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Emerging Technologies Research and Development:

DRAFT Research and Development Opportunities for Building Energy Modeling

April 2019

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Acknowledgments

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List of Acronyms

Acronyms	Description
AEE	Association of Energy Engineers
AIA	American Institute of Architects
API	Application Program Interface
ASE	Alliance to Save Energy
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BCVTB	Building Controls Virtual Test Bed
BEDES	Building Energy Data Exchange Specification
BEM	Building Energy Modeling
BEMP	ASHRAE Building Energy Modeling Professional credential
bEQ	ASHRAE's Building Energy Quotient rating systems
BESA	AEE's Building Energy Simulation Analyst credential
BESTEST	Building Energy Simulation Test
BIM	Building Information Modeling
BLAST	Building Loads Analysis and System Thermodynamics
BMS	Building Management System
BPI	Building Performance Institute
BTO	EERE's Building Technologies Office
CAD	Computer-Aided Design
CBECS	EIA's Commercial Building Energy Consumption Survey
CBI	BTO's Commercial Buildings Integration
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DeST	Designer's Simulation Toolkit
DOAS	Dedicated Outdoor Air System
DOE	U.S. Department of Energy
EDAPT	Energy Design Assistance Program Tracker
EIA	DOE Energy Information Administration
EE	Energy Efficiency
EEM	Energy Efficiency Measure
EERE	DOE's Office of Energy Efficiency and Renewable Energy
EM&V	Evaluation, Measurement and Verification
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
ESCO	Energy Service Company

Acronyms	Description
ET	BTO’s Emerging Technologies Program
EUI	Energy Use Intensity
FEMP	EERE’s Federal Energy Management Program
GSF	Gross Square Footage
HAP	Carrier Corporation’s Hourly Analysis Program
HERS	RESNET’s Home Energy Rating System
HVAC	Heating, Ventilation, and Air Conditioning
IBPSA	International Building Performance Simulation Association
IDF	EnergyPlus’ Input Data Format
IEA-EBC	International Energy Agency-Energy in Buildings and Communities
IECC	International Energy Conservation Code
IES<VE>	Integrated Environmental Solutions’ Virtual Environment
IPMVP	International Performance Measurement and Verification Protocol
LEED	USGBC’s Leadership in Energy and Environmental Design credential
LBNL	Lawrence Berkeley National Laboratory
MHEA	Mobile Home Energy Audit
MulTEA	Multifamily Tool for Energy Auditing
NAICS	North American Industry Classification System
NASA	National Aeronautics and Space Administration
NBI	New Buildings Institute
NC	New Construction
NEAT	National Energy Audit Tool
NIST	National Institute of Standards and Technology
NMBE	Normalized Mean Bias Error
NREL	National Renewable Energy Laboratory
OE	DOE’s Office of Electricity
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
RBI	BTO’s Residential Buildings Integration program
RECS	EIA’s Residential Energy Consumption Survey
REM/Rate	Residential BEM Used for HERS certification
RMI	Rocky Mountain Institute
SDK	Software Development Kit
SF	Square Feet

Acronyms	Description
SEED	Standard Energy Efficiency Data Platform
SEI	ASE's System Efficiency Initiative
TAS	Thermal Analysis Simulation
TBtu	Trillion British Thermal Units
TPEX	BTO's Technology Performance Exchange
TRACE	Trane's Trane Air-Conditioning Economics
USGBC	U.S. Green Buildings Council
VRF	Variable Refrigerant Flow
WIPO	EERE's Weatherization and Intergovernmental Programs Office

Report Purpose, Scope, and Approach

Building Energy Modeling (BEM) is a multi-purpose tool for building energy efficiency (EE). BTO seeks to expand the use and effectiveness of BEM in the design and operation commercial and residential buildings with the goal of achieving persistent reductions in total and peak energy use. This Report outlines recommended steps to achieve this goal, based on technical analysis and stakeholder input. In addition to BTO, this Report can benefit both 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, policy makers, and policy and code enforcement jurisdictions such as states and cities).

This Report was developed in two phases. In the first, BTO worked with a Navigant team to:

- Characterize Current Activities, Markets, and Objectives. We reviewed and characterized existing R&D and market activities, use cases, and drivers.
- Identify Gaps and Barriers. We gathered stakeholder input to analyze needs.
- Define initiatives. We defined a set of initiatives to address identified barriers and R&D opportunities, described goals, and outlined key activities.

Outreach to obtain stakeholder feedback included telephone interviews and workshops with industry experts. Summaries of these workshops are presented in Appendices A and B. This input was used to synthesize barriers and inform recommendations.

The initial phase produced a draft Report, which was released for public review in 2016 and solicited over 400 comments. This second draft incorporates many of those comments while addressing changes that have occurred both at BTO and in the industry.

One significant difference between the first Report draft and this one is that the current draft focuses much more heavily on BTO's own role, portfolio, and activities. BTO is a direct player in the BEM field and transparency about its intentions and future plans is requisite. BTO recognizes that a great number of other public and private organizations contribute to the BEM enterprise. This Report is not a blueprint for the industry as a whole. It is a working document BTO can use to iteratively solicit stakeholder input and synthesize it into a program.

This Report also does not address the use of BEM in support of building-based grid services, a recent BTO initiative called grid-interactive efficient buildings (GEB).

Executive Summary

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) seeks to achieve significant and persistent reductions in energy use in US commercial and residential buildings. Such deep and sustained reductions reduce costs for consumers, help mitigate grid stress and improve electricity 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) in the design and operation of energy efficient buildings. BTO has pursued this goal and invested in BEM since before the rise of DOE 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 supports and directs a number of other initiatives, some in collaboration.

Despite progress in recent years, stakeholders estimate that BEM is used to design only about 20% of new commercial and residential floor area. Use of BEM to support retrofit design is lower, and use of BEM in building operation applications like model-predictive control (MPC) is even more limited.

This Report identifies barriers to increased BEM use in design and operation and activities that address these barriers. 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 policy makers; BEM software developers; HVAC equipment manufacturers; researchers; and educators.

Table ES-1 lists some of these barriers and their associated initiatives, grouped into six topics. These are explored in more detail in Sections 3 through 8.

Table ES-1 Barriers to Increased BEM use and Initiatives Designed to Address Them

Topic	Barriers	Initiatives
Value Proposition	• Clients invest in BEM when it is mandatory (e.g., code-compliance) or provides upfront value (e.g., a green certificate). They decline to invest during design because of skepticism of the value BEM provides over simpler engineering calculations and judgment. • Clients are unaware of the value BEM can provide post-occupancy.	• Develop and document compelling evidence that use of BEM for design and operation leads to robust energy savings. Document the costs associated with BEM. • Develop and promote case studies highlighting the value of BEM. • Leverage reporting programs to track use of BEM.
Predictive Accuracy	• Clients "know" that BEM can generally predict energy use only within 30-50% but do not understand how much this materially impacts BEM applications. They consider energy use prediction as the fundamental capability of BEM and fail to see how, if it cannot do that, it can possibly be good for anything.	• Support empirical validation of BEM engines using well-characterized, well-instrumented test facilities. • Support development and use of methods for model input calibration. • For promotional purposes, use occupied buildings to evaluate progress in predictive accuracy and calibration.
Core Modeling Capabilities	• BEM tools are missing advanced capabilities in areas such as occupant behavior modeling, urban-scale modeling, and grid modeling. • EnergyPlus execution speed is a hindrance in some applications, especially for residential buildings.	• Continue to improve EnergyPlus co-simulation support to leverage capabilities in other simulation engines. • Develop a strategy for linking BTO's detailed envelope modeling tools, THERM, WINDOW, and Radiance with its BEM tools.

		• Continue to invest in EnergyPlus runtime improvements.
Workflow Integration and Task Automation	• BEM engines are not well integrated with design and operation tools resulting in unnecessary manual effort to transfer data from one tool to another, degrading BEM value by increasing both errors and cost. • Mechanical modeling tasks such as generation of code-baseline model from a model of a proposed or existing building are not automated, again degrading BEM value by introducing effort and error.	• Invest in application integration functionality for EnergyPlus. • Work with design authoring tool vendors to improve consistency, robustness, and analyzability of design model exports. • Promote use of OpenStudio Measures and other frameworks for task and workflow automation. • Promote certification for automated BEM tasks such as baseline model generation.
Data Ecosystem	• Detailed equipment performance data used in simulation is outdated. • EIA's RECS and CBECS do not have enough resolution and detail to support benchmarking for BEM use cases. • TMY3 data does not represent the weather buildings will experience throughout their service lifetimes.	• Improve TPEX workflow to provide greater incentive for manufacturers to share performance data. • Leverage BTO projects such as SEED, Asset Score, and Home Energy Score to complement CBECS and RECS. • Leverage BTO activities in sub-metering, sensing, and system monitoring to augment building energy data sets. • Expand the suite of prototype models. • Develop and promote methods for use of uncertainty analysis in BEM applications. • Develop standard methods for deriving future weather data from current climate and weather projection models.
Process Standardization, Credentialing, Education, and Training	• ASHRAE Standard 209 is not widely referenced or required. BEMP and BESA credentials are under-subscribed and not required by programs. • Other than certification, there is no way to gauge modeler expertise, or even for modelers to gauge their own expertise. • BEM curricula are sparse as are BEM training opportunities.	• Lobby for ASHRAE Standard 209 and BEMP/BESA as requirements for GSA and DoD projects. Use AIA, Better Buildings, and utility alliances to promote 209 and modeling credentials. • Leverage AIA 2030 Commitment to connect modeled data to measured data, helping modelers self-evaluate and market. • Establish EnergyPlus and OpenStudio user conferences. • Use competitive solicitations to support BEM faculty research and curriculum development. • Continue IBPSA collaboration to develop online resources and to support participation in conferences.

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

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

Programmatic Initiatives
• Establish a formal process for engaging with and collecting input from BEM stakeholders. • Perform public program-level reviews of BTO’s BEM portfolio at regular intervals, e.g., every three years. • Refresh this Report document at regular intervals, e.g., every five years.

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I Building Energy Modeling (BEM) and its Use Cases

Buildings use 41% of energy consumed in the United States and 70% of the electricity.[1] Building industry professionals use building performance analysis tools to evaluate individual energy-efficiency measures (EEMs) and entire designs to reduce building energy use. 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 onsite 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. 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, 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 is used for activities as diverse as sustainable building design and certification, estimation of energy-efficiency (EE) program incentives, validation of EE program impacts and cost-effectiveness, utility program design, retro-commissioning and energy auditing, energy benchmarking, and optimization of building operations. BEM supports system-level **integrated design** for new construction and retrofits that simultaneously optimizes the building's envelope, systems, and their controls to match its anticipated use profile and local conditions. It also has the potential to support **integrated operation** in which a model incorporates real-time information from sensors, weather forecasts, and the building's energy management system (BEMS) to satisfy energy, cost, and comfort objectives. At a larger scale, BEM supports EE codes, rating and labeling systems, incentive programs, product design, research, and education. BEM can help link these activities and increase accountability for energy performance across the building life cycle.

Integrated design. BEM impacts building energy consumption most directly when it is used to actively inform design of new buildings and major renovations. Integrated design is distinct from BEM done late in a project to demonstrate compliance with energy codes, obtain green certification, or qualify for incentives but not to inform design. Integrated design involves evaluation of multiple design strategies and parametric studies that aim at reducing loads, achieving energy efficiency, maintaining comfort, and minimizing capital costs.[2] ASHRAE Standard 209 "Energy Simulation Aided Design for Buildings except Low-Rise Residential

[1] U.S. Energy Information Administration (EIA). "In 2014, 41% of total U.S. energy consumption was consumed in residential and commercial buildings, or about 40 quadrillion British thermal units.", http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1

[2] Case studies from USGBC/GBCI 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.

Buildings" codifies this process.[3] Integrated design is not required to achieve extremely high levels of energy efficiency. An energy-efficient building can be designed 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 energy-efficient but expensive to build and potentially uncomfortable to occupy. BEM-driven integrated design is needed to quantify EE and occupant comfort and balance these targets against cost and other constraints.

BEM can also inform design indirectly via either static prescriptive guidelines or dynamic online tools that synthesize savings estimates for various EEMs and EEM packages by analyzing the results of large-scale BEM experiments. ASHRAE Advanced Energy Design and Retrofit Guides[4]—which provide building-type and climate zone specific design recommendations for achieving 30% and 50% savings over ASHRAE Standard 90.1-2004—are examples of the former. LBNL's Database of Energy Efficiency Performance[5]—which provides savings estimates and EEM recommendations for offices and retail buildings in California—is an example of the latter. EE codes like ASHRAE Standard 90.1 "Energy Standard for Buildings except Low-Rise Residential Buildings" are also created by analyzing the results of large-scale parametric BEM experiments to derive and vet minimal requirements that consistently provide cost-effective performance. Prescriptive BEM applications like design guides and standards provide less insight and information than integrated uses because they necessarily rely on generic assumptions for inputs such as space planning, occupancy, plug-loads, and even geometry rather than on information specific to the project. However, they also insulate the designer from having to create at least one detailed model, and likely many models if multiple design alternatives and strategies are explored.

Integrated operation. 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 counter-act 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). QCoefficient is one company that provides MPC services to large buildings. BEM applications in building operations like 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 sub-meter data as well as data from thermostats and other sensors—aids model input calibration.

Performance documentation and valuation. BEM also supports EE by helping to *document* and *value* it. Calibrated BEM is an accepted method for measurement and verification (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,"[6] Energy Valuation Organization's (EVO International Performance Measurement and Verification Protocol (IPMVP),[7] NREL's Uniform Methods Project (UMP),[8] and DOE's Federal Energy Management Program's (FEMP) M&V Guidelines.[9]

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[3] https://www.ashrae.org/about/news/2018/ashrae-publishes-energy-simulation-aided-design-standard
[4] http://www.ashrae.org/standards-research-technology/advanced-energy-design-guides
[5] DEEP: A Database of Energy Efficiency Performance to Accelerate Energy Retrofitting of Commercial Buildings, Lee, S.-H. et al.; Lawrence Berkeley National Laboratory, http://cbes.lbl.gov/DEEP.pdf
[6] http://webstore.ansi.org/RecordDetail.aspx?sku=ASHRAE+Guideline+14-2014
[7] http://www.evo-world.org/index.php?option=com_rsform&formId=113&lang=en
[8] http://www.nrel.gov/extranet/ump/draft_protocols.html
[9] http://www.energy.gov/sites/prod/files/2016/01/f28/mv_guide_4_0.pdf

BEM can be used 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 heavily used in both code-compliance and green certification applications.

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 comparison of two simulations: i) the proposed (or actual) building under fixed assumptions, and ii) a minimally compliant version of the proposed or actual building that is derived from the original by the application of prescriptive rules. The widely used ASHRAE Standard 90.1 "Minimum Performance of Commercial Buildings" has two performance paths: "Energy Cost Budget" for compliance and the "Performance Rating Method," commonly known as Appendix G, for both compliance and beyond-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 version, the prescriptive baseline remains fixed at 2004 levels and updates tighten percent improvements over this fixed baseline.[10] 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) Title24, and the codes and regulations of states and local jurisdictions.

Many building "asset rating" systems—which rate the building's physical assets while normalizing or controlling for occupancy and operations—also use BEM. Rating systems such as USGBC's LEED-NC Energy and Atmosphere credit 1, Green Globes, RESNET's Home Energy Rating System (HERS), and IECC's Energy Rating Index (ERI)[11] use the two-simulation self-comparison method. Rating systems such as ASHRAE building Energy Quotient (bEQ), DOE's Home Energy Score[12] and Commercial Energy Asset Score[13] use a single-simulation approach, comparing the building's calculated EUI to a scale. Operational building ratings have to date been statistically or empirically determined,[14] however, they are also a potential driver for increased BEM use (as described in Section Topic 3: Core Modeling Capabilities).

Outcome-based codes. Counter-intuitively, one development that could drive the use of BEM for both design and operation is a shift to outcome-based codes based on measured performance. Outcome-based rating systems, such as the EPA's ENERGY STAR Portfolio Manager,[15] are common but voluntary and generally based on population statistics. Outcome-based codes would be mandatory and based on technically derived EUI targets. Current codes 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 would inherently include accountability of building owners, operators, and tenants for overall building performance.[16] With existing asset-based codes, the use of BEM is focused on comparative performance with standard operating assumptions, often post-design if the code is not stringent. With outcome-based codes, BEM use would shift toward design and emphasize predictive, rather than comparative, modeling

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[10] ASHRAE 90.1-2016 Addendum BM unifies the performance paths by allowing Appendix G to be used for code compliance.

[11] https://www.energycodes.gov/resource-center/training-courses/2015-iecc-%E2%80%93-energy-rating-index-eri-compliance-alternative

[12] https://betterbuildingssolutioncenter.energy.gov/home-energy-score/

[13] https://buildingenergyscore.energy.gov/

[14] Implementation Report June 2009 Draft, Building Energy Quotient, Promoting the Value of Energy Efficiency in the Real Estate Market, ASHRAE Building Energy Labeling Program, Paris-ASHRAE_briefing.pdf

[15] https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager

[16] Getting to Outcome-Based Building Performance, Report from a Seattle Summit on Performance Outcomes, Event Report May 2015, New Buildings Institute, http://newbuildings.org/performance-outcomes-event-report, http://newbuildings.org/sites/default/files/Performance_Outcomes_Summit_Report_5-15.pdf

with intended occupancy and operational parameters. BEM could also be used during periodic compliance checks, to help attribute energy use to the building, to its maintenance and central operation, i.e., the owner and operator, or to tenants. BEM could be needed even if tenant-level end-use sub-metering is available since sub-metering 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.

II BTO's BEM Program

As stated in the Multi-Year Program Plan (MYPP), BTO's overall goal is widespread use of BEM (50% of gross square feet of new buildings and deep energy retrofits).[17] Although not explicitly stated in that goal, BTO also seeks to expand BEM use into applications, such retro commissioning, benchmarking and analytics, and building-related financial transactions.

II.1 Role of government and software development philosophy.

The flagship BTO's current strategy for achieving its BEM goals is the development, maintenance, and support of an open-source, state-of-the-art BEM platform, which consists of the EnergyPlus BEM engine and the OpenStudio BEM software development kit (SDK) and—until April 2020—graphical Application. BTO relies on third-party vendors to incorporate these products into use case-specific tools, and to train and support the respective communities.

BTO's status as a direct player in the BEM marketplace is unusual. It is enabled by the economies of scale of software and motivated by some BEM use-cases where transparency and impartiality are important. As briefly outlined above, 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 third-party vendors away from engine development and towards application integration, simulation services, and user support. Although reduced diversity in the BEM engine space is a negative result, corresponding benefits include greater consistency and greater investment in deployment resulting in overall growth in the BEM market. 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—much less to do so while keeping the tool open-source.

Whereas BTO is a direct player in the BEM market, it cannot be a conventional one. Its goal is not to compete with other players but to enable and support them. To articulate and cement this position, BTO created an unofficial "constitution" for its BEM program:

- **Focus on core capabilities and vendor relationships rather than end-user applications or relationships.** BTO's BEM sub-program should leave end users and end-use applications and services to market actors. This position creates space and incentives for market actors and acknowledges scalability challenges that BTO faces. BTO resources are limited and are better used to support a small number of application vendors than tens of thousands of users. BTO has historically not followed this stated position, most notably by developing and distributing the graphical OpenStudio Application. However, in August 2018, BTO and NREL announced that the OpenStudio Application will be transitioning away from BTO funding management by early 2020.[18]

- **Commercial-friendly open-source licensing.** BTO software can be embedded into other software in part or in whole, modified in proprietary ways, and re-licensed with no "downstream" obligations or implications, supporting a variety of business models.

- **State-of-the-art capabilities.** BTO software pulls the market forward by introducing advanced capabilities and support for new applications. BTO is not interested in replicating existing capabilities.

- **Commercial-grade development and support.** Although commercial vendors do not pay for the right to use EnergyPlus and the OpenStudio SDK and do not receive formal quality and service guarantees, they expect commercial-grade robustness and support. BTO uses state-of-the-art development and

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[17] BTO 2015 Multi-Year Program Plan: http://energy.gov/eere/buildings/downloads/draft-multi-year-program-plan

[18] https://www.openstudio.net/new-future-for-openstudio-application

testing methods and tools to provide the reliability that is 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.

II.2 Project Portfolio

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

Background. 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 California Energy Commission (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 became 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 1990's, 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 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 that included 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 LBNL and the rights 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 major version updates every six months.[19]

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 their products. Enabled by this license, in 2013 Autodesk Corporation led work to translate EnergyPlus source-code from FORTRAN to the more modern 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, EnergyPlus 8.7 was announced as a minimum viable product for residential modeling.

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 interact with end-users or one another. In between is "middleware" that provides abstractions and services on top of the raw 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. Microsoft Windows is an example of a successful middleware in three-tier architecture. Windows allowed application developers to read and write files, and to respond to high-level user messages, insulating

[19] Early history based on Lawrence Berkeley National Laboratory 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)

them from the particulars of disk management and mouse clicks. In doing so, Windows ushered in a wave of new end-user applications and fostered competition among engine (i.e., hardware) manufacturers.

For many years, the BEM industry evolved without a middle layer. Vendors developed applications that were tightly coupled to existing individual engines (e.g., eQuest for DOE-2.2) or developed engines and applications units (e.g., Trane TRACE). The "stove-pipe" development likely contributed to the slow rate of evolution of BEM in comparison to other software technologies. More significantly, the tight coupling of some engines and applications precluded the embedding and direct use of those engines in other applications, e.g., the TRACE engine could not be pulled out of the TRACE application and embedded into an auditing tool.

Historically, BTO followed the non-integrated approach. It focused on the engine—first DOE-2 and now EnergyPlus—and encouraged development of multiple third-party applications. This strategy was slow to materialize because of a combination of low demand for EnergyPlus' advanced modeling capabilities, the high cost of EnergyPlus application development, and BTO's own lack of traditional financial stake in EnergyPlus adoption.

Although DOE still does not have a private-sector-like financial stake in EnergyPlus, other factors limiting adoption have changed. First, as energy codes have become more stringent and as green certificates like LEED have gained adoption, demand for advanced modeling features has grown. Second, BTO began investing in OpenStudio. OpenStudio was originally developed by the National Renewable Energy Laboratory (NREL) as an EnergyPlus geometry plug-in for the SketchUp 3D drawing program. Beginning in 2009, NREL re-architected OpenStudio into an open-source software development kit (SDK) aimed at reducing the effort and improving the value proposition of BEM application development. The SketchUp plug-in and a companion graphical application for editing non-geometry BEM information and viewing simulation results were made into SDK client applications.

EnergyPlus uses files for input and output. Files are static, meaning that application vendors must maintain a shadow internal data model as a user incrementally adds and modifies information. At its base, OpenStudio wraps EnergyPlus inputs and outputs with a dynamic, object oriented data model that allows application vendors to incrementally access EnergyPlus inputs and outputs by calling functions—this is often referred to as an Application Programming Interface (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. 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 common core features like simulation management, model import from schema such as Green Building XML (gbXML)[20] and Industry Foundation Classes (IFC), and export to other calculation engines, including the BEM engines ESP-r and CEN/ISO 13790.

OpenStudio creates the three-layer architecture seen in other computer systems and 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 existing projects onto OpenStudio and encouraging third-party vendors who were developing EnergyPlus applications and services to develop those using OpenStudio instead. Figure II-1 conceptually shows BTO's three-layer BEM architecture and ecosystem of applications, both BTO and otherwise.

[20] https://gbxml.org/

Table II-1 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.

Applications & Services
- Use-case and user-base specific
- Graphical or text based
- Free or for-a-fee
- Open-source or proprietary

Middleware
- Object-oriented model of inputs and outputs
- Application programming interface
- Common helper functions
- Scripting and workflow automation
- Use-case agnostic
- Non-graphical
- Free
- Open-source

Engines
- Physics calculations
- Use-case agnostic
- Non-graphical
- Free
- Open-source

Figure II-1 BTO BEM software architecture and ecosystem.

Table II-1 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/
BuildLAB	APIDAE	Simulation service that supports parametric analysis and optimization, https://apidaelabs.com/
CADSoftSolutions	gEnergy	Web-based interface that provides cloud execution, http://www.cadsoftsolutions.co.uk/software/sketchup-pro/gtools/

DesignBuilder	DesignBuilder	Full-featured Windows interface, also supports lighting and CFD 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 model-predictive control service for large commercial buildings. http://qcoefficient.com/.
Solemma, LLC	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/)
Sefaira	Sefaira Systems	Web-based HVAC selection & 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/
Trane	TRACE 3D Plus	EnergyPlus based version of Trane's TRACE 700 Windows interface, 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	
BayREN	BRICR	Remote energy auditing software initially 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 Title24 non-residential code, http://bees.archenergy.com/software.html
CEC	CBES	For benchmarking and retrofit analysis of small and medium office and retail buildings in California and in 2030 Districts: http://cbes.lbl.gov
Concept3D	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

OpenStudio Measures. One of the unique and most powerful features of the OpenStudio platform is a scripting facility called OpenStudio Measures. This facility, which is analogous to Microsoft Excel Visual Basic macros, allows users to write scripts (short programs) in languages like Ruby, Python, and JavaScript, which OpenStudio then 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 the automation of transformations that correspond to Energy Efficiency Measures (EEMs)—this is also the source of the name Measures. Figure II-2 shows several examples of 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., 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)
```

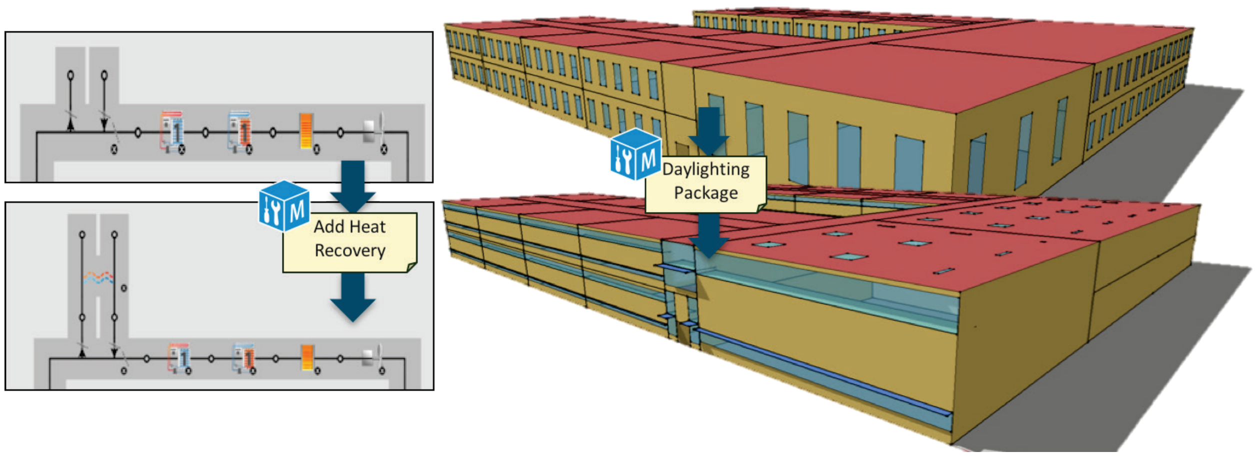

Figure II-2 Examples of OpenStudio measures

Measures form a significant part of the OpenStudio value proposition. Operationally, Measures provide flexible and portable process automation, allowing mechanistic tasks to be executed more consistently and far more 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 probably not—can at least understand what a given Measure does even if they would not be able to write the Measure themselves. Understanding a Measure by inspecting its code is usually much easier—and always much more complete—than doing so by differencing "before-and-after" models. The code snippet in Figure II.2 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 having access to model inputs and simulation outputs via the OpenStudio SDK, Measures have access to local machine and network resources, including the command line and application programming interfaces 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 energy analysis to other analyses.

More recently, other scripting frameworks that work directly with EnergyPlus have been developed, including Eppy[21] and Modelkit.[22] These provide some of the capabilities of Measures along with several ancillary advantages, notably lighter weight.

OpenStudio Standards Gem. One of the most potentially impactful OpenStudio Measures is "Create Performance Rating Method Baseline Building" which automates the creation of a "code baseline" building model from a model of the nominal—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. 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 II-3 shows "before-and-after" snapshots of this Measure. One visible change is the removal of external shading devices.

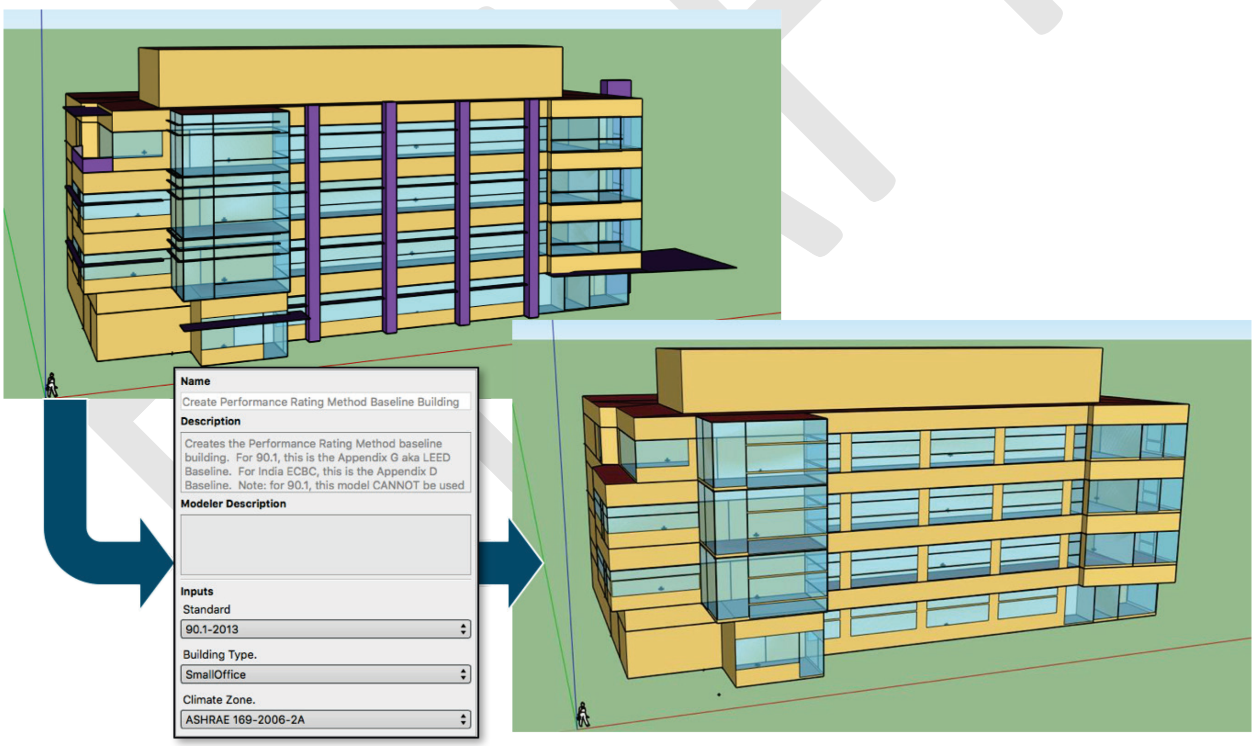

Figure II-3 The "create performance rating method baseline building" measure.

Create PRM Baseline Building is part of the OpenStudio-Standards "gem".[23] 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

[21] https://pythonhosted.org/eppy/
[22] https://bigladdersoftware.com/projects/modelkit/
[23] https://rubygems.org/gems/openstudio-standards

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 (NECB)[24] and Energy Conservation Building Code (ECBC),[25] 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,[26] standard models that are used as the basis for many large-scale analyses including the analyses that inform code updates, design guides, and EE programs.

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, for optimizing building design or for calibrating model inputs using measured data. OpenStudio Measures are 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.

Importantly, OpenStudio Server is not a service to which users can directly submit simulation requests, i.e., there is no http://openstudio.io/. 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 and Autodesk.

OpenStudio 2.0. Over the past few years, BTO has re-architected OpenStudio to make the OpenStudio SDK and Measure evaluation capability more consistent and easier 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. 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. "Single-model" OpenStudio applications are encouraged to use the CLI while OpenStudio Server was itself re-architected to use a single Meta-CLI "master" and multiple CLI "workers."

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 tools. 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. 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 been quite successful and have garnered a significant user community. Recent OpenStudio version updates

[24] http://www.nrcan.gc.ca/energy/efficiency/buildings/eenb/codes/4037
[25] https://beeindia.gov.in/sites/default/files/ECBC%202016_Draft_V8.pdf
[26] https://www.energycodes.gov/development/commercial/prototype_models

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 goals in advancing the real world use of EnergyPlus. However, with the advent of several new private sector interfaces for EnergyPlus, including some leveraging the OpenStudio SDK, BTO has committed to transitioning OpenStudio Application funding and management to one or more third parties by April 2020.[27]

Schema-driven web widgets. OpenStudio 2.0 also introduced a shift in interface component development. Previously, such components are implemented using "desktop" window toolkits like Qt and interacted directly with the OpenStudio API. Beginning with OpenStudio 2.0, interface components were developed using web technologies such as JavaScript and interacted with schematized files. This shift facilitates both cross-platform support and application integration. It also allows interface components to be used standalone, broadening their utility and applicability.

BTO has developed two interface widgets using this architecture. The first is the redesigned Parametric Analysis Tool (PAT) 2.0, which works with the OpenStudio 2.0 workflow architecture. The second is FloorspaceJS,[28] a 2D floor-plan editor that is embedded into the OpenStudio Application, for now as a complement for the SketchUp plug-in and eventually as a replacement for it. For now, these widgets are remaining under BTO control. They may be transitioned to third-party control at a later time.

Spawn-of-EnergyPlus. BTO is currently undertaking a multi-year effort to create an EnergyPlus "clone" that is based on open standard simulation technologies: the Functional Mockup Interface (FMI)[29] for co-simulation and the Modelica equation-based modeling language.[30] Currently named Spawn-of-EnergyPlus (Spawn), this project is supported by IEA Annex 60 "New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards"[31] and IBPSA-World.[32]

FMI provides a way of specifying component models as modules with well-defined interfaces that supports the construction of dynamic "plug-and-play" simulation tools. A modular architecture simplifies the integration of externally developed component models and should allow manufacturers to develop their own models and incorporate them into Spawn. Technology models developed this way can be distributed either open-source or as an executable that includes embedded performance data. Allowing technology models to be shared in a proprietary way could help remove barriers for some manufacturers to make equipment models and performance data available. BTO expects that this capability will shorten the time required to develop and integrate simulation models for new component technologies. Ideally, manufacturers would release new models as they release new technologies, reducing both model lag and BTO resource requirements.

With Modelica, component behavior is described *explicitly* as the component's governing equations, rather than *implicitly* by implementing a solver for those equations as is done in today's BEM engines. The use of Modelica reduces domain specific implementation and maintenance effort by allowing BEM engine developers to focus on physics descriptions (which is their primary area of expertise) rather than numerical solution techniques (which typically is not). Modelica components leverage high-performance numerical solvers that are both domain agnostic and developed by numerical solution experts.

Modelica models are also multi-purpose. Whereas conventional implicit component models with embedded solvers can only be simulated, explicit Modelica models can also be verified, optimized, and—in the case of

[27] https://www.openstudio.net/new-future-for-openstudio-application
[28] https://github.com/NREL/floorspace.js/
[29] https://www.fmi-standard.org/
[30] https://www.modelica.org/
[31] http://www.iea-annex60.org/
[32] https://ibpsa.github.io/project1/

control models—compiled and executed in physical controllers. Modelica is one of the languages used to implement real-world control algorithms. Spawn is intended to create a simulation-controls nexus that supports not only BEM applications like annual energy simulation but also applications in control design and implementation. FMI allows components to be implemented in any language, allowing Spawn to support existing C- and Python- based control design and implementation workflows.

Spawn is also intended to support dynamic, "real-time" BEM applications such as HVAC system monitoring, fault detection and diagnostics, and model-predictive control (MPC)—many stakeholders suggest that building operation could benefit from a predictive, optimization-based approach that incorporates both information about current building, weather, and grid conditions as well as predictions for upcoming conditions. Spawn's modular simulation structure would provide additional benefits for dynamic applications. Some stakeholders maintain that these applications do not require full BEM and that simpler, building-specific reduced-order models or black-box models driven by measured data are sufficient. Others believe that a hybrid approach that combines a detailed model of the systems under control with a reduced-order or black-box model of the building and its loads would work best. Researchers and companies are evaluating these approaches, their strengths and weaknesses, and their target markets. A modular structure facilitates these combinations.

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 co-existing for a while, with development resources shifting from EnergyPlus and towards Spawn gradually over time. EnergyPlus and Spawn also share a significant amount of code, as Spawn re-implements only the HVAC and control modules and reuses the envelope, loads, lighting and shading, and airflow modules from EnergyPlus. 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 EnergyPlus stakeholder value and trust.

URBANopt. EnergyPlus and the OpenStudio API target individual building analysis. OpenStudio Server targets large-scale analysis, but one in which each 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) extends EnergyPlus and OpenStudio with capabilities for district- and campus-scale thermal and electrical analysis. As with OpenStudio, URBANopt will be distributed as an open-source SDK rather than an end-user application or service. BTO will rely on third-party entities to develop and deploy these "last mile" capabilities.

Most simulation tools, including the current version of URBANopt, do not "co-simulate" buildings and shared thermal systems. Instead, they first simulate the buildings individually, collect thermal load profiles and then post-process those in a separate module. This approach is simple and scalable but also fails to capture important system dynamics. URBANopt will leverage Spawn, FMI, and existing Modelica models of advanced shared-thermal systems—e.g., "fifth-generation" low=temperature systems, systems with waste-heat recovery, and systems with bidirectional flow—to model district thermal systems and their operation in a more physically realistic way.

In addition to shared thermal systems, URBANopt will leverage co-simulation to support evaluation of distributed energy resources (DER), microgrids, and electrical distribution systems, supporting BTO's new emphasis on grid responsiveness and interaction.

Other BEM Applications. In addition to the OpenStudio Application, BTO and other DOE offices have funded other BEM-based applications and services. Most of these are significantly narrower and more focused than the OpenStudio Application and several are attached to ongoing strategic efforts.

Table II-2 provides a listing.

Table II-2 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	Façade 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 –
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 multi-building 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 –

I.1 Metrics, Datasets, Benchmarks, and Targets

BTO's overarching goals are stated in terms of energy savings. For each of its technology sub-programs, 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 these targets and achieving these savings. This type of evaluation is more difficult for BEM and other enabling or system-level technologies like sensors and sub-meters than it is for direct component technologies like windows, heat-pumps, and lighting. BEM has additional challenges that are unique to enabling technologies including large unit labor costs, the lack of obvious performance metrics for software, and the difficulty of conducting controlled experiments. Nevertheless, metrics and goals are useful and necessary even in the absence of high-quality datasets 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 this dataset and measure BEM's market penetration and its effectiveness in achieving high design performance.

BEM performance attribution. Figure II-4 illustrates the conceptual EE contributions of BEM via applications like codes, code-compliance, "beyond code" prescriptive EE guidelines, integrated design, green certification, continuous commissioning, and model predictive control. The vertical 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.

For a new construction project, standard practice in the absence of a prevailing EE code would result in a certain energy use intensity (EUI) represented by the dashed line "average existing building." An EE code would result in somewhat lower EUI represented by the bottom of the yellow box. 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. This performance level is marked by the dashed line "code level building." 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. The dashed line "high-performance building" marks this performance level.

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 continuous commissioning (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.

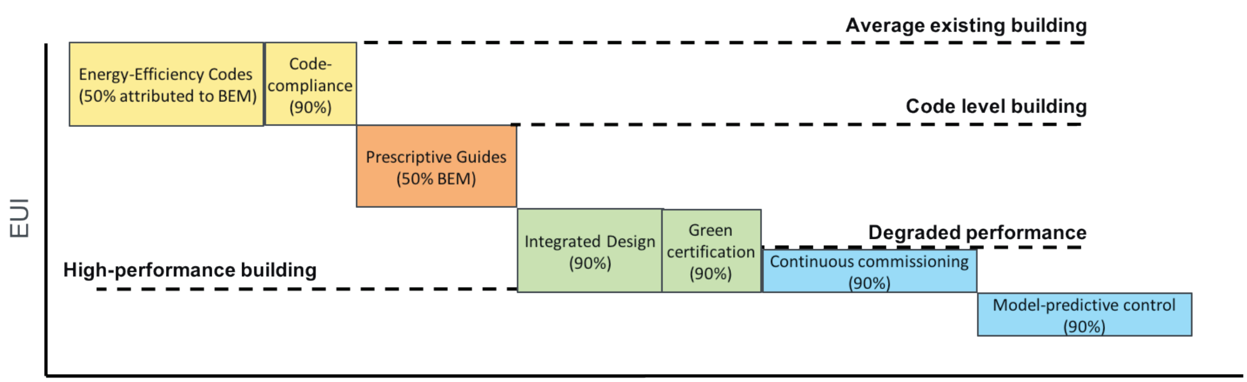

Figure II-4 Conceptual attribution of BEM to building performance

BEM use and effectiveness datasets. Data on the use and effectiveness of BEM is sparse. One available dataset is the AIA 2030 Commitment, which targets zero net-carbon buildings by 2030 and has been tracking US architecture firms' use of BEM in individual design projects since 2013.[33] Firms that sign on to the

[33] The AIA 2030 Commitment includes U.S. based architecture firms, although individual building projects may be abroad.

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.[34] DOE uses the DDx to benchmark and track growth in the use of BEM for integrated design, and specifically the use of EnergyPlus. The DDx research functions allow users to query the database and retrieve aggregate data including number of projects, total floor area, floor-area weighted average design EUI and floor-area weighted EUI reduction over (2003 CBECS) baseline. Table II-3 and Figure II-5 show a number of projects and gross square footage (GSF) data for the years 2013–2016.[35] Each metric is broken down by total projects, modeled projects, and projects modeled using EnergyPlus for commercial new construction and major retrofits, projects that make up the bulk of the Commitment data set. Note, although firms have to report on whether a project was modeled or not, they do not have to report on which tool was used to model—in a given year, 30–60% of the projects leave this field blank.

Table II-3 AIA 2030 Commitment Data for U.S. Commercial Building New Construction

	2013	2014	2015	2016	2017
Projects	1150	2629	4630	6020	7921
Projects modeled	740	1388	2804	2983	3707
Percentage of projects modeled (of total)	**64%**	**53%**	**61%**	**49%**	**47%**
Projects EnergyPlus	44	66	122	165	383
Percentage of Projects EnergyPlus (of modeled)	**6%**	**5%**	**4%**	**6%**	**10%**
GSF (M ft^2)	319	613	1,310	1660	1880
GSF modeled (M ft^2)	222	397	906	775	888
Percentage of GSF modeled (of total)	**70%**	**65%**	**69%**	**47%**	**47%**
GSF EnergyPlus (M ft^2)	31	25	26	29	59
Percentage of GSF EnergyPlus (of modeled)	**14%**	**6%**	**3%**	**4%**	**7%**
Percentage of Modeled EUI reduction over code	**13%**	**17%**	**12%**	**19%**	**13%**
Percentage of EnergyPlus EUI reduction over code	**21%**	**20%**	**25%**	**17%**	**21%**

Although not monotonic, the percentage of modeled projects and square footage has decreased 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 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[36] and one mentioned by multiple stakeholders.

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[34] https://www.energy.gov/eere/buildings/downloads/aia-2030-commitment-design-data-exchange-ddx

[35] 2017 reporting period ends March 31, 2018.

[36] "…models solely as compliance and verification tools (~80% of their current use) to performance and design decision-making tools (~20% of their current use).", *Getting to Outcome-Based Building Performance*, Report from a Seattle Summit on Performance Outcomes, Event Report May 2015, New Buildings Institute, Page 1. http://newbuildings.org/performance-outcomes-event-report

Within the AIA 2030 program, EnergyPlus is the fourth most used engine, it is typically used via interfaces DesignBuilder, OpenStudio, Sefaira, and Other (which likely implies IDF-Editor) . Engines used more frequently than EnergyPlus are Trane's Trane Air Conditioning Economics (TRACE) 700, J.J. Hirsch and Associates' DOE-2.2 (typically with eQuest interface), and Apache (Integrated Environmental Solutions' (IES) Virtual Environment software). Engines used less frequently than EnergyPlus include DOE-2.1E (EnergySoft's EnergyPro) and Carrier's Hourly Analysis Program (HAP).

The AIA 2030 Commitment covers residential projects but the dataset does not include many such projects. A helpful residential dataset comes from the Residential Energy Services Network (RESNET), which tracks use of the Home Energy Rating System (HERS) Index in new home construction. Whereas in commercial new construction certification and rating systems like LEED have only an indirect influence on design, large scale homebuilders actively use the HERS rating and its associated tools—primarily NORESCO's REM/Rate—to create energy-efficient home designs, which can then be replicated.

Table II-4 RESNET Data for U.S. Residential New Construction

	2014	2015	2016	2017	2018
Projects [37]	860,000	950,000	935,000	1,003,031	–
Projects modeled	146,000	190,000	206,000	227,800	236,116
Percentage of Projects Modeled [38]	17%	20%	22%	23%	–
Average HERS Index	63	62	61	62	61

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

Other potential data sources include:

- Utility BEM-based programs such as energy design assistance and number of projects, floor space, and energy savings reported by such programs.
- State and local building codes with BEM-based compliance paths and number of building projects, floor space, and performance levels exercising these paths.

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[39] to convert these to potential energy savings. 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 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;

[37] Census data for 2018 will be posted June 2019.
[38] Ibid.
[39] https://energy.gov/eere/buildings/scout

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 II-5 shows Scout assumptions for new and retrofitted commercial and residential floor area for the period 2017–2030 and corresponding 2030 projected energy savings under several sets of assumptions. The first set of assumptions is "business as usual" and reflects 20% savings for integrated design in new construction, 10% savings for integrated design in retrofits, and an adoption rate of 20%, reflecting estimates of current use. This scenario yields almost 0.5 quads of savings in 2030. The second scenario "max adoption" retains the effectiveness of BEM but increases adoption to 100%. This scenario leads to savings of 2.4 quads. The third scenario "max effectiveness" retains current adoption levels but increases the effectiveness of BEM to 50% savings for new construction and 25% for retrofits. The final scenario "max" maximizes both BEM effectiveness and adoption and yields savings of over 6 quads. This scenario resembles the one described in *Reinventing Fire*, in which RMI estimates that integrated design can account for between 8 and 16 quads of energy savings by 2050.[40] The RMI estimate was generated using a set of high-performance new construction and retrofit projects that achieved deep—greater than 50%—energy savings.

Table II-5 Energy Savings Estimates for Integrated Design in U.S. by 2030

Application	Floor space (Million ft²)	Potential savings (TBtu/yr)			
		Business as usual 20% savings 20% adoption	Max adoption 20% savings 100% adoption	Max effectiveness 50% savings 20% adoption	Max 50% savings 100% adoption
Commercial new construction	29,072	95	477	239	1193
Commercial retrofit	12,628	103	514	257	1285
Residential new construction	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 II.4 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 are the differences 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" energy efficiency improvements. This is most easily seen the 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.

[40] Amory Lovins and Rocky Mountain Institute, *Reinventing Fire*, p. 86.

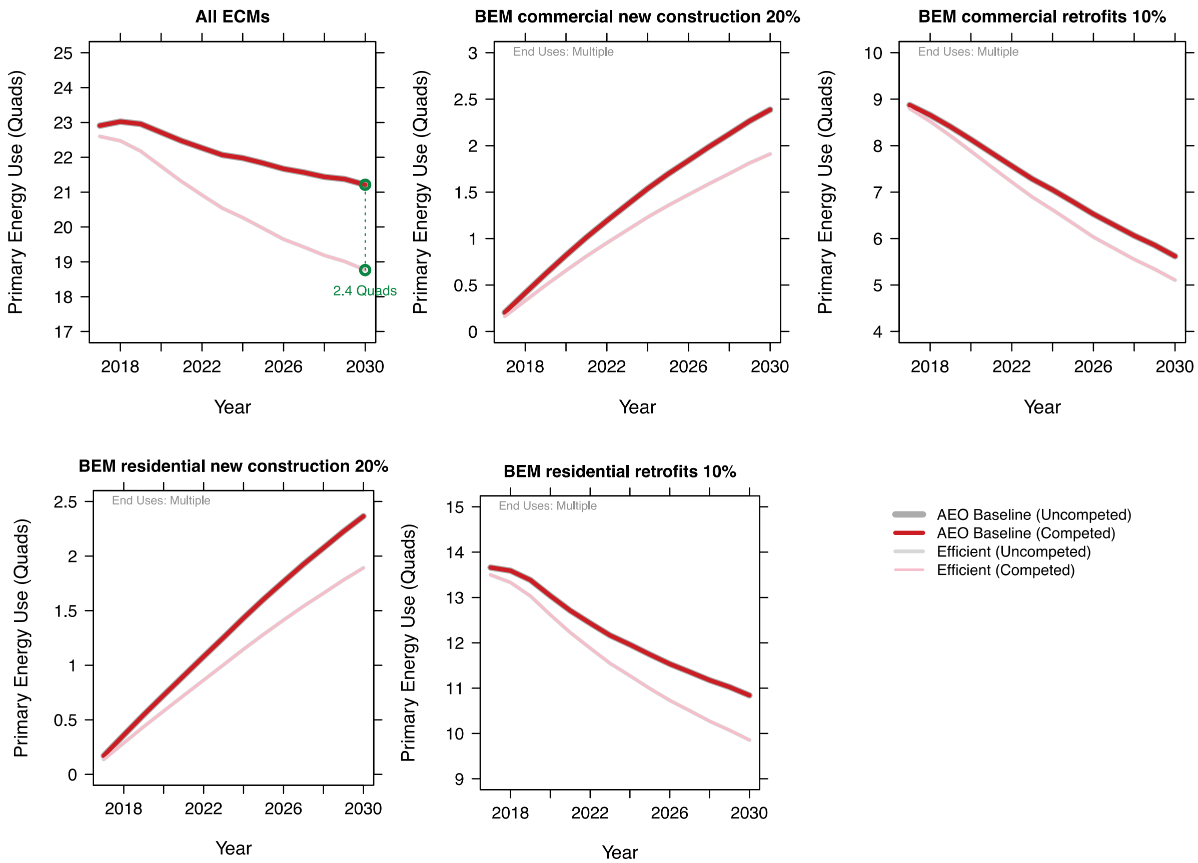


Figure II-5 Scout estimates of potential energy savings due to integrated design and BEM

Direct metrics, benchmarks and targets for BEM use and effectiveness. BTO's goals framework establishes benchmarks and targets for integrated design. This use case contributes most directly to energy efficiency and is the one that DOE is most eager to promote. BTO 2020 goals reference the AIA 2030 Commitment data set. They are:

- **70% commercial new construction floor area modeled.** The 2017 value is 47%.
- **5% of commercial new construction floor area modeled with EnergyPlus.** The 2016 value is 9%.
- **20% reduction in design EUI over prescriptive design for project using EnergyPlus.** The 2017 value is 21%.[41]

BTO currently has no targets corresponding to use of BEM in homes. BTO also does not have metrics, benchmarks, and targets corresponding to operational BEM use cases, which are not yet established enough to generate a visible market signal and which do not have a reporting program analogous to AIA's.

It is worth noting and discussing the fact that the AIA numbers seem to be trending in the wrong direction. Between 2015 and 2016, the percentage of projects modeled, the fraction of projects modeled using EnergyPlus, and the effectiveness of modeling have all decreased! These trends are due to two separate sets of effects. The trends in use of modeling and use of EnergyPlus are related to the fact that the AIA 2030

[41] BTO 2015 Multi-Year Program Plan http://energy.gov/eere/buildings/downloads/draft-multi-year-program-plan

Commitment is growing in number of reporting firms, and total number and square footage of projects reported. In 2015, 152 firms reported on 4,060 projects totaling 1.2 billion square feet. In 2016, 342 firms reported on 5,161 projects totaling 1.5 billion square feet. Firms that reported in 2016 for the first time tended to be both smaller and less focused on building performance than firms who also reported the previous year—these firms model less frequently and sometimes less effectively. The same trend was observed between 2014 and 2015 and, to a lesser degree, between 2013 and 2014. Intuitively, early signatories to the AIA 2030 Commitment were not randomly sampled; firms that valued performance and aspired to achieve 2030 goals "self-selected" into the program. As a result, early 2030 Commitment benchmarks were inflated. As the Commitment has grown, it has become more representative of new and retrofit building stock and benchmarks have become more realistic. It stands to reason that as the Commitment continues to expand, the reported modeling rate may approach the unofficial "industry consensus" rate of 20%.

The decrease in effectiveness of modeling is also 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.

Other potential direct metrics that can be benchmarked and targeted include:

- EDAPT square footage
- EDAPT square footage using EnergyPlus
- EDAPT % predicted EUI reductions for square footage modeled using EnergyPlus
- RESNET % new homes with HERS/ERI score
- RESNET average HERS/ERI score

Future use of these metrics would require analysis for benchmarking purposes, target development potentially using a stakeholder process, and a data sharing agreement between BTO and the relevant organization.

Proxy metrics, benchmarks, and goals. In addition to building level energy savings targets, BTO also has a proxy goal for a metric that does not directly correlate with energy savings but serves as an indicator of the success of BTO's program:

- **12 non-DOE commercially available tools that embed EnergyPlus, with or without OpenStudio.** As of 2017, this number is nine — Autodesk Insight, Bentley's AECOSim, DesignBuilder, Digital Alchemy's Simergy, NORESCO's CBECC-Com, Sefaira Architecture and Systems, Simuwatt , Tian Engineering's BIMHVACTool, and Trane's TRACE 3D Plus, Simuwatt's Buildee, Tian Engineering's BIMHVACTool, and Trane's TRACE 3D Plus, Honeybee from Ladybug Tools, CYPE's CYPETHERM, and BuildSimHub. A dynamic listing of applications and services using EnergyPlus can be found at the IBPSA Building Energy Software Tools Directory.[42]

Other potential proxy metrics include:

- Number of IBPSA members.

[42] https://www.buildingenergysoftwaretools.com/?capabilities=Whole+Building+Energy+Simulation&keys=EnergyPlus

- Number of ASHRAE Building Energy Modeling Professional (BEMP) and AEE Building Energy Simulation Analyst (BESA) certified professionals.
- Number of universities offering BEM courses or degrees.
- Number of BEM training organizations and course offerings.
- Number of registered EnergyPlus users.
- Number of EnergyPlus downloads.
- Number of EnergyPlus training organizations and course offerings.

Incorporating these metrics and targets based on them into the MYPP would require some analysis to determine meaningfulness, additional analysis to develop benchmarks and targets, and perhaps data sharing agreements between BTO and relevant parties. These issues can be illustrated using EnergyPlus downloads as a mule. Figure II-6 shows downloads from the main EnergyPlus site (currently http://energyplus.net/) by EnergyPlus version update stretching back to version 4.0 in 2009. Although these numbers show that EnergyPlus downloads have grown, then do not tell the whole story. For one thing, they do not include downloads of EnergyPlus embedded in other downloaded software packages such as DesignBuilder, Simergy, or TRACE 3D Plus. For another, they do not include uses of EnergyPlus in web services such as Sefaira or Autodesk Insight in which EnergyPlus runs on the cloud and is not downloaded at all.

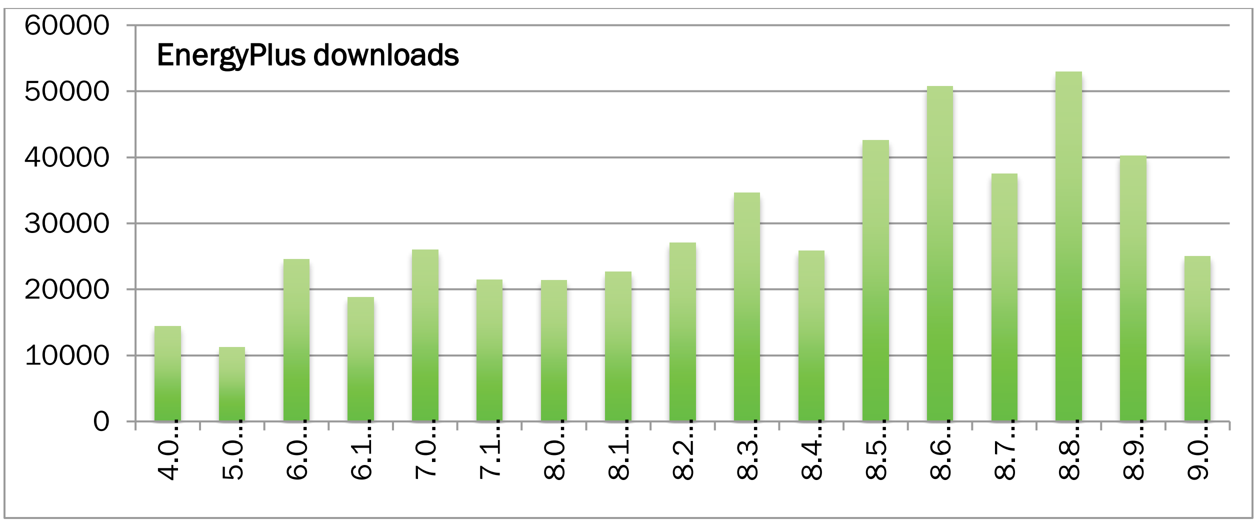


Figure II-6 EnergyPlus downloads by version update.

III Topic 1: Awareness of and Confidence in the BEM Value Proposition

The next six sections detail barriers to widespread and effective use of BEM and propose BTO initiatives designed to address them. This section deals with the overall message of BEM and its place in the enterprise of building energy efficiency. Subsequent sections deal with technical issues such as accuracy (Section 4), core software capabilities (Section 5), workflow integration (Section 6), data (Section 7), and the BEM professional support system (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:

- Clients invest in BEM when its application is mandatory (e.g., code-compliance) or provides 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 situations 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.
- BTO should compile, document, and promote compelling evidence that use of BEM leads to persistent energy savings.

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 and https://2030ddx.aia.org/

III.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.

Building owners and project managers. Potential BEM clients like building owners and project managers are often unaware of the potential uses and benefits of BEM in building design, retrofit planning, 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, however, do little to improve building performance. To achieve deep energy savings, more intensive, iterative, and expensive BEM is needed. Building owners and project managers are less likely to make this additional, voluntary investment. Many question the benefit of BEM over cheaper approaches that rely on simpler engineering calculations, experience and judgment, or a combination. Others may understand the benefit but not be convinced that it is commensurate with the additional cost. Still others may be skeptical that predicted savings will be realized. These prejudices are amplified if the project manager has no financial stake in the building's energy performance.

Architects. Like building owners and projects managers, architects and engineers may also feel that predicted savings will not be realized, due to either construction and installation variances or to variances in occupancy and operation. If a project manager does 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 the architects' take of total design fees.

Architects may feel that their job is to create an attractive building that serves its intended function efficiently and that it is the mechanical engineer's role to design an HVAC system that can efficiently meet the building's loads.

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.

Mechanical engineers. Most energy modeling is performed by mechanical engineers. However, many engineers still design HVAC systems based on simple peak load calculations. Mechanical engineers 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 to use simpler, more conservative approaches that do not expose them to risk. Alternatively, they may feel that their judgement and experience is a good substitute for BEM.

Homebuilders. In the residential market, large-scale homebuilders that 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.

Accumulated benefits of BEM. Building owners, building 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 building operations via model predictive 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.

III.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"[43] 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. 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

[43] http://energy.gov/eere/buildings/articles/shockingly-short-payback-energy-modeling

loads to a degree that allowed substantial reductions and cost savings in HVAC. BTO is currently 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 is currently working with AIA to add DDx functionality to import measured energy use data from sources such as Portfolio Manager.

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 energy efficiency 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) 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 achieve 50% savings over code, how much of these savings can be attributed to BEM? Half of it? 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?

As a decision-support technology, BEM's contribution to EE is difficult to isolate using controlled experiments. Appendix C describes "net-to-gross" factor calculations used in EE programs, and the possibility of adapting these to BEM. If this approach is deemed sufficiently applicable, BTO should consider undertaking such a study.

Another 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 savings are documented, BTO must promote the BEM value proposition 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, especially of BTO-funded BEM tools.[44] 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.

Several organizations have created materials aimed at educating specific BEM stakeholder groups about various applications of BEM and their benefits.

- The Rocky Mountain Institute's (RMI) *BEM Guide for Owners and Managers*[45] is an introduction to BEM for would-be clients and includes guidelines for procuring BEM services, including model Request for Proposal (RFP) and contract language.
- The AIA has created the *Architect's Guide to Integrating Energy Modeling in the Design Process,*[46] which provides a process overview, guidelines for engaging and contracting modeling services, tools listings, information about detailed envelope and lighting models, and covers advanced topics such as calibrated modeling for existing buildings and post-occupancy measurement and verification. AIA is currently developing an updated version.

BTO should promote these resources through its own networks and approach other organizations such as the Building Owners and Managers Association (BOMA) about creating tailored BEM information and engagement guides for their stakeholders.

[44] http://energy.gov/eere/buildings/listings/end-use-breakdown-building-energy-modeling-blog
[45] https://www.rmi.org/wp-content/uploads/2017/05/Building-Energy-Modeling-for-Owners-and-Managers-2013.pdf
[46] https://www.aia.org/resources/8056-architects-guide-to-integrating-energy-modeli

Table III-1 BEM Value Proposition Barriers and Initiatives

Barriers	Initiatives	Priority
Robust empirical correlations. A. 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 in terms of occupant satisfaction and productivity, sale price, and rental income. Matching data that shows BEM cost is reasonable.	1. 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.	–
	2. 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.	–
	3. Explore partnerships with RESNET, BOMA, and other organizations to collect BEM use, impact, and cost data for other use cases.	–
Performance attribution. B. 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.	4. Leverage the DDx establish correlations between BEM and the presence of energy-efficient design elements and EEMs.	–
	5. Leverage the DDx to establish longitudinal correlations between BEM and project performance and cost.	–
	6. Expand the DDx with questions intended to tease out BEM contributions.	–
	7. Conduct a rigorous classical performance attribution for BEM in integrative design and perhaps other use cases.	–
Communications. C. Lack of awareness of BEM and its value proposition among different stakeholders, especially financial decision makers such as building owners and project managers.	8. Leverage AIA and Better Buildings partnerships to develop and publish case studies highlighting the value of BEM for various building types, climates, and design and operation strategies.	–
	9. 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.	–
	10. Promote stakeholder group 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.	–

IV Topic 2: Predictive Accuracy and its Significance

Summary:

- Due to the uncertainty, variability, and quantity of input parameters, BEM is designed to maximize utility via 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.

- BTO should leverage LBNL's and ORNL's user test facilities to conduct key experiments that can definitively quantify the inherent error associated with BEM engines. These results must be packaged for use by both engine developers and BEM professionals, but also for communication to BEM clients and other stakeholders.

- BTO should also 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:

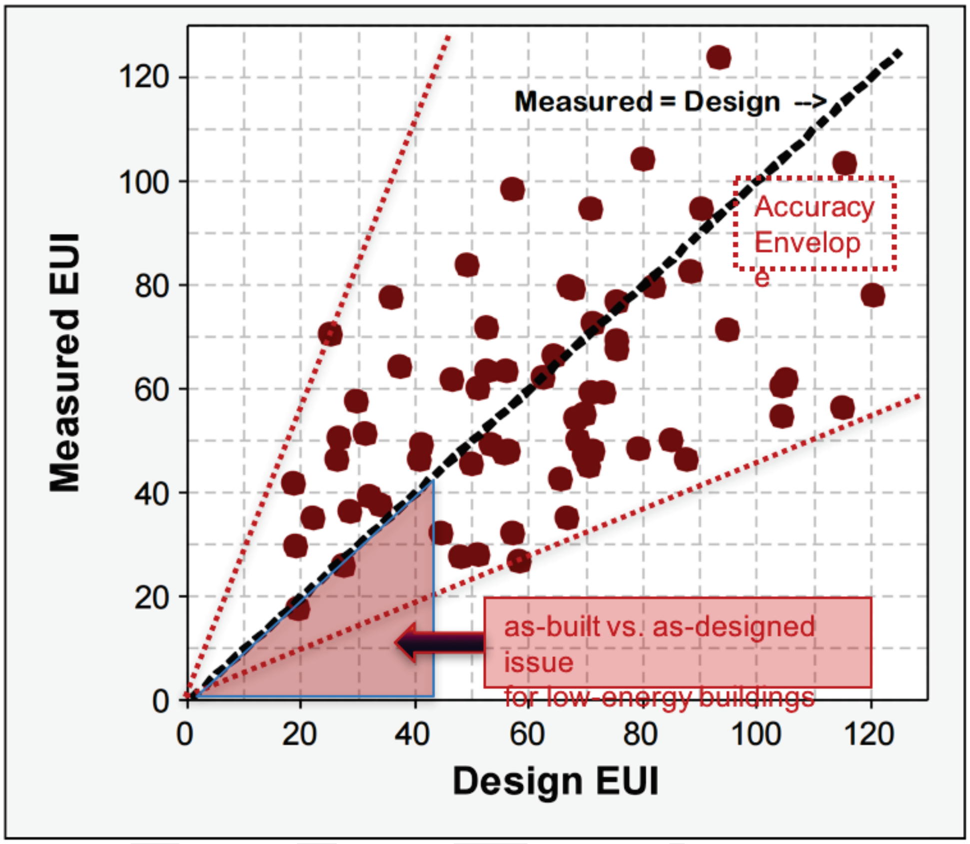
- **Empirical validation and uncertainty characterization of energy Simulation.** A four-year project that uses LBNL FLEXLAB and ORNL FRP test facilities to develop empirical datasets for validating key BEM algorithms. https://energy.gov/eere/buildings/downloads/lab-rfp-validation-and-uncertainty-characterization

- **ASHRAE Standard 140.** Standardized test for testing, diagnosing, and improving BEM software. https://www.energy.gov/eere/buildings/ashrae-standard-140-maintenance-and-development

IV.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 building energy simulation requires detailed information on all aspects of a building's physical assets and operational parameters. At the BEM engine level, the number of individual inputs required to characterize a small building is measured in thousands; for a large building, it can measured in hundreds of thousands. User interfaces do a good job of grouping these inputs and abstracting them to higher-level representation, reducing this number by as much as two orders of magnitude. To be sure, not all inputs contribute significantly to building energy performance and BEM predictive accuracy. However, even if only 10% of inputs 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 simply 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 NBI paper "Energy Performance of LEED New Construction Buildings." Figure IV-1 shows a well-traveled plot from that paper, which in turn shows that BEM can over- or under-estimate measured performance 50% or more, and that BEM tends to under-estimate normalized annual energy 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. That energy-efficient 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.



Source: Energy Performance of LEED® for New Construction Buildings, March 2008. Available: http://www.usgbc.org/Docs/Archive/General/Docs3930.pdf

Figure IV-1 Design (Simulated) Versus Measured EUI 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.

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 sub-metered 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.[47] BTO built two such facilities in the past several years, LBNL's Facility for Low-Energy eXperiments (FLEXLAB) and ORNL's Flexible Research Platform, 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 "Method of Test for Building Energy Computer Simulation Programs."[48,49] 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 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 a large number of errors in BEM engines. However, the lack of empirical results in the standard feeds the perception that BEM engines are not validated against ground truth.

Model input calibration. Modeling of existing buildings—for retrofit analysis, commissioning or dynamic control—can be made more accurate and predictive by using measured consumption data to calibrate uncertain inputs. Manual calibration strategies are well known and several automated calibration tools are available. 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 purpose. Guidelines such as NREL's BESTEST-EX[50] and the ANSI/RESNET calibration standard method of test[51] use known configurations to establish tests for calibration methods that evaluate both output fidelity, input fidelity, and accuracy in savings estimations. Further work is needed to develop more robust calibration procedures and to establish their use in standard practice.

Documents such as ASHRAE Guideline 14 "Measurement of Energy and Demand Savings" and BPI 2400 "Standard Practice for Standardized Qualification of Whole-House Energy Savings Predictions by Calibration to Energy Use History"[52] set output accuracy thresholds for calibrated models. These standards are geared towards manual calibration, whereas current automatic calibration techniques can easily meet these standards. Further accuracy guidelines and targets are needed for automated calibration procedures.

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 applications 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 should be noted that although comparative modeling reduces the

47 IEA ECBCS Annex 58, "Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements," http://www.ecbcs.org/annexes/annex58.htm

48 http://sspc140.ashraepcs.org/

49 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, J. Neymark, J. Neymark & Associates, Golden, Colorado, R. Judkoff, National Renewable Energy Laboratory, Golden, Colorado, http://www.nrel.gov/docs/fy02osti/30152.pdf

50 http://www.nrel.gov/buildings/bestest-ex.html

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

52 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

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.

IV.2 Initiatives

Modern BEM engines such as EnergyPlus include rigorous and well-vetted modeling algorithms. Empirical validation is therefore unlikely to identify internal deficiencies whose mitigation will significantly improve BEM 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 is inherently 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 definitive bounds for external errors associated with various types of inputs and lead to methods for acquiring better values for those inputs and/or to accounting for uncertainty in these inputs in simulation.

Empirical validation and testing. BTO has invested in purpose-built laboratories and test facilities such as LBNL's FLEXLAB and ORNL's FRP that are sufficiently characterized, controlled, and instrumented to support "validation-grade" experiments. BTO has funded one four-year project that uses these facilities to generate validation data sets for ASHRAE standard 140. Depending on the success of the project, BTO should strongly consider funding follow-on projects that emphasize different building physics phenomena and other HVAC systems. Similar facilities exist or are being built around the country (e.g., NIST Zero Energy Residential Test Facility[53]) and the world (e.g., FLEXLAB Singapore[54]). BTO should leverage those facilities to expand the range of available validation-grade data sets to different construction types, system types, and climate zones.

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

Source: LBNL, ORNL.

Figure IV-2 LBNL FLEXLAB and ORNL FRP commercial building user test facilities.7

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 and integrated into larger test suites that combine empirical, analytical, and comparative diagnostic tests. In parallel with empirical validation, BTO should continue to expand the 140 analytical verification and comparative testing framework as a way of both expanding test coverage and discovering areas of disagreement among engines and defining future empirical tests. BTO should encourage BEM vendors to test their engines against the empirical test cases, perhaps by including those test cases in the requirements for IRS 179D software qualifications. The IRS qualified software list[55] is referenced by multiple programs including code compliance programs, green certification programs, and utility EE incentive programs.

EnergyPlus upgrades. Where validation identifies areas of weakness in EnergyPlus, BTO should invest in the development and implementation of improved approaches and algorithms. Where impractical—and even as a stop-gap in cases where algorithm improvements are possible—BTO should invest in the development of simulation protocols that control for this error as well as promote reasonable expectations for projects that use these BEM features.

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

Uncertainty analysis. Validation and testing can effectively 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 encourage 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. In fact, BEM prediction distributions can change throughout the lifetime of an individual project. Early in a design project when building forms and space plans are fluid and system types are unsettled, 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.

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 uncertainty expectations for various BEM analysis. BTO should work with ASHRAE to add uncertainty analysis to Standard 209.

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 increasing spatial and temporal resolutions—interval meter data, smart thermostat data, other data streams from sensors and smart equipment—and the ubiquitous availability of high-throughput computing on the cloud, the cost of automated calibration is shrinking while its potential effectiveness is growing.

BTO has invested in several automated calibration projects including Autotune,[56] the Trinity calibration testing website—which roughly implements the proposed RESNET calibration standard—and more recently a research project on a new 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.[57] 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 yet do not resemble the physical configuration.

Calibration guidelines should be updated and strengthened. Existing guidelines like ASHRAE 14 and BPI 2400 are seemingly aimed at manual calibration, a process that strangely combines tedium with experience and art. Automated calibration can already achieve much 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.

Outreach. An important aspect of these related enterprises is communicating their results to both BEM professionals and BEM clients. Traditional journal publications and conference presentations probably suffice for BEM professionals. However, BEM clients generally do not read technical journals or attend technical conferences. They are also unlikely to be convinced by laboratory experiments, which do not closely resemble real-world buildings.

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.

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[56] https://www.energy.gov/eere/buildings/downloads/core-2012-autotune

[57] https://www.energy.gov/eere/buildings/downloads/benefit-2014-new-hybrid-approach-energy-modeling

Perhaps just as convincing as 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.

Table IV-1 Predictive Accuracy Barriers and Initiatives

Barriers	Initiatives	Priority
Empirical validation and testing. A. BEM is sensitive to many stochastic and difficult to obtain inputs making predictive BEM challenging. At the same time, the inherent error of BEM engines is not quantified and separated from input uncertainty creating the perception that BEM is not a useful enterprise. B. BEM engines are currently tested against one another and analytical results rather than validated against ground truth, reinforcing the perception that BEM is a "house of cards."	1. Support empirical validation of BEM engines using well-characterized well-instrumented test facilities like LBNL's FLEXlab, ORNL's FRP. Codify the results in corresponding empirical test suites in ASHRAE standard 140.	–
	2. Continue to develop ASHRAE Standard 140 analytical and comparative test cases to complement empirical test cases to complement empirical results.	–
Uncertainty analysis. C. BEM clients have unreasonable expectations for precision in BEM prediction. BEM professionals are not accustomed to performing uncertainty analysis.	3. Promote use of uncertainty analysis in BEM applications. Support development of guidelines and approaches for use of uncertainty analysis in different BEM applications.	–
Input calibration. D. Improved calibration methods that enable greater in modeling of existing buildings are not widely used and calibration standards are lax.	4. Support development and use of advanced automated model input calibration methods. Support development of methods of tests and advanced standards for calibration.	–
Outreach. E. Lab tests may not be sufficient to convince skeptics that BEM is sufficiently accurate on real-world occupied buildings	5. For promotional purposes, identify working 'Validation Buildings' to evaluate BEM predictive accuracy and calibration methods.	–

V Topic 3: Core Modeling Capabilities

Summary:

- Current BEM engines including EnergyPlus are deficient in several ways. One deficiency associated specifically with EnergyPlus is relatively slow execution speed, which is important in a number of applications.
- BEM capabilities do not include things such as physical behavior of air distribution systems, urban-context effects, stochastic occupant behavior, and various features needed to support building operation.
- There is confusion in the industry about Spawn-of-EnergyPlus and its role in BTO's BEM and control programs.
- BTO needs to articulate a clear position for Spawn within its BEM and control programs.
- When expanding BEM functionality to new areas such as urban-scale modeling or modeling of electrical-distribution systems, BTO should identify third-party software vendors that can act as channel partners for the new capabilities and help direct scope and functionality.
- BTO should emphasize co-simulation and linkage of its BEM tools to external analyses and resist the temptation to directly expand the scope of EnergyPlus to include new capability areas.

Relevant BTO projects:

- **EnergyPlus.** Open-source, state-of-the-art whole BEM engine. https://energy.gov/eere/buildings/downloads/energyplus-0/ and https://energyplus.net/
- **Spawn of EnergyPlus (Spawn).** Open-source next-generation BEM engine that supports co-simulation in a fundamental way and integrates with control design, verification, and implementation workflows. https://www.energy.gov/eere/buildings/downloads/spawn-energyplus-spawn
- **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 and https://wwwl.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 and https://www.radiance-online.org/
- **THERM/MOISTHERM.** A 2D/3D heat transfer engine for detailed analysis of facades. In a three year project called MOISTHERM, BTO is adding moisture transfer modeling capabilities to THERM. https://www.energy.gov/eere/buildings/downloads/fenestration-software-tools, https://www.energy.gov/eere/buildings/downloads/benefit-2016-moistherm-integrated-heatmoisture-transfer-envelope-modeling, and https://windows.lbl.gov/software/therm/therm.html

V.1 Barriers

The current generation of BEM engines—including EnergyPlus—have an impressive and relatively mature set of capabilities. However, they also share a traditional, monolithic structure that makes it difficult to add capabilities that are significantly beyond those initially envisioned or to link to capabilities in other tools. These shortcomings manifest in maintenance difficulties, poor scalability on large models, and applications where BEM touches other analyses either in different domains (e.g., building control design, air duct design, power distribution simulation), or at different scales (e.g., detailed-façade simulation or urban-scale simulation).

Execution speed. Although it has sped up considerably over the last several years, EnergyPlus is still over an order-of-magnitude (20-30X) slower than other commonly used BEM engines, most notably DOE-2.2. Some of this gap is due to differences in level of physical detail (e.g., separate radiative and convective physics in EnergyPlus vs. combined in DOE-2.2), some to solution approaches (e.g., simultaneous solution of zone conditions and system response in EnergyPlus vs. serial solution in DOE.2.2), some to default settings (e.g., 15-minute time-step in EnergyPlus vs. a minimum hourly time-step in DOE-2.2), and some to implementation.

Slow execution speed is detrimental to interactive and "real-time" applications in building operations. It is inconvenient in traditional iterative modeling workflows. In addition, it adds cost to even in off-line large-scale simulation applications that are not sensitive to execution time. EnergyPlus' execution speed has been mentioned as a barrier in residential applications, where simpler tools that provide seemingly instantaneous feedback currently prevail.

Lag in modeling capabilities. One commonly mentioned deficiency is the delay between when a new technology appears on the market and when that technology can be modeled in BEM tools. This delay can be 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[58] but were not modeled in EnergyPlus until 2011.[59]

The absence of a model for a new technology may depress application and 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 utility—or other EE program administrator—performs a benefit-cost analysis for the service territory.

As stopgaps, BEM professionals may 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 existing technology, e.g., an LED can be accurately modeled as a more efficient version of a 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 the modeling process.

Capabilities supporting use in building operations. Multiple stakeholders mentioned 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. BEM can support optimized building operation via applications such as continuous commissioning (CCx), automated fault detection and diagnosis (FDD) and model predictive control (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. BTO is developing a report that describes the role of BEM in designing and operating grid-interactive efficient buildings (GEB), along with gaps and future needs.

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

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

Integration requirements for on-line "real time" applications are typically more intensive than for traditional off-line applications like design and certification. Whereas off-line applications typically need to integrate with simulation inputs and final outputs, online applications often require interacting with a running simulation, extracting specific values and perhaps injecting new values into the simulation. Although platforms such as LBNL's Building Controls Virtual Test-Bed (BCVTB)[60] exist, channels for BEM engine-Building Management Systems (BMS) communication are missing. Currently, most BEM engines including EnergyPlus lack the capabilities to support building operations, including:

- Ability to model realistic control sequences—as opposed to idealized control—preferably by interpreting and "executing" control code directly.
- Ability to integrate "real-time" data about building conditions and operations—e.g., from a Building Management System (BMS)—in lieu of pre-defined input schedules.
- Ability to save simulation state and re-start from the same state while changing selected state variables.
- Ability to model faulty and degraded equipment.

Air distribution system modeling. Current BEM engines including EnergyPlus model HVAC system interconnections schematically rather than physically, i.e., they model the fact that air moves from one component to another and from components to zones and back but do not model duct geometry and physics, including effects like leakage, heat loss, and pressure drops which can greatly effect HVAC system performance, thermal comfort, and indoor air quality. Where air transfer physical effects are accounted for—e.g., using EnergyPlus' airflow-network components—characteristics such as pressure drops are entered as inputs, leaving the modeler to use defaults or obtain project-specific figures from another analysis tool.

District and urban-scale modeling. BEM is currently a one-building-at-a-time tool. Even larger scale applications that analyze multiple buildings, e.g., portfolio-level retrofit screening and prioritization, are essentially multiple independent copies of single-building analyses. However, there is growing interest in larger-scale models that perform integrated "lock-step" simulation of multiple buildings, potentially along with models of other systems such as district heating and cooling systems, local weather, water systems, transportation, distributed generation and storage systems, and electric micro-grids or the larger grid. Potential applications of such models include analysis of urban micro-climate and design of outdoor spaces, design and operation of district hot and chilled water systems, design and operation of micro-grids and distributed generation and storage systems, utility capacity and resource planning including demand response service planning, land-use planning and zoning, and sustainability and resiliency planning. Urban-scale modeling overlaps with grid modeling and transactive energy applications as most energy transactions are expected to take place between geographically proximal actors. Current BEM tools including EnergyPlus are missing the following capabilities needed to support district and urban scale modeling:

- Ability to integrate "real-time" data about external conditions in lieu of pre-defined input schedules.
- Modeling of radiant exchange with exterior surfaces.
- Integrated physically realistic integrated modeling of advanced district heating and cooling systems.
- Ability to select greater or lesser levels of model detail depending on application.

Other opportunities for scope expansion. Stakeholders suggest other capability sets that BEM could potentially expand to cover:

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[60] https://simulationresearch.lbl.gov/bcvtb

- Comprehensive greenhouse-gas tracking and accounting including direct onsite emissions, refrigerant leakage, and site and region specific emissions calculations for natural gas and electricity use.
- Comprehensive tracking and accounting of water use, reuse, capture, and treatment.
- Stochastic modeling of occupancy, occupant movement, and behavior.
- Comprehensive modeling of indoor air quality.

Stakeholders also suggest improved linkage between BEM tools and existing analysis tools and frameworks for:

- Embodied energy and carbon analysis and life cycle cost calculations.
- Detailed envelope heat and moisture transfer models.
- Detailed lighting models.
- Computational fluid dynamics (CFD) models for detailed indoor and outdoor airflow modeling.

V.2 Initiatives

With two whole-building energy simulation engines, EnergyPlus and Spawn, along with supporting tools in THERM and Radiance, BTO has the opportunity to address some of these issues in a direct and high-impact way.

Continue improving EnergyPlus execution speed. As long as EnergyPlus continues to be used, its execution speed will continue to be an issue. BTO has made some progress on EnergyPlus execution speed in the past several years, as have EnergyPlus clients such as Autodesk, but significantly more progress is needed. BTO has recently awarded a three-year project aimed at reducing EnergyPlus execution time by a factor of ten.[61] The project takes an "all-of-the-above" approach to the problem, including:

- Use of optimized math libraries
- Better algorithms that converge to solutions more quickly
- Improved data structures that support fast search and iteration of components
- Use of vectorization and multi-core parallelization, including large-scale parallelization as on graphical processing units (GPU)
- Code restructuring to eliminate redundant computation
- Reuse of computation across multiple simulations in a workflow

The project is also developing and publishing an EnergyPlus execution speed test suite that combines both synthetic and "real world" models to benchmark and track EnergyPlus performance improvement.

Define Spawn' expected role in BTO's ecosystem and the market. BTO has tried to articulate the relationship between EnergyPlus and Spawn in its BEM portfolio. In parallel, BTO needs to establish and promote new use cases and applications for Spawn, in areas such as control design and implementation and the evaluation of novel systems such as district systems. As a unified BEM-control design platform, Spawn gives BTO the opportunity and responsibility to align its activities in BEM and building controls. In conjunction

[61] https://www.energy.gov/eere/buildings/downloads/energyplus-10x

with the Office of Electricity (OE), BTO developed the VOLTTRON[62] open-source execution platform for building data acquisition, control, and building-to-grid interaction and has adopted it as its standard R&D platform for this area. BTO should investigate synergy between Spawn and VOLTTRON and investigate other ways in which Spawn could complement its control program and project portfolio. BTO could also leverage its relationships with control manufacturers to evaluate and provide directional feedback to the project, and to help define use cases and applications and to eventually act as deployment channel partners in the same way that companies like Autodesk and Trane act as channel partners for EnergyPlus. BTO should work to ensure that Spawn is aligned and synergistic with its building controls Report and strategic initiatives and look for ways for Spawn to contribute to these initiatives.

Emphasize co-simulation over monolithic integration. One of the nominal advantages of Spawn over EnergyPlus is its fundamentally integrated support for co-simulation, i.e., time-step exchange of state information with external simulation modules. EnergyPlus does have support for co-simulation, including support for FMI import and export. However, the engine itself is not designed to do this in a general way.

As it looks to support larger and more comprehensive analyses, BTO should place great emphasis on and give great preference to co-simulation over direct integration. Rather than adding functionality 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. The URBANopt project takes this approach with regards to electrical system, distribution system, and distributed energy resource (DER) simulation.

BTO should go a step further and consider moving some functionality out of EnergyPlus, either into OpenStudio—economic and life-cycle cost calculations are good candidates—or into co-simulation modules as appropriate. Any calculation that does not interact strongly with building heat balance—i.e., that does not *both* impact heat balance *and* is impacted by heat balance—should be considered for this type of re-factoring.

Specific areas for BEM expansion. Stakeholders have mentioned multiple areas for BEM expansion, including district-system and urban-scale modeling, modeling of occupant behavior, modeling of electrical distribution systems, and air-distribution system modeling. BTO labs already have some related projects in some these areas and BTO should consider how these fit into its larger program. When considering expansion into new areas, BTO needs to identify third-party software vendors that can act as channel partners and do so early in the project planning process. These partners would not only help ensure adoption end use, but also help in defining project scope and technical capabilities. An important step in any significant expansion (e.g. to urban-scale BEM) is early engagement of industry stakeholders to assess market conditions and to avoid undue duplication and competition.

One area in which neither BTO nor its labs have an existing program is in HVAC air distribution system modeling. Tools that simultaneously consider air-distribution system effects within whole building physics and energy use could have significant impact on air distribution system design and evaluation. Unlike occupant behavior or electrical system modeling, air distribution interacts strongly with building thermodynamics, implying that it should be integrated into EnergyPlus and Spawn. BTO can work with ASHRAE, which already formed an air-distribution system task group,[63] the Alliance for Sustainable Energy's (ASE) System Efficiency Initiative (SEI),[64] and air distribution system design tool vendors to determine a path forward for integrated analysis.

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[62] https://energy.gov/eere/buildings/volttron
[63] 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
[64] http://www.ase.org/systemsefficiency

Align BTO's detailed heat and moisture transfer tools with its BEM tools. Another widely cited gap in core EnergyPlus capabilities is the ability to model thermal bridges. Like many other BEM engines, EnergyPlus uses a "one dimensional" conduction model that accounts for heat transfer "through" constructions and surfaces but not "across" them and does not model heat conduction at seams between two surfaces. As is the case for air-distribution system models, these effects can be accounted for using tricks such as sub-surfaces with different thermal resistance and capacitance values. However, 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.

Unlike air-distribution system modeling, BTO's portfolio does include a detailed 2D/3D envelope heat transfer model THERM.[65] LBNL is currently refactoring THERM to separate its engine from its interface, and relicensing THERM as open-source software using a license that is compatible with EnergyPlus and OpenStudio. In a separate, competitively awarded project, LBNL and ORNL are adding dynamic moisture-transfer modeling capabilities to THERM.[66]

Given related but different use cases for THERM and BEM and the inherent mismatch between their fundamental conduction heat-transfer models, direct integration of THERM into EnergyPlus is probably not practical or even desirable. However, BTO should look for ways to leverage THERM to address shortcomings in its BEM tools, and to extract more value from both THERM and its BEM platform. BTO should engage both BEM and detailed envelope modeling stakeholders to better understand use cases and develop an integration strategy, perhaps using OpenStudio Measures to prototype various workflows.

[65] https://windows.lbl.gov/software/therm/therm.html
[66] https://energy.gov/eere/buildings/downloads/moistherm-integrated-heatmoisture-transfer-envelope-modeling

Table V-1 Core BEM Capabilities Barriers and Initiatives

Barriers	Initiatives	Priority
EnergyPlus execution speed. A. EnergyPlus' slow execution speed is a hindrance in most applications, and detrimental to some, including residential applications.	1. Continue to emphasize EnergyPlus execution speed, both in individual runs and complete workflows as with the EnergyPlus 10X project	–
Spawn. B. Market confusion about relationship of EnergyPlus to Spawn. C. Market confusion about role of Spawn within BTO's controls program. 4.	2. Articulate and promote a clear position for Spawn within BTO's BEM ecosystem.	–
	3. Work with stakeholders and vendors to develop a deployment strategy for Spawn, preferably leveraging OpenStudio, along with transition plan that will continue to support traditional EnergyPlus users.	–
	4. Work internally to align strategies and activities related to building control design, verification, and execution.	–
Functionality gaps. D. Gaps in core modeling capabilities including air-distribution system modeling and handling of thermal-bridges.	5. Work with stakeholders to understand use cases for combined BEM-detailed envelope analysis. If compelling use cases exist, develop a THERM-EnergyPlus integration plan.	–
	6. Collaborate with ASHRAE and vendors of air distribution system design tools to understand requirements for joint BEM-"3D" air distribution system modeling. Add capabilities to EnergyPlus to support links to air distribution system design workflows.	–
Areas for expansion. E. Potential areas for BEM expansion including urban-scale modeling, occupant behavior modeling, and modeling of electrical systems and grid interactions.	7. Engage stakeholders to understand the use cases and modeling requirements for expansionary BEM areas and to avoid undue and unproductive duplication and competition	–
	8. Identify third-party software vendors that can act as channel partners for new capabilities. Leverage these vendors to define scope and functionality.	–
	9. Give preference to co-simulation over direct integration of new functionality into EnergyPlus.	–

VI Topic 4: Workflow Integration and Task 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. Integration with building operation workflows is in an even more primitive state.
- Many BEM tasks are repetitive, time-consuming and not yet automated, requiring unnecessary manual effort and degrading BEM cost-effectiveness.
- To facilitate BEM integration as well as future evolution of its BEM tools, BTO should engage third-party BEM software developers in a more formal and structured way.
- BTO should invest in application integration features for EnergyPlus, to support vendors that have chosen to bypass OpenStudio and access EnergyPlus directly.
- BTO should leverage its relationships with design authoring tool vendors to improve the state of geometry transfer from design to BEM.
- BTO should promote automation of BEM tasks such as code-minimum baseline model generation, calibration, and design optimization using OpenStudio Measures and other scripting frameworks. In code-minimum baseline generation, BTO should push for certification of automated implementations.

Relevant BTO projects:

- OpenStudio Software Development Kit (SDK). Open-source software development kit (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 Building Components Library (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/ and https://openstudio.net/
- ResStock. ResStock is a statistical building stock modeling framework that produces more robust measure savings estimates. It is currently being extended to commercial and multifamily buildings. https://www.energy.gov/eere/buildings/resstock and https://resstock.nrel.gov/
- 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 and https://wwwl.nrel.gov/buildings/urbanopt.html
- **BuildingSync.** BEDES-compliant standard building audit schema that supports simulation-driven analysis. Developed and managed by BTO's commercial buildings program. https://buildingsync.net/

VI.1 Barriers

For an industry based entirely on computer 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 dampens modeler productivity.

BEM software evolved separately from design workflows, first 2D computer aided design (CAD) and now 3D building information modeling (BIM). Early BEM tools such as Trane TRACE, Carrier HAP, and VisualDOE were separate applications that required modelers to recreate architectural and mechanical designs, a process that consumed significant upfront effort and was prone to interpretation, translation, and general human error. This setup was created because early BEM tools needed a different level of geometric abstraction and detail than that managed by geometry authoring tools, a translation that required human intervention. Its persistence has contributed to BEM's high labor costs and degraded value proposition.

Geometry Input. Modern architectural design tools like Autodesk's Revit and Graphisoft's ArchiCAD use 3D geometry models with parameterized lines, planes, and solid objects including curves. Meanwhile, even advanced BEM engines like EnergyPlus use a simplified "2.5D" geometry model with polygonal planes in 3D space. 3D to 2.5D geometry translation is a complex process that involves simplifications, assumptions, and conventions; and there are numerous edge cases. Unsurprisingly, it is not implemented robustly or uniformly. The BIM model—usually exported in gbXML format—is often not checked for BEM "analyzability." Inconsistencies or flaws in the exported model are detected when it is imported into the BEM tool. If the designer is operating both tools, he or 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. However, their solutions are opaque and work only within their proprietary workflows. These solutions are part of a recent industry trend towards integrated, cloud-based design-analysis workflows. By de-emphasizing exports, these workflows cater to upstream users like architects. However, they reduce transparency and robustness in the translation process.

Non-geometry 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 untested.

Output data. Interoperability pertains not only to BEM inputs, but also to outputs—that can be arbitrarily resolute and large—error messages, and diagnostics. These are also not standardized, complicating the creation of standard reports and diagnostics, as well as tool integration.

Control sequences. Another stubborn source of friction between BEM and other workflows are control sequences for HVAC equipment, HVAC systems, plant systems, lighting systems, and advanced façade systems. Control systems tend to be vertically integrated and the algorithms they implement proprietary. Even if those implementations were open, it is not likely that many BEM engines would be able to interpret and execute them directly—manual translation would be required. Conversely, BEM engines also implement control sequences in ways that cannot be directly ported to building automation systems. EnergyPlus specifically has two control sequence implementation paths. Common "standard" sequences are implemented in an idealized fashion by code in the HVAC simulation loop. For custom control sequences, EnergyPlus supports a bespoke scripting language called EnergyPlus Runtime Language (ERL). Neither the HVAC loop code nor ERL scripts can be interpreted by BAS systems.

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.

Task automation. Within BEM workflows, many mechanical—i.e., uncreative, repetitive—BEM tasks are also not automated, requiring unnecessary manual effort and degrading BEM project cost-effectiveness. Automating these tasks would allow BEM expenditures to shift from low-value, low-creativity tasks to high-value, high-creativity tasks such as performance optimization and design/operation support, reducing the overall cost of BEM.

The task ripest for automation is also one of the most common—generation of a code-minimum baseline BEM from a model of a proposed or existing building. Baseline generation is the main component of performance-path code-compliance as well as green certification, and it is defined by standards such as ASHRAE 90.1 Appendix G. Automation of this particular task is becoming more common. The California Energy Commission (CEC) has automated it for Title24 in CBECC-Com and CBECC-Res. End-user tools like Trane TRACE and Bentley AECOSim Compliance Manager implement ASHRAE 90.1 Appendix G. A similar situation exists on the residential side with the 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” and its software implementations. REM/Rate automates this baseline model generation for code-compliance, HERS/ERI, and Energy Star. The OpenStudio “Standards Gem” uses Measures to generate baseline models for ASHRAE 90.1, Canada’s NECB, and India’s ECBC—while NREL is working with several industry partners to automate the ANSI/RESNET/ICC Standard 301 Energy Rating Index calculation on HPXML files. Proliferation of this capability could be a game changer, as it would make performance rating method applications like code-compliance and green certification effectively “free,” at least for project consultants. On the other hand, because there are no certified implementations of automated ASHRAE 90.1 Appendix G baselining, automatically generated baselines still have to be manually reviewed, degrading productivity for model consumers like code officials and incentive program administrators.

Other candidate tasks for automation include:

- Application of EEMs and EEM packages
- Uncertainty quantification
- Optimization
- Model input calibration
- Generation of diagnostics, reports, and visualizations.

The cost savings from automation could be substantial, but are so far not quantified.

VI.2 Initiatives

BTO should continue to encourage organizations interested in EnergyPlus to do so using the OpenStudio framework, to leverage its automation features in addition to its abstractions. BTO should take the following additional steps.

Develop a structured formal process for collecting inputs from BEM software developers. BTO's strategy demands collection and synthesis of feedback and requirements from (private sector) BEM software vendors. Historically, BTO and the labs have handled this task informally, using direct bi-lateral communication with existing client application vendors, many of whom contribute in-kind labor to EnergyPlus development.

In response to early feedback from the road-mapping workshops, in the summer of 2015 BTO created UserVoice feedback sites for EnergyPlus and OpenStudio. These sites allowed registered users to request, "up-vote,” discuss, and refine enhancements and new features and BTO used the site to prioritize tasks in its annual operating plan (AOP). The sites did not get as much participation and interaction as hoped for, in part, because they were poorly integrated with the primary GitHub Issue sites used by EnergyPlus and OpenStudio developers to report, track, and discuss issues and features. With GitHub adding “reaction” capabilities to

Issues, the teams have migrated the UserVoice content and have switched to a GitHub Issues-based process.[67] To further improve this broad engagement, BTO could hold quarterly or semi-annual 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.

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. What has become clear over the past year is 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. While the EnergyPlus and OpenStudio stakeholder group is growing, it is important to recognize and engage these "anti-stakeholders." The IBPSA-USA Advocacy Committee[68] 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.[69] 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, OpenStudio, or both.

Support application integration for EnergyPlus in addition to OpenStudio. One concern voiced by developers in stakeholder meetings and interviews is that while BTO has chosen 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. In addition to improving the OpenStudio migration path, BTO should invest more heavily in direct-to-EnergyPlus application integration support, addressing issues raised by direct-to-EnergyPlus developers. Now that EnergyPlus is also in C++, BTO should consider opportunities to align the EnergyPlus and OpenStudio objects models and to re-architect the boundary between the two packages, move some of the functionality of into shared modules. The recent addition of support for input and output in key-value Java Script Object Notation (JSON) format in EnergyPlus should facilitate some of these changes.

Table VI-1 lists some suggestions for improving EnergyPlus application integration collected at one of the stakeholder workshop breakout sessions.

[67] https://github.com/NREL/EnergyPlus/Issues and https://github.com/NREL/OpenStudio/Issues
[68] https://sites.google.com/site/ibpsausaadvocacycommittee/home
[69] https://projects.eclipse.org/projects/iot.volttron

Table VI-1 Stakeholder Suggestions for Supporting EnergyPlus Application Integration

Suggestions for Improving EnergyPlus "Developer Friendliness"	Status
Adopt semantic versioning to simplify and clarify backward compatibility rules	Present
Transition to a standard key-value pair input schema and format (e.g., eXtensible Markup Language or JavaScript Object Notation) to simplify version transitions, feature deprecation, and application integration.	Present
Provide option to deliver output in key-pair schema and format.	In progress
Provide option to deliver time series output in compact binary format	In progress
Provide warning, error, and diagnostic messages in a standard format to facilitate bulk handling by automated processes. Adopt standard and consistent warning and error numbering.	In progress
Develop a Command Line Interface (CLI) for greater flexibility in execution specification.	Present
Develop an Application Program Interface (API)	In progress
Adopt a dynamic library architecture for reduced software footprints	Not present
Provide support for language localization	Not present
Provide support for units conversion	Not present

As it continuing to align EnergyPlus and OpenStudio, BTO should add Spawn into the mix to facilitate eventual migration for interested vendors who have invested in direct EnergyPlus access, bypassing OpenStudio.

OpenStudio execution speed. Although most of the execution speed complaints are targeted at EnergyPlus, the OpenStudio API and the Measure framework can also be slow because of a combination of layers of function calls within the API and high-frequency calls into and out of the API from the Ruby Measure interpreter. OpenStudio API and Measure execution speed have not been investigated as thoroughly as has that of EnergyPlus and there are fewer ready ideas on how to improve them. However, this is an important area of work.

Geometry exchange. BIM-to-BEM translation and export problems are best solved in the design authoring tool. A proper design model and correct translation eliminates the need to implement fixes and workarounds in multiple "downstream" analytical 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 the fact that these two surfaces are three inches apart an oversight or intentional"? The ideal workflow would have the design tool embed some analytical 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.[70] This initiative should be 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.

Non-geometry inputs. Currently, BTO supports energy information exchange standards BuildingSync XML (BSXML) and Home Performance XML (HPXML), along with the ASHRAE Standard 205 for equipment performance data. The OpenStudio platform supports these as well as CBECC-Com Standards Data Dictionary

[70] http://gbxml.org/validator/Pages/TestPage.aspx

(SDD)[71] import and gbXML geometry import. Various BTO BEM projects are also working with standards such CityGML (urban-scale 3D geometry),[72] EnergyADE (a building energy modeling extension schema for CityGML),[73] Haystack (a naming/tagging framework for building equipment control points),[74] and Brick (a new semantic web based meta-schema for building energy information).[75] There is a great deal of overlap between these standards. SDD, gbXML, BuildingSync, EnergyADE, and Brick are all BEM schemas and EnergyPlus, OpenStudio, and Asset Score have their own tool-specific input schemas as well. BTO is well positioned to push for consensus, alignment and consolidation of these standards. Standards could be referenced by relevant ASHRAE Standards such as 209.

Simulation outputs. Standardization and exchange is important not only for simulation inputs, but outputs too. Standard outputs facilitate comparison of results across BEM tools and inter-operability with reporting and visualization frameworks. Standard reports and visualizations help create familiarity among BEM clients such as building owners, promoting building energy "literacy" and use of BEM—IBPSA's project StaSiO[76] is based on this premise.

Alongside its activities in standardizing simulation outputs, BTO can push to create standard definitions and structures for simulation outputs. Standards should be aligned with measured data definitions and structures defined in BEDES, BuildingSync and HPXML. Again, these could be referenced in standards such as ASHRAE 209.

Task automation. The OpenStudio Measures framework gives BTO an opportunity to drive progress in the BEM task automation area. BTO should leverage the OpenStudio Standards Gem to promote the use of Performance Rating Method baseline automation. One way to do this is to create a testing and certification framework for automated baseline implementations.[77] This should be a simpler task than the testing framework BTO already funds for BEM engines, ASHRAE Standard 140. Because engines are tested against the physical world, a reference software implementation is infeasible. In contrast, baselining procedures are human-defined making a reference implementation—and automated testing—practical. The CEC has tested CBECC-Com and CBECC-Res and declared them to be reference implementations of the Title24 ACM. BTO could promote the Standards Gem as an open reference implementations of ASHRAE Standard 90.1 baselining and use it to test and certify other implementations, including proprietary ones. BTO can collaborate with ASHRAE and organizations such as GBCI—ASHRAE 90.1 Appendix G is the basis for LEED energy credits—to develop and operate such a framework.

OpenStudio Measures can also be used to prototype and promote automation in other BEM applications. OpenStudio Measures were initially used to implement model transformations corresponding to energy conservation measures. One task that is ripe for automation is model screening, quality assurance (QA), and general "sanity checking." Some utilities are already using OpenStudio to develop custom Measures that screen models submitted to their efficiency programs. These QA Measures check that model inputs and outputs are within reasonable ranges, that baseline and proposed building models differ in some ways (e.g., lighting and equipment efficiencies) and not in others (e.g., occupancy or set-point schedules) and that efficiency program rules are followed (e.g., no fuel switching). QA Measure support could be generalized and

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[71] http://bees.archenergy.com/software.html
[72] https://www.opengeospatial.org/standards/citygml
[73] http://www.citygmlwiki.org/index.php/CityGML_Energy_ADE
[74] https://project-haystack.org/
[75] https://brickschema.org/
[76] https://projectstatsio.com/
[77] Roth, A. "Rulesets are Great. Certified Rulesets are Greater." Proc. 2018 ACEEE Summer Study on Energy Efficiency in Buildings, Aug. 2018. https://aceee.org/files/proceedings/2018/index.html#/paper/event-data/p164

expanded to flag inconsistencies, anomalies, and user errors. An improved building data ecosystem could provide the empirical basis for this process while standard simulation outputs could make such tests universal

Where automation would benefit from testing and certification—QA is a potential example—BTO can support the development testing frameworks, potentially using OpenStudio Measures as references implementations if appropriate. More generally, BTO should promote the use of workflow automation using platforms and toolkits such as Measures, Eppy,[78] Modelkit,[79] and others.

Workflow integration. OpenStudio Measures and scripting more generally can automate workflows that include multiple analyses, connecting APIs or importing and exporting files. For OpenStudio, workflow integration Measures already exist for tools such as Radiance and GLHEpro.[80] BTO should promote the use of OpenStudio Measures and other scripting frameworks to integrate energy analysis with other analyses such as take-off and first cost- analysis, life-cycle analysis, and others.

First-cost analysis is a good mule and case study. 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 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 datasets already exist; examples include RS Means[81] and NREL's National Residential Efficiency Measures Database[82]. BTO should encourage and support the schematization, collection, and publication of EE cost data while developing schema-compatible OpenStudio Measures for cost analysis.

Table VI-2 BEM Task Automation and Workflow Integration Barriers and Initiatives

Barriers	Initiatives	Priority
Geometry translation. A. BIM-to-BEM geometry translation is not robust, requiring modelers to fix up geometry in the BEM tool or recreate it from scratch.	1. Collaborate with vendors of design model authoring tools to improve BIM-to-BEM translation and export. Develop methods to ensure that design models are analyzable and that help designers create analyzable models.	–
BEM input inter-operability. B. Transfer of non-geometry design information—including constructions, zoning, and HVAC and water heating systems and equipment—between design and BEM tools is sparse.	2. Push for alignment and unification among BEM input standards such as gbXML, BuildingSync, EnergyADE, and Brick.	–
	3. Support consensus standards in BTO tools.	–
BEM output inter-operability. C. BEM outputs are not standardized, hampering inter-operability and making comparisons between tools difficult.	4. Work with vendors to develop standard language and structure for BEM outputs that is aligned with BEDES language and structure for measured data.	–

78 https://github.com/santoshphilip/eppy
79 http://bigladdersoftware.com/projects/modelkit/
80 https://hvac.okstate.edu/glhepro/overview
81 https://www.rsmeans.com/
82 http://www.nrel.gov/ap/retrofits/index.cfm

	5. Work with ASHRAE to reference relevant standards such as 209.	–
	6. Support consensus standards in BTO tools.	–
Baseline generation automation. D. Although automation of code-minimum baseline generation is becoming more widespread, implementations are not tested in a consistent way or certified for general or specific use, degrading their potential value.	7. Promote testing and certification of automated baseline generation by engaging the appropriate organizations, including ASHRAE and GBCI.	–
Other task automation and workflow integration. E. Lacking automation of other BEM tasks including parametric analysis, calibration, QA, and diagnostics.	8. Promote use of scripting frameworks for BEM task automation and general workflow integration.	–
EnergyPlus application integration. F. Multiple vendors have invested in direct integration with EnergyPlus, bypassing OpenStudio.	9. Improve EnergyPlus application integration features to assist vendors who access EnergyPlus directly.	–
	10. Continue to align EnergyPlus with OpenStudio to facilitate EnergyPlus to OpenStudio migration.	–
OpenStudio execution speed. G. The OpenStudio API and Measures framework can also be slow.	11. Investigate OpenStudio API execution speed and prioritize execution speed in development.	–

VII Topic 5: The BEM Data Ecosystem

Summary:

- Many BEM use-cases makes heavy use of defaults and standard assumptions and inputs. Many of these are outdated, including detailed equipment performance, default asset, operation, and 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, EPA, and the Energy Information Administration (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 sub-meter 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:

- **Building Energy Data Exchange Specification (BEDES).** Data dictionary of building-energy-related terms and type values. https://www.energy.gov/eere/buildings/building-energy-data-exchange-specification-bedes and https://bedes.lbl.gov/
- **BuildingSync.** BEDES-compliant standard building audit schema that supports simulation-driven analysis. Developed and managed by BTO's commercial buildings program. https://buildingsync.net/
- **ASHRAE Standard 205 and the Technology Performance Exchange (TPEx).** ASHRAE Standard 205 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-140-maintenance-and-development and https://www.tpex.org/
- **Standard Energy Efficiency Data (SEED) Platform.** SEED is a building energy data management platform that supports use cases such as disclosure and audit ordinances. https://www.energy.gov/eere/buildings/standard-energy-efficiency-data-platform
- **Commercial Prototype Building Models and the 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 code 90.1 code version and customized for each climate zone. The OpenStudio Standards gem uses Measures to create these models in OpenStudio format. https://www.energycodes.gov/development/commercial/prototype_models and https://rubygems.org/gems/openstudio-standards/
- **ResStock.** 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 is being expanded to cover commercial and multi-family buildings. https://energy.gov/eere/buildings/resstock and https://resstock.nrel.gov/.

- **Secure Energy Analysis Testbed (SEAT).** This new service will collect and characterize building energy data of various kinds and then allow researchers to submit code that analyzes this data. The service will return the results of the analysis without giving researchers direct access to the data. https://www.energy.gov/eere/buildings/seat/

- **Virtual EBP.** This project 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/ and https://evenstar.ornl.gov/autobem/virtual_epb.

VII.1 Barriers

The BEM enterprise is data intensive, with models requiring hundreds to thousands of inputs and producing hundreds to thousands of output points. 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 sanity checking applications. Weather data for different future climate scenarios was also mentioned as a need.

Manufacturer equipment performance data. Inaccessibility of manufacturer-specific equipment performance data, including equipment-internal control sequences, is one of the more surprising gaps, with engines such as EnergyPlus using performance curves for basic components such as coils and fans that were generated in the 1990s. On its face, detailed simulation-level equipment performance should be straightforward to obtain. In practice, manufacturers are reluctant to share it fearing that it will compromise competitive advantage on one hand and interfere with high-level marketing messages on the other.

As part of a recent project, 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 re-create detailed equipment performance for the entire HVAC product market is not economically scalable.

Asset and operation inputs and measured energy use. Data about reasonable assumptions for unknown or uncertain inputs is also outdated. For commercial buildings, current widely used assumptions are based on the 2012 (or even 2003) Commercial Building Energy Consumption Survey (CBECS) and complemented by resources such as COMNET.[83] For residential buildings, assumptions are based on the 2015 (or 2005) Residential Building Energy Consumption (RECS) and embodied in the Building America House Simulation Protocols.[84]

RECS, and especially CBECS, may not have the breadth or depth to provide meaningful default data. RECS samples about 10,000 homes representing 0.01% of the residential stock. The CBECS samples about 6,000 commercial buildings, representing 0.1% of the commercial stock. Both RECS and CBECS 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 also do not provide a sufficient level of detail to create a credible energy model. Specifically, data is collected using one-time phone interviews conducted by non-experts who are trained for the specific interview task whereas modeling requires on-site audits. EIA does not have the charter or resources to collect this much data at this level of detail.

[83] http://comnet.org/

[84] https://energy.gov/eere/buildings/downloads/building-america-2014-house-simulation-protocols

RECS and CBECS also include measured energy use data. This data is used 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, computers) and is available at greater-than-monthly temporal frequencies (e.g., hourly). Such data is more useful on its own for benchmarking purposes, especially for isolating the effects of individual EEMs. It also significantly improves model input calibration. The RECS and CBECS energy use data lacks this resolution, as do other measured energy data sources including EPA's ENERGY STAR Portfolio Manager and BTO's Building Performance Database (BPD)[85] and Standard Energy Efficiency Data (SEED) Platform.[86]

Typical meteorological year weather data. The third typical meteorological year data set (TMY3)[87] provides typical weather data and is now available for 1,020 U.S. locations. Actual weather data, for use in calibration, can also be obtained for these locations, at low cost. The problem is that TMY3 files—created using weather data from the years 1991-2005—is already out of date for many locations as the ten warmest years on record are all more recent than 2005. It is also certainly not representative of weather in the next 50-100 years, the intended service lifetime of most buildings.

VII.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.

Detailed equipment performance. To address this need at scale, manufacturers must be incentivized to publish the detailed performance data they already have. The technical platform for this data exists in the form of ASHRAE Standard 205 "Standard Representation of Performance Simulation Data for HVAC&R and Other Facility Equipment"[88] which standardizes the specification of equipment performance data for energy simulation. As of 2019, BTO is funding the ASHRAE Standard 205 committee to support automation tasks BTO also created the Technology Performance Exchange (TPEx)[89] to provide a public warehouse for Standard 205 equipment data.

BTO needs to add support for ASHRAE 205 data inputs in EnergyPlus and OpenStudio in a timely fashion. It should also improve TPEx workflow and connectivity to provide manufacturers with greater value and incentive for this data. One potential improvement is a "performance lookup" function in which users and applications can find equipment that matches specified performance characteristics, allowing TPEx to be used for product selection.

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.

Asset and operation inputs and measured energy use. BTO's project portfolio includes the Building Performance Database (BPD),[90] the Standard Energy-Efficiency Data (SEED) platform,[91] Commercial Building Energy Asset Score, and Home Energy Score. BPD and SEED are databases that contain high-level building information and energy use data. BPD contains over one million anonymized records. SEED is used by several cities to implement energy disclosure mandates. SEED data is not public but BTO may obtain

[85] https://energy.gov/eere/buildings/building-performance-database
[86] https://energy.gov/eere/buildings/standard-energy-efficiency-data-platform
[87] http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
[88] http://spc205.ashraepcs.org/
[89] https://www.tpex.org/
[90] https://energy.gov/eere/buildings/building-performance-database
[91] https://energy.gov/eere/buildings/standard-energy-efficiency-data-platform

permissions to perform statistical analysis on the data and publish aggregated results. Asset Score and Home Energy Score collect more detailed data than SEED and BPD and use it to produce energy models. Both Scores are starting to be used for implementing audit mandates, and they are both web applications with backing databases that record all home and building 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 Portfolio Manager or other sources such as utility Green Button services. BTO can use these data sources and the disclosure programs they support to complement RECS and 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 sub-metering, 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.

Prototype models. Updated, expanded information about building assets, operations, and energy use should be turned into prototype models. Prototype models are used for large-scale stock-level analysis, and as starter models for individual building projects. BTO and ASHRAE already maintain prototype building models for common types such as offices, schools, and healthcare facilities. BTO is working with ASHRAE to create additional prototypes for less common space and building types such as supermarkets, data centers, public buildings, and service buildings. This work should expand further to cover university buildings, laboratories, places of worship, tall buildings, and other less common building types. Prototype mixed use buildings are also useful and the OpenStudio Standards gem could be used to support those in a parameterized way.

Probability and uncertainty distributions. Asset, operational, and energy use data needs to be organized and mined not only for representative or typical values, but also for distributions that can support and enhance BEM applications.

BTO should expand and promote the use of statistical methods for building stock-level analyses. Current practice uses a small number of prototype models—often just one—to represent a stock of a certain building type (e.g., office or healthcare) of a certain vintage (e.g., pre-1980 or post 2000) in a certain climate zone (e.g., hot-humid or cold). These prototype models are usually chosen to represent the most common envelope configurations and HVAC system types and operation regimes. However, given the diversity in many aspects of the building stock even “most common” configurations may truly represent only a small fraction of the actual stock. BTO should promote the use of the ResStock statistical stock-model methodology developed at NREL. Rather than choosing most common values out of building configuration data sets, ResStock develops joint probability tables of different configuration dimensions and uses sampling to create a larger and more representative population of prototype models. Analyses based on larger numbers of statistically generated prototypes are more robust than those that use smaller numbers of prototype models, even carefully chosen ones.

Probability distributions are also valuable in single model use cases including design and energy efficiency incentive calculations, where they support uncertainty analysis. Guidance for uncertainty analysis, uncertainty distributions for key parameters including occupancy and weather, automation, and education of both BEM practitioners and clients could all help promote uncertainty analysis,

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. Image of buildings are an example of such data. Image data is increasingly available in various forms (e.g., visible spectrum, infra-red, 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[92] 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. **Weather data**. There is already some activity in the area of future weather data that can be used to evaluate building energy performance across their projected service lifetimes, including commercial services such as WeatherShift.[93] BTO should promote the use of this type of analysis, especially in design to ensure buildings will perform as expected under future weather, and should also support the development of standard, transparent methodologies for producing such data.

Table VII-1 BEM Data Ecosystem Barriers and Initiatives

Barriers	Initiatives	Priority
Equipment performance data. A. Outdated detailed performance data for fans, coils, chillers, and other HVAC equipment.	1. Support ASHRAE Standard 205 performance data in EnergyPlus and OpenStudio. Improve TPEx workflow and connectivity to provide manufacturers with additional incentive to enter product data.	–
	2. Support ASHRAE in expanding Standard 205 to cover additional equipment.	–
	3. Leverage BTO field validation efforts and similar programs to collect, curate, and organize performance about field-installed equipment.	–
Whole-building asset, operation, and energy use data. B. 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.	3. Leverage BTO building energy data projects such BPD, SEED, Home Energy Score, and Asset Score to complement RECS and CBECS with more detailed asset, operational, and energy use data that can be used to develop more current default assumptions and values for BEM projects.	–
	4. Leverage BTO investments and field validation programs in sub-metering, 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.	–
	5. Explore the use of unstructured data sets as a source of building asset and operational data.	–
	6. Expand the set of prototype models, including support for mixed-use prototypes.	–
	7. Analyze existing and new data sets to extract value distributions in addition to typical values. Develop methods for incorporating statistical methods and uncertainty analysis into applications.	–
Weather data. C. TMY3 weather data is not representative of current weather and even less so of future weather likely to be encountered by buildings throughout their service lifetimes.	8. Develop standard methodologies for creating future weather data from current climate and weather projection models. Promote the use of future weather data in design and retrofit BEM applications.	–

[92] https://energy.gov/eere/buildings/virtual-epb/
[93] http://weathershift.com/

VIII Topic 6: Process Standardization, Modeler Credentialing, Training, and Education

Summary:

- ASHRAE Standard 209 standardizes the BEM-driven design-assistance process, but is new and not widely referenced or required. The BEMP and BESA credentials are under-subscribed and not widely required. There is no other way to gauge modeler quality. The combined result is that modeler qualifications are difficult to assess and quality services difficult to procure.
- BEM educational offerings are sparse. Training availability is better, but still largely centered around conferences.
- BTO should promote the incorporation of ASHRAE Standard 209 and BEMP credentials in project requirements, and support ASHRAE in continued development of these standards and certificates.
- 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.
- BTO should continue to support BEM students with conference travel grants and design competitions. BTO should consider expanding its support to young faculty with research and curriculum grants and to graduate students with fellowships.

Relevant BTO projects:

- **AIA 2030 Design Data Exchange (DDx).** The AIA 2030 DDx is being expanded to allow architects to compare simulated energy performance to actual building performance. https://www.energy.gov/eere/buildings/downloads/aia-2030-commitment-design-data-exchange-ddx and https://2030ddx.aia.org/.
- **Conference travel grants to conferences for students and young practitioners. Prize money for student and practitioner BEM competitions.** BTO regularly provides funding that supports conference travel for students and young practitioners to conferences such as IBPSA SimBuild, ASHRAE Building Performance Analysis Conference. BTO also provides prize money for BEM competitions associated with these conferences such as the 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, the Building Energy Software Tools Directory, and the BEM Library. https://unmethours.com/, https://buildingenergysoftwaretools.com/, and https://www.bemlibrary.com/.

VIII.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 U.S. 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 ten years would require the BEM workforce to grow by a factor of ten. 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. The situation is exacerbated by a lack of process standards, creating a "wild west" situation in which quality is difficult to assess and quality services difficult to procure.

Process standards. ASHRAE Standard 209 *Energy Simulation Aided Design for Buildings except Low-Rise Residential Buildings*[94] documents processes and deliverables for BEM tasks in various phases of building design and operation. Standard 209 also covers benchmarking and target setting, site climate analysis, as well as modeler certification and modeling software requirements. ASHRAE Standard 209 is relatively new and not widely referenced or used. Being new, it also has some gaps. It does not deal with the role of uncertainty in BEM deliverables and does not go into output specifics.

Modeler experience and credentialing. The fact that BEM processes are not standardized, or at least under-standardized, leaves project execution to modeler judgment and places emphasis on modeler experience. 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. Inexperience also hurts when reviewing models developed by others. Model review is an important component of code-compliance, green certification, and incentive documentation.

Despite the importance of modeler experience, a professional modeling credential such as ASHRAE's Building Energy Modeling Professional (BEMP)[95] or AEE's Building Energy Simulation Analyst (BESA)[96] is required in few, if any, BEM procurements. Both credentialing programs are under-subscribed, with only 245 U.S. practitioners obtaining the BEMP credential to date.[97] Without credential and experience requirements, stakeholders suggest that cost and schedule pressures can lead design firms to assign BEM tasks to junior staff with little experience in BEM or specific analyses, workflows, and tools.

The open design-measured performance loop. Another barrier to assessing model and modeler quality is the lack of a robust and transparent feedback loop between modeled and measured performance. Design BEM is not predictive (See Section 3), but it is still likely the case that some modelers produce more accurate models than others. Similar correlations can be extracted for BEM software.

Data correlating modeled energy use to measured energy use is not centrally collected and curated. It is likely that many modelers do not even collect this data individually and therefore do not have a quantitative sense of their own level of proficiency, and that if they do they would be resistant to share it.

Education. BEM practitioners often do most of their learning on the job. 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. university with BEM course offerings. A number of international universities also offer BEM educational tracks including Concordia in Canada, Strathclyde University and University College-London in the UK, 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 include within larger Masters and PhD programs. There are a number of BEM textbooks including "Energy Simulation in Building Design"[98] and "Building Performance Simulation for Design and Operation."[99]

Training. 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. BTO replaced lab-provided trainings with a "train the

94 https://www.ashrae.org/standards-research--technology/standards--guidelines/titles-purposes-and-scopes#SPC209P
95 https://www.ashrae.org/education--certification/certification/bemp-building-energy-modeling-professional-certification
96 http://www.aeecenter.org/i4a/pages/index.cfm?pageid=347
97 http://report.ashrae.org/Certification/list?type=BEMP
98 Clarke, J. "Energy Simulation in Building Design," Routledge, 1970. https://www.taylorfrancis.com/books/9781136406768
99 Hensen, J. and Lamberts, R. "Building Energy Simulation for Design and Operation," Routledge, 2012. https://www.routledge.com/Building-Performance-Simulation-for-Design-and-Operation/Hensen-Lamberts/p/book/9780415474146

trainers" program for the OpenStudio Application. This program on-boarded a handful organizations, but has stopped growing and with the OpenStudio Application spinning off in 2020, has no remaining purpose. A somewhat larger handful of organizations provide EnergyPlus training without the benefit of a centralized "train the trainers" program. The adoption of EnergyPlus by companies such as Trane and Autodesk also naturally expanded training availability.

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 but these generally visit larger cities such as San Francisco, Chicago, and Seattle. Online training workshops are also available via vendors, consultants such as Performance Systems Development and Energy-Models.com and subscription services like Performance.Network.[100]

Over the past several years, a few tool-specific training books have been published including "Building Energy Modeling with OpenStudio"[101] and "Building Energy Simulation: A Workbook Using DesignBuilder."[102]

VIII.2 Initiatives

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

ASHRAE Standard 209 and modeler certification. BTO can use its position and network of stakeholders to promote both ASHRAE Standard 209 and the BEMP and BESA credentials. BTO can work with General Services Administration (GSA) and the Department of Defense (DoD) to add Standard 209 and certification requirements to federal projects. It can promote their use in the Better Buildings Challenge and more generally among Better Buildings Alliance partners. BTO is working with AIA to use ASHRAE Standard 209 as the modeling language and framework in the updated Energy Modeling Design Guide.

BTO should support ASHRAE in the continued development of Standard 209 and the continued development and administration of the BEMP credential.

Modeled vs. measured energy use. BTO should 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. Statistical analysis on this data can support BTO's message regarding the value proposition of BEM. BTO should also make this data available to BEM practitioners to allow them to self-assess their skills and proficiencies, improve them, and potentially market them.

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

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

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[100] http://performancenetwork.squarespace.com/

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

[102] Garg, V., Mathur, J., Tetali, S., Bhatia, A. "Building Energy Simulation: A Workbook Using DesignBuilder," CRC Press, 2017. https://www.crcpress.com/Building-Energy-Simulation-A-Workbook-Using-DesignBuilder/Garg-Mathur-Tetali-Bhatia/p/book/9781498744515

Education. One activity BTO may consider supporting directly is the development and promotion of tool-agnostic BEM content and training focusing on building physics and HVAC fundamentals. BTO started along this path with the BEM Library project, but largely staffed by volunteers that effort lost momentum. BTO could provide funding to complete the project.

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 not tied to specific research projects, like those offered by the National Science Foundation. BEM faculty members, through competitive grants for research or program and curriculum development.

Table VIII-1 Process Standards, Education, Training, and Certification Barriers and Initiatives

Barriers	Initiatives	Priority
Standards and credentials. A. ASHRAE standard 209 is new and not widely referenced or required. B. BEM credentials like ASHRAE's BEMP and AEE's BESA are under-subscribed and generally not required for project work.	1. Promote ASHRAE standard 209 and the credentials to BTO's network of stakeholders including Better Buildings.	–
	2. Promote a requirement of ASHRAE standard 209 and BEMP or BESA certification in federal building projects.	–
	3. Support ASHRAE in the continued development of standard 209 and the BEMP credential.	–
Modeler quality feedback. C. There is no feedback loop that correlates measured energy use or savings with predicted energy use or savings for individual modelers or organizations.	4. 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.	–
Education. D. Educational offerings are sparse. Few architecture or engineering programs offer BEM as part of an architecture or engineering curriculum.	5. Continue collaboration with IBPSA to support participation of students and young professionals in BEM conferences, technical meetings, and design competitions.	–
	6. Consider awarding graduate fellowships for BEM research.	–
	7. Use competitive solicitations to support BEM university faculty in research and curriculum and program development.	–
Training. E. In person training opportunities are centered around conferences, and only sparsely available at non-conference times and locations	8. Consider subsidizing conference attached training for all BEM tools.	–
	9. Consider establishing annual EnergyPlus and OpenStudio user conferences	–
	10. Work with ASHRAE and IBPSA to develop tool-agnostic training content for building physics and HVAC.	–
	11. Continue collaboration with IPBSA to develop online resources for BEM community.	–

IX Summary

This Report presents a series of barriers to BTO's goals to increase the effective use of BEM in building design and operation, along with recommendations aimed at addressing them. These barriers and initiatives point to four emerging themes.

- **Communication – there is a need to establish and communicate a clear value proposition for BEM.** Most potential BEM clients like building owners do not properly value BEM. Without explicit budgets for BEM, architects and engineers are dis-incentivized from investing in BEM themselves. Developing and documenting compelling evidence that BEM leads to robust, persistent energy savings will help the market value BEM properly.
- **Cost – there are near-term opportunities to lower the development and labor costs of BEM.** The greatest opportunity to improve the BEM value proposition in the short term is to reduce its cost. Many BEM tasks are unnecessarily labor-intensive and error prone due to poor interoperability, lack of workflow automation, and inaccessibility of supporting data. BTO can leverage its OpenStudio platform, building energy data tools, and relationships with BEM vendors to drive progress in this area.
- **Capability – there are longer-term opportunities to enhance and strategically expand the capabilities of BEM.** Longer-term, there is opportunity to enhance and expand the capabilities of BEM to better support both existing and new use cases in areas such as district-level design, building operations including building-to-grid interactions, and . BTO's EnergyPlus and Spawn-of-EnergyPlus BEM engines—and related engines THERM and Radiance—provide a platform for this growth.
- **Community – there is a continuing need and opportunity to engage with and support the BEM community.** BEM professionals are as important to the success and impact of BEM as the tools themselves. BTO should capitalize on its relationships with professional organizations such as IBPSA, ASHRAE, and AIA to continue supporting BEM professionals with training, education, and resources.

Two overarching recommendations for the program are:

- Perform formal public program-level reviews of BTO's BEM portfolio at regular intervals, e.g., every three years.
- Refresh this report document at regular intervals, e.g., every five years

A. West Coast Workshop Summary (6-9-2015)

U.S. Department of Energy's Research and Development Opportunities for Building Energy Modeling

Stakeholder Discussion Workshop Summary – Battelle, Pacific Northwest National Laboratory (PNNL), Seattle, WA

June 9, 2015 (Seattle, Washington)

Summary

On June 9, 2015, Navigant Consulting, Inc., on behalf of the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), hosted a stakeholder discussion workshop to identify research and development (R&D) needs and critical knowledge gaps related to increasing the use of whole building energy modeling (BEM) tools. This workshop covered expanding the use of BEM tools and improving their functionality. Discussion focused on issues pertaining to BEM tools in general, as well as BTO's EnergyPlus and OpenStudio. BTO is the office through which DOE funds research to support emerging building technologies, with the aim of reducing total building-related energy consumption by 50% by the year 2030

BTO hosted the workshop at PNNL's Battelle facility in Seattle, Washington. Seventeen stakeholders participated, including university researchers, national laboratories, manufacturers, software developers, and representatives from industry organizations. A list of attendees and their affiliations is included at the end of this Appendix.

Objective

The objectives of this workshop were:

- Identify current challenges for developers and users.
- Find ways to significantly increase the impact of BEM in the design and operation of energy efficient buildings, and in support of related activities such as code compliance and utility energy efficiency programs.
- Establish and prioritize areas of research that will aid in the increased use of BEM.

Process and Results

Discussions at the workshop included a large group brainstorming session as well as smaller breakout group sessions. Each attendee participated in one of two breakout sessions. During the West Coast workshop, attendees could choose from the following topic areas:

- Codes and BEM: Relationship and Strategies
- Developer Friendliness[103]

The group brainstorming and breakout sessions together generated numerous R&D activities for BTO to consider (hereafter "initiatives"). At the conclusion of the workshops, Navigant posted all of the initiatives on

[103] The terminology used in the workshop for this breakout group was 'vendor friendliness', however Navigant adopted the term 'developer friendliness' for the report based on feedback from stakeholders.

the wall and asked the participants to prioritize the initiatives by voting on the ones that they felt were most valuable and promising for BTO to undertake. Each participant received 5 votes (stickers) to distribute among the different initiatives as they saw fit (regardless of topic area). Table A-1 shows the proposed initiatives.

Table A-1 High Priority R&D Initiatives

Session	Initiative	Votes
Codes/BEM Breakout Group	Establish an example software tool ruleset that a state or local government could adopt and modify to reflect the specific performance thresholds in its code	7
Codes/BEM Breakout Group	Establish a general framework for software tool rulesets that a state/local government could use to develop and encode its own ruleset	4
Codes/BEM Breakout Group	Develop a staged strategy that a state and local government could follow to gradually increase the use of performance-based compliance paths in its codes.	6
Developer friendliness	Facilitate adoption of new releases by simplifying the IDF converters that ship with new releases of EnergyPlus and improving backward compatibility of new versions of EnergyPlus "automatic updating"	4
Developer friendliness	Address developer needs by making available better coverage of HVAC systems, improve formatting of diagnostic messages, to handle in bulk by automated processes, the ability to compile EnergyPlus, and implement Units Conversion	10
Developer friendliness	Researcher needs; modularity, ability to dial in different levels of detail, better quality inputs, transparency of equipment performance curves	19
Developer friendliness	Execution time, features, complexity; reduce redundancies in code, improve usability, upfront diagnostics, create better integration of data on top of engine, for example from BMS	7
Developer friendliness	Limitations of intelligent defaults; outsource to ASHRAE, transparency vs. simplicity: defaults should run without crashing	3
Developer friendliness	Adequacy of EnergyPlus architecture; reduce footprint of software; improve API with pluggable architecture	9

Table A-2 shows the list of key challenges and barriers to increasing the effective use of BEMs in the design and operation of energy efficient buildings, and in support of activities and programs, as identified by stakeholders.

Table A-2 Challenges and Barriers for use of BEMs

Challenges and Barriers
Code-driven rulesets don’t reflect actual performance
Designs can be inherently inefficient, yet BEM user is perceived to be in error
Prescriptive paths to compliance are becoming more stringent—prescriptive paths are no longer a viable option for many buildings
BEM needs to keep up with technologies
Tough to qualify for incentives if using a prescriptive design
TMY weather data set used can have big impact on results—can be issue for buildings on the border of climate regions
Everyone’s intelligent defaults are different

The following tables in sections below document each proposed R&D initiative; these tables reflect the raw outputs of the workshop. The tables, therefore, do not perfectly reflect a single category of initiatives, but rather, documentation of the conversations that transpired during the session. The ideas from the workshop are divided by the breakout session where they arose.

Summary of Building Codes Breakout

State and local governments establish residential and commercial building energy codes, often adopting provisions in the International Energy Conservation Code (IECC), ASHRAE Standard 90.1, or other industry standards. While most building codes provide prescriptive paths for code compliance, a state or local government can also establish alternative performance-based paths that require Building Energy Modeling (BEM) to demonstrate compliance. Performance-based paths offer greater design flexibility to building owners and designers, allowing them to trade off the cost and performance characteristics for a multitude of building components and systems. This increased design flexibility can help overcome stakeholder resistance to adoption of stricter energy codes, accelerating the rate at which state and local governments can drive code-enabled energy savings. Codes that offer performance-based paths generally include, or require the development of, computer-process-able forms of a code's energy-related requirements known as rulesets.

This breakout group outlined three options that BTO could pursue to facilitate expanded use of BEM to meet code requirements. These options either a) make it easier for state and local governments to adopt codes that incorporate performance-based alternatives, or b) make it easier to develop user-friendly BEM tools that can be used to demonstrate code compliance.

- ***Option 1:*** Establish an example software tool ruleset that a state or local government could adopt and modify to reflect the specific performance thresholds in its code
- ***Option 2:*** Establish a general framework for software tool rulesets that a state/local government could use to develop and encode its own ruleset
- ***Option 3:*** Develop a staged strategy that a state and local government could follow to gradually increase the use of performance-based compliance paths in its codes. A state and local government that elects to implement the strategy would introduce minimal BEM requirements in early years, then gradually increase requirements over time. This approach would ease the transition to performance-based compliance paths by allowing building designers and modelers to gradually develop the skills and processes needed.

Table A-3 R&D Codes and BEM: Relationship and Strategies

Initiative
Establish an example software tool ruleset that a state or local government could adopt and modify to reflect the specific performance thresholds in its code
Establish a general framework for software tool rulesets that a state/local government could use to develop and encode its own ruleset
For compliance, make BEM minimal to start, then increase over time toward 100% BEM-based compliance

Performance-based codes and LEED are driving BEM use—use the trend toward performance-based codes to increase BEM use

- M&V required in Sweden
- Seattle is considering M&V requirements
- it is tough to qualify for utility program incentives using a prescriptive building design—use performance compliance paths to qualify for incentives

Summary of Developer Friendliness Breakout

Table A-4 R&D Developer Friendliness

Initiative

Facilitate adoption of new releases

- simplify the IDF converters that ship with new releases of EnergyPlus
- improve backward compatibility of new versions of EnergyPlus (so that developers tools that use prior versions will still operate with the new release of EnergyPlus) - "automatic updating"

Developer needs

- make available better coverage of HVAC systems (*i.e.*, steam humidifiers)
- improve formatting of diagnostic messages, particularly so they can better be handled in bulk by automated processes
- some developers want the ability to compile EnergyPlus
- implement Units Conversion--support for localization (OpenStudio has it; EnergyPlus does not have it)

Researcher needs

- modularity
- ability to dial in different levels of detail (tradeoff with uncertainty)
- better quality inputs (this refers to more choice of defaults)
- transparency of equipment performance curves

Execution time, features, complexity

- reduce redundancies in code
- improve usability, upfront diagnostics
- create better integration of data on top of engine, for example from BMS

Limitations of intelligent defaults

- outsource to ASHRAE
- transparency vs. simplicity: defaults should run without crashing

EnergyPlus architecture adequate?

- API/pluggable architecture is desirable
- software is perceived to have a large footprint "inadequate"

Improve outreach to ensure no surprises about new releases of EnergyPlus

- Should BTO own the engine?

Obtain bug fixes using “GitHub”

Develop Energy Management System improvements using

- FMI
- Modelica
- Python

Establish share-ability across engines

Enable portfolio level analyses

Enable analysis of district energy systems

Enable richer set of outputs such as utility demand response

Establish Open Office question and answer sessions
Enable more information available during sizing runs
Enable the software to anticipate user intent
Enable data integration and expert models on top of engine • Pre-simulated runs, sanity checking • Multi-core parallelized analysis

Summary of Group Brainstorm Session

Table A-5 R&D Initiatives from the Group Brainstorm Session

Group Brainstorm – 7 Total Initiatives	
BEM support for commissioning and operation	2
Identify and understand impactful use of BEM	1
Characterize and drive down all sources of uncertainty	1
Improve communication of results to client	1
Link design and operation	1
Model existing buildings with operational faults	1
Model occupant behavior	1

Next Steps

Navigant, in consultation with BTO, will continue to refine and develop these R&D initiatives though additional research and follow-up interviews with individual stakeholders. Navigant will combine any duplicate or overlapping initiatives to ensure that all initiatives are unique. We will use a combination of qualitative criteria and stakeholder voting in developing final recommendations of the top R&D initiatives for BTO to consider. The opportunity assessment will serve as a guide for BTO and its partners on how best to increase the use and effective use of BEM.

Workshop Attendees

The stakeholder discussion workshop brought together 17 individuals representing a range of organizations across the industry. Table A-6 lists all the attendees and their affiliations.

Table A-6 Stakeholder Workshop Attendee List

Attendee Name	Organization
Jim McNeill	Affiliated Engineers
Peter Alspach	Arup
Krishnan Gowri	Autodesk
Brian Owens	CLEAResult
Richard See	Digital Alchemy
Amir Roth	BTO
Taylor Roberts	Group 14 Engineering
Tianzhen Hong	Lawrence Berkeley National Laboratory

Michael Wetter	Lawrence Berkeley National Laboratory
Philip Haves	Lawrence Berkeley National Laboratory
Mark Nieman	McKinstry Co.
Scott Horowitz	National Renewable Energy Laboratory
Emily Cross	Navigant Consulting, Inc.
Robert Zogg	Navigant Consulting, Inc.
Dimitri Contoyannis	NORESCO
Michael Rosenberg	Pacific Northwest National Laboratory
Scott Criswell	Wrightsoft Corp.

B. East Coast Workshop Summary (6-15-2015)

U.S. Department of Energy's Research and Development Opportunities for Building Energy Modeling

Stakeholder Discussion Workshop Summary – Navigant Offices, Washington D.C.

June 15, 2015 (Washington D.C.)

Summary

On June 15, 2015, Navigant Consulting, Inc., on behalf of the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), hosted a stakeholder discussion workshop to identify research and development (R&D) needs and critical knowledge gaps related to increasing the use of whole building energy modeling (BEM) tools. This workshop covered expanding the use of BEM tools and improving their functionality. Discussion focused on issues pertaining to BEM tools in general, as well as BTO's EnergyPlus and OpenStudio. BTO is the office through which DOE funds research to support emerging building technologies, with the aim of reducing total building-related energy consumption by 50% by the year 2030

BTO hosted the workshop at Navigant's offices in Washington, D.C. Twenty-eight stakeholders participated, including university researchers, national laboratories, manufacturers, software developers, and representatives from industry organizations. A list of attendees and their affiliations is included at the end of this Appendix.

Objective

The objectives of this workshop were:

- Identify current challenges for developers and users.
- Find ways to significantly increase the impact of BEM in the design and operation of energy efficient buildings, and in support of related activities such as code compliance and utility energy efficiency programs.
- Establish and prioritize areas of research that will aid in the increased use of BEM.

Process and Results

Discussions at the workshop included a large group brainstorming session as well as smaller breakout group sessions. Each attendee participated in one of two breakout sessions. During the East Coast discussion session, attendees could choose from the following topic areas:

- Role of BEM in Building Operation
- BEM to Support Utility Efficiency Programs

The group brainstorming and breakout sessions together generated numerous R&D activities for BTO to consider (hereafter "initiatives"). At the conclusion of the workshops, Navigant posted all of the initiatives on the wall and asked the participants to prioritize the initiatives by voting on the ones that they felt were most valuable and promising for BTO to undertake. Each participant received 5 votes (stickers) to distribute among the different initiatives as they saw fit (regardless of topic area). Table B-1 shows the proposed initiatives.

Table B-1 High Priority R&D Initiatives

Session		
Role of BEM in Building Operation	1. Existing Buildings: no existing model from the design phase—may need to develop from scratch, use reference buildings, use a simpler model than used for building design, use Google Earth and match building to reference building (relates to Initiative 6 below)	8
Role of BEM in Building Operation	2. For New Construction: Need streamlined modeling process from conceptual design through building operation, supporting data standards, contractual requirements to enforce (relates to Initiative 7 below)	19
Role of BEM in Building Operation	3. Demonstrate that it Works: show that it is cost-effective, show that it saves energy/energy costs (supported by Initiative 12 below)	11
Role of BEM in Building Operation	5. Standardize Process/Procedures for Energy Monitoring: define faults, define allowable bounds—measured vs. simulated	10
BEM to Support Utility Efficiency Programs	6. Streamline Evaluation, Measurement, and Verification (EM&V): Update reference buildings with real data: anonymize and share data (relates to Initiative 1 above)	8
BEM to Support Utility Efficiency Programs	7. Streamline Evaluation, Measurement, and Verification (EM&V): Create communication bridges, to increase interoperability from concept through to incentive (relates to Initiative 2 below)	7
BEM to Support Utility Efficiency Programs	9. BEM for Deep Energy Retrofit: Use calibration to utility data: make sure to specify what data shall be included in the calibration	7
BEM to Support Utility Efficiency Programs	12. BEM for Database Development: Data sharing is desirable to support cost-effective decision-making; make TPEx[a] available, make data sharing standard, provide large amounts of data (supports Initiative 3 above)	15

a) NREL's Technology Performance Exchange: https://performance.nrel.gov/

Table B-2 shows the list of key challenges and barriers to increasing the effective use of BEMs in the design and operation of energy efficient buildings, and in support of activities and programs, as identified by stakeholders.

Table B-2 Challenges and Barriers for use of BEMs

Challenges and Barriers
Tracking and sharing data difficulties pertaining to privacy, proprietary nature of data, data gathering and transfer, formatting and data cleaning
Identifying the essential data needed for BEM
Not all actors (architects, engineers, and sustainability consultants) understand their role in moving BEMs forward
Building owners either do not have interest or skill to use the BEM
Difficult to estimate unregulated plug loads for use in BEM
Difficult to measure energy use
Interoperability is difficult for current BEM tools
BEM can be time-consuming, however oversimplification (such as developing prescriptive databases) can lead to inaccurate results

The following tables document each proposed R&D initiative; these tables reflect the raw outputs of the workshop. The tables therefore do not perfectly reflect a single category of initiatives, but rather, documentation of the conversations that transpired during the session. The ideas from the workshop are divided by the breakout session where they arose.

Table B-3 R&D Roles of BEM in Building Operation

Initiative
Taxonomy of Building Operation (three components): • Implementation of control sequences • Health of building systems • Forecasts for both the building and the outside world

Initial ideas/questions generated:
• Are models sufficiently accurate? How far out can we project?
• Third-Party Services:
  o Building owner either doesn't care or doesn't have the skills
  o Provide load curtailment and other energy-related services
  o Do third parties need BEM to provide these services?
    ▪ Is BEM sufficiently accurate?
    ▪ Is BEM too expensive?

To what extent can reference buildings (aka, templates) be used? • What time step is needed?
How does one measure energy use? • Sensors fail • Build measuring capability into appliances/equipment?
More data will be available as more cities require building ratings
How does one predict occupancy/usage?
Need "multi-fidelity" models

Table B-4 R&D BEM to Support Utility Efficiency Programs

Initiative

1. BEM as a tool to streamline Evaluation, Measurement, and Verification (EM&V)
  a. Option D of the International Performance Measurement and Verification Protocol (IPMVP) requires utility data calibrated BEM modeling
    i. LEED used to require this, but instead will be moving toward
      1. Advanced sub-metering and trending
      2. Continuous commissioning requirements
  b. BEM can help streamline EM&V if we
    i. Update reference buildings with real data such that reference buildings can be used to reduce Program Administrator (Utility) costs associated with BEM
      1. Related to this is the need to be able to anonymize and share data, to overcome barriers to the high costs associated with BEM—this is particularly important in the context of utility programs, which are required to show cost-effectiveness with indicators such as the Societal Cost Test and Program Administrator Cost Test.
    ii. Sort out how to estimate unregulated (hourly) plug loads, which are a wild card when using BEM to assess savings (baseline model minus efficient model), and plug loads (or 'non-measure-loads') may not be properly estimated, causing estimated savings from BEM to be incorrect when scrutinized through third-party evaluation.
      1. An additional related risk to the utility is when the evaluator uses a different tool and approach than the utility used
      2. Inputs are variable
    iii. Increase interoperability (concept → incentive) by creating communication bridges
  c. Align the intent of the model with the level of effort
  d. There is a large change in percent predicted savings when the baseline model is calibrated to utility data

        i. Large residential potential
        ii. Standardized buildings (BEM) would be helpful
    e. Automate the Quality Assurance steps of modeling

2. **BEM to promote deep energy retrofits *(i.e.*, >30% reduction over baseline)**
    a. What is the benefit of BEM
        i. BEM + big data?
        ii. BEM vs. big data?
        iii. BEM:
            1. Looks at building as a whole
            2. Accounts for interrelationships between systems
            3. Allows for cost optimization
            4. Needs precise component data for accuracy and good decision-making
            5. How do defaults relate to:
    a. Non-measured energy (*i*.e., plug loads)
    b. Rooms affected (not all rooms are affected by specific measures, but all rooms have to appear in the model)
        iv. Use calibration to utility data
            1. Make sure to specify what data shall be included in the calibration
    a. Use the latest research to inform unknowns (for example, someone pointed out that much is known about occupant behavior, but no one includes it in models)
        v. Use asset scoring as a first screening step to identify which buildings should receive more detailed full BEM attention
        vi. Use BEM as an optimization tool (when deciding order of operations for measures, which retrofits to do first, or at all etc.).

3. **BEM for Database Development for Prescriptive Measures (or other)**
    a. Risks of using databases are:
        i. Actual inputs and assumptions may be very different that those used to generate the database outcomes
        ii. New technologies and approaches may not be easily or quickly updated, in reality
        iii. Additional Cons to using Databases:
            1. Assumed BEM buildings are too similar/uniform (*i.e.*, not representative of actual buildings)
            2. Interactivities may not be accurate
            3. Difficult to keep up with new technologies
            4. Occupant behavior is better understood with new research, however will not be accounted for in a prescriptive model
            5. What a project is allowed to claim savings for (in a utility program) is different from the predicted usage of the final building (two separate problems)
    b. Data sharing is desirable to support cost-effective decision-making
        i. Make TPEX available
        ii. Make data sharing standard, provide large amounts of data

Table B-5 R&D Discussion from the Group Brainstorm Session - Metrics

Initiative

Brainstorm Ideas for Metrics:
• Survey IBPSA Members
  ○ Coordinate with IBPSA and ASHRAE to tap work in progress
• Measure growth in memberships and attendance at key conferences
  ○ Poll AIA Conference attendance
  ○ Poll ASHRAE Conference attendees
  ○ IBPSA SimBuild
• Poll ASHRAE members during membership renewal
• Add BEM question to building permit applications
• Work with key organizations to determine how many owners are using BEM
  ○ International Facility Management Association (IFMA)
  ○ Building Owners and Managers Association (BOMA)
  ○ Commercial Building Energy Alliance (CBEA)
• Random sample of buildings
  ○ EIA Commercial Building Energy Consumption Survey (CBECS)
  ○ EIA Residential Energy Consumption Survey (RECS)
• Determine energy savings from BEM
  ○ What portion of savings is attributable to BEM?
  ○ AIA is working on this for their self-reporting sample (2030 Commitment)
• City (or district) project—GSF modeled
• EPA ENERGY STAR Portfolio Manager
• Record number of building owners/operators who say they operate their buildings using BEM

Table B-6 R&D Discussion from the Group Brainstorm Session - Gaps

Initiative
Gap: Accountability. This gap pertains to accountability of the larger BEM community, meaning those who perform BEM on behalf as clients and those who develop BEM software tools, to the end users they respectively serve (accountability of design professionals to their clients, and accountability of software developers to their end users). The issue being addressed was the issue of credibility of BEM: how to increase the perceived credibility of BEM, thereby increasing the value proposition, and increasing the uptake of BEM.

• Need measurement/benchmarks
  ○ Benchmarks based on measurement, and measurement itself, will serve two purposes: demonstrate to clients that the BEM community holds itself accountable, and simultaneously, consistently provide an outward measure of buildings held to a higher standard. The problem of attribution to BEM was not clarified here—a building with low energy use relative to its peers can achieve this without BEM. Therefore measurement and benchmarking would need to be particular to BEM.
  ○ Measurement could utilize utility meter data, submetered data from a customer-installed system, or a combination, as a basis for comparison of BEM outputs (hourly kWh, MCF, water use) with measured quantities.
    ▪ Benchmarking could be relative to each building against itself, or could be against peers in its CBECS, NAICS, or other defined group, for example.

Initiative

• What else can we do?
  o LEED predicted vs. actual
    ▪ This refers to measurement/benchmarking specific to high performing buildings
    ▪ The benefit of focusing on this subset of all buildings is that LEED models are generally very thoroughly vetted, and therefore represent BEM models that have undergone a high degree of quality control. For a LEED verified model, the inexperience of the BEM user has largely been eliminated by the time the model is accepted for LEED credit. Therefore, discrepancies in predicted building vs. actual building using LEED models could be said to more closely represent factors associated with discrepancies in building inputs and software tool algorithms, rather than decision-making of the BEM user.
• LEED Dynamic Plaque
  o This was a particular type of LEED certification that I believe is intended to recognize ongoing persistence of LEED measures
  o Share Data: by sharing data, there is the perception that there will be greater quality of outcomes of building models, such as low energy use and sustainability
  o Remove barriers to tracking and sharing data
    ▪ This refers to the perception of the difficulties associated with tracking and sharing data, such as privacy, proprietary nature of data, data gathering and transfer, formatting and data cleaning which can be time-consuming.
    ▪ Removing barriers to enable to free flow of data should also refer to identification of which data is most needed, and what questions it is trying to answer.
  o Quality Assurance/Quality Control for data: without proper labeling and protocols, low quality data is worse than no data at all because it can be misleading, wasting immense amounts of time (for example calibrating BEM to placeholder utility data) and resulting in poorly informed decisions resulting from BEM that do not represent the expected buildings
    ▪ Protect consumers
      » Poor data quality affects BEM software developers, design professionals who use BEM, and the owners and clients who are the ultimate beneficiaries (or victims) of decisions made using BEM

• Change building codes to make BEM the most desirable option
  o By creating prescriptive paths with fewer options, BEM-based compliance paths become desirable for building owners and design professionals due to more design options
  o BEM-based paths can more easily avail themselves of emerging technologies than prescriptive paths can, to the extent these are available or implementable in BEM
• Credential BEM practitioners
  o Overall this action reduces costs associated with BEM.
  o Throwing less experienced staff into energy modeling does not necessarily save money in the long run, and reduces the credibility of both their firms and BEM itself when models fail to predict actual cost and energy use/demand outcomes.
  o Credentialing BEM practitioners is beneficial to all stakeholders, including the BEM practitioners themselves.
  o It is not clear whether it can be said to guarantee additional energy savings, however credentialing would almost certainly result in BEM cost and time savings, as well as increased credibility.
  o Additionally, this is a way the BEM community can take demonstrate accountability.
• Separate conceptual vs. compliance model
  o This refers to the fact that there is no reason that an initial conceptual model for a project is expected to bear any resemblance to the eventual model used to determine compliance (with codes, where BEM is used as the methodology for compliance).
  o Within the idea of accountability, there needs to be recognition that there is not a one-size-fits-all model—there needs to be room for both conceptual and compliance models for the same building, without there being a perceived conflict if these are different.

Initiative

• Integrate BEM in educational systems
  ○ Teach BEM modeling in more schools
  ○ Which software?
  ○ Which types of schools?
• Single accepted model vs. larger software market
  ○ What is more desirable? Is it easier to have accountability if there is a single well vetted engine/platform, or is a free market with several options the best path to accountability of BEM, in terms of actual accuracy, actual outcomes, and perceived value?

Gap: Overall picture and individual firm contributions to the system
• Common understanding is required.
• In order to further BEM in the marketplace and increase BEM usage, we will go further faster if all stakeholder firms and organizations work together on the essential items as collectively and collaboratively agreed upon.
• There is a general feeling that while we are moving in the right direction, particularly with organizations such as IBPSA, individual firms such as architects, engineers, and sustainability consultants, may not be clear how they fit in and what they can contribute to move BEM forward.
• Enterprise level platform for program administrators
  ○ Align city and regulated utility efficiency project decisions
  ○ “Open Efficiency” (uses OpenStudio)
    ▪ Commercialization award
    ▪ SEED
  ○ Alignment
    ▪ OpenStudio export/standardization
    ▪ EDAPT/API
    ▪ Asset Score
    ▪ Portfolio Manager
    ▪ API

Next Steps

Navigant, in consultation with BTO, will continue to refine and develop these R&D initiatives though additional research and follow-up interviews with individual stakeholders. Navigant will combine any duplicate or overlapping initiatives to ensure that all initiatives are unique. We will use a combination of qualitative criteria and stakeholder voting in developing final recommendations of the top R&D initiatives for BTO to consider. The opportunity assessment will serve as a guide for BTO and its partners on how best to increase the use and effective use of BEM.

Workshop Attendees

The stakeholder discussion workshop brought together 28 individuals representing a range of organizations across the industry.

Table B-7 lists all the attendees and their affiliations.

Table B-7 Stakeholder Workshop Attendee List

Attendee Name	Organization
Ming Hu	American Institute of Architects
Melissa Wackerle	American Institute of Architects
David Bosworth	BUILDlab

Richard Lord	Carrier Corporation
Jared Langevin	BTO
Pat Phelan	BTO
Amir Roth	BTO
Jan Kosny	Fraunhofer Center for Sustainable Energy Solutions
Mike Witte	GARD Analytics
Jason Glazer	GARD Analytics
Gail Hampshire	Green Business Certification
Ed Barbour	Navigant Consulting, Inc.
Emily Cross	Navigant Consulting, Inc.
Robert Zogg	Navigant Consulting, Inc.
Stuart Dols	NIST
Lisa Ng	NIST
Kyle Benne	NREL
Mark Davis	Office of Naval Research
Mark Spector	Office of Naval Research
Nora Wang	Pacific Northwest National Lab
Chris Balbach	Performance Systems Development
Greg Thomas	Performance Systems Development
Sandro Plamp	QCoefficient
Teresa Rainey	Skidmore, Owings & Merrill
Jelena Srebric	University of Maryland
Wangda Zuo	University of Miami
Dennis Knight	Whole Building Systems

C. Attribution Studies for Regulatory Compliance

Attribution Studies for Energy Efficiency Program Evaluation for Regulatory Compliance

The concept of attribution studies used in energy efficiency (EE) program evaluation for regulatory compliance could be used to quantify attribution of energy efficiency savings to Building Energy Modeling (BEM) software tool use.

In attribution studies, a net-to-gross factor, NTG = 1 – FR + SO, is developed based on a sample of projects studied. In the case of BEM tools, FR and SO would be defined as:

- **Free ridership (FR):** A number between zero and one that measures whether the same design decisions would have occurred anyway, absent the BEM tool.
- **Spillover (SO):** A number between zero and one that credits a given project with building design decisions made for other projects, not modeled using BEM, based on the BEM building model for this given sampled project.

Using the same approach as EE program NTG analysis, the net savings attributable[104] to the BEM tool would be the apparent impact of BEM,[105] times NTG, which is typically a number between zero and one (when there is no spillover). Thus, if FR is high, such as 1.00, the attribution study concludes that user would have made the same decision without BEM and the net savings attributable to BEM would be low (potentially zero).

FR and SO are generally developed using a battery of surveys of participants (users), and sometimes non-participants (non-users) of an EE program (or potentially a BEM software tool). The primary differences between an EE program NTG analysis and a BEM tool attribution NTG analysis would be the specific questions in the survey battery and the target populations for the surveys. The process of scoring the responses of various decision makers, where the questions are designed to determine what would have happened absent the BEM tool, would be similar.

The benefit of attributing energy savings to BEM tools using the same methodology as for EE program evaluation, in particular New Construction (NC) program evaluation, is that the methodology is established and rigorous.

Regarding the determination of apparent savings, in a review of utility New Construction (NC) projects incentivized using BEM recently evaluated for three utilities, Navigant found that, while the weighted-average evaluated electricity apparent savings for a sample of projects was within a few percentage points of the originally reported savings for the sample, about half the projects in the sample saved significantly less than the utilities originally estimated based on BEM inputs used at the time the energy efficiency measures were incentivized. The BEM inputs were later found to have changed for the 'actual' evaluated building compared to what was originally expected.

Thus, for a given individual owner of a single building, there can be both perceived and real risks regarding whether BEM results for his or her building are reliable enough to support decision making based on the BEM

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104 Net Savings Attributable = Apparent Savings from BEM x NTG Factor

105 The 'Apparent Savings from BEM' could potentially be derived from AIA study aggregate results, and the NTG attribution could then be applied to these apparent savings to calculate the net savings attributable to BEM. Alternatively, an approach similar to an EE program impact evaluation could be undertaken to determine the BEM apparent savings (baseline building energy use minus efficient building energy use) for a sample of buildings the population of interest, in this case the population of all buildings modeled using BEM during a specified time period (perhaps a period of several years).

model. As suggested by the results of NC program evaluations mentioned above, for about half the projects, the projects save less than expected due to changes in basic BEM input values, such as quantity, capacity, and efficiency of equipment, building occupancy, and equipment schedules. From the point of view of a building owner, the level of effort they are willing to invest for their design BEM model may not match their own acceptable risk tolerance for lower than expected savings. As discussed above in this report, a higher level of effort in the BEM building model reduces uncertainty in the BEM energy calculation.

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