and adoption. BTO began funding OpenStudio in 2011 and in 2012 reoriented its BEM deployment strategy around the OpenStudio platform. BTO began migrating its existing projects onto OpenStudio and encouraging third-party vendors who were developing EnergyPlus applications to target the OpenStudio SDK instead. Figure 3 conceptually shows the three-layer architecture of BTO's BEM software.

[22] The EnergyPlus development team is currently adding these abstractions to EnergyPlus.
[23] https://gbxml.org/
[24] https://hpxmlonline.com/

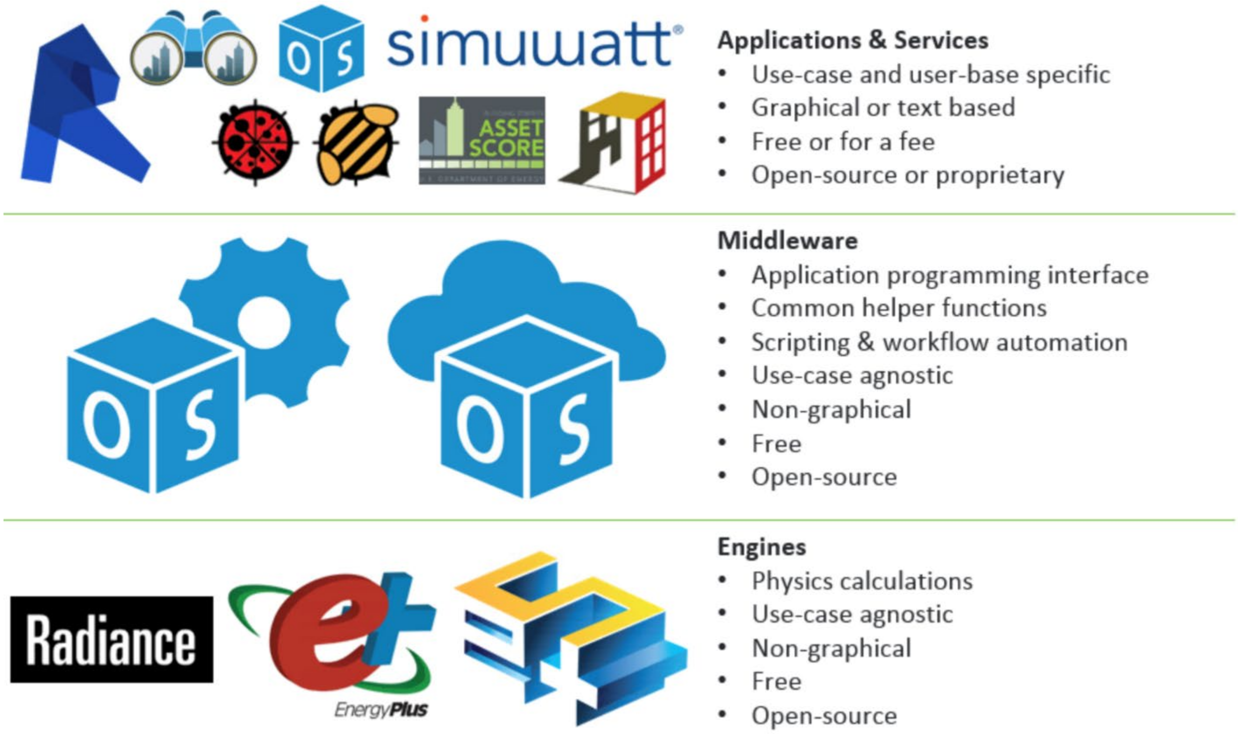


Figure 3. BTO BEM software architecture and ecosystem

Table 2 lists current non-BTO tools that use EnergyPlus, either directly or via OpenStudio. Most recently developed tools have leveraged OpenStudio, and several vendors that started along the direct EnergyPlus path are in the process of transitioning to OpenStudio-based development.

Table 2. Non-DOE BEM Tools That Use EnergyPlus and OpenStudio

Developer	Tool	Comments
Uses EnergyPlus Directly		
Autodesk	Insight 360	Revit and FormIt addition for automated background energy analysis on the cloud: https://insight360.autodesk.com/
Bentley Systems	AECOSim	Full-featured Windows interface, also supports ASHRAE 90.1 code-compliance: http://www.bentley.com/en-US/Products/AECOsim/
Big Ladder Software	District Zero	Energy, waste, and water community and district planning tool
Big Ladder Software	Modelkit/ Params	Embedded-Ruby template system for rapid EnergyPlus input file creation: https://bigladdersoftware.com/projects/modelkit/
Bractlet	Bractlet Intelligence Platform	EnergyPlus-based "digital twin" that supports operational optimization and capital upgrades: http://bractlet.com/
DesignBuilder	DesignBuilder	Full-featured Windows interface, also supports lighting and computational fluid dynamics simulation: http://designbuilderusa.com/
Digital Alchemy	Simergy	Full-featured Windows interface supports BIM/IFC import: http://simergy.d-alchemy.com/
EnSimS	jEPlus/JESS	Simulation and parametric/optimization services and service frameworks: http://www.jeplus.org/wiki/doku.php
MIT	UMI	Rhino-based Urban Modeling Interface: http://urbanmodellinginterface.ning.com/
QCoefficient	QCoefficient	EnergyPlus-based MPC service for large commercial buildings: http://qcoefficient.com/
Solemma	DIVA-for-Rhino	Daylighting and energy plug-in for Rhino: http://diva4rhino.com/ (ArchSim, the EnergyPlus plug-in for Grasshopper 3D modeler is now part of DIVA-for-Rhino: http://archsim.com/)
Solemna	Climate Studio	EnergyPlus- and Radiance-based architectural design tool: https://www.solemma.com/ClimateStudio.html
Sefaira	Sefaira Systems	Web-based HVAC selection and sizing tool for early-stage design: http://sefaira.com/sefaira-systems/
	Sefaira Architecture	Revit and SketchUp plug-in for energy analysis: http://sefaira.com/sefaira-architecture/
Tian Building Engineering	BIM HVAC Tool	BIM-enabled buildings analysis platform: http://building-engineering.de/
Trane	TRACE 3D Plus	EnergyPlus based follow-on to TRACE 700: http://www.trane.com/commercial/north-america/us/en/products-systems/design-and-analysis-tools/analysis-tools/trace-3d-plus.html

Uses EnergyPlus via OpenStudio		
Autodesk	Systems Analysis	Whole-building energy model including HVAC for Autodesk Revit: https://blogs.autodesk.com/revit/2019/08/21/revit-systems-analysis/
BayREN	BRICR	Remote energy auditing used to identify retrofit candidates among small and medium commercial buildings in the Bay Area: https://energy.gov/eere/buildings/downloads/san-francisco-bayren-integrated-commercial-retrofits
BuildSim	BuildSimHub	GitHub-style project management and collaboration software for EnergyPlus and OpenStudio: http://buildsimhub.net/
CEC	CBECC-Com	Performance-path compliance for CA Title 24 non-residential code: http://bees.archenergy.com/software.html
CEC	CBES	Benchmarking and retrofit analysis of small and medium office and retail buildings in California and in 2030 Districts: http://cbes.lbl.gov
Simuwatt	Simuwatt	Tablet-based tool for ASHRAE level 2 and 3 energy audits: http://www.simuwatt.com/
Ladybug Tools	Honeybee	Open-source Grasshopper3D plugin for connecting to EnergyPlus, OpenStudio, Radiance, and DaySim: http://www.ladybug.tools/honeybee.html
NEEA/BetterBricks	Spark	Online energy and financial evaluation tool for office-building renewal (deep retrofit) projects: https://buildingrenewal.org/get-started/spark
Perkins and Will	SPEED	Web and cloud-based parametric optimization for architectural design: https://speed.perkinswill.com/
Topologic	Topologic	Non-manifold topology library for architectural design and analysis applications: https://topologic.app/software/

OpenStudio Measures. One of the most powerful features of the OpenStudio platform is a scripting facility called Measures. Analogous to Microsoft Excel Visual Basic macros, Measures are scripts (short programs) written in languages like Ruby, Python, and JavaScript, which OpenStudio executes. OpenStudio Measures have access to the OpenStudio API, which they can use to query and manipulate model inputs and simulation outputs. The original and still most common use of OpenStudio Measures is automating transformations that correspond to EEMs—this is also the origin of the name Measures. Figure 4 shows several OpenStudio Measures. The code is a snippet from a Measure that upgrades wall insulation. The before-and-after pairs demonstrate Measures that add heat recovery to an air system and that configure a building for daylighting. The daylighting example illustrates the surgical power of Measures. This Measure applies different transformations based on both space type and orientation—skylights are added only to certain spaces, e.g., for gymnasiums, east- and west-facing fenestration is eliminated while shading is added to south-facing fenestration.

```
replace exterior wall orig construction with new
model.getSurfaces.each do |s|
   if s.outsideBoundaryCondition == "Outdoors" and s.surfaceType == "Wall"
         if s.construction.name.get_s == orig
            s.setConstruction(new)
```

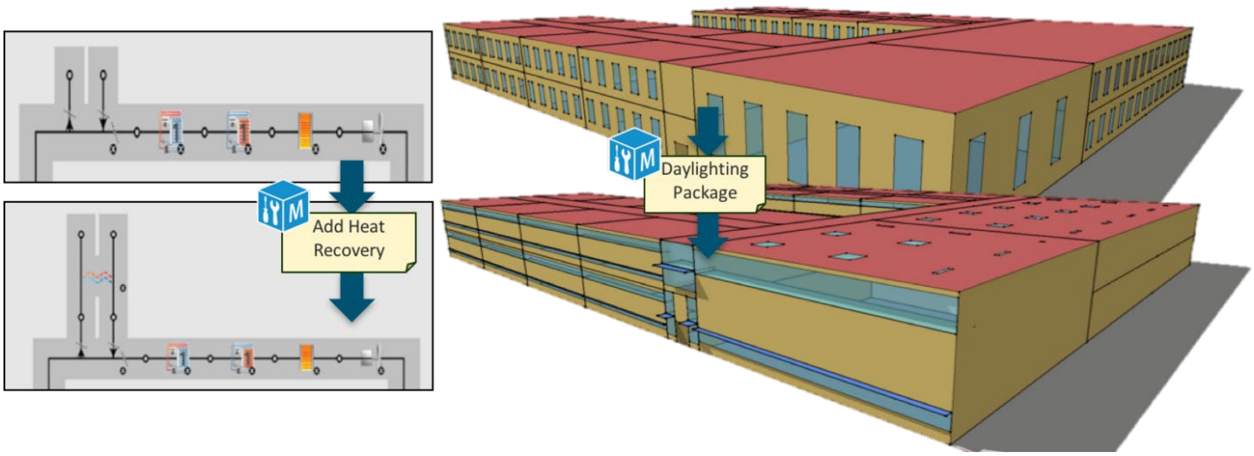


Figure 4. Examples of OpenStudio Measures

Measures form a significant part of the OpenStudio value proposition. Operationally, they provide flexible and portable process automation, allowing mechanistic tasks to be executed consistently and cost-effectively, and to be embedded in new applications such as large-scale analysis. At a higher level, Measures are a compact and transparent way to codify and share BEM knowledge. Measures are typically short enough that even BEM professionals that are not familiar with computer programming—and most are not—can at least understand what a given Measure does even if they would not be able to write it themselves. Understanding a Measure by inspecting its code is usually much easier—and always more complete—than doing so by differencing "before-and-after" models. The code snippet in Figure 4 demonstrates this. With minimal explanation, even a non-programmer should be able to tell that this code snippet performs a "search-and-replace" on exterior wall constructions. In addition, many BEM professionals *do* have some computer programming experience. Measures allow BEM professionals to create custom workflows for themselves, their organizations, and the BEM community at large. Many of the Measures available on the Building Component Library (BCL) (https://bcl.nrel.gov/) were created and shared by BEM professionals.

In addition to model inputs and simulation outputs, Measures have access to local machine and network resources, including the command line and APIs of other applications and services. This makes Measures a tool for general BEM workflow automation. Measures have been written for custom reporting, visualization, model quality checking, and for connecting BEM to other analyses.

OpenStudio also supports EnergyPlus Measures that operate on EnergyPlus input (i.e., Input Data Format, or IDF) files rather than OpenStudio models. These allow access to EnergyPlus features that are not available via the OpenStudio API and allow users that work with EnergyPlus to use OpenStudio SDK's simulation management features.

Other scripting frameworks that work directly with EnergyPlus have been developed, including Eppy[25] and Modelkit.[26] These provide some of the capabilities of Measures and have ancillary advantages, notably lighter weight and gentler learning curves. Commercial tools such as Integrated Environmental Solutions' Virtual Environment (IES-VE) also have some scripting capabilities.

OpenStudio Standards Gem. One of the most useful OpenStudio Measures is "Create Performance Rating Method Baseline Building," which automates—at this point partially, but ultimately completely—the creation of a "code baseline" building model from a model of the actual or proposed building, so the performance of the two can be compared. This transformation and subsequent comparison is a key component of performance-path code compliance, green certification, asset rating, and financial incentive calculations. Although a modeler does need to review the results of the Measure as well as nominal and baseline simulation results, baseline automation frees up modeler time and budget for tasks that are both more creative and more directly beneficial to building performance, e.g., investigating strategies to inform design and operation. Figure 5 shows "before-and-after" snapshots of this Measure. One visible change is the removal of exterior shading.

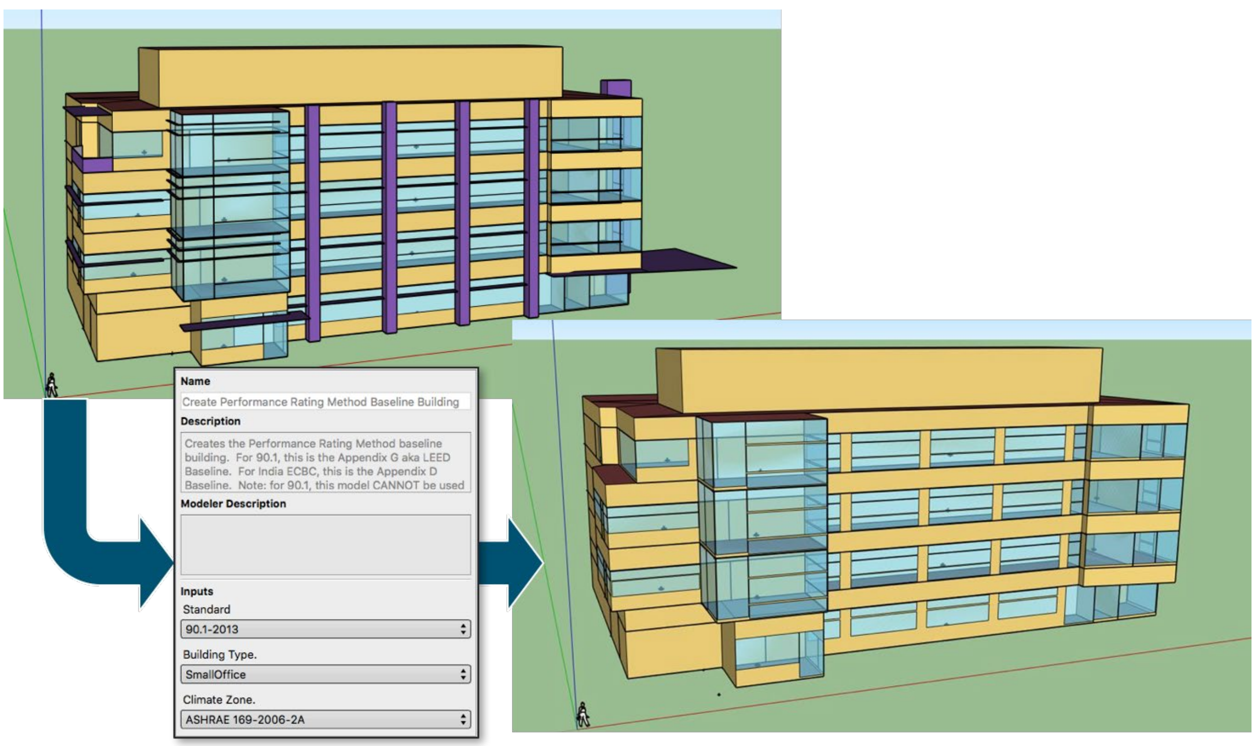


Figure 5. OpenStudio Standards "Create Performance Rating Method Baseline Building" Measure

[25] https://pythonhosted.org/eppy/
[26] https://bigladdersoftware.com/projects/modelkit/

Create PRM Baseline Building is part of the OpenStudio Standards "gem."[27] A gem is a packaged distribution of Ruby scripts and related resources. The Standards gem contains a library of functions for parametrically configuring building envelopes, systems, and schedules. The Create PRM Baseline Building Measure applies these functions to an existing model with parameter values corresponding to building type, climate zone, and code vintage. Parameter values are stored in Excel workbooks that parallel ASHRAE Standard 90.1 tables and which the Measure reads. A structure that parallels the Standard makes the Measure more transparent and easier to customize for other standards that resemble ASHRAE 90.1. Canada and India are already using OpenStudio Standards gem-based implementations for their National Energy Code for Buildings[28] and Energy Conservation Building Code,[29] respectively.

The OpenStudio Standards gem contains a second Measure, Create DOE Prototype Building Model, which combines the functions and parameter spreadsheets in slightly different ways to create OpenStudio models of DOE's Commercial Reference/Prototype Buildings,[30] standard models that are used as the basis for many large-scale analyses including those that inform code updates, design guides, and EE programs. These models were originally defined in EnergyPlus. In OpenStudio format, Measures can be applied to them.

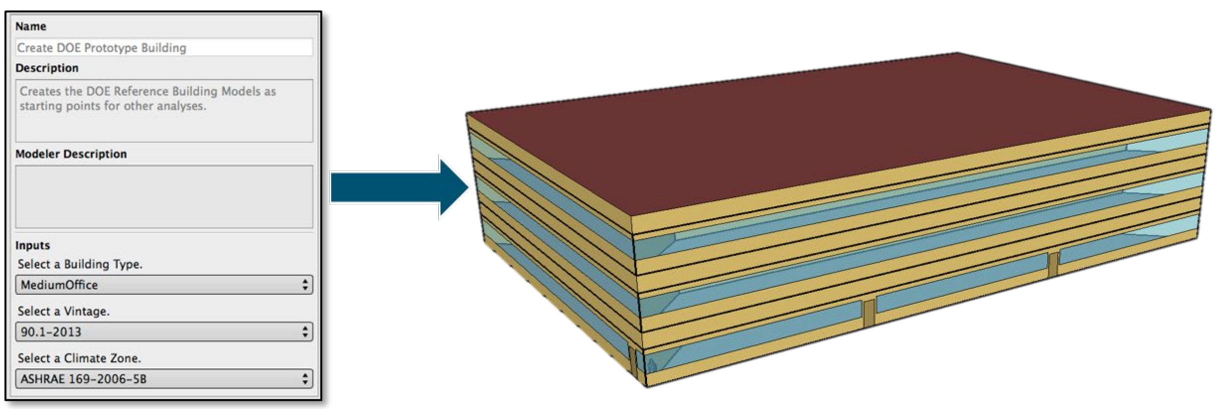


Figure 6. OpenStudio Standards "Create DOE Prototype Building" Measure

ResStock™. Traditional building-stock analysis uses prototype models and scales their results using floor area multipliers. A drawback of this approach is that each building type of each vintage in each climate zone is represented by a single model. In reality, there is significant variety within buildings types of the same vintage and in the same climate zone—in geometry, in constructions, in systems, and in use and operations. A single model may represent the most common configuration, but that configuration may be a small plurality. ResStock[31] is a more robust methodology for stock modeling that uses joint probability distributions for building

[27] https://rubygems.org/gems/openstudio-standards
[28] http://www.nrcan.gc.ca/energy/efficiency/buildings/eenb/codes/4037
[29] https://beeindia.gov.in/sites/default/files/ECBC%202016_Draft_V8.pdf
[30] https://www.energycodes.gov/development/commercial/prototype_models
[31] https://www.nrel.gov/buildings/resstock.html

assets and operations, and replaces individual prototype models with an arbitrarily sized population of prototypes creating by sampling these distributions. Originally developed for residential stock modeling, ResStock has been extended to commercial stock modeling under the name ComStock™.

OpenStudio Server. OpenStudio targets automation. One place where automation is most powerful is large-scale BEM, simulation of hundreds and thousands of building variants for purposes such as determining typical savings for different EEMs, optimizing design, or calibrating model inputs using measured data. OpenStudio Measures is a good mechanism for systematically generating, organizing, and indexing large numbers of related simulation variants. OpenStudio Server is a module that can orchestrate large numbers of simulations on a local machine, a local cluster of machines, or the cloud. Cloud support is especially important because many smaller users do not have access to dedicated high-throughput computing resources, and at the same time do not have time to run large analyses on their laptops. With a credit card and OpenStudio Server, anyone can perform an analysis comprising hundreds of simulations for under $30 and in under 30 minutes. It is important to note that OpenStudio Server is not a service to which users can directly submit simulation requests, i.e., there is no http://openstudioserver.io/ (click on the link and you'll see). Rather, it is a module that allows vendors and advanced users to set up such services or to perform ad hoc large-scale analyses. Cloud-based simulation services are available from private vendors including BuildSimHub, Autodesk, and others.

OpenStudio 2.0. Over the past few years, BTO has re-architected the OpenStudio SDK to make Measure evaluation capability more consistent and simpler to integrate into applications and services. This new architecture, launched in 2016, is OpenStudio 2.0. The core component of the 2.0 architecture is OpenStudio Command Line Interface (CLI), a 150-Megabyte (MB) executable that includes the OpenStudio SDK, a Ruby interpreter, and some Measures including the Standards gem. The CLI executes OpenStudio Workflow (OSW) files, which consist of a seed model and a sequence of Measures. It targets "single model" applications like the OpenStudio Application.

A second component is the Meta-CLI, a script that takes an OpenStudio Analysis (OSA) file that describes a large-scale analysis—i.e., a collection of seed models, a collection of Measures and parameter values, and rules for combining seed models with Measures and parameters—and produces a set of OSW files. OpenStudio Server was re-architected to use a single Meta-CLI "master" and multiple CLI "workers." Figure 7 shows the OpenStudio 2.0 workflow architecture.

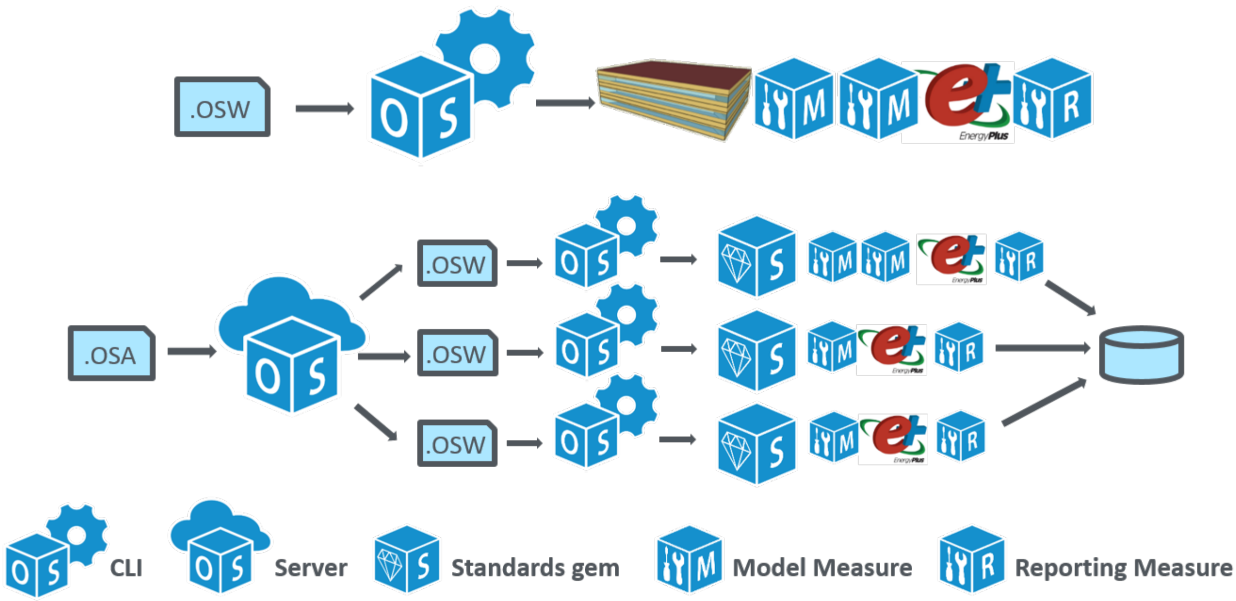


Figure 7. OpenStudio 2.0 workflow architecture for single model analysis (top) and parametric analysis (bottom)

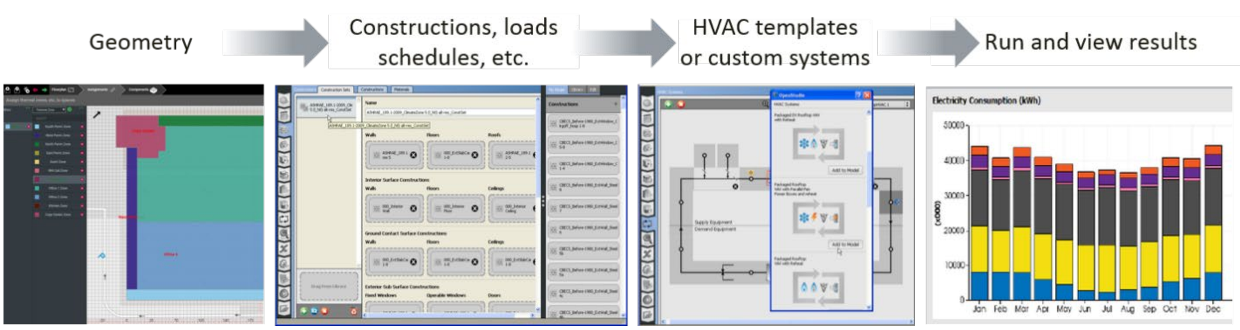


Figure 8. OpenStudio Application

OpenStudio Application. Although most of the OpenStudio code and development effort goes to the SDK, the most visible and identifiable parts of the OpenStudio project are the graphical OpenStudio Application and Parametric Analysis Tool (PAT). The OpenStudio Application is a traditional desktop "single model" development workflow that resembles eQuest, TRACE, and other BEM applications. It includes a SketchUp plug-in for geometry creation and editing, and a companion application with tabs for editing constructions, schedules, and HVAC systems; configuring simulation parameters; running simulations; and viewing simulation results. Newer versions of the Application replace the SketchUp plug-in with a 2D geometry editing widget called FloorSpaceJS. The PAT application takes seed models produced by the OpenStudio Application and allows users to select Measures and configure small- to large-scale parametric analyses.

The OpenStudio Application and PAT have garnered a significant user community. Recent OpenStudio version updates have been downloaded over 35,000 times each. According to the

AIA 2030 Commitment DDx, OpenStudio is the third most popular EnergyPlus interface behind Sefaira and "Other"—which likely means IDF Editor. The success of the OpenStudio Application has helped BTO meet many of its internal goals in advancing the use of EnergyPlus. However, with several new private sector interfaces for EnergyPlus, including some leveraging the OpenStudio SDK, BTO ceased OpenStudio Application funding and management in April 2020.[32] The source code is available on GitHub[33] for third parties interested in cloning it and continuing to maintain it independently. For the time being, BTO will continue to fund and update PAT, in large part because it uses PAT internally to conduct large-scale prototypical studies. For the time being, it will also continue to support FloorSpaceJS.

Other BEM Applications. In addition to the OpenStudio Application, BTO and other DOE offices have funded other BEM-based applications and services. Most are significantly narrower and more focused than the OpenStudio Application and several are attached to rating programs. Table 3 provides a listing.

Table 3. DOE BEM Applications and Services

Application	DOE Office Program	Short Description	Support
Home Energy Scoring Tool	BTO Residential Buildings Program	Web-based tool that rates the asset energy performance of a home, and identifies cost-effective upgrade opportunities. Currently uses DOE-2.1E; will transition to EnergyPlus. Free, but not open-source. http://homeenergyscore.lbl.gov/	2009–
Commercial Building Energy Asset Scoring Tool	BTO Commercial Buildings Program	A tool that rates the asset energy performance of a commercial building and its major systems and identifies cost-effective asset upgrade opportunities. Uses EnergyPlus and OpenStudio. Free but not open-source. https://buildingenergyscore.energy.gov/	2012–
BEopt	BTO Residential Buildings Program	Residential design optimization tool that uses DOE-2.2 and EnergyPlus. Deprecated in favor of OpenStudio. https://beopt.nrel.gov/	2002–2016
MulTEA	Weatherization Office	Audit tool for multifamily buildings. http://developers.buildingsapi.lbl.gov/project-gallery/project-gallery---hes/weatherization-assistant-multea---ornl	2011–
COMFEN/ RESFEN	BTO Windows Program	Facade tools that use EnergyPlus and Radiance for single-zone thermal and visual analysis. https://windows.lbl.gov/software/comfen/comfen.html, https://windows.lbl.gov/software/resfen/resfen.html	1996–
COMcheck	BTO Codes Program	Tool that checks for compliance with IECC, ASHRAE 90.1, and a number of state-specific commercial building energy codes. https://energycode.pnl.gov/COMcheckWeb/	1996–

32 https://www.openstudio.net/new-future-for-openstudio-application
33 https://github.com/NREL/OpenStudioApplication/

Application	DOE Office Program	Short Description	Support
Weatherization Assistant (NEAT/MHEA)	Weatherization Office	Audit and retrofit recommendation software for stationary and mobile homes. Will migrate to EnergyPlus and OpenStudio platform. http://weatherization.ornl.gov/assistant.shtml	N/A
Facility Energy Decision System (FEDS)	Federal Energy Management Office	Audit, retrofit recommendation, and project planning software for single and multibuilding facilities. Free for federally funded projects. https://www.pnnl.gov/feds/	2003–
Scout	BTO Cross-Cutting Program	National EE technology impact assessment model. Uses EnergyPlus and OpenStudio to evaluate some measures. https://energy.gov/eere/buildings/scout	2014–

Spawn and BEM controls tools. Controls are an increasingly important part of building EE. Although many load reduction strategies are static, deep reductions require lighting and plug-load control and sometimes control of traditionally static envelope elements like windows. HVAC components and systems also increasingly rely on controls to achieve efficiency. Designing, rating, and otherwise evaluating a modern EE building must be done in the context of its control strategies.

Unfortunately, there is currently a disconnect between BEM and control workflows. With a few exceptions like IDA ICE[34] and TRNSYS[35], modern BEM engines like EnergyPlus use load calculations to deduce HVAC operation from high-level descriptions. In each time step, they first calculate the internal and weather-driven thermal loads on the zone, then they calculate the heating or cooling the HVAC system can provide, and finally use the difference between these to calculate updated zone conditions. Physical control sequences are not defined in terms of loads, but in terms of temperature readings and valve and damper positions. The control strategies modeled by EnergyPlus and other BEM engines may be "correct" (i.e., they may produce intended HVAC system behaviors and zone conditions), but they cannot be extracted from the BEM environment and translated for execution on control hardware. They must be manually interpreted and rewritten for those platforms. This is a lengthy process that can be prone to error. Often, rather than interpreting a modeled control strategy, a controls engineer may simply fall back to a known and trusted control sequence.

To bridge this gap, BTO is undertaking a multiyear effort to create an EnergyPlus "clone"—currently called Spawn-of-EnergyPlus or just Spawn—that uses dynamic HVAC simulation and can interpret physically realistic control sequences. Spawn is intended to support control design and implementation workflows. It is also intended to support dynamic applications such as FDD

[34] https://www.equa.se/en/ida-ice
[35] http://www.trnsys.com/

and MPC, although whether detailed physics-based modeling—as opposed to reduced order or purely data-driven modeling—is necessary for these applications is an open question.

Spawn reuses the envelope, lighting, and loads modules of EnergyPlus and couples them to a new HVAC and controls modules. The new modules are implemented in the Modelica equation-based modeling language.[36] Traditional simulation models are imperative; they describe a system and its control strategy indirectly by describing how they are to be simulated. As a result, they only support simulation. Modelica models are declarative; they describe the system and its control strategy directly and as a result are more easily repurposed. Modelica models can be simulated. They can also be verified, optimized, and—in the case of control models—compiled and executed on physical controllers. Modelica is one of the languages used to implement real-world control algorithms.

Modelica should also confer software development benefits. Specifically, it should reduce domain-specific implementation and maintenance efforts by allowing BEM engine developers to focus on physics (which is their primary area of expertise) rather than numerical solution techniques (which typically is not). Modelica solvers and simulation engines are domain agnostic and developed by numerical solution experts. Spawn leverages the Modelica Buildings Library created by International Energy Agency (IEA) Annex 60, "New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards,"[37] and currently developed and maintained by IBPSA-World as "Project 1."[38] It also uses the JModelica compiler.[39]

Spawn also heavily relies on the Functional Mockup Interface (FMI) co-simulation standard[40] for co-simulation. Co-simulation is the ability of two simulation engines to synchronize, exchange data, and converge to solutions on a time step basis. EnergyPlus has supported co-simulation for some time via an ad hoc feature called External Interface. In turn, this feature has been used in ad hoc co-simulation toolkits and environments like MLE+[41] and the Building Control Virtual Testbed (BCVTB).[42] FMI is an open standard that enables co-simulation in a general way and is supported by over 100 tools, including EnergyPlus. But whereas EnergyPlus supports FMI for external communication, Spawn also uses FMI internally to communicate between its own modules. This internally modular architecture should allow Spawn to integrate externally developed component models, including proprietary ones. BTO expects that this capability will shorten the time required to develop and integrate models for new component technologies. Ideally, it allows manufacturers to release models for new technologies along with those new technologies, reducing both model lag and BTO resource requirements. The FMI

[36] https://www.modelica.org/
[37] http://www.iea-annex60.org/
[38] https://ibpsa.github.io/project1/
[39] https://jmodelica.org/
[40] https://www.fmi-standard.org/
[41] http://www.madhurbehl.com/mleplus.html
[42] https://simulationresearch.lbl.gov/bcvtb/

standard allows components to be implemented in any language, allowing Spawn to support component modeling and control design and implementation workflows implemented in any language, not just Modelica.

BTO is complementing Spawn with two other projects. The Open Building Control (OBC) project[43] is developing a library of high-performance control sequences in a Modelica subset called Control Description Language (CDL), along with commissioning and translation tools. The Building Operations Testing (BOPTEST) project[44] is developing a set of Modelica/FMI benchmarks for control and FDD algorithms.

Spawn is not intended as an immediate or even medium-term replacement for EnergyPlus. Given the success and adoption of EnergyPlus, as well as the new applications and users Spawn targets, BTO envisions EnergyPlus and Spawn coexisting for a while, with development resources shifting from EnergyPlus and toward Spawn over time. BTO plans to reuse the OpenStudio SDK and Measures infrastructure to provide users and client applications with access to Spawn, simultaneously reusing that functionality and providing a transition path. BTO will continue to support EnergyPlus and its current client vendors and users to avoid eroding their value and trust.

URBANopt. EnergyPlus, Spawn, and OpenStudio target individual building analysis. OpenStudio Server targets large-scale analysis, but one in which individual simulations are independent of one another, e.g., design alternatives for a single building or measure evaluation on different building types in different climate zones. URBANopt (Urban Renewable Building And Neighborhood optimization) adds capabilities for district- and campus-scale thermal and electrical analysis.

Most district system simulation tools, including Big Ladder's District Zero, IES's Intelligent Virtual Network,[45] and the current version of URBANopt,[46] do not co-simulate buildings and shared thermal systems. They do not simulate their interactions within the time step; instead, they first simulate the buildings individually, collect thermal load profiles, and use those as input to a separate thermal system module. This approach is simple to implement and scales well, but also fails to capture some dynamics and building-system interactions that are less important in traditional district systems but play a bigger role in low-temperature "fifth-generation" systems, systems with waste-heat recovery, and systems with bidirectional flow. A new version of URBANopt[47] will leverage Spawn, FMI, and existing Modelica libraries of shared-thermal system models to model district thermal systems and their control in a more physically detailed realistic way. Co-simulation will also allow URBANopt to evaluate of distributed energy resources and electrical distribution systems, supporting BTO's new emphasis on grid

[43] https://www.energy.gov/eere/buildings/open-building-control-1
[44] https://www.energy.gov/eere/buildings/boptest-building-operations-testing-framework
[45] https://www.iesve.com/icl/ivn
[46] https://www.nrel.gov/buildings/urbanopt.html
[47] https://www.energy.gov/eere/buildings/urbanopt

responsiveness and interaction. As with EnergyPlus, Spawn, and OpenStudio, URBANopt will be distributed as an open-source SDK rather than a packaged end-user application.

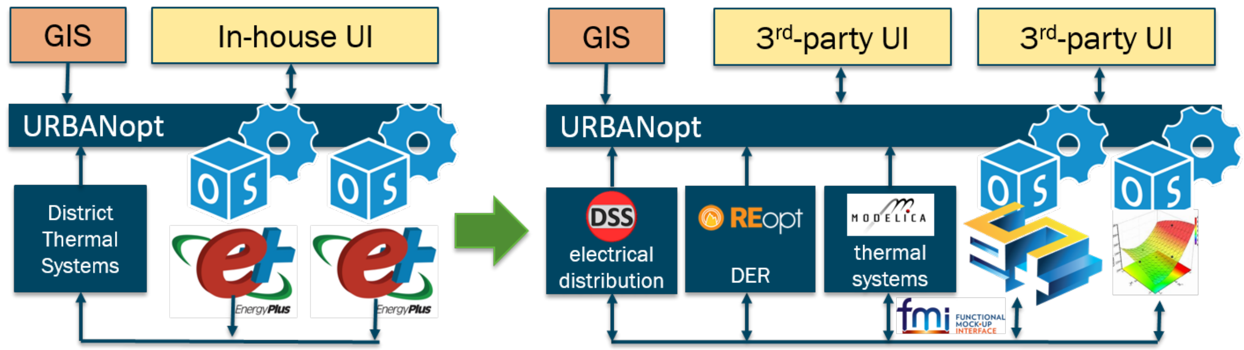


Figure 9. URBANopt: existing sequential simulation (left) and new co-simulation (right) implementations

2.3 Metrics, Data Sets, Benchmarks, and Targets

BTO's overarching goals are stated in terms of energy savings. For each technology subprogram, BTO assesses that technology's contribution to energy savings, benchmarks and tracks relevant industry status, sets performance and cost targets for the technology, and measures the effectiveness of its own initiatives in meeting those targets and achieving those savings. This type of evaluation is more difficult for BEM and other enabling or system-level technologies like sensors and submeters than it is for direct component technologies like windows, heat pumps, and LEDs. BEM has additional challenges that are unique to enabling technologies, including large unit labor costs, lack of obvious functionality- or accuracy-oriented component performance metrics for software, and difficulty of conducting controlled experiments. Nevertheless, metrics and goals are useful even in the absence of high-quality data sets and watertight attribution methods.

For BEM, BTO uses a performance attribution methodology based on analysis of a large set of building design project data. Metrics and targets are also set in terms of this data set and measure BEM's market penetration and its effectiveness in achieving high design performance.

BEM use and effectiveness data sets. Data on the use and effectiveness of BEM is sparse. One available data set is the AIA 2030 Commitment, which targets zero net-carbon buildings by 2030 and has been tracking U.S. architecture firms' use of BEM in individual design projects since 2013.[48] Firms that sign on to the Commitment report on the performance of all of their projects, and on use of BEM. DOE collaborates with AIA on the development of the 2030 Design Data Exchange (DDx), an online portal for 2030 reporting and research.[49] DOE uses the DDx to benchmark and track growth in the use of BEM for integrated design. The DDx research functions allow users to query the database and retrieve aggregate data, including number of

[48] The AIA 2030 Commitment includes U.S.-based architecture firms, although individual building projects may be abroad.
[49] https://www.energy.gov/eere/buildings/downloads/aia-2030-commitment-design-data-exchange-ddx

projects, total floor area, floor-area weighted average design EUI, and floor-area weighted EUI reduction over (2003 CBECS) baseline. Table 4 shows the number and gross square footage (GSF) of commercial new construction and major retrofit projects for the years 2013–2018.[50]

Table 4. AIA 2030 Commitment Data for U.S. Commercial Building New Construction

	2013	2014	2015	2016	2017	2018	2019
Projects	1150	2629	4630	6020	7921	8459	10118
Projects modeled	740	1388	2804	2983	3707	4309	6504
Percentage of projects modeled (of total)	**64%**	**53%**	**61%**	**49%**	**47%**	**51%**	**64%**
GSF (M ft^2)	319	613	1,310	1660	1880	1680	2080
GSF modeled (M ft^2)	222	397	906	775	888	862	1530
Percentage of GSF modeled (of total)	**70%**	**65%**	**69%**	**47%**	**47%**	**51%**	**74%**
Percentage of modeled EUI reduction over code	**13%**	**17%**	**12%**	**19%**	**13%**	**9%**	**10%**

Although not monotonic, the percentage of modeled projects and square footage had been decreasing over time as the 2030 Commitment has grown and reporting has increased. This is an intuitive and instructive trend. The Commitment is a voluntary program and early adopters were performance-oriented firms whose portfolios look good relative to commitment goals. As the Commitment has grown, firms less focused on performance have signed on. It is reasonable to extrapolate that if 100% of design projects were reported, the percentages of projects and square footage using BEM would drop further, perhaps even to 20%, a frequently quoted number and one mentioned by multiple stakeholders (Frankel, Edelson, and Colker 2015). That trend reversed sharply in 2019 as a number of large firms committed to modeling 100% of their projects.

The decrease in effectiveness of modeling above code is related to the increasing stringency of codes. The AIA 2030 Commitment assumes that performance for non-modeled projects corresponds to the performance level associated with the prevailing code for the building type and climate zone. As states and jurisdictions adopt more stringent codes, performance of non-modeled projects rises. These artifacts are built into the AIA 2030 Commitment program. It may be worthwhile considering how to control for them.

The AIA 2030 Commitment data set does not include many residential projects. A helpful residential data set comes from RESNET, which tracks use of the HERS Index in new home construction. Whereas in commercial new construction certification and rating systems like

[50] 2019 reporting period ends March 31, 2020.

LEED have only an indirect influence on design, large-scale homebuilders actively use the HERS rating and its associated tools to create EE home designs, which can then be replicated.

Table 5. RESNET Data for U.S. Residential New Construction

Sources: U.S. Census and RESNET[51]

	2014	2015	2016	2017	2018	2019
Homes	860,000	950,000	935,000	1,003,031	1,094,695	1,255,100
Rated Homes	146,000	190,000	206,000	227,800	236,116	241,909
Percentage of Homes Rated	17%	20%	22%	23%	22%	19%
Average HERS Index	63	62	61	62	61	59

In contrast with commercial new construction, the use of BEM in residential new construction appears to be growing, along with predicted performance—a lower HERS Index is better with a score of zero representing a zero-net energy (ZNE) home.

Potential energy savings estimates for BEM. From the AIA 2030 and RESNET data, we estimate that BEM can reduce EUI by 20% in commercial and residential new construction. Separate data for retrofits is not available, but we estimate that BEM can yield 10% savings in these projects, given greatly reduced flexibility in building form.

We use Scout[52] to convert per project energy savings estimates to out-year national energy savings potential. Scout is a tool developed at NREL, LBNL, and BTO that builds on annual building stock and flow data and projections—total floor space, new floor space, etc.—from the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO). Scout takes these and plays them forward in time with different mixes of EEMs. Scout EEMs are characterized by applicability to building type (commercial or residential), project type (new construction, retrofit, or replacement), end use (lighting, heating, ventilation, etc.), and fuel type (electricity, natural gas, etc.); performance improvement; lifetime; time of introduction to market; and incremental cost. Scout competes EEMs against one another under different adoption assumptions, apportioning market share according to cost-effectiveness criteria. The AEO projections include "built in" energy savings. This allows Scout to calculate energy savings for individual EEMs in a more realistic setting.

Table 6 shows Scout assumptions for new and retrofitted commercial and residential floor area for the period 2017–2030 and corresponding 2030 projected energy savings under four different scenarios. The "business as usual (BAU)" scenario reflects 20% savings for integrated design in new construction, 10% savings for integrated design in retrofits, and an adoption rate of 20%,

[51] https://www.resnet.us/articles/over-241000-homes-hers-rated-in-2019/
[52] https://energy.gov/eere/buildings/scout

reflecting estimates of current use. This scenario yields almost 0.5 quads of savings in 2030. The "Adoption" scenario retains the effectiveness of BEM but increases adoption to 100%. This scenario leads to savings of 2.4 quads. The "Effectiveness" scenario retains current adoption levels but increases the effectiveness of BEM to 50% savings for new construction and 25% for retrofits. The final "Max" scenario maximizes both BEM effectiveness and adoption, and yields savings of over 6 quads. This scenario resembles the one described in *Reinventing Fire*, in which the Rocky Mountain Institute (RMI) estimates that integrated design can account for between 8 and 16 quads of energy savings by 2050 (Lovins 2011). The RMI estimate was generated using a set of high-performance new construction and retrofit projects that achieved deep energy savings, greater than 50%.

Table 6. Energy Savings Estimates for Integrated Design in the United States by 2030

Application	Floor space (million ft^2)	Potential savings (TBtu/yr)			
		"BAU" 20% savings 20% adoption	"Adoption" 20% savings 100% adoption	"Effectiveness" 50% savings 20% adoption	"Max" 50% savings 100% adoption
Commercial new	29,072	95	477	239	1193
Commercial retrofit	12,628	103	514	257	1285
Residential new	37,398	94	473	236	1183
Residential retrofit	28,315	197	984	492	2460
Total	107,413	489	2,448	1,224	6,121

Figure 10 shows the year-by-year data for the maximum adoption case. The red lines are the AEO "baseline" case, and the pink lines are the "efficient" or EEM case. In a given year, energy savings is the difference between the corresponding points on the two lines. A few notes about interpreting Scout graphs: First, the graphs show only the applicable energy market segments—they do not show the entire commercial and residential building stocks, only the portions associated with new construction and retrofit. For instance, in 2017, the commercial new construction energy market—i.e., energy consumed by new construction—accounts for 0.1 quads, whereas the commercial retrofit energy market—buildings old enough to be considered eligible for retrofit—accounts for 9 quads. Second, energy market effects accumulate year to year so, for instance, the commercial new construction market is seen as growing despite the fact that projections for new square footage are relatively flat. Third, the AEO baseline case includes "built in" EE improvements. This is most easily seen in the retrofit energy market. The existing building stock is expected to shrink as old buildings are demolished and replaced by new buildings—that part of the market effectively "migrates" from existing to new construction—while existing buildings are expected to improve somewhat.

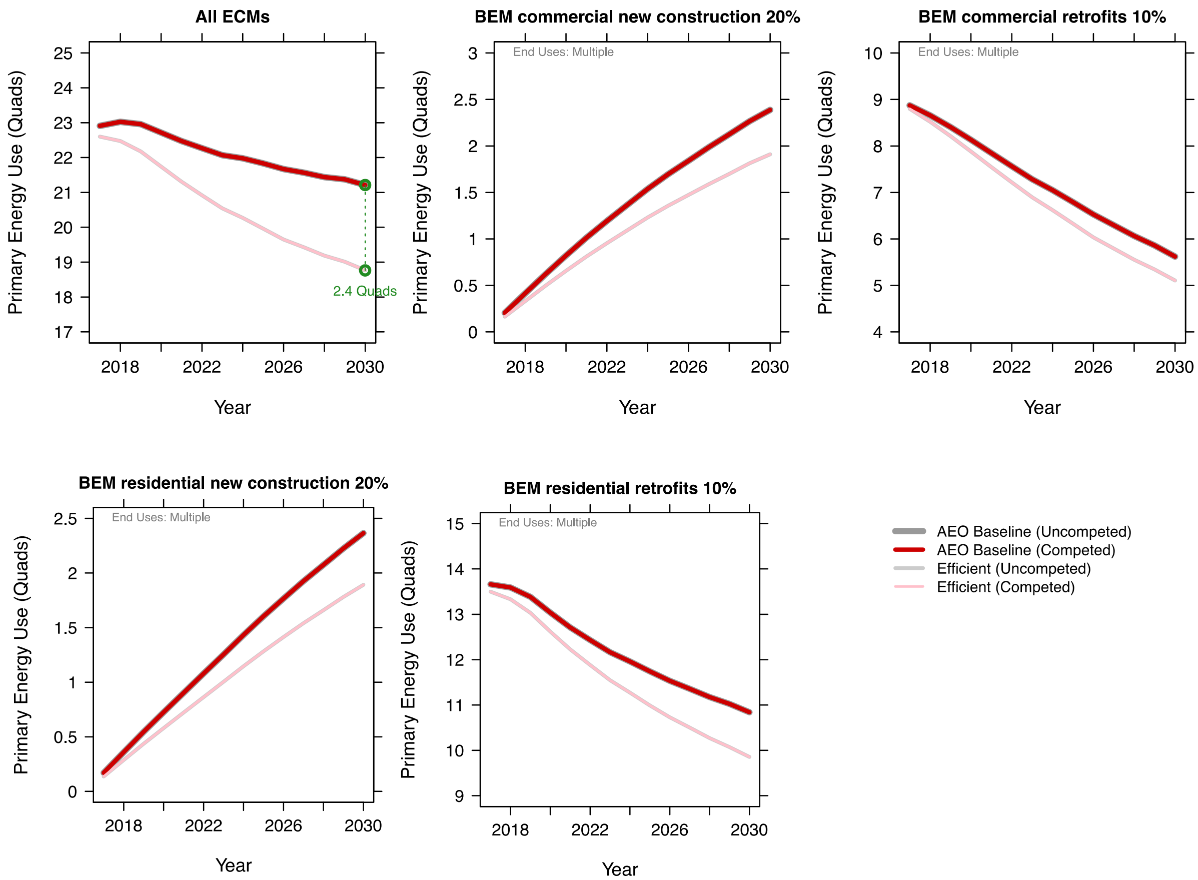


Figure 10. Scout estimates of potential energy savings due to integrated design and BEM

Direct metrics, benchmarks, and targets for BEM use and effectiveness. Direct metrics are ones that measure the use of BEM in specific building EE projects. Established in the 2015 MYPP, BTO's goals framework establishes benchmarks and targets for integrated design for commercial buildings (BTO 2016). This use case contributes most directly to EE and is one that DOE is eager to promote.

The MYPP also has stated goals for BTO-funded BEM tools. These are in the process of being removed and will not be referenced in this document.

As noted by a number of stakeholders, these metrics do not provide sufficient insight into the use of BEM. For instance, they do not distinguish late-stage use of BEM for mechanical design and equipment sizing from early-stage use of BEM to reduce loads. They also do not correlate the use of BEM with specific design—and design EUI—changes. BTO will work with AIA to augment 2030 reporting to support more nuanced and meaningful metrics.

BTO will explore complementing the AIA 2030 data set with data from other existing sources:

- Energy design-assistance utility programs
- Building performance certificate programs like LEED and WELL
- State and local building energy code compliance and enforcement programs. These have the advantage of covering all buildings, not only ones that use BEM for design, certification or code-compliance.

Leveraging this data likely requires data sharing agreements between BTO and the relevant organization, followed by benchmarking analysis and stakeholder engagement for target setting.

BTO will also investigate opportunities for collaborating with the appropriate organizations to collect project-level data that currently does not fall under a central reporting program. Energy savings performance contract (ESPC) projects are a notable example.

BTO currently has no targets corresponding to use of BEM in homes. It also does not have metrics, benchmarks, and targets corresponding to operational BEM use cases, which are not yet sufficiently established to generate a visible market signal.

Proxy metrics, benchmarks, and goals. Proxy metrics do not directly measure use of BEM in building EE projects, but may provide some (potentially leading) indications about growth in BEM use. The MYPP currently has a single proxy metric related to the number of EnergyPlus-based third-party products, but BTO will discontinue use of this metric. Alternative proxy metrics include:

- Number of ASHRAE Building Energy Modeling Professional (BEMP) certified professionals, although there is some sense that this certification primarily targets compliance modeling
- Number of IBPSA-USA members and number of IBPSA-USA local chapter members
- Number of attendees at BEM conferences
- Number of universities offering BEM courses and degrees and number of students enrolled in these courses and graduating with these degrees
- Number of independent BEM trainings and course offerings and attendance.

BTO will engage IBPSA-USA to help collect some of this data and, synthesize appropriate metrics, and establish targets.

3 Topic 1: Predictive Accuracy and Consistency

The next six sections detail barriers to widespread and effective use of BEM and propose BTO initiatives designed to address them. The first sections address technical issues such as accuracy (Section 3, this one), core modeling capabilities (Section 4), automation (Section 5), and supporting data (Section 6). The final sections deal with the BEM professional support system (Section 7) and the BEM market (Section 8). Each section includes a bulleted high-level summary, a listing of relevant BTO projects, a discussion of barriers, a discussion of initiatives, and a summary table that matches the latter to the former.

Summary:

- Due to the quantity of input parameters and the uncertainty and stochasticity associated with many of them, predictive BEM is notoriously difficult. To sidestep this problem, BEM use cases are designed around comparative analysis instead of absolute energy prediction. Poor predictive accuracy for new buildings remains a popular weapon of BEM skeptics. Meanwhile, BEM practitioners and their clients also express a desire for greater predictive accuracy.
- Exacerbating the problem of poor predictive accuracy, inconsistency across tools due to implementation variances and across modelers due to variances in experience, judgement, interpretation, and other factors provides further ammunition to skeptics and frustrates clients.
- For some use cases, including code compliance, ratings, certificates, and incentives, consistency among software is more important than accuracy. For these use cases, there may be a temptation to "solve" the consistency problem by mandating a single engine. However, this approach does not address the greater source of inconsistency that comes from modelers themselves and may also obscure accuracy issues.
- BTO should leverage LBNL's and ORNL's user test facilities to conduct key experiments that can quantify the error inherent in BEM engines. These results must be packaged for use by engine developers and BEM professionals, but also for communication to BEM clients and other stakeholders.
- Testing standards that improve the accuracy consistency of BEM software ranging from engines to standard rulesets are also likely to improve BEM results in individual projects as well as the reputation of BEM as a whole. BTO should continue to support existing standards and encourage vendors to contribute to standard development and contribute reference data.
- Use cases that emphasize and reward predictive accuracy such as ESPCs and outcome-based codes can create a virtuous accuracy cycle for both software and practitioners. BTO should look to elevate and promote these use cases as its scope allows.

- BTO should emphasize work on calibration and uncertainty analysis and their applications in standard practice. These are more likely to improve the performance of BEM in the field.

Relevant BTO projects:

- **Empirical validation and uncertainty characterization of energy simulation.** A completed four-year project that uses LBNL FLEXLAB and ORNL Flexible Research Platform (FRP) test facilities to develop empirical data sets for validating key BEM algorithms is now being followed by three additional projects performing additional experiments and leveraging a broader set of facilities including NREL's iUNIT modular apartment and the National Institute of Standards and Technology's (NIST's) NZERTF (net-zero energy research test facility).
https://www.energy.gov/eere/buildings/downloads/lab-rfp-validation-and-uncertainty-characterization
https://www.energy.gov/eere/buildings/empirical-validation-energy-simulation-flexlab
https://www.energy.gov/eere/buildings/empirical-validation-energy-simulation-etna
https://www.energy.gov/eere/buildings/empirical-validation-energy-simulation-frp-iunit-and-nzertf
- **ASHRAE Standard 140.** Standardized test suite for diagnosing and improving the consistency and accuracy of BEM engines.
https://www.energy.gov/eere/buildings/ashrae-standard-140-maintenance-and-development
- **ASHRAE Standard 229P.** A proposed standard reporting schema and open-source tool for diagnosing and improving the accuracy and consistency of BEM ruleset implementations.
https://www.energy.gov/eere/buildings/ashrae-standard-229p-development

3.1 Barriers

Many BEM clients and even some practitioners have substantial concerns over the ability of BEM to accurately predict real-world building energy use. Accurate predictive BEM requires detailed information on all aspects of a building's physical assets and operational parameters. At the engine level, the number of individual inputs required to characterize a small building is measured in the thousands; for a large building, it can grow to hundreds of thousands. Middleware and user interfaces can group inputs and abstract them, reducing their numbers. And of the remaining inputs, not all contribute significantly to building energy performance and BEM predictive accuracy. Still, even if only 10% are significant, collecting or estimating this subset is still burdensome. Many of these inputs are stochastic—detailed occupancy, lighting, and plug-load schedules are the classic examples here. Others are difficult to obtain or cannot be known with any confidence before the building is constructed and occupied—infiltration and internal thermal mass are examples. This combination of factors makes predicting day-to-day energy use using BEM a difficult proposition. Intuitively, energy use prediction is the basic capability of BEM. Non-practitioners—including many BEM clients—have a difficult time understanding how, if it cannot do this simple thing, BEM can be good for anything at all!

This perception is fed by high-profile publications like the 2008 New Buildings Institute paper, "Energy Performance of LEED New Construction Buildings" (Turner and Frankel 2008). Figure 11 shows two well-traveled plots from that paper, which in turn show that BEM can over- or under-estimate measured performance 50% or more, and that BEM tends to under-estimate EUI use relative to actual for higher-performing (low design EUI) buildings. These are not unexpected results. The LEED process is based on comparative modeling using standard operating assumptions; LEED models do not *try* to predict energy use. The idea that EE buildings will under-perform in practice is also intuitive. When design EUI is low, most construction and operating variances will tend to increase energy use, and the real-world energy consumption will be driven by occupant behavior. In the residential sector, BEM has generally good predictive accuracy for new construction, but poor accuracy for older homes with variable construction methods and insulation levels. This can lead to an over-prediction of energy savings from efficiency upgrades, especially if models are not calibrated to usage data. Such over-prediction—or under-realization—of savings is another high-profile "failure" of BEM.

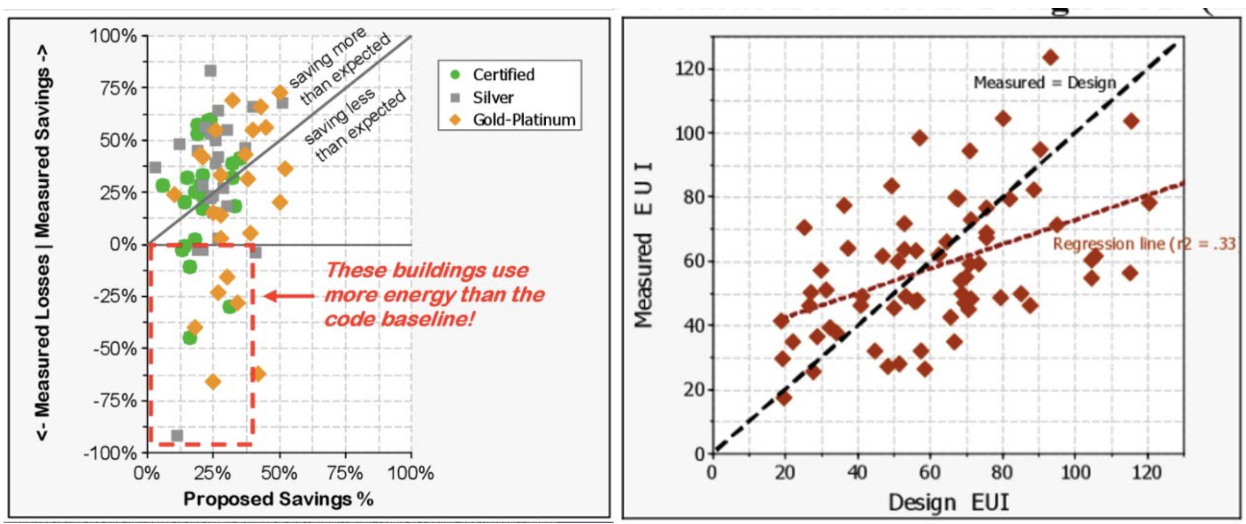


Figure 11. Predictive accuracy of energy models for LEED buildings

Virtually all stakeholders agree that simulated energy performance can vary from measured energy performance by 30% or more unless the model is specifically calibrated to actual building use and operation. The variability between simulated and actual energy performance of buildings is due to both internal (tool) and external (user-input) error, but the relative contribution of each of these components is unclear. This distinction is significant from a public perception standpoint. Input error can be reduced via calibration, more intelligent defaults, better quality checking processes, and additional user training, but errors in the fundamental tools of the trade cast the entire enterprise into doubt and create skepticism among BEM professionals. The sense among BEM professionals is that inputs are a greater source of error—perhaps even far greater—than assumptions or bugs in the software. However, this has not been shown convincingly, or communicated to BEM clients.

BEM may be wrong, but it is useful. Despite the challenges of predicting building energy consumption, BEM provides useful, actionable information via comparative analysis. As generalized in the famous George Box quote, "All models are wrong; some are useful." To sidestep the challenges of input data collection, most BEM use cases are intentionally comparative. Rather than being used to predict absolute energy use of a single building configuration, BEM is typically used to estimate relative differences in energy use between two or more configurations. Because many of the uncertain inputs are fixed across the simulations, their effect is largely canceled out with the result that relative savings calculations are typically much more accurate than absolute consumption calculations. It is noted that although comparative modeling reduces the importance of absolute predictive accuracy, it does not eliminate it. For one, better predictive accuracy often results in better comparative accuracy. For another, certain applications such as net-zero design are inherently predictive.

Uncertainty about uncertainty. There is a significant amount of uncertainty and stochasticity built into many BEM use cases, especially early in a project when less data is available and fewer decisions have been made. At the onset of a design project for instance, building forms and space plans are fluid and system types are unsettled, and uncertainty distributions can be large. As design decisions are nailed down, uncertainty ranges will shrink. However, even a final design will include some uncertainty related to weather, building occupancy and use, plug and process loads, and variances in construction.

The fact that many BEM use cases are comparative mitigates uncertainty, but does not eliminate it. However, uncertainty analysis is rarely used in practice. BEM results—energy use, peak demand, and other metrics—are often reported as points with no uncertainty bands or confidence intervals. This practice reinforces the expectation that BEM should be accurate and magnifies the frustration when its predictions are off.

There are a number of reasons uncertainty analysis is missing from common practice. For one, it can be difficult to strike the right balance with uncertainty analysis. Results with unrealistically narrow uncertainty bands reinforce false assumptions about accuracy. On the other hand, overly wide uncertainty bands create the opposite perception that BEM is just a guess and makes it difficult to act based on associated results. Uncertainty bands and distributions for key inputs are also difficult to ascertain. Finally, sound uncertainty analysis requires multiple simulations for which computing bandwidth may not be available.

Accuracy vs. consistency. The perception of BEM engine inaccuracy is reinforced by inconsistencies among BEM engines—"not only does BEM not agree with measured energy use, different engines don't agree with one another!" Again, although much of this inconsistency comes from modelers rather than the software tools they use, the perception of inconsistency accrues to the tools and BEM as a whole.

In common BEM use cases, including code compliance, ratings, and incentives, consistency is in fact more important than accuracy, especially considering the fact that accuracy can be difficult to assess. In these, inconsistency can lead to gaming in which modelers choose software that gives "better" answers and a subsequent "race to the bottom" among vendors to give modelers the answers they want with minimal effort.

Some programs have sidestepped the consistency issues by mandating a single implementation. Notable examples include the CEC's CBECC-Com and CBECC-Res compliance software, which require the use of EnergyPlus and CSE (California Simulation Engine), respectively, and BTO's Commercial Building Asset Score and Home Energy Score, which use EnergyPlus and, for the time being, DOE-2.1E. Although single-engine approaches are expedient, and may be justified in certain cases on grounds that go beyond expediency, they are not without problems. For one, they occlude accuracy issues in the chosen engine, and even eliminate some motivation to address them as doing so would create inconsistencies across different engine versions. From a practical standpoint, they can be difficult to integrate with existing workflows, ultimately forcing modelers to work in multiple tools and perhaps perform duplicate work. Finally, it fosters ill will among vendors that use competing engines. The CEC relaxed its mandate and created a testing framework for certifying other engines after vendor complaints. RESNET considered a single-engine approach to address consistency issues with HERS, but ultimately decided to continue updating its existing HERS engine testing framework.

Validation vs. testing. Ironically, BEM's reputation for inaccuracy is also publicly undermined by the procedure used to test BEM engines! Empirical validation requires fine-tuned well-controlled experiments. For a building, this means submetered energy consumption data, along with detailed design, construction, and operational knowledge. However, most buildings are too complex and have too many unknowns to support "validation-grade" experiments. Specially fitted and richly instrumented test facilities where it is possible to empirically determine BEM inputs are better experimental platforms, but these are expensive to build and operate (Roels 2017). BTO built two such facilities in the past several years, LBNL's FLEXLAB and ORNL's FRP, and several validation experiments are in progress. However, definitive results will not be available for some time, and algorithm coverage will be low for some time longer.

Because of the dearth of empirical data, BEM engines have historically been only minimally and opportunistically validated, but more extensively tested. This is the approach taken by ASHRAE Standard 140, [53] "Method of Test for Building Energy Computer Simulation Programs" (Neymark and Judkoff 2002). BEM engines are initially checked for agreement with analytical solutions, which exist for a relatively small number of simple and often idealized configurations. Engines that pass the analytical tests are compared to one another on more complex, realistic tests, adding realism one dimension at a time to improve diagnostic power. A significant amount of testing under a wide variety of conditions provides some of the confidence associated with

[53] http://sspc140.ashraepcs.org/

validation—if multiple programs get similar answers, it is more likely that they are all right than that they are all wrong in exactly the same way. ASHRAE Standard 140 has uncovered many errors in BEM engines. ASHRAE Standard 140 is recognized as a sound, if not complete, framework for BEM engine testing, continuous improvement, and convergence, and it is used as the basis for certifying engines for various applications. The central application is performance documentation for the IRS 179D tax credit. To qualify, software must submit ASHRAE Standard 140 test results and meet a number of other criteria. The IRS qualified software list[54] is referenced by multiple programs, including code compliance programs, green certification programs, and utility EE incentive programs. That said, even with ASHRAE Standard 140 well established, the lack of empirical results in the Standard feeds the perception that BEM engines are not validated against ground truth.

In addition to a lack of empirical reference data sets, ASHRAE Standard 140 suffers from a number of other shortcomings, several related to its coverage and development "velocity" and several to its scope. On the velocity side, it has poor coverage in some important areas of BEM with no tests for chilled/hot water coils, evaporative cooling, heat exchangers, chilled beams, heating and cooling plant systems, service hot water systems, water coils, chilled beams, heat exchangers, evaporative cooling, and air and water distribution systems. There are no tests for daylighting despite the fact that daylighting calculations are part of EE codes. Many existing tests have outdated results from engines that have not been in active development or even use in years. These shortcomings are due to limited bandwidth of committee members, many of whom are volunteers, and limited incentives for engine developers to participate in the development process and contribute reference results, also a volunteer activity. Exacerbating this particular problem is the fact that Trane and Carrier, two vendors that have historically developed their own proprietary engines and contributed ASHRAE Standard 140 reference results, have adopted EnergyPlus.

ASHRAE Standard 140 also has a significant scope limitation in that it includes only reference results, not acceptance criteria, i.e., result ranges that are considered "acceptable." ASHRAE Standard 140 leaves the question of setting acceptance criteria to standards and programs that reference it, most of which also ignore the issue and accept any program that submits ASHRAE Standard 140 results, regardless of what these results are. The absence of acceptance criteria perpetuates consistency problems and eliminates the incentive to investigate and address outlier calculations.

A second, less serious scope limitation is that despite the fact that many BEM use cases are comparative, ASHRAE Standard 140 includes primarily tests for individual configurations and not tests that compare the relative differences between two different configurations. This is ironic given that many BEM use cases are set up as comparisons between two related configurations—the ASHRAE Standard 90.1 Appendix G "Performance Rating Method" uses comparative modeling and has both code-compliance and beyond-code applications. Fortunately, ASHRAE

---

[54] https://www.energy.gov/eere/buildings/qualified-software-calculating-commercial-building-tax-deductions

Standard 140 test suites are designed so that individual tests typically differ from one another in small controlled ways that isolate different phenomena. It should not be difficult to synthesize relative difference test suites from the existing absolute configuration test suites. If ASHRAE Standard 140 scope expands to include acceptance criteria, acceptance criteria for relative difference tests can be created.

Testing of BEM rulesets. Accuracy and consistency issues plague not only BEM physics engines but also surrounding BEM software. One category of BEM software that has recently received significant attention is implementations of "rulesets," model transformation procedures like ASHRAE Standard 90.1 Appendix G that undergird both code-compliance and beyond-code programs. Although rulesets are human defined and do not present the same setup and measurement difficulties associated with building physics experiments, their software implementation is still plagued by inconsistencies due to differences in interpretation of sometimes ambiguous textual descriptions and software bugs. And although a testing framework exists for BEM engines, one for rulesets does not. The absence of a testing program for software BEM ruleset implementations increases the human effort associated with reviewing models created by rulesets and their relationship the nominal building models they were derived from.

Model input calibration. Modeling of existing buildings—for retrofit analysis, commissioning, or dynamic control—can be made more accurate and predictive by using measured data such as energy use and zone temperatures to calibrate uncertain inputs. Manual calibration strategies are well-known and several automated calibration tools are available. Measured data of various kinds is also becoming more readily available and at greater temporal resolutions via devices such as smart meters and smart thermostats. Recent research has even shown that targeted inverse modeling can directly calculate difficult-to-obtain inputs such as internal thermal mass and infiltration rates from smart meter zone temperature streams (Hong and Lee 2019). Documents such as ASHRAE Guideline 14, "Measurement of Energy and Demand Savings," and Building Performance Institute's BPI 2400, "Standard Practice for Standardized Qualification of Whole-House Energy Savings Predictions by Calibration to Energy Use History,"[55] set output accuracy thresholds for calibrated models. These standards are geared toward manual calibration, whereas current automatic calibration techniques can easily meet these standards. Further accuracy guidelines and targets are needed for automated calibration procedures.

One concern with calibrated models is that they may produce the "right answers" (i.e., energy use estimates) for the "wrong reasons" (i.e., a fortuitous combination of input settings that does not correspond to actual conditions) and render the models unsuitable for further analytical purposes. Guidelines such as NREL's BESTEST-EX[56] and the ANSI/RESNET calibration

[55] http://www.bpi.org/Web%20Download/BPI%20Standards/BPI-2400-S-2012_Standard_Practice_for_Standardized_Qualification_of_Whole-House%20Energy%20Savings_9-28-12_sg.pdf

[56] http://www.nrel.gov/buildings/bestest-ex.html

standard method of test[57] use known configurations to establish tests for calibration methods that evaluate both output fidelity, input fidelity, and accuracy in savings estimations.

Missing accuracy feedback loops. The fact that predictive accuracy is difficult to achieve has driven the BEM industry to reformulate use cases to de-emphasize it. While this approach has made BEM more utilitarian, it has also had the unfortunate side effect of severing the accuracy feedback loop. BEM results are rarely revisited and compared to the performance of the actual building. Even if a comparison is made, it rarely reflects back to the modeler and often is not even shown to the modeler. Conscientious modelers who use more accurate engines, more appropriate assumptions, and more rigorous QA (quality assurance) procedures to produce more accurate predictions are not rewarded, nor are the tools they use. Similarly, less conscientious modelers and less accurate tools are not penalized for inferior accuracy. Without predictive accuracy to serve as a metric for BEM quality, the focus has shifted to cost reduction instead with the predictable result being an effective negative pressure on accuracy. The rare exceptions are use cases like ESPCs where project finances are directly tied to the accuracy of predicted energy savings. In these projects, BEM is a well-financed activity that seeks out and rewards well-trained, experienced and conscientious modelers, accurate tools, sound and rigorous procedures, and the intentional incorporation of measured data and feedback into the BEM process. Other use cases like outcome-based codes and the design of net-zero energy and net-zero energy buildings also emphasize predictive accuracy and have the same positive impacts on BEM process, quality, and resourcing.

3.2 Initiatives

Modern BEM engines do make some simplifications in the name of computational tractability. For instance, EnergyPlus only models 1D heat transfer through surfaces and cannot derive the presence of thermal bridges from the input model itself. Other common simplifications include assumptions about perfect air mixing, conflation of radiative and convective heat transfer effects, assumptions about the ability of HVAC systems to meet thermal loads, and modeling of idealized control. Nevertheless, BEM engines implement advanced algorithms that have been developed and tested in the context of these simplifications, and have been well-described in peer-reviewed literature. Empirical validation is therefore unlikely to identify internal deficiencies whose mitigation will significantly improve BEM engine predictive accuracy. Nevertheless, characterizing and documenting the accuracy of BEM engines is important. Empirical validation will support the BEM value proposition by (presumably) showing that BEM engines are accurate. It will help set reasonable expectations for accuracy of various aspects of BEM. It may lead to the development of methods for addressing different sources of internal error, such as comparative modeling to cancel out the effects of the error. Finally, it will set

[57] http://www.resnet.us/blog/wp-content/uploads/2016/10/ANSI-RESNET-1201-2016-SMOT-for-Calibration-Methods.pdf

definitive bounds for external errors associated with various types of inputs and lead to methods for acquiring better and/or accounting for uncertainty in these inputs.

Work is also needed to address related issues in uncertainty analysis, calibration, and software consistency. Finally, where there are opportunities to create or reinforce positive accuracy feedback loops (e.g., outcome-based codes and ESPCs), these should be pursued.

Empirical validation. BTO has invested in purpose-built whole-building test facilities at LBNL (FLEXLAB) and ORNL (FRP) that are sufficiently characterized, controlled, and instrumented to support "validation-grade" experiments. BTO funded a four-year project that uses these facilities to generate data sets for ASHRAE Standard 140. That project also developed an uncertainty quantification framework for quantitatively reasoning about the uncertainty in both test-facility measurement and simulation. Critically, the uncertainty framework allows the calculation of "signal-to-noise" metrics for evaluating whether a set of experimental results meet validation criteria.

A subset of these results is undergoing ASHRAE Standard 140 review and will be published as part of the standard in the future. BTO has already launched follow-on projects at LBNL, ORNL, NREL (with a modular apartment that can be tested both indoors and out), and at NIST (using their Zero Energy Residential Test Facility[58]). BTO is also attempting to repurpose the results of some older experiments for the standard.

Assuming the process of turning empirical data sets into standard-worthy reference proves fruitful, BTO should continue to support such experiments as long as test facilities can be configured to produce meaningful new data sets, e.g., ones that examine different building physics phenomena, system types, or climate effects. BTO should look to leverage appropriate test facilities outside the national laboratories (e.g., FLEXLAB Singapore[59]) to increase the scope of this activity.

In addition to purposely designed validation experiments, BTO should look to leverage other selected experiments being conducted at FLEXLAB, FRP, and other test facilities—i.e., experiments funded by other organizations and/or for purposes other than BEM validation—to develop additional validation data sets. This will likely require additional work on the part of experimental project teams and additional funding from BTO. BTO should use the lessons learned from the initial round of FLEXLAB and FRP experiments to develop and publish requirements for "validation-grade" experimental design, data collection, and documentation so that project teams wishing to contribute data can plan accordingly and potentially apply for additional funding.

Empirical data sets should be codified in new ASHRAE Standard 140 tests.

[58] https://www.nist.gov/el/net-zero-energy-residential-test-facility
[59] https://flexlab.lbl.gov/singapore

Figure 12. LBNL FLEXLAB (top), ORNL FRP (bottom left), and NREL iUnit (bottom right) test facilities

Source: LBNL, ORNL, NREL

ASHRAE Standard 140. In addition to empirical reference results, BTO should continue to fund other needed content and process improvements to ASHRAE Standard 140.

A joint working group representing ASRHAE Standards 90.1 and 140 and supported by BTO has recommended that ASHRAE Standard 140 be expanded to include both comparative tests and acceptance criteria for individual tests.

BTO should continue to support the expansion of the analytical verification and comparative testing framework as a way of both expanding test coverage, and discovering areas of disagreement among engines, and defining needed empirical tests.

Automation could improve both the development velocity of the Standard and its accessibility and utility. Currently, test specifications are distributed and published in document (i.e., PDF) form while test results are submitted as spreadsheets, which are combined manually to form reference results. Distributing test specifications and collecting results in a schematized form would accelerate testing, and opens up the possibility of integrating ASHRAE Standard 140 testing more tightly into the development process of different engines. True, finding an input schema that works for all BEM engines has been a long-standing industry goal that continues to elude—different BEM engines use input specifications that differ not only in format, but also in content—however, there is renewed demand enthusiasm for such a schema. BTO should support schematization and automation in support of ASHRAE Standard 140 development and application.

The most significant improvement in ASHRAE Standard 140 would be an increase in the number of actively developed BEM engines that participate in simulation trials and contribute reference results. Currently, BTO supports the development of the standard (i.e., the definition of the tests, the curation of the results, and the authoring and publishing of the document) directly. Separately, it also funds the participation of EnergyPlus in the standard making process and the contribution of EnergyPlus reference results. Representatives of other BEM engines—typically members of the corresponding development teams—participate and contribute on their own time. BTO should strongly consider paying representatives of other engines to participate and contribute results. Increased participation in the standard development process would improve consistency in addition to accuracy.

ASHRAE Standard 229P. Recently, BTO has backed the creation of a new proposed ASHRAE Standard 229P, "Evaluating Ruleset Implementations in BEM Software."[60] This Standard aims to establish per-project reporting guidelines and a reporting schema for software that implements BEM rulesets. This schema is intended to support checking of ruleset implementations by comparing reports for pre- and post-ruleset building models. ASHRAE Standard 229P working group plans to develop an open-source checking tool for ASHARE Standard 90.1-2019 Appendix G. The standard and schema are being developed in a way that allows them to be referenced and reused by other ruleset standards such as California Title 24 ACM and ANSI/RESNET/ICC 301.

Uncertainty analysis. Empirical validation and testing can bound the error due to BEM calculations, attributing remaining error—or rather uncertainty—to model inputs. Input uncertainty is present to some degree in every BEM analysis and project, but explicit uncertainty analysis is not.

BTO should work with professional organizations to promote the use of meaningful uncertainty analysis in BEM applications like design, incentive calculations, and operational support, and to set client expectation that BEM predictions are ranges and distributions, not points. For the design use case, the use of uncertainty analysis in BEM could be codified in a guideline such as ASHRAE Standard 209. BTO should support data collection and research to understand the prevailing loci and magnitudes of uncertainty in building assets, use, and operations. It should then use this data to develop meaningful protocols and set realistic expectations for uncertainty analysis in various BEM use cases. These distributions, protocols, and targets should be codified in Standards guideline documents.

Automated model input calibration. For existing building projects, uncertainty in model inputs can be reduced using calibration. With fine-grained measured energy use and environmental and building data becoming increasingly available at greater spatial and temporal resolutions—interval meter data, smart thermostat data, and other data streams from sensors and smart

[60] https://www.energy.gov/eere/buildings/ashrae-standard-229p-development

equipment—and cheap high-throughput cloud computing, the cost of automated calibration is shrinking while its potential effectiveness is growing.

BTO has invested in several automated calibration projects. Autotune[61] identified the most promising algorithm and configuration for calibration in the BEM domain. This algorithm is now available as an Analysis gem for OpenStudio Server. There is also an OpenStudio Server Analysis gem for Bayesian calibration, which combines calibration with uncertainty analysis. LBNL researchers have developed a selective inverse modeling approach that uses an inverted zone heat balance equation to perform targeted calibration on infiltration and internal thermal mass inputs using zone temperature data streams from smart thermostats.[62] This capability is available as an EnergyPlus feature. BTO has also funded a recent small business project on the use of machine learning in calibration.[63] Additional investment is needed in these directions. Work is specifically needed on a problem that plagues automated calibration, getting "the right answer for the wrong inputs," i.e., identifying input combinations that match measured consumption data but do not resemble the physical configuration. Manual calibration, a process that strangely combines tedium with experience and art, is less prone to this problem because human judgement is involved at every step of the process. Finding ways to combine the best aspects of automated and manual calibration—hopefully resulting in a process that is 98% automated and not the other way around—would represent meaningful progress.

BTO has previously invested in a model calibration testing harness called Trinity. Continued development of calibration testing and benchmarking methods is needed.

Calibration guidelines should be updated and strengthened. Existing documents like ASHRAE Guideline 14 and BPI 2400 are seemingly aimed at manual calibration. Automated calibration can already achieve better results and its use should be strongly encouraged. BTO should work with ASHRAE and BPI to strengthen calibration guidelines to reflect the improving capabilities of automated calibration.

Positive accuracy feedback loops. The most difficult but perhaps most important role for BTO is to reinforce the positive accuracy feedback loops that exist in BEM use cases such as zero-net energy (ZNE) design, ESPCs, and compliance with outcome-based codes, and to create ones in use cases that currently do not have them. However, BTO should continue to look for opportunities to do so. Although it is doubtful that BTO can directly create demand for accurate BEM in use cases that do not currently value it, BTO may at least be able to illuminate and quantify the relationship between modeling accuracy and modeling task cost. Through a partnership with AIA and its 2030 Commitment, BTO has been tracking the use of BEM in design for a number of years. This tracking has recently expanded to include post-occupancy measured energy use data and modeling cost data, although both of these fields are optional. This

[61] https://www.energy.gov/eere/buildings/downloads/core-2012-autotune
[62] https://www.energy.gov/eere/buildings/downloads/benefit-2014-new-hybrid-approach-energy-modeling
[63] https://www.energy.gov/eere/buildings/sbir-2018-building-energy-calibration-based-parameter-estimation-and-machine-learning

data could be mined for correlations between accuracy and other variables such as cost or specific tools.

Client awareness. An important aspect of these related enterprises is communicating their outcomes and the implications of those outcomes to BEM professionals and their clients. Journal publications and conference presentations may suffice for BEM professionals. However, BEM clients generally do not read technical literature or attend technical conferences. They are also unlikely to be convinced by laboratory experiments, preferring real world examples and testimonials from counterparts in their industries.

Real-world buildings may not be a good source of validation-grade data, but their use to document and track progress in predictive BEM accuracy and calibration can be more convincing and compelling to skeptical stakeholders. BTO should use appropriate well-documented, well-understood, and well-monitored buildings (such as ASHRAE Headquarters) as potential BEM test-bed buildings and promote “experiments” that use such buildings. A worthy complement to a small number of detailed case studies would be a larger pool of buildings that individually have less instrumentation and less rigorous characterization, but that collectively could be used to statistically benchmark and track progress in BEM engine accuracy, calibration capabilities, and other aspects of the alignment between measured and modeled energy consumption.

In addition to better information about the accuracy of BEM engines and related software, BEM clients also need to be better informed about the role BEM plays in their projects, the importance of absolute accuracy to that role, and the typical degrees of predictive uncertainty associated with that role at various stages of the project. Finally, BEM clients should be educated about the reality that, as with everything else, predictive accuracy can be improved with additional cost.

Table 7. Predictive Accuracy Barriers and Initiatives

Barriers	Initiatives
Empirical validation. Predictive BEM is challenging. At the same time, the inherent error of BEM engines is not quantified and separated from input uncertainty creating the perception that the BEM enterprise is built on shaky tools. That BEM engines are currently tested against one another and analytical results rather than validated against ground truth reinforces this perception.	Support empirical validation of BEM engines using well-characterized and instrumented test facilities like LBNL's FLEXLAB, ORNL's FRP, NREL's iUnit, and NIST's NZERTF.
Engine testing. In addition to a lack of empirical data, ASHRAE Standard 140 suffers from several shortcomings including poor coverage in some significant aspects of BEM, and shrinking participation and contributions from engine vendors.	Expand ASHRAE Standard 140 analytical and comparative test coverage.
	Invest in ASHRAE Standard 140 development and testing automation.
	Financially compensate vendors to participate in and contribute to Standard 140 development.
Ruleset testing. Implementation consistency and fidelity plague not only BEM engines, but other BEM software components such as ruleset implementations.	Support ASHRAE Standard 229P for ruleset implementation testing. Promote the application of the 229P framework to non ASHRAE rulesets.
Uncertainty analysis. BEM clients have unreasonable expectations for precision in BEM prediction. BEM professionals are not accustomed to performing uncertainty analysis.	Support development of guidelines and protocols for uncertainty analysis in different BEM use cases.
	Codify and promote the use of uncertainty analysis in different BEM use cases, e.g., in ASHRAE Standard 209 for design assistance.
Model input calibration. Improved calibration methods that enable greater in modeling of existing buildings are not widely used and calibration standards are lax.	Support development and use of advanced automated model input calibration methods.
	Support development of methods of tests and advanced standards for calibration.
Missing feedback loops. Predictive accuracy is valued in only a few use cases. In most, low modeling cost is valued, exacerbating the accuracy problem.	Promote BEM use cases with positive accuracy feedback loops.
	Demonstrate the relationship between BEM accuracy and BEM effort and cost.
Client awareness. Lab tests may not be sufficient to convince skeptics that BEM is sufficiently accurate on real-world occupied buildings. There is a general lack of understanding about the importance of predictive accuracy in different BEM use cases, the degree of uncertainty that is inherent in different BEM use-cases at different project stages, and the correlation between predictive accuracy and modeler effort.	Identify showcase buildings that can be used to evaluate and promote BEM predictive accuracy and calibration methods.
	Educate BEM clients about the specific role of BEM in various use cases, the importance of predictive accuracy to each of these use cases, and the uncertainty inherent in each of these use cases.

4 Topic 2: Core Modeling Capabilities

As this document transitions to issues related to BEM software, we reiterate that this report only directly deals with BTO-funded and managed software. BTO recognizes that the BEM universe includes many other public and private sector software packages, some that interact with BTO software and others that do not. BTO's goal is to make its software as valuable to the BEM community and its range of vendors as possible. The barriers described apply to BTO software, primarily the EnergyPlus BEM engine, and the Spawn BEM controls engine. The corresponding initiatives are designed to address these barriers with the larger goal in mind.

Summary:

- Missing or poor workflows and guidance for using advanced EnergyPlus features like thermal bridges, duct pressure drops, and pressure-driven airflow more generally.
- Lack of support for use of EnergyPlus and BEM more generally in control and operations applications.
- Lack of support for co-simulation and integration of EnergyPlus and BEM more generally in larger, multidomain analyses.
- EnergyPlus's monolithic structure makes it difficult to reuse its component models elsewhere, e.g., in other engines.
- BTO should develop guidance, and where appropriate, workflows for using advanced BEM features. One example could be a workflow linking THERM outputs to EnergyPlus thermal-bridge inputs.
- BTO should continue to clarify the role of Spawn and URBANopt within its tools ecosystem and their anticipated roles in the market.
- BTO should emphasize co-simulation and linkage of its BEM tools to external analyses in favor of directly expanding the scope of EnergyPlus into new areas.
- As part of the EnergyPlus re-engineering effort, BTO should focus on making different EnergyPlus components and modules available as libraries.
- BTO should perform significant market research and stakeholder outreach before starting significant new BEM software projects.
- BTO should look for additional ways to allow users, vendors, and other stakeholders to contribute to its development planning and prioritization processes.

Relevant BTO projects:

- **EnergyPlus.** Open-source, state-of-the-art BEM engine.
  https://www.energy.gov/eere/buildings/downloads/energyplus-0/
  https://www.energy.gov/eere/buildings/downloads/energyplus-10x
  https://energyplus.net/
- **Spawn of EnergyPlus (Spawn).** Open-source BEM-controls engine that supports co-simulation in a fundamental way and integrates with control design, verification, and implementation workflows.
  https://energy.gov/eere/buildings/downloads/spawn-energyplus-spawn/ and https://srg-lbl.github.io/soep/
- **URBANopt.** An EnergyPlus/Spawn- and OpenStudio-based SDK for modeling campuses and districts that include shared thermal resources, distributed energy resources, and microgrids.
  https://www.energy.gov/eere/buildings/urbanopt
  https://nrel.gov/buildings/urbanopt.html
- **Radiance.** Open-source, state-of-the-art lighting simulation tool. Originally managed as part of BTO's windows program.
  https://www.energy.gov/eere/buildings/downloads/radiance/
  https://radiance-online.org/
- **THERM.** A 2D/3D heat transfer engine for detailed analysis of facades. In a four-year project, BTO is adding moisture transfer modeling capabilities to THERM.
  https://energy.gov/eere/buildings/downloads/fenestration-software-tools/,
  https://www.energy.gov/eere/buildings/downloads/benefit-2016-moistherm-integrated-heatmoisture-transfer-envelope-modeling/
  https://windows.lbl.gov/software/therm/therm.html

4.1 Barriers

EnergyPlus is a mature engine with a significant range of advanced capabilities. It is by no means perfect and has a sizeable list of known issues, both small and significant (difficulties with non-convex spaces are long-standing), missing features, and wish-list items. Radiance and THERM are similar. As of this writing, Spawn is in beta. The point of this section is not to enumerate the defects in these tools—for EnergyPlus at least there is a GitHub issues page[64] for this specific purpose—but to outline several broad categories of missing or inadequate functionality that represent barriers to BEM tasks.

Lack of guidance for characterizing certain phenomena and building configurations. Almost every meaningful calculation in every BEM engine relies on some externally specified

[64] https://github.com/NREL/EnergyPlus/issues/

input. The choice of where to place the boundary between inputs and calculations determines the flexibility and complexity of the model and its applicability to different use cases. More detailed models require more detailed inputs and perform more, and more complex, calculations.

EnergyPlus embodies a number of design choices that simplify internal calculations and reduce the granularity and complexity of inputs. These simplifications model some default behavior, but can be over-ridden to effectively model and account for more detailed phenomena. Configuring and parameterizing these more advanced models requires care, experience, and inputs that many modelers do not know how to obtain or impute from inputs they can obtain.

One widely cited example is the ability to model thermal bridges. EnergyPlus uses 1D surface conduction models that account for heat and moisture transfer through surfaces but not across them, and does not model conduction at seams between two surfaces. These effects can be accounted for using "tricks" such as subsurfaces with different thermal and moisture resistance and capacitance values, but EnergyPlus cannot calculate these resistance and capacitance values itself from its geometry and construction inputs; the modeler must calculate these in another tool and bring them into EnergyPlus. Guidance and automation for this process are lacking.

A second widely cited example is the ability to model pressure drops in ducts. As with thermal bridges, EnergyPlus can account for user-supplied pressure drops in HVAC air-distribution performance calculations but cannot calculate these from duct-layout specifications. More generally, EnergyPlus's pressure-driven airflow simulation features are difficult to configure using inputs that are readily available from specification or measurement. Natural ventilation, ventilated facades, and large atria are frequently mentioned as difficult to configurations to model.

These and other advanced features are rarely used because they are difficult to set up properly.

Lag in availability of models for new components and systems. One commonly mentioned deficiency is the delay between when a new technology appears on the market and when that technology can be modeled. This delay can last several years—chilled beams entered the market in 2007 and were not modeled in EnergyPlus until 2009. It can be many years—variable refrigerant flow (VRF) systems entered the market in the 1980s[65] but were not modeled in EnergyPlus until 2011 (Nigusse and Raustad 2013). The absence of a model for a new technology may depress deployment of that technology. Designers and engineers may be wary of recommending or using a technology if they cannot evaluate it quantitatively. Incentives for the technology are usually not available until the EE program administrator performs a benefit-cost analysis for their service territory.

As stopgaps, BEM professionals employ workarounds, attempting to model new technologies as variants or hybrids of technologies that are available in their tool of choice. This approach works if the new technology is—from a thermal system standpoint—a more efficient version of an

[65] "VRF systems have been used in Japan since the 1980s": https://en.wikipedia.org/wiki/Variable_refrigerant_flow

existing technology, e.g., an LED can be accurately modeled as a more efficient version of a compact fluorescent lamp (CFL). If the new technology is qualitatively different than any existing technology in its dynamics or interactions—VRF systems took a long time to model in part because the way they serve the loads of multiple zones and transfer load from one zone to another is different than the operation of other space conditioning systems—modelers must resort to bespoke workarounds. These often misrepresent emerging technologies, yielding erroneous results and eroding confidence in BEM. Ad hoc modeling approaches also typically differ from one modeler to the next, exacerbating inconsistency and feeding the perception that BEM is an art rather than a science. Implementing workarounds also adds cost to BEM tasks and processes.

Lack of capabilities supporting use in building operation and grid interactions. Multiple stakeholders mentioned lack of support for building operations as a key gap in light of the growing importance of demand response (DR) and other aspects of building-to-grid integration. With greater variance in supply due to increasing penetration of intermittent renewables such as wind and solar and a changing load mix that includes a greater number of electric vehicles, building owners and operators will be financially motivated to not only operate their buildings more efficiently, but more responsively. BTO has a new cross-cutting program called Grid-interactive Efficient Buildings (GEB)[66] that looks at the intersection of EE and demand flexibility with a focus on turning building loads and behind-the-meter distributed energy resources into grid assets.

BEM can support building operation via applications such as CCx, automated FDD, and MPC. BEM can also be used to design buildings that are inherently more flexible in their energy use and better able to respond to dynamic grid conditions. In 2019, BTO published a report that describes the role of BEM in GEB, and identifies gaps and opportunities (Roth and Reyna 2019). The most significant gaps identified all dealt with lacking integration with different domains of models and workflows: (1) control design and implementation workflows, (2) advanced district thermal generation, distribution and storage, and (3) electrical distribution models.

The fundamental capability required to support many of these is co-simulation. At a high level, co-simulation is the ability to exchange information with external data streams—other models, building energy management systems, etc.—within the simulation time step, perhaps even multiple times within the time step in order to support convergence to a next-state solution. Co-simulation stands in contrast to traditional “offline” BEM use cases in which the outside world interacts with a simulation only via initial inputs and final outputs. EnergyPlus’s external interface and energy management system (EMS) can be used to jury-rig co-simulation, and tools such as the Building Controls Virtual Test Bed (BCVTB)[67] simplify this task. EnergyPlus has also recently added the capability to export itself as an FMU (functional mockup unit) for co-simulation purposes. However, true co-simulation capabilities are limited by EnergyPlus’s

[66] https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings
[67] https://simulationresearch.lbl.gov/bcvtb

internal structure and solution approaches. Improved support for co-simulation would support not only building operations, but also enable more sophisticated workflows that integrate whole-building energy models with other models such as computational fluid dynamics (CFD) for indoor and/or outdoor airflow modeling, or integrate multiple building models into a neighborhood- or urban-scale simulation.

Related to co-simulation is the capability to save simulation state and restart simulations from the same state, possibly with changes to selected variables. This capability is useful in applications such as MPC, where it allows the parallel exploration of multiple control strategies starting from a given point in time.

A separate capability needed to support control workflows is the ability to simulate real-world control sequences by interpreting them and executing them directly. The current lack of interoperability and portability of control sequences results not only in productivity loss, but also in deviations between simulated and measured results. For new buildings, control engineers must interpret sequences specified by modelers. For existing buildings, modelers must determine which built-in control sequence most closely matches the one implemented in the BAS. The capability to directly execute physically realistic control sequences is difficult to “retrofit” into EnergyPlus, but is one of the main distinguishing features of Spawn.

Monolithic structure and underutilization of libraries. Scientific applications dominated the early days of computing. These applications were written in languages like FORTRAN which were designed for speed rather than for software reusability and maintainability. In the mid-1980s, the rise of the personal computer and the development of popular operating systems enabled tremendous growth in consumer software applications and gave rise to discipline of software engineering, which emphasized modularity, maintainability, reusability, and testability—initially at the expense of execution speed—and promoted object-oriented languages like C++ and Java. Although EnergyPlus development began in the 1990s and the first version was not released until 2001, a significant amount of its initial code came from FORTRAN programs, and development in FORTRAN continued until 2013. The subsequent translation to C++ was syntactic only. EnergyPlus was somewhere around one million lines of code at the time and a manual translation and re-engineering effort was impractical, and so automated translation methods were used. The new codebase retained the original FORTRAN architecture, although C++ did enable a gradual transition to a more modular, object-oriented design.

Nearly seven years after the transition to C++, although much re-engineering progress has been made in some areas of the code, EnergyPlus’s overall monolithic structure remains. This structure makes it difficult to add new capabilities, especially ones that are significantly beyond those initially envisioned and do not fit neatly within the rigid structure of the code. It makes it difficult to link to capabilities in other software. It limits the pool of developers—because portions of the code are not cleanly separated from other portions, developers have to be familiar with a lot of code before they can make meaningful contributions. It also makes it difficult to reuse subcomponents of EnergyPlus—e.g., the plant simulation module, or the psychrometrics calculations—in other BEM engines and applications, and for EnergyPlus itself to use external libraries. EnergyPlus is open-source software, and a number of vendors and third-party developers do manually extract components of interest from EnergyPlus, but this process is significantly more difficult than it could be. Combined with the lack of an API that gives access to EnergyPlus internal calculations, this makes EnergyPlus an all-or-nothing proposition and limits its utility and the benefit of its development.

Insufficient opportunities for stakeholder input on development planning. The aforementioned GitHub issues page and its predecessor UserVoice site allow users and other stakeholders to report EnergyPlus bugs, request and vote on new features, and generally track development progress. There are annual requests for input on EnergyPlus development priorities. Third-party application vendors that contribute in-kind labor to EnergyPlus development use direct interactions with the development team. EnergyPlus development is also prospectively "merit reviewed" for renewal once every three years, and retrospectively "peer reviewed" on the off years. The other projects use technical advisory groups as opposed to more public-facing mechanisms. They are reviewed on similar timelines. Despite the presence of these mechanisms, it appears that more opportunities for interaction and feedback are needed. A more public version of the strategic three-year prospective review may be beneficial.

4.2 Initiatives

With two BEM engines, EnergyPlus and Spawn, along with supporting engines THERM and Radiance, BTO has the opportunity to address some of these issues in a direct way.

Guidance and workflows for advanced simulation features. EnergyPlus cannot discover and characterize phenomena like envelope thermal bridges and duct pressure drops from physical descriptions and first principles, but can account for phenomena if they are properly characterized externally and properly configured as EnergyPlus inputs. Investment is needed in developing guidance and, where appropriate, workflows for using these features.

BTO's portfolio includes the THERM detailed envelope heat and moisture transfer engine.[68] Given the related but different use cases for THERM and EnergyPlus, and BEM more generally along with performance considerations, direct integration or even co-simulation of THERM and EnergyPlus is not practical and probably not even desirable. Developing guidelines and best practices for translating THERM outputs to BEM inputs—and where appropriate, automation—is more practical. Building information modeling (BIM)-to-THERM-to-BEM workflows would further help close the gap between BIM and BEM.

BTO's portfolio does not include tools for calculating duct pressure drops from layout diagrams but such tools exist. Duct layout may also be available in BIM. Again, developing guidance—and where appropriate automation—for using BIM and other tools to create useful per-project

[68] https://windows.lbl.gov/software/therm/therm.html

inputs for BEM tools is needed. ASHRAE's air-distribution system task group[69] and the Alliance for Sustainable Energy's System Efficiency Initiative (SEI)[70] have both looked at this issue and can be consulted, along with vendors of air distribution system design and analysis tools on a viable and valuable path forward.

In some cases, research—using simulation, physical experiments, or both—may be needed to identify the most accurate and expedient ways to represent complex phenomena using primitives or payloads in EnergyPlus or other BEM engines. BTO should support this research through the labs, ASHRAE, IBPSA, or a combination.

Spawn and BTO's BEM control ecosystem. EnergyPlus has a built-in library of standard HVAC control options and also supports user-defined control sequences. The March 2020 version of EnergyPlus, 9.3.0, allows these user-defined control sequences to be written in python. These capabilities are well suited to evaluating different control options in traditional BEM applications. They not as well suited to supporting control applications like control design and implementation, MPC, and others.

BTO has tried to articulate the intended role of Spawn in its portfolio and in the larger software ecosystem on its website,[71,72] and in various publications including this document. While continuing to improve control related capabilities in EnergyPlus—most recently and notably via the python EMS feature—BTO needs to maintain internal and public clarity about the roles of EnergyPlus and Spawn for the benefit all stakeholders, but primarily vendors and their clients.

Emphasis on co-simulation over direct integration. One of the nominal advantages of Spawn over EnergyPlus is its fundamentally integrated support for co-simulation, at least in the section that is re-implemented in Modelica, "beginning" with the room air- and heat-balance model and extending out to the HVAC system and plant.

As it looks to support larger and more comprehensive analyses both for its own internal purposes and as platforms for third-party analysis, BTO should place great emphasis on and give great preference to co-simulation over direct integration. Rather than adding functionality directly to EnergyPlus and Spawn, functionality it subsequently has to pay to maintain, BTO should focus on linking to existing external engines. Even if new capabilities must be developed, these should leverage the co-simulation paradigm so that the EnergyPlus and Spawn cores can be kept as lean as possible and the new capabilities can be as reusable as possible. The URBANopt project takes this approach with regards to electrical system, distribution system, and distributed energy resource simulation.

Emphasis on simulation flows over direct integration. Where co-simulation is not necessary and pre- or post-processing in pipeline fashion is sufficient—this is the case when the calculation

[69] https://www.ashrae.org/standards-research--technology/technical-committees/section-disbanded-mtgs/mtg-hpas-high-performance-air-handing-systems-for-buildings-except-low-rise-residential
[70] http://www.ase.org/systemsefficiency
[71] https://www.energy.gov/eere/buildings/building-energy-modeling-project-portfolio
[72] https://www.energy.gov/eere/buildings/downloads/spawn-energyplus-spawn

doesn't interact tightly with heat-balance—direct integration should be avoided even more strictly.

For pre-processing, the ability to override selected inputs or internal variables with external calculations, via either API callbacks or files, is sufficient. For post-processing, the required capability is to export specific internal calculations again either via files or API calls. OpenStudio uses Measures to set up Radiance and GLHEpro[73] as EnergyPlus pre-processors. Energy cost and greenhouse gas (GHG) calculations could similarly be implemented as post-processing steps. EnergyPlus currently contains integrates several modules that could be factored out as either pre- or post-processing steps, simplifying the engine and improving modularity and reusability.

Emphasis on use and creation of libraries. For the past several years, EnergyPlus has been undergoing a methodical (i.e., slow) re-engineering effort focused on improving its performance and on taking advantage of C++ features and object-oriented design methodologies to make the code easier to maintain.

An additional focus of this effort should be on increasing the use of standard libraries within EnergyPlus, both by replacing existing custom code with external libraries where suitable ones are available and, where appropriate, by re-engineering portions of EnergyPlus itself as libraries that can be reused elsewhere. EnergyPlus already uses a number of external libraries including WinCalc[74] for detailed fenestration modeling, Kiva[75] for ground heat-transfer simulation, and Penumbra[76] for GPU-based solar shading calculations, as well libraries for linear algebra, reading and writing different formats, and other functions. Examples of EnergyPlus modules that could be replaced with libraries or themselves become libraries include psychrometrics, weather modeling, geometry, daylighting, plant simulation, and others.

Additional and more formal mechanisms for collecting stakeholder feedback on development projects. BTO has some mechanisms for collecting project-level feedback and guidance at the granularity of an individual feature and others for collecting it at an annual level. Opportunities for program-level feedback are available at lower frequencies, via mechanisms such as this document and its associated RFI (Request for Information) and the program-level review BTO piloted in 2019.

To improve this broad engagement, BTO could hold quarterly or semiannual webinars inviting users and developers to float ideas and concerns interactively. BTO could also hold annual stakeholder meetings—similar to user conferences for popular development platforms or software packages—to discuss new developments and future priorities.

73 https://hvac.okstate.edu/glhepro/overview
74 https://energy.gov/eere/buildings/downloads/fenestration-software-tools/
75 https://bigladdersoftware.com/projects/kiva/
76 https://bigladdersoftware.com/projects/penumbra/

The "GitHub issues" sites, webinars, and user conferences are broad engagement instruments. For the BTO-private sector developer partnership to work effectively going forward, the parties need a more structured, focused, formal process exchanging information, perspectives, needs, and concerns. Over the past several years it has become clear that an important constituency comprises the set of vendors who do not use EnergyPlus and/or OpenStudio and are concerned about scope creep and an inappropriate level of competition from these products. It is important to recognize stakeholders, hear their concerns, and account for them. The IBPSA-USA Advocacy Committee[77] has acted in this role since 2017 and was the driving force behind BTO's decision to transition the OpenStudio Application. BTO plans to continue to engage with this group and could look to formalize this relationship and its communications with a Memorandum of Understanding (MOU).

At an extreme, BTO could set up a governing consortium and financial "container" for the EnergyPlus and OpenStudio projects as it recently did with the VOLTTRON project, which is now part of the Eclipse Foundation family of projects.[78] BTO would contribute priorities and funds to the consortium, but cede decision-making power. BTO should consider whether such a structure is viable and desirable for EnergyPlus and its other software development projects.

[77] https://sites.google.com/site/ibpsausaadvocacycommittee/home
[78] https://projects.eclipse.org/projects/iot.volttron

Table 8. Core Capabilities Barriers and Initiatives

<table>
<tr><th>Barriers</th><th>Initiatives</th></tr>
<tr><td rowspan="3">Lack of guidance and workflows for using advanced EnergyPlus functionality. Workflows and general guidance is missing for leveraging advanced simulation capabilities such as thermal bridges and natural ventilation.</td><td>Work with stakeholders to understand needs and potential workflow solutions for leveraging detailed envelope analysis in BEM. Leverage THERM to prototype and test workflows and develop guidance.</td></tr>
<tr><td>Work with stakeholders to understand needs and potential workflow solutions for other advanced simulation features such as duct pressure drops and pressure-driven airflow. Develop guidance for proper configuration and use of these features.</td></tr>
<tr><td>Work with stakeholders to identify areas of BEM that need additional basic research and support ASHRAE, IBPSA, or BTO directed projects to conduct it.</td></tr>
<tr><td>Lack of support for control and other operational applications. EnergyPlus is not well suited to supporting building control applications. The position of Spawn vis-à-vis EnergyPlus is not clear.</td><td>Continue to articulate a clear position and value proposition for Spawn and URBANopt within BTO's BEM ecosystem and the market.</td></tr>
<tr><td>Difficulty in creating large or multidomain analyses using EnergyPlus. Incomplete support for co-simulation and inflexibility in some key inputs make it difficult to incorporate EnergyPlus into larger analyses, e.g., neighborhood- and urban-scale BEM.</td><td>BTO should continue to emphasize support for co-simulation and input and output flexibility and give preference to these approaches over adding functionality to EnergyPlus proper.</td></tr>
<tr><td>Limited availability of general-purpose BEM libraries. EnergyPlus's monolithic structure makes it difficult to reuse its component models as building blocks in other tools and analyses.</td><td>As part of the ongoing EnergyPlus re-engineering effort, emphasis should be placed on making selected modules available as libraries and on increasing the use of libraries within EnergyPlus.</td></tr>
<tr><td rowspan="2">Mechanisms for integrating stakeholder feedback into larger-scale project planning.</td><td>Conduct market research and extensive stakeholder outreach before starting large development efforts in new areas.</td></tr>
<tr><td>Explore additional ways of allowing modelers, vendors, and other stakeholders to participate in and contribute to tool development planning and prioritization.</td></tr>
</table>

5 Topic 3: Interoperability and Automation

Summary:

- Although the situation is improving, BEM tools are still poorly integrated with existing architectural and mechanical design workflows, leading to unnecessary effort, error, and cost. 3D BIM to 2.5D BEM geometry translation continues to lag.
- Interoperability among BEM engines is lacking on both simulation input and output sides. Vendors have little incentive to export to common formats, allowing users to take models to competing tools, which favors integrated solutions—preferably on the cloud—that lock users into their platforms.
- A number of BEM tasks are repetitive, time-consuming, and not yet automated, requiring unnecessary manual effort and degrading BEM cost-effectiveness. Where automation exists, it is implemented inconsistently, making it difficult to rely on.
- BTO has chosen the OpenStudio SDK as its application integration and automation platform, but a number of vendors and developers prefer interacting with EnergyPlus directly.
- BTO should support vendor-driven consensus standards for BEM input and output, implement those standards in its own tools, and incentivize vendors to implement them as well.
- BTO should promote automation of BEM tasks and procedures such as automated baseline generation. BTO should support the development of testing and certification framework to improve quality and consistency among these implementations.
- BTO should invest in application integration features for EnergyPlus, and emphasize modularity and component reuse in the OpenStudio SDK itself.

Relevant BTO projects:

- **OpenStudio Software Development Kit (SDK).** OpenStudio is an open-source SDK for BEM applications using EnergyPlus. The SDK includes an API for manipulating model inputs and simulation outputs, API, bindings for a number of scripting languages, a Server image, a set of Measures distributed on the BCL and the OpenStudio-Standards gem which includes Measures for creating prototype buildings and performing ASHRAE 90.1 Appendix G baseline transformations.
  https://energy.gov/eere/buildings/downloads/openstudio-0/
  https://openstudio.net/
- **Commercial Prototype Building Models and OpenStudio Standards gem.** To support ASHRAE research and standard development, BTO has developed prototype EnergyPlus models for 16 commercial building types. These are updated for each 90.1 code version and customized for each climate zone. Measures use the OpenStudio Standards gem to

create these models in OpenStudio format.
https://www.energycodes.gov/development/commercial/prototype_models
https://rubygems.org/gems/openstudio-standards/

- **ASHRAE Standard 229P "Evaluating Ruleset Implementations in BEM Software" Development.** 229P is a recently proposed ASHRAE Standard that aims to develop and framework, test suite, and tools for testing and certifying implementations of rulesets like ASHRAE 90.1 Appendix G baseline automation. 229P aims to improve consistency among BEM rulesets in the way that ASHRASE Standard 140 does for BEM physics engine implementations.
https://energy.gov/eere/buildings/ashrae-standard-229P-development/
- **BuildingSync.** A schema for commercial building audit data recommended by ASHRAE Standard 211 and supported by a number of BTO tools.
https://www.energy.gov/eere/buildings/buildingsync
https://buildingsync.net/

5.1 Barriers

For an industry based entirely on software, BEM requires a surprising amount of tedious "manual" labor. Compared to other software industries—e.g., electronic commerce, web publishing, social media, and gaming—BEM suffers from a lack of standards, automation, and workflow integration. This state of affairs degrades modeler productivity and the cost effectiveness of BEM.

BIM-to-BEM geometry translation. Modern architectural design tools like Autodesk's Revit and Graphisoft's ArchiCAD use 3D BIM geometry with parameterized lines (which may be curved), surfaces, and solids. Meanwhile, most advanced BEM engines like EnergyPlus use a simplified "2.5D" geometry model with polygonal planes in 3D space. 3D-to-2.5D geometry translation, perhaps the most significant component of a group of translations often referred to as BIM-to-BEM, is a complex and treacherous process that involves simplifications, assumptions, and conventions. One of the conventions concerns whether the plane representing a wall should be placed at the center of the wall, on its inside surface, or on its outside surface—this convention has obvious implications for wall area and room air-volume calculations. Other conventions concern where recessed windows are placed, how columns are represented, and how curved surfaces are broken into planar ones. The number of edge cases is numerous.

Unsurprisingly, BIM-to-BEM translation is not implemented robustly or uniformly. BIM geometry is typically exported for analysis in a standalone BEM tool; the gbXML format is commonly used for this purpose. The BIM model and the gbXML export are often not checked for BEM "analyzability," e.g., that all spaces are fully enclosed by surfaces. Inconsistencies or flaws in the exported model are detected when it is imported into the BEM tool. If the designer is operating both tools, she has a chance at deciphering the errors and correcting the design model. Often, however, the designer hands the export off to a modeler who must guess at design intent and then fix the BEM model manually or recreate it in the BEM tool from scratch. The process is repeated as the design model evolves, and the costs associated with it reduce the number of BEM iterations that can be achieved within a given time period and for a given budget.

A number of companies including Autodesk and Sefaira—whose tools automatically translate 3D Revit models to 2.5D EnergyPlus models and execute them in the cloud—have addressed these problems to some degree. These solutions are proprietary and may differ in their approaches and assumptions. By de-emphasizing exports, these workflows cater to upstream users like architects. However, they reduce transparency and robustness in the translation process.

ASHRAE has supported research projects on this topic, most notably RP-1468, "Development of a Reference Building Information Model (BIM) for Thermal Model Compliance Testing."[79] BTO has also previously sponsored the development of several tools in this area including the Space Boundary Tool[80] and the gbXML Validator.[81] However, BIM-to-BEM translation remains a significant barrier in practice.

Non-geometry BEM inputs. Geometry represents only part of the input to an energy model. Other BEM inputs that are available in architectural and mechanical design tools include construction and glazing materials, space type and zone assignments, lighting, and HVAC system components, configurations, and control schemes. Project-specific assumptions about occupancy and plug-load schedules as well as other requirements like ventilation may be available as well. Exports of this data are sparse and exchange schemas are largely unused and untested.

These types of inputs are needed not only for models of specific buildings, but also for prototype building models and baseline models associated with procedures such as Standard 90.1 Appendix G. The fact that these inputs are not available in a standard electronic form impedes the automation of common modeling tasks associated with standards, and the automation of standard development itself. The BEM industry has been slow to adopt shared file formats for model inputs. As with any industry, there are technical challenges to interoperability. Previously developed interchange formats were engine specific, e.g., gbXML was initially targeted at the DOE-2 engine and proved a mismatch for other engines. However, the greater challenges come from the business side. Vendors prefer proprietary formats that prevent them from easily migrating to competing tools. Recent years have seen the migration of BEM workflows to the cloud. The cloud supports collaboration, provides elastic computing resources, and combats software piracy, but also enables workflows in which users cannot have local copies of data. This mindset and approach protects vendors from one another but also inhibits vendor-neutral applications like standards automation and software certification.

[79] https://www.techstreet.com/standards/rp-1468-development-of-a-reference-building-information-model-bim-for-thermal-model-compliance-testing?product_id=1868055
[80] https://simulationresearch.lbl.gov/projects/space-boundary-tool
[81] https://gbxml.org/validator/Pages/TestPage.aspx

IBPSA-USA has recently created a committee to develop a tool-neutral input schema called BDE (Building Data Exchange).[82] The premise is that a development process that includes multivendor consensus should lead to greater adoption.

BEM outputs, including error messages. Whereas there are clear business rationales for the lagging state of BEM input interoperability, the lagging state of BEM output interoperability is more difficult to explain. Standardization of BEM outputs—variable and meter names, units and unit conversions, time series representations, reports, and even error and diagnostic messages—would greatly simplify tool integration, the processing and analysis of BEM results, and the comparison and testing of BEM engines. IBPSA-USA's Project StaSiO (Standard Simulation Outputs)[83] takes a step in this direction, although its focus is on visualization and communication of BEM results to architects and clients rather than on data models and software interoperability.

Ruleset automation, testing, and certification. BEM workflows include several tasks that are mechanistic, uncreative, detailed, and tedious, contribute only indirectly to building performance, but consume modeler effort and degrade BEM project cost-effectiveness. A ubiquitous example is the generation of a code-minimum baseline model from a proposed building model as described in procedures like ASHRAE 90.1 Appendix G. Automating these tasks would allow BEM expenditures to shift to high-value, high-creativity tasks such as performance optimization and design/operation support, reducing BEM cost and improving its value to clients.

Automation of this particular task is becoming more common. The CEC has automated it for Title 24 in CBECC-Com and CBECC-Res. A number of tools implement ASHRAE 90.1 Appendix G. Several others implement its residential analog ANSI/RESNET/ICC 301-2014 "Standard for the Calculation and Labeling of the Energy Performance of Low-Rise Residential Buildings using an Energy Rating Index." The OpenStudio Standards gem has been used to implement baseline automation for Canada's National Energy Code for Buildings and India's Energy Conservation Building Code and to partially implement automation for ASHRAE 90.1-2010 Appendix G.

Automated baseline generation improves modeler productivity, but without a testing framework to ensure implementation accuracy and consistency, automatically generated baselines still have to be manually reviewed, degrading productivity for model consumers like code officials and incentive program administrators, an important and often forgotten subset of the BEM profession. BTO is supporting a new proposed standard ASHRAE Standard 229P, "Evaluating Ruleset Implementations in BEM Software," whose goal is to create a testing and certification framework for ruleset implementations like ASHRAE 90.1 Appendix G and ANSI/RESNET/ICC 301-2014. An initial standard and associated testing toolkit is expected in 2022.

[82] https://www.ibpsa.us/news/call-members-ibpsa-usa-building-data-exchange-bde-committee
[83] https://projectstasio.com/

Automation, testing, and certification of other tasks. Baseline generation is not the only task that is amenable to automation. Other tasks include calibration, sensitivity and uncertainty analysis, EEM evaluation and design optimization, reporting and visualization, and even model QA. These can be implemented within shrink-wrapped applications or using open scripting frameworks like OpenStudio Measures, Eppy,[84] and Modelkit.[85] As with baseline generation, the automation of some tasks—especially tasks involved in financial or regulatory transactions—may benefit from testing and certification frameworks to improve consistency and ensure minimal functionality and quality standards.

Automation and workflow integration with EnergyPlus and the OpenStudio SDK. One concern voiced by developers in stakeholder meetings and interviews is that while BTO has invested in OpenStudio as its application and service integration platform, a number of vendors have been working with EnergyPlus since before the development of OpenStudio and have invested heavily in direct EnergyPlus access. These vendors and ones that are developing their own integration and automation frameworks for EnergyPlus would benefit from integration features such as standard input and output formats and APIs in EnergyPlus itself.

There is also the sense that the same modularization that is being applied to EnergyPlus should also be applied to the OpenStudio SDK to allow its various components to be reused independently, e.g., to allow the model and simulation results manipulation API to be used independently of OpenStudio Server and other workflow management features, and vice versa. The OpenStudio 2.0 architecture was a move in this direction.

5.2 Initiatives

As the availability and use of both vendor-provided and user-defined automation increases and as interest in shared data formats and interoperability is renewed, BTO has an opportunity to support automation and workflow integration more broadly by backing standards for data exchange, testing, and software certification.

BIM-to-BEM geometry translation. BIM-to-BEM translation and export issues are best addressed in the design authoring tool. A proper design model and correct translation eliminates the need to implement fixes and workarounds in multiple “downstream” analysis tools including BEM tools. In addition, the design authoring tool has the designer herself available to fix the design model and disambiguate design intent—“are these two surfaces intended to be three inches apart or is that an oversight”? The ideal workflow would have the design tool embed some checking logic that helps the designer create a consistent and analyzable model.

BTO should engage design model authoring tool vendors and work jointly with them to address this problem. BTO already supports a gbXML export validation initiative.[86] This could be

[84] https://github.com/santoshphilip/eppy
[85] http://bigladdersoftware.com/projects/modelkit/
[86] http://gbxml.org/validator/Pages/TestPage.aspx

expanded with additional tests. BTO should collaborate with vendors to develop tests that should be applied to geometry translation within design authoring tools—whether or not the geometry is exported to an external tool—to ensure geometry interpretation consistency and analyzability.

To the extent that geometry translation approaches and best practices are understood and a consensus exists, it may be advantageous to define these formally using a standard and test suite. This standard would be similar in concept and mechanics to ASHRAE Standard 140. It would include descriptions and drawings of 3D BIM models, along with BIM files, and corresponding expected 2.5D BEM exports. To the extent that translation approaches are not well understood or consensus does not exist, additional and more consolidated and directed research and development is needed in support of this standard. BTO should support these activities.

BEM input and output schema. Currently, BTO supports energy information exchange standards BuildingSync XML (BSXML) and Home Performance XML (HPXML), along with ASHRAE Standard 205P for equipment performance data. The OpenStudio platform supports these as well as CBECC-Com Standards Data Dictionary (SDD)[87] import and gbXML geometry import. Various BTO BEM projects are also working with standards such CityGML (urban-scale 3D geometry),[88] EnergyADE (a BEM extension for CityGML),[89] Haystack (a naming/tagging framework for developing object models that describe building systems),[90] and Brick (a new semantic web-based meta-schema for building energy information).[91] BTO is supporting and participating in the development of IBPSA-USA's BDE schema, with the hope that the IBPSA-USA umbrella and a process that includes up-front vendor consensus can avoid the creation of yet another schema that achieves limited market adoption.[92]

Standardization and exchange is important not only for simulation inputs, but also outputs, including reports, error messages and diagnostics. ASHRAE Standard 229P will develop standard reports that can be used to check ruleset implementations. This could form the basis of a broader effort to standardize BEM output. Again, standard BEM output should be less controversial than standard BEM input as it does not provide the model portability that some vendors would consider counterproductive to their business model. EEMs and their parameters are also candidates for standardization.

Often, BEM inputs and outputs correspond to data that can be measured and appears in standard forms and reports, such as audits. BTO is involved in a number of non-BEM data standardization and collection efforts including BEDES (Building Energy Data Exchange Specification)[93] and the SEED (Standard Energy Efficiency Data) Platform.[94] Schematic alignment between BEM

[87] http://bees.archenergy.com/software.html
[88] https://www.opengeospatial.org/standards/citygml
[89] http://www.citygmlwiki.org/index.php/CityGML_Energy_ADE
[90] https://project-haystack.org/
[91] https://brickschema.org/
[92] http://xkcd.org/927/
[93] https://www.energy.gov/eere/buildings/building-energy-data-exchange-specification-bedes
[94] https://www.energy.gov/eere/buildings/standard-energy-efficiency-data-seed-platform

tools and measured data tools could contribute to closing the modeled-measured performance gap. Again, BTO is well positioned to drive this alignment.

As consensus standards emerge, BTO should lead by supporting them in its own tools and consider providing financial incentives for third-party vendors to support them in theirs.

Ruleset automation, testing, and certification. BTO has supported testing protocols for BEM engines for many years, and these have been used to support software certification or qualification programs. Testing and certification of software implementations of discrete, human-defined BEM procedures is both conceptually and practically much simpler than testing and certification of software implementations of building physics (Roth 2018). BTO supports a testing and certification standard for code-related rulesets like ASHRAE 90.1 Appendix G and could expand this effort to other types of human-defined BEM processes like EEM definitions and QA procedures. One of the important ways in which human-defined rules are simpler to implement and test than building physics is that they can be designed to be simple to implement and test. An important component of ruleset software testing is providing feedback to the organizations charged with defining the rulesets to simplify software implementation and testing.

Application integration for EnergyPlus. BTO should invest more heavily in EnergyPlus application integration support, addressing issues raised by direct-to-EnergyPlus application and middleware developers. The addition of an API and support for input and output in JSON (Java Script Object Notation) format and time series output in CBOR (Concise Binary Object Representation) are steps in this direction. Re-engineering, integration, or disaggregation of selected utilities and pre- and post-processors is another. Adding the concepts of Space and Space Type, which are useful in both architecture and standards applications, is another. Other potential changes include schematization of output variables and meters, schematization of error and warning messages, and support for language localization. To the extent possible, changes to input and output schema should align with BEM industry consensus standards, such as IBPSA-USA's BDE.

At the time OpenStudio was conceived, EnergyPlus was still written in FORTRAN and structurally unable to support some of the desired features including an object-oriented API. With EnergyPlus now written in C++ and becoming increasingly object-oriented itself, the opportunity exists to realign the EnergyPlus and OpenStudio objects models and to re-architect the boundary between them, move some of the functionality into shared modules. Spawn should be added the mix to facilitate eventual migration for interested vendors who prefer direct EnergyPlus access, bypassing OpenStudio.

OpenStudio modularization. The OpenStudio SDK 2.0 architecture created a cleaner separation between modeling and simulation management, allowing developers to use modeling APIs and scripting in conjunction with other simulation frameworks and to use OpenStudio Server components with other APIs and scripting frameworks. BTO should look for opportunities to further modularize OpenStudio and related project to allow their individual components to be used a la carte. One effort that is already underway is the separation of the data and lookup tables from the OpenStudio Standards gem from the Measure code—the latter is specific to the OpenStudio API, the former is generic and is essentially a machine readable transcription of tables appearing in standards documents. Similar benefits could be reaped by, where possible, cleanly separating underlying data from code in ResStock and other tools.

Table 9. BEM Interoperability and Automation Barriers and Initiatives

Barriers	Initiatives
BIM-to-BEM geometry translation and export. BIM-to-BEM geometry translation is not robust, requiring modelers to fix up geometry in the BEM tool or recreate it from scratch.	Support research to develop fundamentally sound methods and rules for translating 3D BIM geometry to 2.5D BEM geometry. Develop standard test suites to test translation and export. Collaborate with design model authoring tool vendors to improve BIM-to-BEM translation and export to help designers create sound analyzable models.
BEM input, output, and related schema. Transfer of information to and from BEM tools is characterized by either an overabundance or formats or no formats at all. BEM vendors have few incentives to support interoperability, naturally preferring to lock their users in to their offerings.	Use the IBPSA-USA BDE project or another consensus process that includes BEM vendors to develop a tool-neutral schema for BEM input.
	Use a consensus process to develop and promote BEM output and reporting schema, which do not threaten vendor business models in the way that BEM input schema do.
	Support consensus schema in BEM tools and provide financial incentives to third-party vendors to do the same.
Ruleset automation, testing, and certification. Many BEM procedures that surround and basic physics simulation can be automated. Although automation is proliferating, testing and certification of this subset of BEM software is lagging, leading to inconsistencies and suppressing use, especially for regulatory or financial use cases.	Leverage standard output and reporting exchanges, and to the degree possible input exchanges, to develop testing and certification frameworks for BEM rulesets.
	Promote use of open scripting frameworks to prototype automation for BEM rulesets and general workflow integration.
EnergyPlus application integration. Multiple vendors have invested in direct integration with EnergyPlus, bypassing OpenStudio.	Improve EnergyPlus application integration features to assist vendors who access EnergyPlus directly.
OpenStudio modularity. Vendors and developers may want to reuse components and subcomponents of the OpenStudio ecosystem, without committing to the entire platform.	Beyond OpenStudio 2.0, investigate ways of allowing OpenStudio data resources to be used separately from OpenStudio API-driven code.

6 Topic 4: Data Ecosystem

Summary:

- Many BEM use cases makes heavy use of default, standard assumptions and inputs. A number of these are outdated, including detailed equipment performance, default asset, operation, use for different building types in different climate zones, and even typical year weather data.
- Energy use data in resources such as Portfolio Manager and the Building Performance Database is not available at high temporal resolution or with end-use disaggregation, hampering multiple BEM applications.
- BTO can leverage its own building energy data projects as well as relationships with ASHRAE, the U.S. Environmental Protection Agency (EPA), and the EIA to expand and organize, interconnect, curate, and grow the BEM data ecosystem, including both input (asset and operations) and output (measured energy use) data.
- The BEM data ecosystem would be enhanced by submeter and sensor data. BTO has active programs in these areas and could use field demonstration projects to add this data to selected records.
- For existing buildings, there are additional opportunities to mine unstructured data sources such as aerial and street view images.

Relevant BTO projects:

- **DOE Commercial and Residential Prototype Models and OpenStudio Standards.** Models representing typical instances of buildings such as offices, retail outlets, and single-family and multifamily homes are used represent entire building stocks in analyses such as code updates, utility EE program design, and R&D portfolio management. BTO supports the development of standard prototype model suites of commercial buildings that are customized for each ASHRAE climate zone and each ASHRAE 90.1 code version, and of single-family residential models updates to each IECC code version. The OpenStudio Standards gem creates OpenStudio Model (OSM) versions of the commercial prototype models, allowing OpenStudio Measures to be applied to them and facilitating their use in large-scale analyses.
https://www.energycodes.gov/development/commercial/prototype_models
https://www.energycodes.gov/development/residential/iecc_models
- **ResStock, ComStock, and End-Use Load Profiles.** ResStock is a methodology for statistically robust building stock modeling. Standard practice relies on individual prototypes to represent an entire type, vintage, and climate category, selecting the most common envelope characteristics, system types, etc. ResStock uses sampling to create a range of prototypes creating a more representative and robust baseline from which to

evaluate EEMs. Originally developed for residential buildings, ResStock has been expanded to cover commercial and multifamily buildings. As part of its new focus on building-to-grid integration and the time of use value of electricity and "electricity-efficiency" measures, BTO is using a number of data sets to calibrate ResStock and ComStock to hourly end-use profiles as observed by regional electricity grids.
https://energy.gov/eere/buildings/resstock
https://energy.gov/eere/buildings/downloads/end-use-load-profiles-us-building-stock
https://resstock.nrel.gov/

- **Standard Energy Efficiency Data (SEED) Platform.** SEED is a building energy data management platform that supports use cases such as city building energy disclosure and audit ordinances.
https://www.energy.gov/eere/buildings/standard-energy-efficiency-data-platform
- **ASHRAE Standard 205P and the Technology Performance Exchange (TPEx).** ASHRAE Standard 205P is a performance-mapping standard for simulating HVAC and refrigeration equipment. TPEx is an online database of equipment performance data.
https://www.energy.gov/eere/buildings/ashrae-standard-205-maintenance-and-development
https://www.tpex.org/
- **IGSDB (International Glazing and Shading Database).** An online database of thermal and optical properties of glazing and shading products.
https://www.energy.gov/eere/buildings/downloads/fenestration-software-tools
- **Virtual EPB.** This project, with the Electric Power Board (EPB) of Chattanooga, is developing methods for creating energy models from a combination of structured and unstructured data sets including GIS data and Street View data.
https://www.energy.gov/eere/buildings/virtual-epb/
https://evenstar.ornl.gov/autobem/virtual_epb
- **Machine Learning of Unstructured Data for Improved Efficiency Analysis.** This project is developing methods of extracting building envelope characteristics from satellite, flyover, and drone imagery.
https://www.energy.gov/eere/buildings/unstructured-data-machine-learning-improved-efficiency-analysis
https://buildings.lbl.gov/emis/machine-learning

6.1 Barriers

The BEM enterprise is data intensive, with models requiring hundreds to thousands of inputs and producing hundreds to thousands of outputs. With so many inputs and outputs, the industry relies heavily on defaults and benchmarks. Many stakeholders cited BEM input and output data as areas that deserve attention. Specific pain points include equipment performance data, prototype models for less common building types such as places of worship, laboratories, and university buildings, and detailed asset, operational, and measured data from occupied buildings for benchmarking and QA applications. Weather data for different future climate scenarios was also mentioned as a need.

Prototype models. Models representing typical instances of buildings such as offices, retail outlets, and single-family and multifamily homes are used represent entire building stocks in analyses such as code updates, utility EE program design, and R&D portfolio management. BTO supports the development two standard suites of prototype models: (1) commercial buildings that are customized for each ASHRAE climate zone and each ASHRAE 90.1 code version, and (2) single-family homes updated for each climate zone and each IECC code version. The models are developed and distributed in EnergyPlus input format (IDF) and are documented in standard Excel Spreadsheet templates. Over the past several years, BTO has worked with ASHRAE to develop additional commercial prototype models that expand coverage of the commercial building stock from 70% to 80%. New prototypes include a courthouse, a supermarket, and a university building. Prototypes for a data center and a skyscraper are under development.

The prototype models have played a central role in the development of ASHRAE and IECC codes, and in several other applications. However, their broader use—as starter or comparison models for design projects, for instance—has been limited because of their unavailability in schemas other than EnergyPlus IDF and because documentation required to replicate them in other schemas is insufficient. The rigidity of the models—manifesting in the difficulty in creating models with different geometries or mixed-use buildings that combine multiple prototypes—has also been noted as a shortcoming.

Even within the code development use case, the prototype models suffer from a lack of rigorous quality assurance practices and a disconnect from the EnergyPlus development process which sometimes yields jarring performance deltas when static models are run using different EnergyPlus versions.

The OpenStudio Standards gem is a collection of data files and Ruby functions that read them and create OpenStudio Model (OSM) versions of the commercial prototype models. OpenStudio Measures can be applied to OSM models to systematically explore design spaces, facilitating their use in large-scale analyses. The OpenStudio Standards gem offers some degree of parameterization for the prototypes, specifically it can apply prototype loads, schedules, and systems to models with different geometries and space plans.

Asset characteristic, operational characteristic, and measured energy use distributions. Large, representative data sets of building asset and operational characteristics and corresponding energy use are an important BEM resource. These data sets serve as benchmarks, as the source of defaults and assumptions for unknown or unspecified inputs, and as probability distributions for uncertainty analysis.

Data sets that are currently underpin these use cases are outdated in some areas and sparse in others. Current widely used input assumptions and EUIs are based on the 2012 (or even 2003) CBECS and the 2015 (or 2005) RECS. These data sets underpin applications such as EPA's ENERGY STAR® Portfolio Manager and Target Finder.

RECS, and especially CBECS, may not have the breadth or depth to provide meaningful default inputs and reference and target EUIs. RECS samples about 10,000 homes, representing 0.01% of the residential stock. CBECS samples about 6,000 commercial buildings, representing 0.1% of the commercial stock. Both target representativeness at the census division level, a coarse granularity that does not line up with climate zones. Despite a greater sampling rate, CBECS may be less representative than RECS given the significantly greater diversity that exists in commercial buildings. RECS and CBECS records do not provide a sufficient level of detail to create a credible energy model. Specifically, data is collected using phone interviews conducted by non-experts who are trained for the specific interview task whereas modeling requires on-site audits. EIA may not have the charter or resources to collect this much data at this level of detail. For BEM purposes, resources such as COMNET[95] Building America House Simulation Protocols[96] can complement CBECS and RECS, respectively.

RECS and CBECS also include measured energy use, which is used both for benchmarking and to calibrate the EIA engineering models and refine asset and operational inputs. Energy use data is significantly more useful if it is disaggregated by end use (e.g., heating, lighting, office equipment) and available at greater than annual or monthly temporal resolution. Such data is useful on its own for benchmarking purposes, especially for isolating the effects of individual EEMs. It also significantly improves model input calibration. Because submetering is still uncommon in commercial buildings and even more so in residential buildings, RECS and CBECS lack this resolution, as do other measured energy data sources including EPA's ENERGY STAR Portfolio Manager and BTO's Building Performance Database (BPD)[97] and the SEED Platform.[98]

An important component in the operation of a building—and in its simulated behavior—is the stochastic behavior of its occupants. Resources such as ASHRAE's Global Climate Database II[99] have some information, but in general data about occupant behavior is still relatively sparse and not well correlated with building asset variables and energy use.

HVAC equipment performance data. Consumers may be familiar with HVAC equipment performance rating metrics like Seasonal Energy Efficiency Rating (SEER) and Coefficient of Performance (COP), which relate equipment energy use to heating and cooling delivered. However, these metrics characterize equipment performance under a small fixed set of operating

95 http://comnet.org/
96 https://energy.gov/eere/buildings/downloads/building-america-2014-house-simulation-protocols
97 https://energy.gov/eere/buildings/building-performance-database
98 https://energy.gov/eere/buildings/standard-energy-efficiency-data-platform
99 https://comfortdatabase.com/

conditions. In practice, equipment performance varies across parameters such as air (or water) flow rate, inlet temperature, and temperature lift. In a given year, a piece of equipment may encounter a wide range of operating conditions and thus accurate annual BEM simulation requires a description of equipment performance across the full operating condition range. This information may be conveyed in the form of a set of analytical curves or a point-wise map with an interpolation procedure.

On its face, detailed equipment performance data should be one of the easier BEM inputs to obtain. In practice, manufacturers are reluctant to share it on the grounds that it will compromise competitive advantage on one hand and interfere with high-level marketing on the other. As a result, engines such as EnergyPlus use default performance curves for coils and fans that were generated from data gathered in the 1990s. As part of a recent project on empirical validation, NREL used its HVAC test harness to map the performance of two rooftop units, a SEER 10 and a SEER 13. This type of BTO-funded lab work may be justified for equipment that is very common or for new products that show great promise for energy savings and for which BTO wants to accelerate market uptake. However, using a laboratory test harness to recreate detailed equipment performance for the entire HVAC product market is not economically scalable. To address this need at scale, manufacturers must be incentivized to publish their detailed in-house performance data.

ASHRAE Standard 205P, "Standard Representation of Performance Simulation Data for HVAC&R and Other Facility Equipment,"[100] standardizes the specification of equipment performance data for energy simulation and works with manufacturers to publish this data. As of 2019, BTO is funding the ASHRAE Standard 205P committee to support standard expansion and automation. BTO has also created TPEx,[101] a public online warehouse for Standard 205P data. As of May 2020, TPEx contains a significant number of entries, but in only a small number of categories including rooftop units, boilers, and ductless minisplits and VRF systems. Data for such components as chillers, fans, and coils is missing.

In addition to test-stand data for new equipment, data is needed for equipment as it is installed—sometimes incorrectly or poorly—in the field, and for old and degraded equipment. Data about types and prevalence of equipment faults is also needed for both large-scale analysis and for analysis of existing buildings.

Material and construction assembly performance data. As with HVAC, characteristic data is also needed for envelope materials and constructions, including thermal and moisture performance as well as visual performance for glazing products and window assemblies.

Thermal material and construction data for windows and opaque assemblies is housed in the BCL, where it is available in OpenStudio (OSM) and EnergyPlus (IDF) format and presumably translatable to other formats in a straightforward way. For optical data, LBNL maintains and

[100] http://spc205.ashraepcs.org/
[101] https://www.tpex.org/

updates the International Glazing Database (IGDB)[102] for simple glazing products and more recently the Complex Glazing Database (CGDB)[103] for complex, light-diffusing or redirecting products such as blinds and shades. The IGDB and CGDB have also recently moved to an online warehouse.[104] LBNL tools and code libraries can combine elements from these databases to calculate the thermal and optical properties of complete window assemblies.

Weather data. Created by NREL, the third typical meteorological year (TMY) data set (TMY3)[105] provides typical weather data for 1,020 U.S. locations representing the years 1991–2005. This data is obviously out of date, as the past 10 years are the warmest on record. TMYx[106] is a non-profit effort that synthesizes TMY data using Integrated Surface Database (ISD)[107] weather data from the National Oceanic and Atmospheric Administration's (NOAA's) National Center for Environmental Information; the most recent TMYx update covers the years 2004–2018. Weather data for specific years—e.g., for calibrating models of existing buildings—is available for cost from several commercial services.

Typical weather data, and even recent year weather data, cannot be expected to represent weather over the next 50–100 years, the intended service lifetime of most buildings. Over the past 20 years, several methodologies have been developed to project future weather data based on different International Panel on Climate Change (IPCC) emissions and warming scenarios. Stochastic models and morphing models provide future weather data through commercial services including WeatherShift[108] from Arup and IES as well as universities.[109]

Although the state of typical year, actual year, and future year weather data can currently be described as acceptable, it does not lend itself to a scalable business model, as weather files created for a specific project can be reused freely for other nearby projects.

Data for life-cycle analyses. Energy analysis is rarely done for energy's sake—energy is often a proxy for cost, GHG emissions, or both via compound metrics like California's Time Dependent Valuation (TDV) (Ming et al. 2016). Electric utility rates are available the OpenEI (Open Energy Information) U.S. Utility Rate Database[110] via both an HTML interface and an API, but natural gas rates are missing. OpenEI also includes hourly GHG factors for U.S. grids[111] that were developed using simulation and calibration to annual GHG measurements. These are based on 2008 data and available as Excel spreadsheets. WattTime[112] provides access to historical and

[102] https://windows.lbl.gov/software/igdb
[103] https://windows.lbl.gov/software/cgdb
[104] https://igsdb.lbl.gov/
[105] http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
[106] https://climate.onebuilding.org/
[107] https://www.ncdc.noaa.gov/isd
[108] http://weathershift.com/
[109] https://energy.soton.ac.uk/ccworldweathergen/
[110] https://openei.org/apps/USURDB/
[111] https://openei.org/doe-opendata/dataset/hourly-energy-emission-factors-for-electricity-generation-in-the-united-states
[112] https://watttime.org/

real-time marginal GHG emissions on a grid basis. NREL is currently developing a tool called Cambium[113] that can project hourly electricity prices and GHG rates based on load and generation resource scenarios.

Capital costs are combined with BEM-driven operating cost analysis to form various life-cycle cost (LCC) analyses. Cost-effectiveness—payback period, return on investment, net present value, or another economic metric that weighs capital or implementation cost against operational cost savings—is a critical aspect of many energy analyses. In new construction and retrofit design, EEMs are evaluated by cost-effectiveness. Cost-effectiveness is also a criterion in the setting of incentive levels, and determination of suitability for mandatory code requirements. Although not a direct input to energy models, capital and installed cost data is an input to many BEM-powered analyses and applications. Cost data sets already exist; examples include RS Means[114] and NREL's National Residential Efficiency Measures Database,[115] and integrated cost-effectiveness analyses are emerging via applications like cove.tool.[116]

The GHG analog of capital cost is embodied carbon, embodied carbon tools and databases including NIST's Building for Environmental and Economic Sustainability (BEES),[117] OneClick LCA,[118] Kieran Timberlake's Tally,[119] EPD-Quicksheet from Architecture 2030,[120] Impact Estimator for Buildings from Athena Sustainable Materials Institute,[121] and others.

Unstructured data. BEM applications may also benefit from "unstructured" data, i.e., data that contains building-energy-relevant information but in which that information is not explicitly coded. Images of buildings are an example of such data. Image data is increasingly available in various forms (e.g., visible spectrum, infrared, Light Detection and Ranging [LIDAR]), and various vantage points (e.g., aerial or street view). Image analysis can yield information about geometry, constructions, and externally visible building equipment such as compressors, rooftop units, cooling towers, and others. BTO already supports some research in this area via projects such as virtual EPB[122] and should consider growing this investment, especially if it can leverage publicly available data sets.

Images are relevant not only outside of buildings but inside them as well. Low-resolution video can be analyzed to extract occupancy while infrared images can augment conventional thermostats in determining surface temperatures and occupant thermal comfort.

[113] https://energy.gov/eere/buildings/downloads/spia-flexible-loads/
[114] https://www.rsmeans.com/
[115] http://www.nrel.gov/ap/retrofits/index.cfm
[116] https://cove.tools/
[117] https://nist.gov/services-resources/software/bees/
[118] https://www.oneclicklca.com/
[119] https://kierantimberlake.com/pages/view/95/tally/
[120] https://architecture2030.org/epd-quicksheet/
[121] https://athenasmi.org/our-software-data/impact-estimator/
[122] https://energy.gov/eere/buildings/virtual-epb/

6.2 Initiatives

With existing relationships with EIA and ASHRAE, and with a number of building energy data projects of its own, BTO is well positioned to improve the state of the BEM data ecosystem.

Prototype models. BTO can enhance prototype models and expand their utility in several ways. One needed change that can be implemented immediately is a more rigorous testing procedure that is tied to EnergyPlus updates and that improves model quality and prevents unintended performance discontinuities.

Improved documentation is another important task, as is the availability of the prototype models in a standard schema that can be more easily translated to other engines and workflows. Currently, there is no consensus on an engine-neutral BEM-to-BEM schema that can be the target of such an effort. However, there is renewed interest and activity around developing such a schema, and the prototype models provide this effort with another motivating use case.

The OpenStudio Standards gem provides the opportunity to parameterize the prototypes, including creating prototypes with different geometries, different numbers of floors, mixed-use prototypes, and perhaps even prototypes of entire districts. The OpenStudio Standards gem is currently being split into separate code and data gems. The data gem contains the ASHRAE 90.1 tables that drive the default values for space loads, schedules, constructions, system types, and equipment efficiencies. It can be used by other platforms to recreate the prototypes, complete with parameterization as necessary.

Asset and operation inputs and measured energy use. BTO's project portfolio includes the SEED platform,[123] which contains high-level asset and operational descriptors and energy use data and which is used by cities to implement building energy disclosure mandates. SEED is used by several cities to implement energy disclosure mandates and contains audit data in BuildingSync[124] format for cities that have implemented audit mandates. SEED data is not public, but BTO may be able to perform statistical analysis on the data and publish aggregated results.

Commercial Building Energy Asset Score[125] and Home Energy Score[126] also collect audit data, and support audit mandates. Both are web applications with backing databases that record all entries. As with SEED, these records may not be publicly available on a building-by-building basis, but may be available for statistical analysis. Asset Score and Home Energy Score records do not have associated measured energy use data, but it may be possible to cross-reference that information from other sources such as Portfolio Manager or utility Green Button services. BTO can use these data sources and the disclosure programs they support to complement RECS and

[123] https://energy.gov/eere/buildings/standard-energy-efficiency-data-platform
[124] https://www.energy.gov/eere/buildings/buildingsync
[125] https://www.energy.gov/eere/buildings/building-energy-asset-score
[126] https://www.energy.gov/eere/buildings/downloads/home-energy-score

CBECS. BTO can collaborate with EIA to understand the statistical significance and representativeness of these data sets.

BTO should also look to leverage its investments and programs in submetering, sensing, and building-system monitoring to augment these data sets with higher frequency—hourly, 15-minute, or even greater resolution—data for end use, occupancy, zone conditions, and HVAC system state. Some of this data, especially electricity end uses, would directly support benchmarking while enabling improved model calibration, quality assurance, and default assumptions.

A recent BTO project has the potential to tie together many of these data sources and address many of these issues in a holistic way. ResStock and ComStock are new building stock modeling methodologies that rely on creating model populations from joint probability distributions of building asset and operation descriptors. As part of its recent co-emphasis on building-grid integration and the temporal aspects of electricity use and EE, ResStock and ComStock are being calibrated to hourly electricity end-use profiles using available submeter data and fusion of a number of other data sets, including some proprietary ones. Although detailed submeter data is available for only a few U.S. locations, the transformations encoded in the calibrated asset and operational distributions may be transferrable from one region to others, especially for end uses like lighting and plug loads that are not likely to vary greatly with geography. The calibrated asset and operational distributions that result from this project, and the individual building end-use profiles that can be synthesized from them can form a much richer, more resolute, and more useful basis for default modeling assumptions and benchmarks.

Equipment performance data. ASHRAE Standard 205P and TPEx provide a sound platform for the standardization and dissemination of detailed HVAC equipment performance data. Additional investment is needed to make these more complete and, in the case of TPEx, more usable. A key goal is creating an environment, both technical and otherwise, that incentivizes manufacturers to share data. At a minimum, such an environment would consist of timely support for ASHRAE 205P performance maps in EnergyPlus and other BEM engines. Potential components include improvements to TPEx search and filter functionality including a "performance lookup" function that can find equipment that matches specified performance characteristics, allowing TPEx to be used for product selection. It should also improve TPEx workflow and connectivity to provide manufacturers with greater value and incentive for this data.

In addition to "laboratory" performance data, BEM would also benefit from performance data for equipment installed in the field and for older, degraded, and faulty equipment. Such data could also be supplied by manufacturers, but would likely need to be supplemented with field-data collection efforts. BTO has a number of field validation programs that may be able to contribute such data.

Material and construction data. Window and envelope material and construction data is also within the scope of ASHRAE Standard 205P and could also be stored in TPEx. In the meantime, this data is stored in the BCL. As with equipment data and TPEx, BTO could also improve BCL functionality around material and construction data access, as well as support the characterization of new materials and assemblies as well as of the performance of materials and assemblies under installed and time-degraded field conditions.

Weather data. BTO should promote the use of future weather data in building design to ensure buildings will perform as expected under future weather, and should also support the development of standard, transparent, and scientifically sound methodologies for producing such weather files.

BTO could also look at improving the state of the weather data business model. One possibility is supporting the development of methods to create weather files that are hyper-specific to a particular project and location (e.g., weather files that account for microclimate and/or adjacent buildings) and minimize reusability. Another possibility is providing financial support to weather-data activities that are currently done on a volunteer basis.

Utility rate data. OpenEI's U.S. Utility Rate Database (USURDB) provides a sound platform for utility rate data but requires sustained investment to ensure completeness and freshness.

Capital cost and embodied energy data. BTO should promote and support the standardization, schematization, collection, and publication of building capital cost and embodied energy and GHG data at a granularity that can support effective EE analysis and decision making for new and existing buildings. As in Section 5 on "Interoperability and Automation," the emphasis here should be on developing and supporting data standards that facilitate workflow integration and data use rather than providing data, data services, or packaged analytical solutions.

Table 10. BEM Data Ecosystem Barriers and Initiatives

Barriers	Initiatives
Prototype models. Commercial and residential prototype models are sensitive to EnergyPlus version changes, and are not easy to leverage on non-EnergyPlus-based platforms.	Install a rigorous quality assurance and regression testing process for the prototype models to improve stability across EnergyPlus versions.
	Expand the set of prototype models, including support for mixed-use and neighborhood/district prototypes. Expand prototype parameterization.
	Improve documentation and cleanly separate prototype data from code to allow prototypes to be more easily ported to other simulation platforms.
Whole-building asset, operation, and energy use for benchmarking and default assumptions. The RECS and CBECS data sets that are used as the basis for determining default values and assumptions for building asset and operation inputs and benchmarks for energy use are not updated and analyzed quickly enough and have insufficient detail and granularity.	Leverage BTO building energy data projects such as SEED, BuildingSync, Home Energy Score/Asset Score, and ResStock/ComStock to complement RECS and CBECS with more detailed asset, operational, and energy use data that can be used to develop more current and granular default assumptions and values for BEM projects.
	Leverage BTO field validation programs in submetering, sensing, and building system monitoring to augment building asset and energy use data sets with time series of end-use breakdowns and internal building conditions.
Equipment performance. Outdated detailed performance data for fans, coils, chillers, and other HVAC equipment. Missing data for field installed and degraded equipment.	Support ASHRAE in expanding Standard 205P.
	Improve TPEx workflow and connectivity to provide manufacturers with additional incentive to contribute product data.
	Leverage BTO field validation efforts and similar programs to collect, curate, and organize performance about field-installed and degraded equipment.
Weather. TMYx weather data is not representative of weather likely to be encountered by buildings throughout their service lifetimes.	Evaluate methodologies for creating future weather data from climate projection models. Promote the use of future weather data in design and retrofit BEM applications.
Capital cost and embodied energy. Data supporting life-cycle analysis is scattered and poorly connected to BEM-driven operational analysis.	Support and promote the development of standard schema for aggregating and sharing cost and embodied energy data at a granularity that supports cost and energy life-cycle analysis.

7 Topic 5: Educational and Professional Support

Summary:

- BEM educational offerings are sparse. Packaged exercises and labs are available for only a few tools.
- Availability of in-person BEM training is improving, but still largely centered around conferences.
- The BEMP credential is under-subscribed and not widely required, and there is no other suitable and expedient way to assess modeler quality and to allow modelers to advertise their work and advance in their careers.
- BTO should continue to support BEM students with conference travel grants and design competitions. BTO should consider extending support to young faculty with National Science Foundation (NSF)-style research and curriculum grants and to graduate students with NSF-style fellowships.
- BTO should support the development of tool-neutral educational and training materials.
- BTO should promote the BEMP credential in its stakeholder networks and support ASHRAE in its development and administration.
- BTO should leverage the AIA 2030 Commitment DDx to “close the loop” between modeled and measured performance and provide modelers feedback on the quality and fidelity of their models.

Relevant BTO projects:

- **Conference travel grants for students and young practitioners.** BTO provides funding that supports travel for students and young practitioners to conferences such as ASHRAE Building Performance Analysis Conference (BPAC), IBPSA-World Building Simulation, ASHRAE/IBPSA Building Performance Analysis Conference and SimBuild (BPACS) and Simulation in Architecture and Urban Design (SimAUD). It also provides prize money for BEM competitions such as the ASHRAE Low-Down Showdown.
- **Support for online practitioner resources.** BTO has provided one-time funding to create online resources such as the UnmetHours peer-to-peer help forum and the Building Energy Software Tools Directory.
  https://unmethours.com/
  https://buildingenergysoftwaretools.com/

7.1 Barriers

An important component of the BEM ecosystem are BEM professionals themselves. By most accounts, the BEM profession has not reached saturation in the United States. Estimates put the total number of modelers at between three and five thousand. To model all U.S. commercial buildings at a nominal frequency of 10 years would require the BEM workforce to grow by a factor of 10. With a sparse and distributed workforce, few firms have more than a handful of modelers on staff. Many modelers work alone. Apprenticeship, an important professional process in many other engineering disciplines, does not play a significant role at scale.

An often-forgotten class of BEM professionals are those who review BEM submissions for code compliance or beyond code programs. Although they may require less subject matter depth than "active" modelers and less experience with the mechanics of BEM and specific BEM software, reviewers require broad knowledge of BEM and its various tools, their capabilities, and outputs to go along with deep knowledge of the relevant codes. As with modeling itself, training and experience help in model review.

Education. Few have formal training in BEM since only a handful of architecture and mechanical engineering programs include BEM as part of the curriculum. MIT, Penn State University, Texas A&M University, Georgia Tech University, Oklahoma State University, University of California-Berkeley, University of Colorado-Boulder, and University of Maryland-College Park are notable U.S. universities with BEM course offerings. A number of international universities offer BEM tracks including Concordia in Canada, Strathclyde University and University College-London in the United Kingdom, KU-Leuven in Belgium, Tsinghua University in China, and CEPT University in India. There are no BEM professional degrees, but many of the universities listed above have research masters and PhD programs.

As a well-documented, open-source BEM engine with a broad range of capabilities, EnergyPlus is the most widely used BEM engine in academic research, with citations in over half the papers published in IBPSA and ASHRAE simulation conferences.

There are a number of BEM textbooks including, *Energy Simulation in Building Design* (Clark 2001), *Building Performance Simulation for Design and Operation* (Hensen and Lamberts 2012), and *Design Energy Simulation for Architects* (Anderson 2014). Tool-specific textbooks and workbooks include *Building Energy Modeling with OpenStudio* (Brackney et al. 2018) and *Building Energy Simulation: A Workbook Using DesignBuilder* (Garg et al. 2017). Many commercial BEM software vendors offer free or discounted licenses for educational use. Fewer offer tool-specific teaching materials or packaged exercises or labs.

The number of faculty specializing or even well-versed in BEM is relatively few and most universities will have at most one. Faculty looking to develop course materials including labs and exercises are not likely to have access to existing materials or a support network beyond perhaps their advisor and immediate graduate school cohort.

Training. With few BEM degree programs, BEM practitioners often do most of their learning on the job. And with few practitioners all told, most do it alone. Prior to 2012, BTO subsidized lab-provided EnergyPlus trainings, mostly at ASHRAE and SimBuild conferences but sometimes in locations close to national labs. BTO terminated this practice in order not to compete with private-sector training offerings. A handful of organizations provide EnergyPlus training, and the adoption of EnergyPlus by third-party vendors has naturally expanded training availability. BTO sponsored a short-lived "train the trainers" program for the OpenStudio Application that on-boarded a handful of organizations. With the OpenStudio Application spun off 2020, this program has no remaining purpose.

In-person training opportunities are increasingly common, but still not widespread. Vendor-provided training is largely attached to conferences such as ASHRAE and IBPSA. Vendors and consultants such as Big Ladder Software offer standalone "traveling" workshops that visit larger cities such as San Francisco, Chicago, and Seattle. Online training workshops are also available via vendors, training consultants such as Energy-Models.com[127] and subscription services like Performance.Network.[128] IBPSA-USA offers recorded training videos for members.[129] AHSRAE Learning Institute and IBPSA-USA offer tool-neutral BEM workshops several times a year, both in-person and online.

Modeler assessment, credentialing, and marketing. The documented production of high-quality work is the basis of career advancement and growth, for promotion in large organizations, and for freelance business development. The BEM enterprise currently provides few mechanisms to assess the quality of modeling projects and to reward and promote quality modelers.

One method to assess modeler quality is via association with high-performance energy-efficient building projects, although this approach is oblique and relies on the assumption that modeling played a significant role in the project. A more robust method is correlation between modeled and measured energy use. Few BEM applications are predictive—and some like code-compliance and related use cases are explicitly non-predictive, but it is still likely the case that some modelers produce more accurate and useful models than others. Unfortunately, data correlating modeled energy use to measured energy use is not centrally collected and curated. It is likely that many individual modelers do not collect or even have access to this data individually, do not have a quantitative sense of their own level of proficiency, and may be resistant to share these metrics if they do not know how it compares to that of other modelers, or if other modelers do not share it themselves.

127 https://energy-models.com/
128 http://performancenetwork.squarespace.com/
129 https://www.ibpsa.us/videos/all

The alternative or complement to a project portfolio is a professional credential that signifies knowledge and experience. There are two BEM professional credentials: ASHRAE's BEMP[130] and the Association of Energy Engineer's (AEE's) Building Energy Simulation Analyst (BESA)[131] is required in few, if any, BEM procurements. ASHRAE Standard 209, "Energy Simulation Aided Design for Buildings," requires a BEMP- or BESA-certified professional either perform or supervise the work, but that standard itself is not widely adopted. Both credentialing programs are under-subscribed, with only 370 U.S. practitioners obtaining the BEMP credential to date.[132] Without credential requirements, cost pressures can lead firms to assign BEM tasks to junior staff with little experience in BEM or specific analyses, workflows, and tools. Modeler inexperience can manifest in misuse of the software, use of defaults where project-specific values are needed, or misinterpretation of results. Perhaps most significantly, inexperience manifests as an inability to quickly recognize and diagnose the inevitable careless error, by identifying unexpected results. With no way to assess model and modeler quality, modeler inexperience is difficult to recognize and disincentivize. Ironically, anecdotes suggest that the use of inexperienced modelers does not in fact reduce modeling project cost, and may increase it. While more experienced and credentialed modelers may charge higher rates, they often needs fewer hours to produce more robust results.

Inexperience also hurts in model review, an important component of code-compliance, certification, and incentive programs.

7.2 Initiatives

BTO can enhance the state of BEM practice and support BEM practitioners by supporting and augmenting existing efforts.

Education. BTO supports BEM students with design competition prize money and conference travel grants. BTO could expand this support. BTO could extend student support with graduate fellowships, like those offered by the NSF. BTO could also sponsor summer internships for BEM students at universities or national labs that conduct BEM research.

For BEM faculty, BTO could offer NSF-style early career development awards for research, education, or both. It could also offer smaller competitive research solicitations that are exclusive to universities. BTO should support the creation of a forum, potentially under the umbrella of IBPSA, where BEM educators can exchange ideas and support one another in the development of BEM educational materials.

Training. BTO-funded lab-provided training should remain a thing of the past, but BTO should continue to support and encourage private-sector training. Subsidizing the cost of training

[130] https://www.ashrae.org/education--certification/certification/bemp-building-energy-modeling-professional-certification
[131] http://www.aeecenter.org/i4a/pages/index.cfm?pageid=347
[132] http://certificants.ashrae.org/Search/

associated with conferences could boost attendance of both training workshops and the conference itself.

Popular software packages and even programming languages often have annual "user conferences" where users share the latest case studies and ideas, learn about the latest features and developments, and provide feedback to industry. An EnergyPlus user conference could perform double duty as a stakeholder meeting, bringing together both users and vendors.

BTO may consider direct support for the development of tool-agnostic BEM education and training content and training focused on building physics and HVAC fundamentals. The BEMBook Wiki[133] is a volunteer project; it is missing a significant amount of content. BTO could provide funding to complete this project in either its current form or a more useful one. Training and content specific to BEM review is also needed and could benefit from BTO support.

Modeler assessment and credentialing. BTO can use its stakeholder network to promote the ASHRAE BEMP credential and ASHRAE Standard 209 that requires it. BTO can work with General Services Administration (GSA) and the Department of Defense (DOD) to add BEMP certification requirements to federal projects. It can promote its use in the Better Buildings Challenge and more generally among Better Buildings Alliance partners. BTO should support ASHRAE in the continued development and administration of the BEMP credential.

BTO can leverage the AIA 2030 DDx, its role in ENERGY STAR Portfolio Manager and SEED, and its growing relationship with utilities to help close the loop on modeled and measured energy use and savings. BTO should also make this data available to modelers to allow them to assess their own skills and proficiencies, and potentially market them.

[133] https://bembook.ibpsa.us/

Table 11. Education and Professional Support Barriers and Initiatives

Barriers	Initiatives
Education. Educational offerings are sparse. Few architecture or engineering programs offer BEM as part of an architecture or engineering curriculum.	Continue collaboration with IBPSA to support participation of students and young professionals in BEM conferences, technical meetings, and design competitions.
	Consider awarding graduate fellowships for BEM research.
	Use competitive solicitations to support BEM faculty in research and curriculum development.
Training. In-person training opportunities are centered around conferences, and only sparsely available at non-conference times and locations	Subsidize conference-attached BEM training.
	Work with ASHRAE and IBPSA to develop tool-agnostic training content for building physics and HVAC.
	Continue collaboration with IBPSA to develop online resources for BEM community.
Modeler credentialing. The BEMP certificate is under-subscribed. BEMP is not required by any program or procurement.	Support ASHRAE in developing and administering the BEMP credential. Use stakeholder networks to promote BEMP requirements in projects and procurements.
Modeler feedback. There is no feedback loop that correlates measured energy use or savings with predicted energy use or savings for individual modelers or organizations.	Leverage the AIA 2030 Commitment DDx along with Portfolio Manager to close the loop between design and measured performance. Make this information available to BEM professionals to allow them to assess their own skills.

8 Topic 6: Market and Value Proposition

Summary:

- Building owners and project managers invest in BEM when its application is mandatory (e.g., code compliance) or delivers immediate financial benefits (e.g., green certification). They decline to invest in more impactful applications like design-assistance because the value BEM provides in those applications is not well documented.
- Architects and engineers may be reluctant to invest in BEM if they feel they can achieve similar results without it. This is exacerbated if BEM services have to be contracted out.
- Because EUI prediction is inherently difficult, many BEM use cases have been reformulated to de-emphasize absolute prediction. However, without predictive accuracy as a quality metric, the focus has shifted to cost with many projects emphasizing BEM cost minimization rather than BEM value maximization.
- ASHRAE Standard 209 and the BEMP credential are indicators of quality for BEM deliverables and professionals, respectively. However, they have not been widely adopted.
- BTO should compile, document, and promote compelling evidence that use of BEM leads to persistent energy savings.
- BTO should promote the use of ASHRAE Standard 209 and BEMP credentials in project requirements.

Relevant BTO projects:

- **AIA 2030 Commitment DDx.** BTO collaborates with AIA to develop the 2030 Commitment Design Data Exchange reporting and research portal.
  https://www.energy.gov/eere/buildings/downloads/aia-2030-commitment-design-data-exchange-ddx
  https://2030ddx.aia.org/

8.1 Barriers

BEM presents a different value proposition to different building stakeholders. Because of their different vantage points and incentives, these stakeholders may fail to see or to accept this value proposition, creating barriers to BEM adoption. The difficulty in measuring and thus rewarding quality BEM work exacerbates the problem, creating a “race to the bottom” that emphasizes minimization of BEM costs rather than the maximization of its benefits.

Value proposition for owners and managers. Potential BEM clients like building owners and project managers are often unaware of the potential use and benefit of BEM in design and building operation. At present, many are willing to invest in cheap, one-time applications of BEM either to satisfy mandatory code requirements or to obtain an immediate benefit such as a green certificate or an EE incentive payment. When making this investment, they may not know what BEM is or what plays in these processes other than that it is a necessary ingredient.

Code compliance and green certification are end-of-project BEM applications that do more to document building performance than to actively inform and improve it. To achieve deep energy savings, more intensive, iterative, and expensive BEM is needed. Owners and managers are less likely to make this additional investment. Some question the benefit of BEM over cheaper approaches that rely on simpler engineering calculations, experience and judgment, or a combination. Others understand the benefit but are not convinced that it is commensurate with the additional cost. Still others are skeptical that predicted savings will be realized. These prejudices are amplified if the manager has no financial stake in the building's performance.

The Rocky Mountain Institute's (RMI) "BEM Guide for Owners and Managers" (Franconi et al. 2013) is an introduction to BEM for owner and manager clients and includes guidelines for procuring BEM services, including model Request for Proposal (RFP) and contract language. The IBPSA-USA BEM Library[134] also provides some of these materials along with additional background. The adoption and use of these resources is not clear.

Value proposition for architects. Like owners and managers, architects and engineers may also feel that predicted savings will not be realized, due to variances in either construction and installation or occupancy and operation. If project managers do not explicitly budget for BEM, architects may be reluctant to invest if they feel they can achieve comparable results without it, especially if BEM services must be contracted out reducing architects' take of total design fees. Alternatively, architects may feel that their job is to create an attractive building that serves its intended function and that EE is the mechanical engineer's job.

These factors may reinforce one another when architects bid for jobs. In preparation for bidding, architects typically explore multiple concepts in a short amount of time before settling on the design they will put forward. Because bids are not paid work and because each design concept requires a new model, modeling is not likely to be used. Unfortunately, owners typically select bids based on form and envelope characteristics that have significant impact on performance. After the bid is won, it may be difficult to change these aspects.

Vendors such as Sefaira[135] and cove.tool[136] have identified early-stage design as the "valley of death" for BEM and have developed products that target it explicitly, while design firms such as Perkins+Will[137] have developed in-house solutions. The AIA created the "Architect's Guide to Integrating Energy Modeling in the Design Process" in 2012 (AIA 2012). This document provides a process overview, guidelines for engaging and contracting modeling services, tools listings, information about detailed envelope and lighting models, and advanced topics such as calibrated modeling for existing buildings and post-occupancy measurement and verification.

---

[134] https://www.bemlibrary.com/
[135] https://sefaira.com/
[136] https://www.cove.tools/
[137] https://speed.perkinswill.com/

AIA updated this document in 2019 with the "Architect's Guide to Building Performance: Integrating Building Simulation in the Design Process" (AIA 2019). The new document introduces the ASHRAE Standard 209 framework and includes some examples and guidance for early-stage analyses like shading, daylighting, and shoebox facade modeling. Despite these efforts, the use of BEM in early-stage design continues to lag according to AIA 2030 DDx. One noted gap is the lack of guidance for including BEM in project proposals and for contracting with BEM service providers.

Value proposition for mechanical engineers. Most energy modeling is performed by mechanical engineers. However, many engineers still design HVAC systems based on simple peak load calculations. They may feel that it is the architect's responsibility to design a building with low thermal loads and that their job is to design a robust system to meet the given loads. They may be reluctant to use BEM to design more aggressive systems, preferring simpler, more conservative approaches that do not expose them to liability. Alternatively, they may feel that judgement and experience is a good substitute for BEM.

Value proposition for homebuilders. In the residential market, large-scale homebuilders both design and build homes and prefer the design flexibility afforded by performance-path compliance. The barrier here is code officials who are more comfortable with prescriptive-path compliance.

Value proposition for authorities having jurisdiction. Code authorities, often called authorities having jurisdiction (AHJs), are high-volume consumers of BEM results, reviewing documentation for projects choosing performance-path code-compliance options. Whereas for stakeholders associated with specific building projects, BEM presents a benefit-cost tradeoff—specifically the flexibility to trade prescriptive requirements in one aspect of the building for above-code efficiency in another aspect—for AHJs it presents only the cost entailed in hiring and training BEM reviewers. Improving the value proposition for AHJs by reducing the cost of BEM review while increasing the benefit of performance-path compliance and projects that use it will improve the overall BEM experience and value proposition for individual projects.

Accumulated benefits of BEM. Owners, managers, architects, and engineers alike are almost universally unaware of the benefits BEM can provide post-occupancy and throughout the lifetime of the building, from ensuring the building continues to operate as designed and commissioned to optimizing operations via advanced control to optimal planning of upgrades and retrofits.

Individual stakeholders see BEM as episodic, providing decision-support benefits in discrete, distinct applications, each likely requiring its own model. Individually, they may fail to see BEM as a continuous process that provides benefits on demand and that updating and reusing a model across applications amortizes the cost of model creation.

Recognizing, rewarding, and procuring quality BEM. Section 3, "Predictive Accuracy and Consistency," referenced the lack of positive feedback loops on predictive BEM accuracy.

Because predictive accuracy is inherently difficult in many BEM use cases due to the stochastic nature of weather, occupancy, and use. Knowing this, many BEM use cases have been re-formulated to de-emphasize predictive accuracy and focus on comparisons instead. However, an unfortunate side-effect of this development has been that without a clear and intuitive alternative definition of the quality of a BEM deliverable—and by association the quality of the modeler that delivered it—the remaining concrete objective becomes cost. If they explicitly mention BEM at all, many procurements emphasize the minimization of BEM cost for mandatory deliverables rather than the maximization of BEM benefit, which when applied correctly far outstrips BEM costs.

Quality indicators for BEM professionals and deliverables include ASHRAE's BEMP credential for the former and Standard 209, "Energy Simulation Aided Design for Buildings except Low-Rise Residential Buildings,"[138] for the latter. Standard 209 documents processes and deliverables for BEM tasks in various phases of building design and operation. It also covers benchmarking and target setting, site climate analysis, as well as modeler certification and modeling software requirements. It also specifies project requirements such as the use of a BEMP-certified modeler to either perform or review the work. ASHRAE Standard 209 is relatively new and not widely referenced or required. The BEMP credential is more established but, absent Standard 209, rarely specified in procurements.

8.2 Initiatives

Overcoming these barriers requires (among other things) articulating a clear overarching value proposition for BEM along with specific value propositions for each application and each stakeholder group.

BTO should support—and where possible directly undertake—analyses to document and communicate these value propositions. The first step is collecting compelling evidence that BEM leads to robust energy savings, up-front cost savings, and perhaps improved ancillary benefits such as higher sale and rental prices and greater tenant satisfaction, and that it does so cost-effectively. The latter specifically target building owners and project managers with the hope that the increased value those stakeholders place on BEM will trickle down to professionals like architects and engineers.

Establishing robust correlations. The BTO article, "The Shockingly Short Payback of Energy Modeling," used project data from the architecture firm HOK to show that, for a variety of new construction and retrofit projects, investments in BEM ranging from $40,000 to $140,000 had payback periods of three months or less (DOE 2016). In some projects, BEM even had instantaneous payback—paying for itself before the building was occupied by identifying areas in which costs could be cut without negatively impacting energy use or helping to reducing loads to a degree that allowed substantial reductions and cost savings in HVAC. BTO is currently

[138] https://www.ashrae.org/standards-research--technology/standards--guidelines/titles-purposes-and-scopes#SPC209P

working with AIA to gather additional BEM cost and payback data via the 2030 Commitment DDx. With AIA DDx data it will also be critical to ultimately "close the loop" and correlate modeled energy savings with measured energy savings. BTO recently worked with AIA to add DDx functionality to import measured energy use data from sources such as Portfolio Manager. This connection can be used not only to provide individual modelers with feedback, but also to establish correlation between predicted and measured energy and between the use of BEM in design and realized savings.

Anecdotally, it is known that green certifications such as USGBC LEED or RESNET HERS can increase the sale price or rental unit price of a building. There are also indications that EE is tied to better cash flow and lower default rates, higher tenant satisfaction and retention rates, and even higher occupant productivity, all providing additional value to the building owner. There is potential to partner with USGBC and other organizations to cross-reference data that would draw out correlations between use of BEM and these additional benefits to building owners.

BTO should also consider collaborating with trade organizations like Building Owners and Managers Association (BOMA), International Facility Management Association (IFMA), and Commercial Building Energy Association (CBEA) to collect data about the use, effectiveness, and costs of BEM in building operation.

Performance attribution. Data from HOK and the AIA 2030 DDx establishes correlation between BEM and energy savings, up-front cost savings, and ancillary benefit. However, it does not perform a sound attribution of these savings *to* BEM. For a project that uses BEM and achieves 50% savings over code, how much of these savings can be attributed to BEM? Half? Less? More? How much savings could have been achieved using simpler calculations or past experience? For projects that do not use BEM, how much of the final performance should be attributed to the fact that BEM was not used and how much to the fact that energy performance was not a priority?

One possibility is to establish correlations between the use of BEM and the presence of specific design elements and EEMs that are closely associated with energy savings and occupant satisfaction, such as use of daylighting or HVAC systems that achieve high thermal comfort. Some EEMs—daylight harvesting, radiant systems, natural ventilation, and the use of thermal mass—are fundamentally difficult to design without BEM. BTO and AIA should consider expanding the DDx to draw out these correlations.

The contributions of BEM could also be drawn out by tracking use of BEM, the presence of EEMs, and predicted performance throughout the design cycle. Correlations between the use of BEM in the project and the appearance of EEMs, or relationships between early performance targets and final design performance with or without BEM could also help isolate the contributions of BEM.

The good news about BEM performance attribution is that early data is so overwhelmingly positive—payback periods on the order of 1–2 months—that BEM looks cost-effective even with very conservative attribution estimates of 10%–20%.

Case studies. For maximum impact, large-scale analyses should be complemented with compelling case studies, preferably highlighting different project types, building types, climate zones, and combinations of EEMs. BTO should collaborate with individual firms and owners to develop these case studies, leveraging the AIA and the various Better Buildings networks.

Outreach. As the value of BEM is documented, BTO should promote it to various stakeholder audiences. BTO should leverage its existing partnership and outreach vehicles such as the Better Buildings and its venues. BTO should actively promote its findings through publications and presentations in relevant trade journals and conferences. It should also collaborate with trade organizations on specific outreach activities.

BTO has a blog aimed at documenting applications of BEM, although as part of DOE communications, it focuses on DOE/BTO-funded projects.[139] Additional promotion and outreach via these channels and others is needed to continue to raise awareness about different uses of BEM, their benefits, and their synergies. BTO should promote these resources through its own networks and approach other organizations such as the BOMA and CBEA about creating tailored BEM information and engagement guides for their stakeholders.

Recognizing, rewarding, and procuring quality BEM. As mentioned in previous sections (Section 3, "Accuracy and Consistency," and Section 7, "Educational and Professional Support"), establishing standards, metrics, and indicators for quality BEM can create a positive cycle that improves BEM deliverables, enhances BEM value for individual projects, and creates additional demand for high-quality BEM. In addition to the empirical correlations above, BTO can use its position and network of stakeholders to promote existing quality guidelines and credentials such as ASHRAE's Standard 209 and BEMP. BTO can work with GSA and DOD to add Standard 209 and BEM requirements to federal projects. It can promote their use in the Better Buildings Challenge and more generally among Better Buildings Alliance partners. As with BEMP, BTO should support ASHRAE in the continued development of Standard 209.

Promoting high BEM-value use cases. Improving methods for measuring and indicating the quality of BEM is one way to exert positive pressure and create positive feedback in the BEM market. Another is to promote use cases that build in this feedback via a fundamental reliance on BEM. Such use cases include ESPCs, net-zero design, and outcome-based codes—use cases that directly tie BEM to measured performance.

Current building EE codes like ASHRAE 90.1 apply only to the building's physical assets and ignore post-construction, operational, and occupancy effects, relieving associated actors of responsibility for building performance. Outcome-based codes based on technically derived EUI

[139] http://energy.gov/eere/buildings/listings/end-use-breakdown-building-energy-modeling-blog

targets inherently include accountability of building owners, operators, and tenants for overall building performance (New Buildings Institute 2015). With existing asset-based codes, the use of BEM is focused on performance relative to a theoretical baseline under standard operating assumptions. If the code is not stringent, BEM can be safely deferred until the end of the design. Outcome-based codes would shift BEM use toward design and emphasize predictive modeling with intended occupancy and operational parameters. Outcome-based codes would also incentivize the use of BEM during periodic compliance checks, to help attribute energy use to the building, to its maintenance and central operation, or to tenants. BEM could be used even if tenant-level end-use submetering is available since submetering may not be able to directly account for the effects of the envelope. BEM would also be more heavily used during code development, to establish target EUIs. Overall, outcome-based codes would create virtuous cycles that reward both the most productive uses of BEM and the most productive and highly skilled BEM professionals.

BTO's Residential Buildings Integration and Commercial Buildings Integration programs already promote net-zero design via initiatives such as Solar Decathlon,[140] Zero Energy Ready Homes (ZERH),[141] and Zero Energy Buildings.[142] BTO should continue to pursue and promote these use cases and highlight the role BEM plays in them. BTO should similarly promote other high BEM-value use cases, as applicable. By creating positive pressure and feedback loops within the BEM marketplace, these use cases will improve the general state of BEM, its tools, practices, and practitioners, and enhance the value proposition of all BEM use cases.

[140] https://www.solardecathlon.gov/
[141] https://www.energy.gov/eere/buildings/zero-energy-ready-homes
[142] https://www.energy.gov/eere/buildings/zero-energy-buildings

Table 12. BEM Value Proposition Barriers and Initiatives

Barriers	Initiatives
Robust empirical correlations. Lack of a robust data set that correlates use of BEM in projects to predicted and measured energy savings and to benefits such as reduced construction costs, and greater building value. Matching data that shows BEM cost is reasonable.	Continue to collect BEM use, cost, and cost-effectiveness data via the AIA 2030 DDx. Expand the DDx to "close the loop" with measured data.
	Explore partnerships with USGBC and other organizations to cross-reference data about occupant satisfaction and retention, sale and rental prices, and other ancillary benefits with AIA BEM data.
	Explore partnerships with RESNET, BOMA, and other organizations to collect BEM use, impact, and cost data for other use cases.
Performance attribution. Lack of evidence and analysis that shows how much energy savings should be attributed to BEM as opposed to factors such as engineering judgement or simpler calculations.	Leverage AIA's 2030 DDx to establish correlations between BEM and the presence of EE design elements.
	Leverage AIA's 2030 DDx to establish correlations between BEM and project performance and cost.
	Expand DDx with questions to isolate BEM contributions.
	Conduct a rigorous classical performance attribution for BEM in integrated design and perhaps other use cases.
Communications. Lack of awareness of BEM and its value proposition among different stakeholders, especially financial decision makers such as building owners and project managers.	Leverage AIA and Better Buildings partnerships to develop and publish case studies highlighting the value of BEM for various building types, climates, and design strategies.
	Promote findings and case studies on the BTO website, in articles in trade journals, and in conference presentations. Leverage the AIA, ASHRAE, and Better Buildings to reach a broader audience.
	Promote stakeholder-specific BEM engagement guides such as RMI's "BEM for Owners and Managers" and AIA's "Architect's Guide to Energy Modeling." Work with other organization to develop engagement and educational tools for other stakeholder groups.
	Support the development of materials that guide architects in adding BEM to project proposal and procuring outside BEM services.
Recognizing and rewarding quality BEM products and professionals. ASHRAE Standard 209 is new and not widely referenced or required. BEM credentials like ASHRAE's BEMP and AEE's BESA are under-subscribed and generally not required for project work.	Promote ASHRAE Standard 209 and the BEMP credential requirement in federal projects and more generally via BTO's network of stakeholders including Better Buildings.
	Support ASHRAE in the continued development of Standard 209.
High BEM-value use cases. Common use cases like code compliance and even conventional building design do not place inherent value on BEM.	Use stakeholder networks to promote use cases that place inherent value on BEM, including ESPCs, outcome-based codes, and net-zero design. By creating positive feedback in the BEM marketplace, these use cases will improve the value proposition for all BEM use cases.

9 Program-Level Recommendations

In addition to feedback on specific initiatives to address BEM barriers, stakeholders provided recommendations about BTO BEM program management.

Regular program level review. BTO projects are planned and executed in three-year cycles. Competitively awarded projects are typically three years long. Long running projects like EnergyPlus are chopped up into three-year periods for execution purposes.

For the past six years, BTO has used a set review protocol for its projects. Projects are prospectively "merit reviewed," sometimes competitively and sometimes not. Awarded projects are then retrospectively "peer reviewed," typically two years after award. For long-running projects, the results of the peer review inform the subsequent merit review. This process is well established at the project level.

In 2019, BTO piloted program-level peer review using BEM as the test subject. The review looked both retrospectively and prospectively at the program as a whole, used 12 reviewers (with at least two representatives from each category including practitioners, academics, software vendors, program administrators, government agencies, and NGOs) as opposed to the more traditional four or five, and was driven by the draft of this document. A number of new BTO initiatives, modifications and redirections to existing initiatives, and changes to this document were generated at this review. BTO should continue to open up its BEM program to program-level review on a regular basis.

Updates to this document. Regular program-level reviews should be accompanied by regular updates to this document and public requests for comment. The process produces reference documents and gives the larger BEM community the opportunity to provide feedback on the program.

Continued dialog and collaboration with the IBPSA-USA Advocacy Committee. The IBPSA-USA Advocacy Committee helped to collect and synthesize RFI feedback from IBPSA membership and subsequently provided additional feedback to proposed revisions and extensions to the draft. BTO has met with the committee monthly since its inception. Continued dialog and collaboration with the committee can provide more regular and agile feedback on program activities and plans.

References

AIA. 2012. "An Architect's Guide to Integrating Energy Modeling in the Design Process." American Institute of Architects. http://content.aia.org/sites/default/files/2016-04/Energy-Modeling-Design-Process-Guide.pdf.

AIA. 2019. "Architect's Guide to Building Performance." American Institute of Architects. http://content.aia.org/sites/default/files/2019-06/AIA_BPSGuide_2019_FINAL.pdf.

Anderson, K. 2013. *Design Energy Simulation for Architects*. Routledge. https://www.routledge.com/Design-Energy-Simulation-for-Architects-Guide-to-3D-Graphics/Anderson/p/book/9780415840668.

Brackney, L., Parker, A., Macumber, D., and Benne, K. 2018. *Building Energy Modeling with OpenStudio: A Practical Guide for Students and Professionals.* Springer. https://www.springer.com/us/book/9783319778082.

BTO. 2016. *Building Technologies Office: Multi-Year Program Plan. Fiscals Years 2016–2020.* U.S. Department of Energy Office of Energy Efficiency and Renewable Energy.

Clarke, J. 2001. *Energy Simulation in Building Design*. Routledge. https://www.taylorfrancis.com/books/9781136406768.

DOE. 2016. "The Shockingly Short Payback of Energy Modeling." https://www.energy.gov/eere/buildings/articles/shockingly-short-payback-energy-modeling.

Franconi, Ellen, Kendra Tupper, Blake Herrschaft, Craig Schiller, and Robert Hutchinson. 2013. "Building Energy Modeling for Owners and Managers: A Guide to Specifying and Securing Services." Rocky Mountain Institute. https://www.rmi.org/wp-content/uploads/2017/05/Building-Energy-Modeling-for-Owners-and-Managers-2013.pdf.

Frankel, Mark, Jim Edelson, and Ryan Colker. 2015. *Getting to Outcome-Based Building Performance.* Seattle Summit on Performance Outcomes, Event Report. New Buildings Institute. Page 1: "…models solely as compliance and verification tools (~80% of their current use) to performance and design decision-making tools (~20% of their current use)." https://newbuildings.org/sites/default/files/Performance_Outcomes_Summit_Report_5-15.pdf.

Garg, V., Mathur, J., Tetali, S., Bhatia, A. 2017. *Building Energy Simulation: A Workbook Using DesignBuilder.* CRC Press. https://www.taylorfrancis.com/books/9781315368894.

Hensen, J. and Lamberts, R. 2012. *Building Energy Simulation for Design and Operation.* Routledge. https://www.routledge.com/Building-Performance-Simulation-for-Design-and-Operation/Hensen-Lamberts/p/book/9781138392199.

Hong, T., and Lee, S-H. 2019. "Integrating physics-based models with sensor data: An inverse modeling approach." *Building and Environment*. 154: 23-31. https://www.sciencedirect.com/science/article/pii/S036013231930160X.

Lovins, Amory. 2011. *Reinventing Fire.* Rocky Mountain Institute. Page 86. https://rmi.org/insight/reinventing-fire-industry/.

New Buildings Institute. 2015. "Getting to Outcome-Based Building Performance, Report from a Seattle Summit on Performance Outcomes, Event Report." http://newbuildings.org/sites/default/files/Performance_Outcomes_Summit_Report_5-15.pdf.

Neymark, J., and Judkoff, R. 2002. *International Energy Agency Building Energy Simulation Test and Diagnostic Method for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST), Volume 1: Cases E100–E200.* National Renewable Energy Laboratory, Golden, Colorado. NREL/TP-550-30152. http://www.nrel.gov/docs/fy02osti/30152.pdf.

Nigusse, Bereket and Richard Raustad. 2013. *Verification of A VRF Heat Pump Computer Model in EnergyPlus*. Florida Solar Energy Center. http://www.osti.gov/scitech/servlets/purl/1093843.

Roels, Staf. 2017. "Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (Annex 58)." International Energy Agency, Energy in Buildings and Communities Programme. https://www.iea-ebc.org/Data/publications/EBC_PSR_Annex_58.pdf

Roth, A. 2018. "Rulesets are Great. Certified Rulesets are Greater." 2018 ACEEE Summer Study on Energy Efficiency in Buildings. https://calbem.ibpsa.us/wp-content/uploads/2019/11/ACEEE_CertifiedRulesets_Roth.pdf.

Roth, Amir, and Janet Reyna. 2019. *Grid-interactive Efficient Buildings Technical Report Series: Whole-Building Controls, Sensors, Modeling, and Analytics."* U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/GO-102019-5230. https://www1.eere.energy.gov/buildings/pdfs/75478.pdf.

Turner, Cathy, and Mark Frankel. 2008. *Energy Performance of LEED for New Construction Buildings."* New Buildings Institute. https://newbuildings.org/sites/default/files/Energy_Performance_of_LEED-NC_Buildings-Final_3-4-08b.pdf.

U.S. Energy Information Administration (EIA). 2020. "How much energy is consumed in U.S. buildings?" http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1.

Z. Ming et. al. 2016. "Time Dependent Valuation of Energy for Developing Building Standards." Energy and Environmental Economics, Inc. https://www.ethree.com/wp-content/uploads/2017/01/TN212524_20160801T120224_2019_TDV_Methodology_Report_7222016.pdf.

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

For more information, visit:

energy.gov/eere/buildings/building-energy-modeling

DOE/GO-102020-5467 ▪ November 2020