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Development of building energy asset rating using stock modelling in the USA

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The US Building Energy Asset Score helps building stakeholders quickly gain insight into the efficiency of building systems (envelope, electrical and mechanical systems). A robust, easy-to-understand 10-point scoring system was developed to facilitate an unbiased comparison of similar building types across the country. The Asset Score does not rely on a database or specific building baselines to establish a rating. Rather, distributions of energy use intensity (EUI) for various building use types were constructed using Latin hypercube sampling and converted to a series of stepped linear scales to score buildings. A score is calculated based on the modelled source EUI after adjusting for climate. A web-based scoring tool, which incorporates an analytical engine and a simulation engine, was developed to standardize energy modelling and reduce implementation cost. This paper discusses the methodology used to perform several hundred thousand building simulation runs and develop the scoring scales.

Keywords: Asset Score; energy rating; Latin hypercube sampling; EnergyPlus

1. Introduction and background

Building energy rating policies are mandatory in more than 30 countries worldwide. The most commonly known rating system in Europe is the European Union (EU) Energy Performance of Buildings Directive (EPBD), enacted in 2002 (EPBD 2013). The EPBD requires building energy rating and disclosure in all member states for both commercial and residential properties. Australia, Brazil and China also have passed building energy rating laws over the last eight years (McCabe and Wang 2012). However, given the variety of commercial buildings, a robust and consistent framework for evaluating building stocks is still lacking. The work presented in this paper uses stock analysis to provide a basis for benchmarking.

The two most common building-energy-rating indices adopted in the policies mentioned above are asset ratings and operational ratings. Asset ratings use modelled energy use to evaluate the as-built physical characteristics of buildings under standardized operating conditions. Operational ratings use measured energy use to evaluate the actual building performance based on the specific operational choices. These two indices are expected to provide complementary information about a building's overall efficiency. However, it is often difficult to make a direct comparison of the two indices because of the discrepancy between modelled and measured energy use. Due to the wide variations in factors related to building operation and maintenance, the difference between modelled and measured energy use cannot simply be attributed to a few known variables, such as operating schedules and number of occupants. Many studies have revealed such discrepancies but are not yet able to fully explain the variability (Johnson 2003; Turner and Frankel 2008; Bloomfield and Bannister 2010). This poses a challenge to developing a creditable asset rating system in the absence of actual energy use data, which are often used to verify or calibrate energy models.

The predominant energy rating system currently in use in the USA is ENERGY STAR Portfolio Manager® (ESPM), created by the US Environmental Protection Agency (EPA 2015). ESPM allows a building owner to compare actual energy use to similar buildings. Ratings are predicted on a statistical scale (i.e. percentile ranking) based on 2003 Commercial Buildings Energy Consumption Survey (CBECS) data (EIA 2006). The usability of ESPM is limited by the requirements of whole-building utility data, sample size in the CBECS database, and lack of means to isolate building physical characteristics and occupant behaviour (McCabe and Wang 2012).

To fill in the gap, the US Department of Energy (DOE) started developing a national asset rating system in 2012. The rating system and tool, known as the Building Energy Asset Score, is a voluntary national scoring system for commercial and multi-family residential buildings. The goal of the score is to encourage improvement of energy-related building characteristics by enabling building own-

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*Corresponding author. Emails: nora.wang@pnnl.gov, na.nora.wang@gmail.com ers and managers to compare their building infrastructure against peers and tracking the energy efficiency impacts of building upgrades over time. The Asset Score will also help other building stakeholders (i.e. building investors, tenants, financiers and appraisers) understand the relative efficiency of different buildings in a way that is independent of occupancy and operational choices.

Challenges to developing a national asset rating system include accurate data input and a consistent modelling method. A study of more than 7000 UK properties with Energy Performance Certificates (asset rating in England and Wales) showed no apparent correlation between energy ratings and total income on commercial properties (Cudworth et al. 2010). This raised a strong concern over the accuracy of the rating itself. A review of the EU experience under EPBD suggested that model accuracy can be improved by simplifying the data acquisition and subsequently increasing the number of default values required for the calculation (BPIE 2010). With simplified data inputs, the deviation from calculated performance to actual building performance is reduced from 30% to 10% (BPIE 2010). Simplified data acquisition also requires less expertise, time and effort, and therefore reduces implementation costs and increases adoption of rating systems.

Various approaches have been taken to standardize energy modelling. ISO 13790:2008, widely applied in Europe to calculate building energy performance, defines the calculation methods according to a set of normative statements about functional building category, assumed usage scenario, system efficiency and so on. For example, the UK Department of Communities and Local Government adopted the fully prescribed monthly quasi-steady-state method and developed it into a simplified asset-based calculation procedure – Simplified Building Energy Model (BRE 2010). The monthly calculation method gives more accurate results on an annual basis, but large relative errors occur in the months close to the beginning and the end of the heating and cooling season (ISO 13790:2008, Section 5.3). One may argue that the accuracy of the calculated energy use is less relevant because the asset rating does not need to predict actual energy consumption. Rather, it guarantees the ranking of a building on a relative scale, which in the case of the European energy asset rating system is the energy performance coefficient of the rated building and the baseline building (Lee, Fei, and Augenbroe 2011). However, an oversimplified approach may limit the future development of a potential link between the calculated and the measured building energy performance via, for example, automated model calibration, which has made significant progress thanks to supercomputers and machine learning technology (Sanyal et al. 2014). Establishing such a link in the future is essential for building owners, operators and tenants to gain insight into their building systems and operations and develop actionable strategies accordingly. Moreover, building a full-scale energy model streamlines the process of benchmarking, energy audit and retrofit, when a model generated for asset rating can be used for retrofit analysis.

This paper presents the methodology for developing a national asset rating system in the USA to meet the above-mentioned criteria – credibility, validity, affordability and potential for further growth. A web-based Asset Scoring Tool allows users to create standardized energy models, run real-time thermodynamic simulations, and obtain an Asset Score Report that includes building scores, system evaluations and building upgrade opportunities. A score is calculated based on the modelled source energy use intensity (EUI) after adjusting for climate. The Asset Score does not rely on a database or specific building baselines to establish a rating. Rather, distributions of EUI for various building use types were constructed using Latin hypercube sampling (LHS) and converted to a series of stepped linear scales to score buildings. Asset Scores were tested on more than 400 buildings, and the results are also discussed in this paper.

2. Asset Scoring Tool

Conventional building energy modelling is in many ways as much art as science in that each modeller needs to apply a substantial amount of judgement. This judgement leaves room for different interpretations of standards and different approaches to modelling a specific situation. While this flexibility has its advantages, it can create challenges when trying to compare models created by different individuals. Standards such COMNET's (2010) Commercial Buildings Energy Modelling Guidelines and Procedures provide a standard modelling approach for building energy modelling professionals; however, full compliance and quality assurance still require significant effort from both end users and policy makers.

To increase standardization compared with an approach that requires users to build their own energy models, and to reduce implementation costs for users, the Asset Score employs a web-based evaluation tool built on OpenStudio® and EnergyPlus (DOE EERE 2015). A sub-hourly, whole-building EnergyPlus simulation can provide the level of detail required to model the most complex buildings being built today and produce results in which end users can have greater confidence. The drawback of a full-scale modelling approach is that if users need to provide all inputs required to build a detailed model, the tool will be limited to the most experienced user group and the modelling process will be highly time consuming and costly.

The Asset Scoring Tool integrates an analytical engine, which estimates building parameters not entered by users, to enable a more simplified data collection method. The analytical engine is based on the Facility Energy Decision System (FEDS™), which is designed for quick and scalable building energy audits and analyses over single buildings as well as large groups of buildings (PNNL 2014). Generated input values are arrived at by several

Table 1. Model input generation methodology.

Minimum user inputs	Inferred values for energy model	Values based on
Roof type	Roof assembly U-value, insulation thickness/R-value	Roof type, building location, year of construction, wall type, use type
Wall type	Wall assembly U-value, Insulation thickness/R-value	Wall type, building location, year of construction, use type
Window framing type and glass type	Window U-value, solar heat gain coefficient	Window framing type and glass type
Lighting type and % of floor served	Number of fixtures	Standard illuminance levels for the building space type
Cooling equipment type	Cooling coefficient of performance	Equipment type and year of manufacture (assuming typical replacement rates based on the type of equipment)
Heating equipment type and fuel	Heating efficiency	Equipment type and year of manufacture (assuming typical replacement rates based on the type of equipment)
	Thermal zone layout and perimeter zone depth	Building footprint dimension
Service hot water type and fuel	Hot water system efficiency	Equipment type and year of manufacture (assumed to be year of construction if not entered by users)

means. All are based on user inputs, such as building location and vintage, with examples highlighted in Table 1.

In addition to providing data-driven inferences, the analytical engine also calculates system capacities and parameters that are difficult to obtain, such as infiltration rates and fan static pressure. The inferred values, combined with additional assumptions and settings specific to the Asset Score approach, enable the Asset Scoring Tool to produce the required detailed inputs from a small subset of user inputs. Given this approach, the tool reduces the time and expertise required to model a building accurately while supporting variable and complex commercial buildings.

The Asset Scoring Tool also provides feedback on potential opportunities in areas of heating, ventilation, and air conditioning (HVAC) equipment, envelope, glazing, service hot water and lighting. The tool performs a life-cycle cost assessment of retrofit measures, using a modified version of the life-cycle methodology required for federal buildings in the USA, as specified in the US Code of Federal Regulations (10 CFR Part 436). Relying on the algorithms and costs defined in FEDS (PNNL 2014) and COMNET (2010), the Asset Scoring Tool automatically generates a building upgrade model including all identified retrofit measures. The predicted energy consumptions of the current and potential buildings are then compared to give the user an estimate of the potential energy savings should all measures be implemented as modelled in their building.

3. Model inputs and operation assumptions

3.1. Standard operating conditions

The Asset Score is generated by simulating building performance under a standard set of typical operating and occupancy conditions. The operating assumptions include thermostat settings; number of occupants; and receptacle, process and hot water loads. Schedules of operation for HVAC, lighting and other systems also are standardized. All assumptions are derived from ASHRAE Standard 90.1-2013 and DOE prototype buildings models when not specified in the ASHRAE standard. Prototype buildings are a set of EnergyPlus models developed by Pacific Northwest National Laboratory (PNNL) as part of DOE's support of ASHRAE Standard 90.1. The prototype buildings represent 80% of the commercial building floor area in the USA for new construction, including both commercial buildings and multi-family residential buildings (Thornton et al. 2011). The prototype models include 16 commercial building types in 17 climate locations (across all 8 US climate zones) for recent editions of Standard 90.1. The Asset Score uses the most current version of Standard 90.1 (2013) as references for building EnergyPlus models.

Assuming all buildings of a similar type have identical hours of operation and occupancy patterns allows the Asset Scoring Tool to focus on the as-built efficiency of a building. By focusing only on buildings' physical characteristics and removing occupancy and operational variations, the rating system allows equivalent comparisons between differently operated buildings.

3.2. User inputs and sensitivity analysis

The Asset Score evaluates the as-built physical characteristics of buildings that contribute to their overall energy efficiency. The physical characteristics evaluated include the building envelope, the mechanical and electrical systems, and other major energy-using equipment, such as commercial kitchen and refrigeration systems.

A large-scale one-at-a-time sensitivity analysis was performed to verify that the Asset Score data set covers the most important building characteristics that affect a building's efficiency level. The sensitivity building characteristics are determined by varying each parameter independently while all others are held constant. A series of base models were generated that represented various building types and their typical physical and system configurations in all climate locations. The base models were simplified ASHRAE Standard 90.1-2004 prototype buildings generated by the Asset Scoring Tool. The building characteristics, geometry, envelope constructions, lighting systems and HVAC system configurations were determined through the DOE/PNNL prototype buildings (DOE EERE 2014). ASHRAE 90.1-2004 buildings were chosen to represent average buildings in the technical development of Asset Score. The 2004 edition of Standard 90.1 is also used as a stable baseline for future energy code development because "after 2004 the prescriptive requirement in Standard 90.1 started becoming too complex to develop clear rules that result in consistent modelling of baseline" (Rosenberg et al. 2015, 3.4).

Thirty-five variables were individually simulated (no interactive effect) within the bounds of the defined minimum, mean and maximum values to quantify the variables' range of impact on each building type, within each of the 15 representative climate locations in the USA (Note that 2 of total 17 representative locations are not within the USA) Table 2 gives the input variables analysed. The ranges of the variables were defined as multipliers of the base values, allowing the variables to be reused with differing base model inputs. Each model was run and evaluated using the Typical Meteorological Year 3 (TMY3) weather files for the 15 locations. The base values from the 2004 prototype models were defined as the mean values. The minimum and maximum inputs ranges were developed based on the vintage of the existing building stock and the best technologies on the market. The ranges were reviewed by invited architects, mechanical engineers and building scientists.

The sensitivity analysis identified all inputs that are important to determining a building's efficiency level, as well as their level of impact by building use type, size and location. Overall, interior lighting power density, heating system efficiency, floor-to-floor height and air handler fan efficiency are the most sensitive parameters for most of the use types. The ranking of the sensitive variables for different use types changes by climate zone. The inputs and outputs of each case are documented in the Asset Score technical protocol (Wang et al. 2015).

4. Existing scoring methodologies and challenges

4.1. Existing methodologies

There are several ways to deliver information on building energy performance to consumers. Various types of scales have been used in the existing building asset and operational rating systems, including the following:

- *Scale reflecting physical units*: This type of scale is based on a certain type of physical unit. For example, the EnergyGuide label (mandated by the US Energy Policy and Conservation Act of 1975 and directed by the US Federal Trade Commission) – a yellow tag attached to most household appliances in the USA – uses a physical scale (supplemented with cost information), such as kilowatt-hours per year in the case of refrigerators, supplemented with the expected annual operating cost. Another example is fuel efficiency rating (miles per gallon in the USA, UK, Canada; litres per 100 km in other countries) for vehicles. Although physical units can communicate technical information to consumers, consumers may be unable to easily judge if they are unfamiliar with the units. Building energy units such as MJ/m^2 (kBtu/ft^2 in the USA) do not mean enough to most consumers without engineering or energy

Table 2. Examined asset score variables.

No.	Variables	No.	Variables
1	Air Handler Fan Efficiency	19	Location
2	Aspect Ratio	20	Orientation
3	Chilled Water Reset	21	Perimeter Zone Depth
4	Chiller Pump Control	22	Roof Construction Type
5	Condenser Pump Control	23	Roof U-Value
6	Cooling Efficiency	20	Shading Height above Window
7	Cooling Tower Control	25	Shading Projection Factor
8	Daylighting Control	26	Gross Floor Area
9	Economizer	27	Supply Air Temperature Reset
10	Fan Control	28	Wall Construction Type
11	Fan Static Pressure Reset	29	Wall U-Value
12	Floor Plate Area	30	Water Heater Efficiency
13	Floor R-Value	31	Window Solar Heat Gain Coefficient
14	Floor-to-Floor Height	32	Window Sill Height
15	Heating Efficiency	33	Window U-Value
16	Heating Fuel Type	34	Window Visible Light Transmittance
17	Interior Lighting Power Density	35	Window-to-Wall Ratio

knowledge. The Asset Score aims to promote market transformation and educate consumers, and the public may have difficulty interpreting an absolute energy scale. In addition, an asset rating for buildings is more complicated than those for appliances and vehicles due to the impact of local climate. An unprocessed EUI does not offer a direct comparison among similar buildings across different climate locations.

- *Scale converting physical units into categories*: Physical units can be converted into a category system, which can be presented in letters, stars or other symbols. Compared with continuous numeric scales, categorical scales have been shown to improve comprehension because they are easy to recognize and are quickly deciphered (Thorne and Egan 2002). Viewers can more easily gauge a building's performance relative to other buildings or a reference point. Letter grades have been used in multiple building rating systems such as the Building Energy Quotient from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE 2015) and the UK Energy Performance Certificate (DCLG 2012). Building Energy Quotient coverts a ratio of the modelled energy use and baseline energy use into seven bins represented by letters from A + to F. Energy Performance Certificate uses an A-to-G chart to represent a scale of 1 to 100. In Ireland, the A-to-G scale for building energy rating is furthered divided into 15 bins using designators of A1, A2, A3, etc., based on primary energy use per unit floor area per year (kWh/m^2/year) (Stationery Office Dublin 2006). In China, the asset rating has five levels, from one to five stars with the five-star level representing the most energy efficient buildings (Chinese State Council 2008). While stars and grades simplify things for consumers, a binned system also has drawbacks. Use of a binned system can appear qualitative. Consumers may have different interpretations of the meaning of a B- or C-rated building, for instance. The number of bins is also important. Too many bins may complicate the system, while too few bins can make it hard for a building to improve from one bin to the next and may not appropriately reflect the investments made and the savings being achieved.
- *Scale converting physical units into a continuous numeric score*: Physical units or ratios can also be converted into a score or index that consumers may understand easily. ESPM, for example, uses a 100-point percentile rank scale based on supporting databases that provide statistical representation of a given building type (EPA 2015). A statistical scale like ESPM is not appropriate for the Asset Score because there is insufficient data on energy use of existing buildings under common operating conditions.

After considering the alternatives, a 1- to 10-point scale with 0.5-point intervals was selected for the Asset Score. The energy asset rating scale should be easily and broadly understood with little misinterpretation. Compared with a letter scale, the 10-point scale will likely cause less prejudgement. For example, the New York City Health Department (2012) requires restaurants to post letter grades (A, B or C) showing sanitary inspection results. A B-rated restaurant implies some degree of violation of the city and state food safety requirements. In this case, an energy asset rating of B may carry a similar negative meaning. In comparison, a mid-range scoring building can still be considered good, depending on the market average. The asset rating scale also needs to provide enough granularity for buildings to show improvements over time as upgrades are made. The Asset Score scales are divided into multiple sections. For different building use types, each additional half-point on the scale corresponds to a predefined reduction in source EUI. In the low score sections, the EUI range is larger. This means that a building with a lower score (higher EUI) needs to achieve more EUI reduction to obtain an additional half-point. As a building becomes more efficient, it is usually more difficult and costly to further reduce its energy use; therefore, the scale appears to be less stringent on the high score end. The scoring method is discussed in Section 5.

4.2. Challenges of choosing a baseline for a ratio scale

To convert modelled energy use into a rating, a baseline building is often used by setting the rating metric to be the ratio of the rated building's energy use to that of a baseline building. The baseline building can be the same building designed to meet energy efficiency code requirements or a typical building such as a DOE prototype building (DOE EERE 2012).

The ratio method using a code-compliant baseline has two potential challenges: selecting the proper codes and evaluating different fuel types. Different scoring systems rely on different baseline buildings. For example, the 2009 version of the US Green Building Council's Leadership in Energy and Environmental Design (LEED) for New Construction and Major Renovations (USGBC 2009) requires that the baseline building performance rating be calculated according to the building performance rating method in Appendix G of ASHRAE Standard 90.1-2007. The recently launched LEED v4 refers to ASHRAE Standard 90.1-2010. The evolvement of building energy codes creates a moving target.

A code-compliant baseline building does not reflect the difference in fuel types because the baseline building and the rated building are modelled with the same type of HVAC system. For example, if the rated building has electric resistance heating, the baseline building is also modelled with electric heating. The electric heating system may appear to be efficient because both the rated and baseline buildings have 100% efficient heating systems. Using grid-purchased electricity (mainly from fossil–fuel power plants in the USA) to heat a building, especially in a heating dominant climate, is likely an in efficient option. Hence, the choice of primary heating fuel and the impact on source energy use is not reflected through such a comparison.

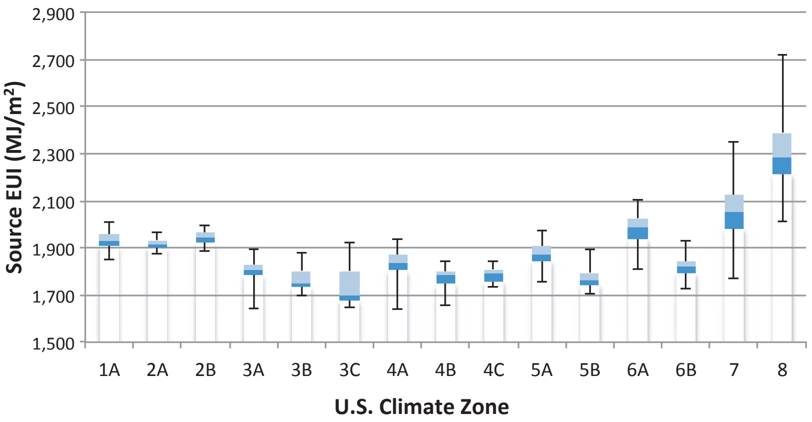
A fixed baseline also poses two challenges: choosing the most appropriate benchmark and the accuracy of using a representative city for other climate locations in the same climate zone. A chosen benchmark building should be comparable to the rated building in terms of building size, function and geographic location. For example, the set of reference buildings (precedents of the prototype buildings) includes three sizes of offices: large office is 46,319 m^2 (498,588 ft^2), medium office is 4982 m^2 (53,628 ft^2) and small office is 511 m^2 (5500 ft^2) (DOE EERE 2012). The modelled site energy uses of post-1980 construction (compliant with ASHRAE Standard 90.1-1989) for these three reference buildings in Chicago are 715 MJ/m^2 (63 kBtu/ft^2), 750 MJ/m^2 (66 kBtu/ft^2) and 818 MJ/m^2 (72 kBtu/ft^2), respectively. In reality, there are no distinct cut-off points to define small, medium and large office buildings. It is difficult, if not impossible, to choose a single number as the fixed benchmark line for each building type. In addition, only 16 building use types have been developed to represent approximately 70% (NREL 2011) of the commercial buildings in the USA. The remaining 30% might be difficult to represent by the typical reference building approach, so the application of asset rating to all commercial buildings would be limited.

Fifteen cities (see Figure 1) in the USA representing the 15 climate locations (8 climate zones with different moisture regimes) are often used by researchers to investigate energy use variations across the country. However, energy use data from one climate location is inadequate as a direct baseline to rate other buildings in the same climate zone. Figure 1 shows that, within each climate zone, the difference between the highest and lowest modelled source energy use of the prototype medium office (compliant with ASHRAE Standard 90.1-2004) varies from 114 to 681 MJ/m^2 (10–60 kBtu/ft^2) when the weather location changes. The prototype buildings were developed following corresponding requirements in ASHRAE Standard 90.1 for specific climate zones. In other words, the models have the same geometry but slightly different envelope characteristics and system configurations. Within each climate zone, the variations in energy use arise from variations in the specific weather files.

For the reasons discussed above, the Asset Score does not directly use a baseline model as the benchmark. Instead, it converts modelled source EUI into a score. The following section discusses how a series of rating scales were developed using LHS analysis.

4.3. *Stock energy use data and modelling*

Construction of EUI distributions for various building types is essential to developing a rating system. The



Zone 1A: Miami, Florida (hot, humid);
Zone 2A: Houston, Texas (hot, humid);
Zone 2B: Phoenix, Arizona (hot, dry);
Zone 3A: Memphis, Tennessee (hot, humid);
Zone 3B: El Paso, Texas (hot, dry);
Zone 3C: San Francisco, California (marine);
Zone 4A: Baltimore, Maryland (mild, humid);
Zone 4B: Albuquerque, New Mexico (mild, dry);
Zone 4C: Salem, Oregon (marine);
Zone 5A: Chicago, Illinois (cold, humid);
Zone 5B: Boise, Idaho (cold, dry);
Zone 6A: Burlington, Vermont (cold, humid);
Zone 6B: Helena, Montana (cold, dry);
Zone 7: Duluth, Minnesota (very cold);
Zone 8: Fairbanks, Alaska (extremely cold).

Figure 1. Modelled building energy use of prototype medium office at 15 climate locations (in color online).

CBECS (EIA 2006) is a national survey that collects information on the stock of US commercial buildings, their energy-related building characteristics, and their energy consumption and expenditures. It is the most robust dataset and is often used as a resource to understand the nation's building stock and as the basis of a benchmarking tool such as ESPM. However, measured energy consumption reflects a building's as-built efficiency with its actual operational conditions. It is impossible to disaggregate CBECS data and separate the impacts of building operation and maintenance. Moreover, CBECS data do not cover all of the building use types.

Stock modelling can generate EUI distributions that are more relevant in setting the Asset Score scale. Currently there is no robust and consistent framework for benchmarking performance simulation. Previous stock modelling efforts have shown usefulness in evaluating technology assessments for the US sector. The Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector (Griffith et al. 2007) modelled each of the CBECS buildings with the limited data provided. Once base models were generated, potential technologies could be modelled and evaluated. CBECS weights were used to aggregate the results to a national/regional level. The result of this study showed the potential impact of future technologies; however, there was no attempt to interpolate (or extrapolate) the building characteristics or combine unique sets of technologies.

5. Scale development using LHS

To simulate the large parameter space efficiently, the LHS method was used to generate stratified samples to obtain numerical results – modelled energy use distributions, in this case. Using LHS over a conventional Monte Carlo method allows for far fewer samples to be run to evaluate a similar parameter space.

5.1. Base models and input sampling

A series of base models that represent various building types and their typical physical and system configurations in all climate locations were first generated. The base models are simplified ASHRAE Standard 90.1-2004 prototype buildings generated by the Asset Scoring Tool. The same base models were used for sensitivity analysis as described in Section 3.2. The building characteristics, geometry, envelope constructions, lighting systems and HVAC system configurations were determined through the prototype buildings.

The sensitivity analysis provided an initial list of variables that significantly influence building energy use. Each variable was given an input distribution representing typical efficiency range based on the vintage of existing building stock as well as current technologies on the market. The lowest- and highest-efficiency values defined the minimum and maximum limits. The most likely values (modes) were the values defined in the baseline models. Most often these values were defined as ASHRAE Standard 90.1-2004 code requirements. As an example, Table 3 lists the evaluation ranges defined for a few envelope parameters. The minimum value was defined on the basis of the pre-1980s DOE Commercial Reference Building models (DOE EERE 2012) and the maximum value was defined on the basis of ASHRAE Standard 90.1-2013, Appendix A, which provides thermal property values representing the best available envelope constructions.

The parameters are sampled with a LHS algorithm to ensure uniform sampling across the probability distributions. Using LHS creates a smoother distribution where the data follow the input distribution more accurately using fewer samples.

Input distributions were generated using the probabilities from the samples defined above. Each simulation was run and the resulting output distribution probability density function was generated. (See Figure 2 for an example of inputs of air handler efficiency and outputs of source energy use.) The outputs for each variable were individually evaluated to verify the base models ran as expected and the sampling method applied perturbations correctly. Tornado plots were generated to show the sensitivity of each parameter, as compared to all other parameters.

5.2. Modelled EUI distribution

The office building type is used as an example to describe the procedure of scale development. More than 40,000 simulation runs were completed for the office use type,

Table 3. Example of evaluation ranges developed for envelope parameters.

Display name	Units	Minimum	Mode	Maximum	Distribution
Floor R-value (slab-on-grade)	K m^2/W (ft^2 F hr/Btu)	RSI-0 (R-0)	RSI-0 (R-0)	RSI-5 (R-27)	Triangular
Wall wood siding U-value	W/K m^2 (Btu/hr ft^2 °F)	USI-1.31 (U-0.23)	USI-0.5 (U-0.089)	USI-0.182 (U-0.032)	Triangular
Roof built-up wood deck U-value	W/K m^2 (Btu/hr ft^2 °F)	USI-5.68 (U-1)	USI-0.35 (U-0.063)	USI-0.091 (U-0.016)	Triangular
Window U-value	W/K m^2 (Btu/hr·ft^2 °F)	USI-6.93 (U-1.22)	USI-3.23 (U-0.57)	USI-0.681 (U-0.12)	Triangular

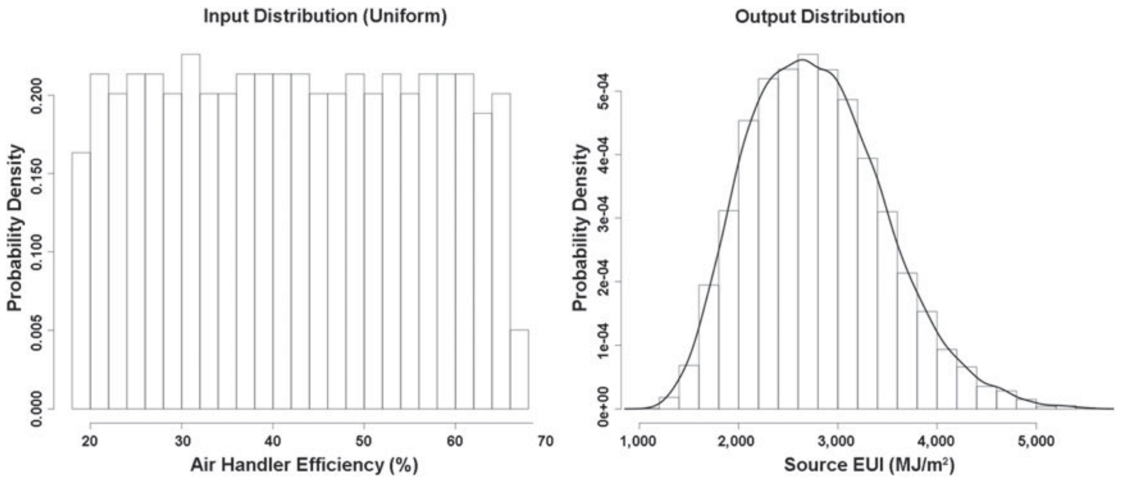


Figure 2. Example plots of a single input (air handler efficiency) distribution and the overall output (EUI) distribution.

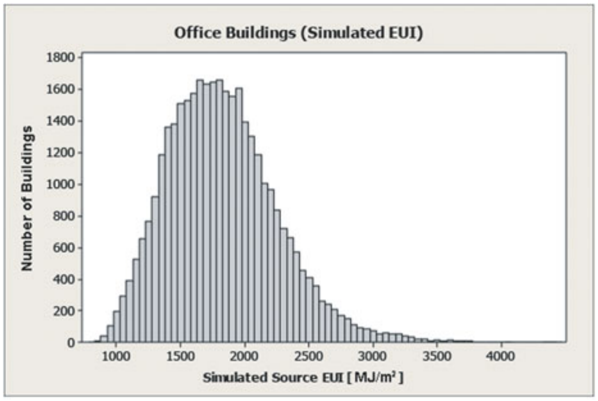


Figure 3. Simulated source EUI for office use type (in color online).

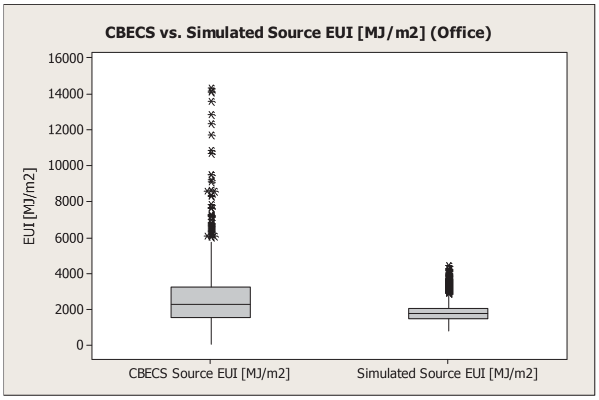


Figure 4. Box plot of office source EUI from CBECS and simulations (in color online).

including small, medium and large office buildings. The output is a large set of building energy use across the 15 climate locations (Figure 3). To account for climate variability and enable a fair comparison between energy use of buildings at different locations, EUIs that are sensitive to weather are adjusted before a building is scored. A series of corresponding weather coefficients were developed and applied to the modelled site HVAC EUI values (Wang, Goel, and Makhmalbaf 2013; Makhmalbaf, Srivastava, and Wang 2013). Equation (1) shows how adjusted EUI (MJ/m^2 or kBtu/ft^2) is calculated.

$$\begin{aligned}&\text{Adjusted EUI}_{\text{Weather Site A}}\\&\quad= \text{Heating Coefficient}_{\text{Weather Site A}}\\&\qquad\times \text{Heating EUI}_{\text{Weather Site A}}\\&\qquad+ \text{Cooling Coefficient}_{\text{Weather Site A}}\\&\qquad\times \text{Heating EUI}_{\text{Weather Site A}}\\&\qquad+ \text{Fan Coefficient}_{\text{Weather Site A}} \times \text{Fan EUI}_{\text{Weather Site A}}\\&\qquad+ \text{Other EUI}_{(\text{not weather dependent})}. \qquad (1)\end{aligned}$$

A total site EUI is then calculated and converted to source EUI.

In Figure 4, a box plot compares the distribution of simulated source EUIs for office buildings with that of EUI data from the CBECS database. Energy use data by fuel type for the 976 buildings where the principal building activity is ‘Office’ were extracted from CBECS. The source energy use of each office building was calculated using the national average site-to-source conversion factors developed by the U.S. EPA (2013). The same set of conversion factors was adopted in the Asset Score.

Although less applicable than the simulations, CBECS data nevertheless provide an additional reference for evaluating the reasonableness of Asset Score scales. A t-test yielded low p-values and indicated that the two data sets are statistically different. As shown in Figure 4, the simulation data have a much narrower distribution (mean = 1817 MJ/m^2, standard deviation = 432 MJ/m^2) than CBECS (mean = 2657 MJ/m^2, standard deviation = 1806 MJ/m^2) and lower energy use in general. CBECS raw data include a larger variation of building operations and occupancy (from partially occupied to extremely long operation hours) and miscellaneous loads (from standard office loads to heavy IT loads on trading floors). In addition, in a simulated environment, building systems are maintained in a perfect condition and operate at a higher efficiency level than those in the real world. These factors all contribute to the extremely low and high energy use in the CBECS data. Despite these discrepancies and the fact that simulated results seldom match measured data unless models are tightly calibrated, the stock simulation results show as a subset of the CBECS data as expected. Future studies can further investigate the contributing factors by varying the operational assumptions.

5.3. *Developing rating scales based on EUI distributions*

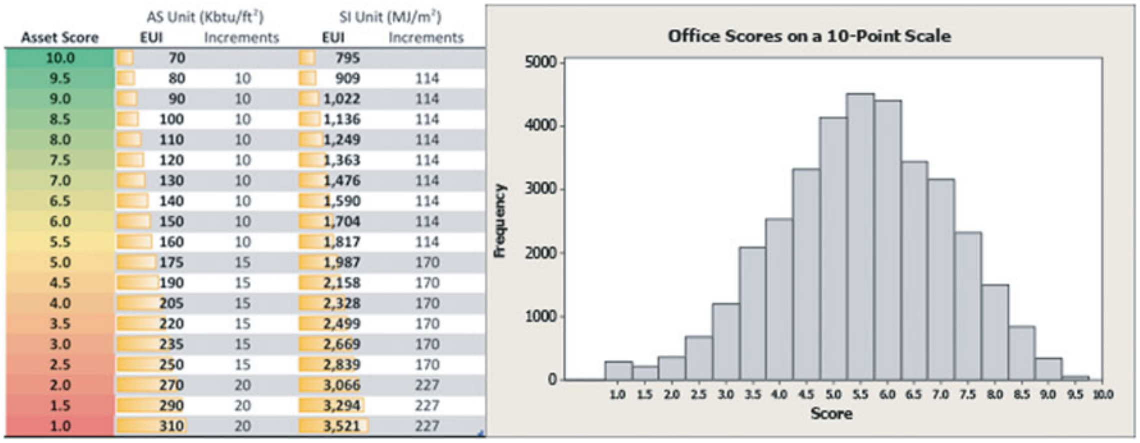
Developing the energy asset scoring scale begins with defining the EUI for the two endpoints, 1 and 10, with the high end of the scale representing highly efficient buildings. The corresponding EUI for an Asset Score of 10 reflects the lowest expected energy use achievable given current efficient building technologies and no renewables, as modelled by the current version of the Asset Scoring Tool. The low end of the scale (an Asset Score of 1) represents inefficient buildings. Yet the corresponding EUI for an Asset Score of 1 is not the least efficient building in today's commercial and multi-family residential building stock; cutting off the tail end of the lowest performers ensures that the whole scale is not skewed towards the low-efficiency end.

To be effective, the energy asset scoring scale needs to reflect the variability within the building stock and recognize the energy efficiency improvements of both low- and high-efficiency buildings. A uniform scale is simple to implement. On a uniform scale, the EUI decrement, that is, the amount of energy reduction required to earn an additional point, is constant across the entire scale. However, because it is usually more costly to further reduce energy use in a highly efficient building where low-cost measures have already been implemented, progressive bins are used to define the scale – that is, the EUI decrement is smaller at the high end of the 10-point scale and larger at the low end of the scale.

A progressive binning method was used to establish an appropriate scale for the Asset Score. To establish a standard method for developing the progression of bins across building use types, four control points were set for the Asset Score 10-point scale for each building type:

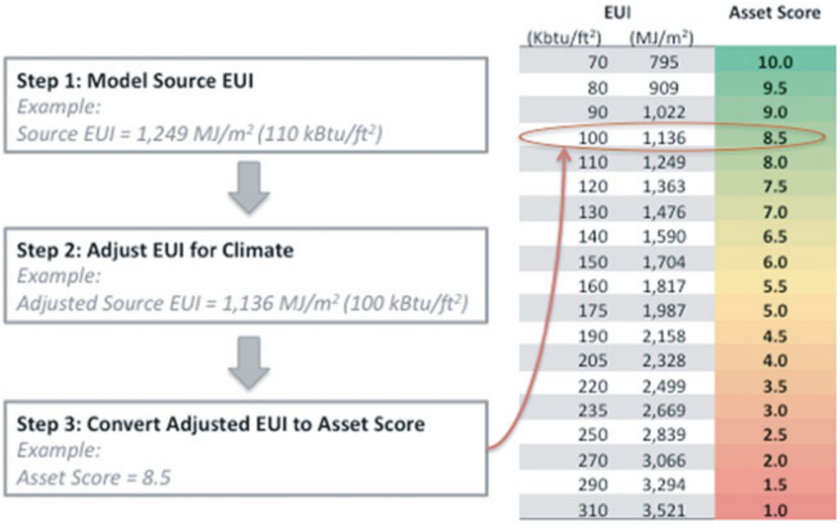
- *Minimum EUI*: Achievement of this EUI or lower entitles a building to receive a score of 10. Minimum EUI was set to be equal to the minimum EUI achieved in the simulation environment (which corresponds to the upper 5th to 10th percentile in CBECS data set).
- *High-performance building EUI*: Achievement of this EUI entitles a building to receive a score in the 8–9 range. EUI for a high-performance building was set to be equal to 30% lower than that of a prototype building complying with minimum requirements of ASHRAE Standard 90.1-2004.
- *Average building EUI*: Achievement of this EUI entitles a building to receive a score in the 5–6 range. EUI for an average building was set to be equal to the median EUI achieved in the simulation environment.
- *Maximum EUI*: A building with an EUI of this level or greater will receive a score of 1. Maximum EUI was set to be equal to the lower 95th percentile of simulated EUI.

A score table was developed based on this methodology. The simulation data (shown in Figure 3) were then scored to test the developed scale. Figure 5 shows the score distributions of the simulated data. The mean score is 5.5



	AS Unit (Kbtu/ft^2)		SI Unit (MJ/m^2)	
Asset Score	EUI	Increments	EUI	Increments
10.0	70		795	
9.5	80	10	909	114
9.0	90	10	1,022	114
8.5	100	10	1,136	114
8.0	110	10	1,249	114
7.5	120	10	1,363	114
7.0	130	10	1,476	114
6.5	140	10	1,590	114
6.0	150	10	1,704	114
5.5	160	10	1,817	114
5.0	175	15	1,987	170
4.5	190	15	2,158	170
4.0	205	15	2,328	170
3.5	220	15	2,499	170
3.0	235	15	2,669	170
2.5	250	15	2,839	170
2.0	270	20	3,066	227
1.5	290	20	3,294	227
1.0	310	20	3,521	227

Figure 5. Score distributions of simulation data (in color online).



Step 1: Model Source EUI
Example:
Source EUI = 1,249 MJ/m^2 (110 kBtu/ft^2)

Step 2: Adjust EUI for Climate
Example:
Adjusted Source EUI = 1,136 MJ/m^2 (100 kBtu/ft^2)

Step 3: Convert Adjusted EUI to Asset Score
Example:
Asset Score = 8.5

EUI (Kbtu/ft^2)	EUI (MJ/m^2)	Asset Score
70	795	10.0
80	909	9.5
90	1,022	9.0
100	1,136	8.5
110	1,249	8.0
120	1,363	7.5
130	1,476	7.0
140	1,590	6.5
150	1,704	6.0
160	1,817	5.5
175	1,987	5.0
190	2,158	4.5
205	2,328	4.0
220	2,499	3.5
235	2,669	3.0
250	2,839	2.5
270	3,066	2.0
290	3,294	1.5
310	3,521	1.0

Figure 6. Asset Score calculation steps (in color online).

with a standard deviation of 1.5. If we assume that the modelled office stock can represent the population, 95% of the buildings will be scored between 2.5 and 8.5 (within two standard deviations).

5.4. Score calculation

The overall methodology for determining a building's Asset Score includes three steps, as illustrated in Figure 6.

- *Step 1*: Source EUI is obtained by running a whole-building energy simulation using the Asset Scoring Tool. The tool maps all of the postal codes in the USA to over 1000 weather stations in EnergyPlus (Hathaway et al. 2013).
- *Step 2*: The modelled EUI is adjusted to account for local climate.
- *Step 3*: An Asset Score is assigned based on the adjusted source EUI and the predefined scale for each use type.

Table 4. An example of prorated scores for a mixed-use building.

	Building A		Building A with 20% energy reduction in office portion		Building A with 20% energy reduction in retail portion	
Total floor area	9290 m^2 (100,000 ft^2)		9290 m^2 (100,000 ft^2)		9290 m^2 (100,000 ft^2)	
Use type	Office	Retail	Office	Retail	Office	Retail
Floor area	6503 m^2 (70,000ft^2)	2787 m^2 (30,000 ft^2)	6503 m^2 (70,000 ft^2)	2787 m^2 (30,000 ft^2)	6503 m^2 (70,000 ft^2)	2787 m^2 (30,000 ft^2)
Source energy use	7385 GJ (7000 MBtu[a])	9495 GJ (9000 MBtu)	5908 GJ (5600 MBtu)	9495 GJ (9000 MBtu)	7385 GJ (7000 MBtu$^{)}$	7596 GJ (7200 MBtu$^{)}$
Total energy saving	N/A		1477 GJ (1400 MBtu)		1899 GJ (1800 MBtu)	
Source EUI	1136 MJ/m^2 (100 kBtu/ft^2)	3407 MJ/m^2 (300 kBtu/ft^2)	909 MJ/m^2 (80 kBtu/ft^2)	3407 MJ/m^2 (300 kBtu/ft^2)	1136 MJ/m^2 (100 kBtu/ft^2)	2726 MJ/m^2 (240 kBtu/ft^2)
Asset Score by use type	8.5	2.0	9.5	2.0	8.5	4.0
Weighted by floor area						
% of floor area	70	30	70	30	70	30
Overall score by floor area	6.5		7.0		7.0	
Additional points after savings	N/A		*0.5*		*0.5*	
Weighted by energy use						
% of energy use	44	56	38	62	49	51
Overall score by energy use	4.5		4.5		6.0	
Additional points after savings	N/A		*0*		*1.5*	

[a] MBtu is million British thermal units.

5.5. *Scoring for mixed-use buildings*

A weighted rating is used to evaluate mixed-use types: each use is rated separately and then the weighted rating is computed based on the area (m^2 or ft^2) of each use type in the overall building. Table 4 provides an example of an office/retail mixed-use building. The office and retail portions are assessed separately using their corresponding scales. Then, the weighted ratings for the mixed-use commercial property are calculated based on the individual rating and floor area of each use type.

Another weighting approach could be in proportion to the total energy use instead of the total floor area. However, a weighted overall rating by energy use cannot consistently represent the overall energy efficiency of a mixed-use building and its use-type portions. In the example in Table 4, the overall scores based on percentage of energy use are more influenced by the retail portion – a use type with high energy intensity. The original score is close to the score of the retail portion, although it accounts for only 30% of the total floor area. A 20% energy reduction in the office portion does not affect the overall score. A 20% energy reduction in the retail portion will affect the overall score more. This would lead building owners to ignore the energy efficiency of the office portion.

Using floor area as a weighting factor does not favour or penalize a building for its use types. It can also fairly reflect the energy reduction of each portion of the building. As shown from the example scenarios illustrated in Table 4, the overall score improvement is proportional to the overall energy savings. Therefore, a mixed-use building's score is prorated based on the percentage of floor area of each use type.

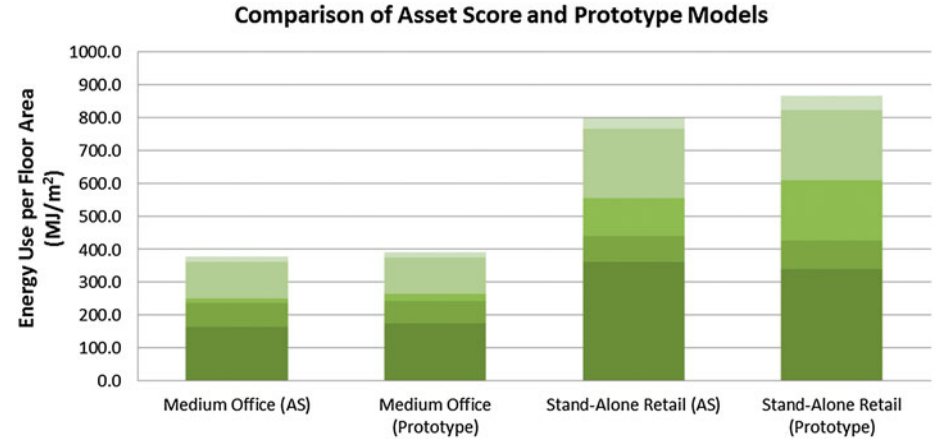
6. Verification and testing

It is a challenging task to verify the stock simulation, as there is no "true" value to benchmark the simulated EUI distributions. As discussed in Section 5.2, the CBECS database was used to verify the distribution of simulated data obtained. It is expected that the modelled EUI distribution is a subset of the measured data because imperfect building operations, lack of proper maintenance and occupant behaviour tend to increase actual building energy consumption. Although the means of two EUI distributions are unlikely to perfectly match, one could expect the major portions of the two data set to overlap, as shown in Figure 4.

The testing was focused on two areas: (1) whether a simplified Asset Score model can fully represent the efficiency of a building and (2) whether the Asset Score scale can effectively differentiate buildings. The testing results are discussed below.

6.1. *Test the simplified asset score models*

The simplified prototype buildings were used as base models for both sensitivity analysis and stock simulations. During the simplification process, detailed thermal zones based on building space functions were combined into one as in the Asset Scoring Tool. The internal loads were also



	Medium Office (AS) MJ/m^2 (kBtu/ft^2)	Medium Office (Prototype) MJ/m^2 (kBtu/ft^2)	Stand-Alone Retail (AS) MJ/m^2 (kBtu/ft^2)	Stand-Alone Retail (Prototype) MJ/m^2 (kBtu/ft^2)
Heating	164.3 (14.5)	173.6 (15.3)	361.2 (31.8)	340.6 (30)
Cooling	73.5 (6.5)	68.6 (6)	78.9 (7)	86.5 (7.6)
Fans and Pumps	14.2 (1.3)	22.5 (2)	115 (10.1)	182 (16)
Interior Lighting	108.9 (9.6)	111 (9.8)	210.3 (18.5)	214.6 (18.9)
Service Hot Water	16.2 (1.4)	16.3 (1.4)	34.2 (3)	42.8 (3.8)

Figure 7. Comparison of Asset Score models and prototype building models (medium office and stand-alone retail) (in color online).

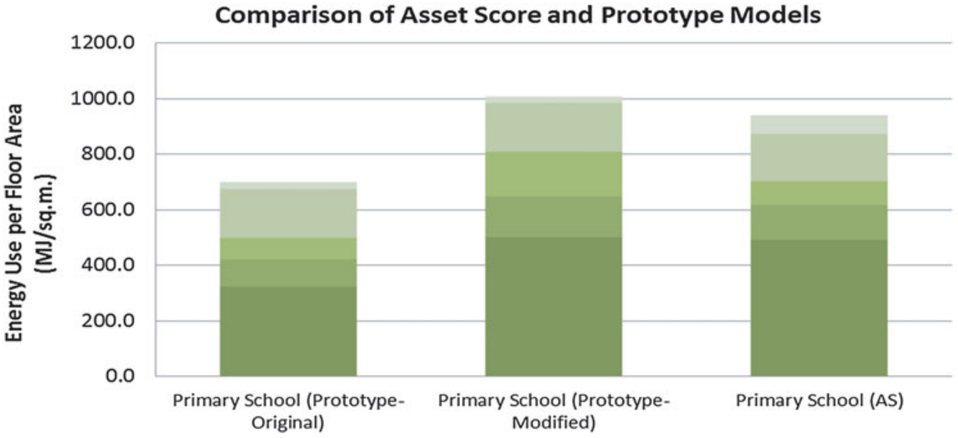
simplified to the whole-building average. The Asset Scoring Tool models a building as one block except when different portions of a building are served by various types of HVAC systems or a building has more than one use type, as in the example discussed in Section 5.5. The Asset Scoring Tool provides specific rules for how to simplify building geometry and define mixed-use buildings.

The modelled results from the Asset Scoring Tool were compared to the original prototype buildings as model verification. Figure 7 shows three selected prototype buildings representing the major use types – Office, retail, and school. Miscellaneous loads are not included in the comparison because they are not user inputs in the Asset Scoring Tool, although they affect the space heating and cooling loads. The Asset Scoring Tool, at present, does not model kitchen equipment or the corresponding exhaust air requirements, which resulted in some discrepancies in heating and cooling energy consumption between the school models. The Asset Score model results are comparable to the prototype model results when the prototype models have similar internal loads and ventilation requirements. The site EUIs of medium office and standalong retail calculated from the Asset Scoring tool are 3% and 8% lower than those calculated from the detailed prototype models. The difference in fan energy use in the retail prototype is caused due to night cycle fan control, which is not modelled in Asset Score. Night cycle control causes the fan to cycle during unoccupied times to meet loads. The Asset Score assumes that fans remain off during unoccupied hours. For constant volume fans, this assumption may cause a larger EUI difference. When translated to scores, these differences are within the half-point range. This means that a building using the simplified modelling approach is likely to be scored the same as one using a detailed model.

When analysed against a more complex prototype building such as primary school, the EUI difference increased (Figure 8). In the primary school prototype, these differences were caused by different internal loads and ventilation requirements. The prototype model was then modified to have the same ventilation and internal loads as the Asset Score model for an 'apples-to-apples' comparison. Despite more detailed geometry and system configuration for the prototype models, the results were found to be comparable, with a whole-building EUI variation of less than 4%. The difference in fan energy consumption is attributed to night cycle control in the prototype models, which causes the fan to cycle to meet loads during unoccupied hours and results in higher fan energy use, specifically for constant volume fans.

6.2. *Test the scale on pilot buildings*

In 2012, DOE began initial pilot testing of the Asset Score, resulting in improvements to the Asset Scoring Tool. In 2013 and 2014, DOE continued to assess the Asset Score through additional pilot testing and a variety of technical evaluations and performance analyses. As of February 2015, more than 500 buildings have been scored, comprising 18 use types (a majority of which are office buildings



	Primary School (Prototype—Original) MJ/m^2 (kBtu/ft^2)	Primary School (Prototype—Modified) MJ/m^2 (kBtu/ft^2)	Primary School (Asset Score) MJ/m^2 (kBtu/ft^2)
Heating	323.7 (28.5)	502.3 (44.2)	492.9 (43.4)
Cooling	98.8 (8.7)	147.6 (13)	122.7 (10.8)
Fans and Pumps	77.2 (6.8)	159 (14)	88.6 (7.8)
Interior Lighting	176 (15.5)	176 (15.5)	169.2 (14.9)
Service Hot Water	22.7 (2)	22.7 (2)	68.1 (6)

Figure 8. Comparison of Asset Score models and prototype building models (primary school) (in color online).

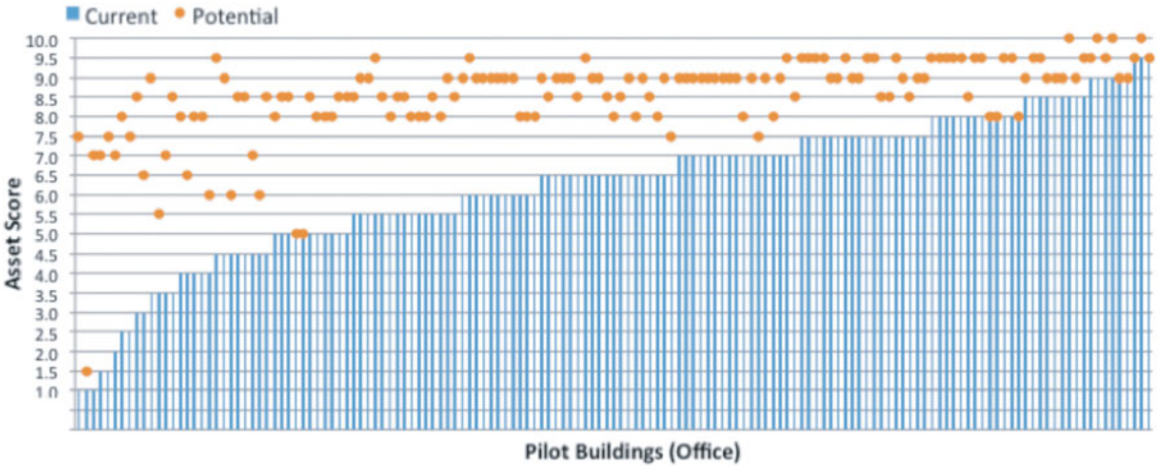


Figure 9. Score distribution of pilot office buildings (in color online).

Table 5. Score improvements and energy savings of 428 pilot buildings.

Building rank by score	Average current score	Average potential score	Average score improvement	Average energy savings identified
Low score (bottom 1/3)	3.0	7.0	4.0	42%
Average score (mid 1/3)	6.0	8.5	2.5	33%
High score (top 1/3)	8.0	9.0	1.0	21%

and schools) and various sizes (ranging from less than 929 m^2 (10,000 ft^2) to over 92,903 m^2 (1 million ft^2)) across multiple climate zones. Figure 9 shows the score distribution for the 149 office buildings. Along with a building's current Asset Score, the Asset Scoring Tool performs life-cycle cost analysis to suggest a package of possible energy efficiency upgrades. A second energy model with the identified building upgrades is used to estimate a building's potential Asset Score if improvements were made.

The relatively even distribution of the pilot building scores indicates that the predefined scales can differentiate high-performance buildings from low-efficiency buildings. Also, most buildings can achieve recognizable rating improvements with cost-effective upgrades. An analysis of 428 pilot buildings of various use types (Table 5) suggests that, on average, buildings with low, medium and high scores have the potential to reduce their energy use by 42%, 33% and 21% and earn an additional 4, 2.5 and 1 points, respectively.

6.3. Limitations and future work

Validation of the EUI distributions and individual buildings models is challenging. One can use calibrated energy models to generate an asset rating. However, while this approach can validate energy models, it requires more user inputs and assistance from professional modellers. High implementation cost is a barrier to wide adoption of benchmarking. The developed Asset Score scales have been shown to be effective and robust via testing on a large number of real buildings. They can also provide a solution for evaluating the impact of capital improvements over time. With more Asset Score users in the future, additional validation can be carried out by obtaining the users' utility data and comparing their distribution patterns against those of the modelled results.

7. Conclusions

This paper presents the development of a national asset rating system and tool in the USA. A web-based Asset Scoring Tool allows users to create simplified energy models, run real-time thermodynamic simulations and obtain a standard Asset Score Report. The Asset Score uses a scoring process that addresses limitations associated with existing benchmarking and rating methodologies. It provides a viable and market-acceptable solution to the unique problem of scoring existing buildings based on standard operation assumptions and energy simulations. It provides an approach to compare scores of different buildings of various use types across climate zones. The scoring scale and scoring process also address the challenge of scoring mixed-use buildings.

The Asset Score uses stock simulation to develop a series of predefined scales for various building types, where each point on the 10-point scale corresponds to a source energy use value (expressed as EUI). A building's score is calculated based on the simulated energy use for that building without the need to create a baseline or reference building. When an existing database is used to establish a benchmark, its applicability or accuracy is often restricted by the contents of the database. The method presented in this article allows the Asset Score to rate a broad range of building types, including mixed-use buildings, which is often a challenge due to the lack of granularity in any existing building database. It is almost impossible to characterize all mixed-use buildings that may exist, as mixed-use development has gained popularity in building design and urban planning.

The stock simulation methodology and results presented in this paper can be used as a framework for similar stock analysis in the future. A series of LHS analyses were performed on the Asset Score input variables, down-selected through sensitivity analyses. The analysis simulated and examined each building type with various combinations of building characteristics (Asset Score inputs) using ASHRAE Standard 90.1-2004 prototype buildings (DOE EERE 2014) as base models. These building models represented a wide range of buildings – from the likely least efficient to the likely most efficient buildings in 15 climate locations with thousands of variations in between. For Asset Score analysis, samples were drawn and used to predict energy use of different building types under standard operating conditions and in different climate zones. One can vary the operating conditions or control other variables for studies with other purposes.

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References

10 CFR Part 436. 1999. "Federal Energy Management and Planning Programs." U.S. Code of Federal Regulations.

ANSI/ASHRAE/IESNA Standard 90.1-2004. *Energy Standard for Buildings Except Low-rise Residential Buildings*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ANSI/ASHRAE/IESNA Standard 90.1-2007. *Energy Standard for Buildings Except Low-rise Residential Buildings*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ANSI/ASHRAE/IESNA Standard 90.1-2013. *Energy Standard for Buildings Except Low-rise Residential Buildings*. Atlanta, GA American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2015. *Building Energy Quotient: ASHRAE's Building Energy Labeling Program*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. http://www.buildingenergyquotient.org/.

Bloomfield, C., and P. Bannister. 2010. "Energy and Water Benchmarking in the Retail Sector: NABERS Shopping Centres." Proceedings of the 2010 ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy-Efficient Economy, Washington, DC.

BPIE. 2010. *Energy Performance Certificates across Europe. From Design to Implementation*. Brussels: Building Performance Institute Europe. http://bpie.eu/energy_performance_certificates.html and http://dl.dropbox.com/u/4399528/BPIE/BPIE_EPC_report_2010.pdf.

BRE. 2010. *A Technical Manual for SBEM*. Watford: Building Research Establishment, Ltd. http://www.ncm.bre.co.uk/filelibrary/SBEM_Technical_Manual_v3.5.a_01Mar10.pdf.

Chinese State Council. 2008. "Regulation on Civil Building Energy Efficiency." The Central People's Government of the People's Republic of China. http://www.gov.cn/zwgk/2008-08/07/content_1067038.htm.

COMNET. 2010. *Commercial Buildings Energy Modeling Guidelines and Procedures*. Vancouver, WA: Commercial Energy Services Network. http://www.comnet.org/sites/default/files/images/COMNET-MGP-2.pdf.

Cudworth, C., R. Graham, R. Martinez Diaz, and B. Olaluwoye. 2010. *Third Draft, Analysing Energy Performance Certificates (EPCs) with Financial Performance Information in the Commercial Property Industry of England & Wales*. London: RICS Education Trust/IPD. http://www1.ipd.com/Pages/DNNPage.aspx?DestUrl = http%3A//www.ipd.com/sharepoint.aspx%3Ftabid%3D3070.

DCLG. 2012. *Improving the Energy Efficiency of Our Buildings: A Guide to Display Energy Certificates and Advisory Reports for Public Buildings*. London: Department for Communities and Local Government. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/51164/A_guide_to_display_energy_certificates_and_advisory_reports_for_public_buildings.pdf.

DOE EERE. 2012. *Commercial Reference Buildings. Office of Energy Efficiency and Renewable Energy*. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. http://www1.eere.energy.gov/buildings/commercial/ref_buildings.html.

DOE EERE. 2014. *Commercial Prototype Building Models*. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. http://www.energycodes.gov/commercial-prototype-building-models.

DOE EERE. 2015. *EnergyPlus Energy Simulation Software*. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. http://apps1.eere.energy.gov/buildings/energyplus/.

EIA. 2006. *Commercial Buildings Energy Consumption Survey*. Washington, DC: U.S. Department of Energy, Energy Information Administration. http://www.eia.gov/emeu/cbecs/.

EPA. 2013. *ENERGY STAR Portfolio Manager Technical Reference: Source Energy*. Washington, DC: U.S. Environmental

Protection Agency. https://portfoliomanager.energystar.gov/pdf/reference/SourceEnergy.pdf.

EPA. 2015. *Use Portfolio Manager*. Washington, DC: U.S. Environmental Protection Agency. Accessed May 17, 2015. http://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager.

EPBD. 2013. *Implementing the Energy Performance of Buildings Directive (EPBD): Featuring Country Reports 2012*. ISBN 978-972-8646-27-1. http://www.epbd-ca.org/Medias/Pdf/CA3-BOOK-2012-ebook-201310.pdf.

Griffith, B., N. Long, P. Torcellini, and R. Judkoff. 2007. *Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-550-41957. http://www.nrel.gov/docs/fy08osti/41957.pdf.

Hathaway, J. E., T. C. Pulsipher, J. Rounds, and J. A. Dirks. 2013. *Statistical Methods for Defining Climate-Similar Regions around Weather Stations Using NLDAS-2 Forcing Data*. Richland, WA: Pacific Northwest National Laboratory. PNNL-98705.

ISO 13790:2008. *Energy Performance of Buildings – Calculation of Energy use for Space Heating and Cooling*. Geneva: International Organization for Standardization.

Johnson, J. 2003. *Is What They Want What They Get? Examining Field Evidence for Links between Design Intent and As-Built Performance of Commercial Buildings*. Vancouver, WA: New Buildings Institute. http://www.newbuildings.org/sites/default/files/IsWhatTheyWantWhatTheyGet200307.pdf.

Lee, S., Z. Fei, and G. Augenbroe. 2011. "The Use of Normative Energy Calculation Beyond Building Performance Rating Systems." In Proceedings of Building Simulation 2011, International Building Performance Simulation Association, Sydney, Australia, 2753–2760.

Makhmalbaf, A., V. Srivastava, and N. Wang. 2013. "Simulation-based weather normalization approach to study the impact of weather on energy use of buildings in the US." 13th Conference of International Building Performance Simulation Association, Chambéry, Frankrijk, 26–28.

McCabe, M. J., and N. Wang. 2012. *Commercial Building Energy Asset Rating Program – Market Research*. Richland, WA: Pacific Northwest National Laboratory. PNNL-12310.

New York City Health Department. 2012. "How We Score and Grade." http://www.nyc.gov/html/doh/downloads/pdf/rii/how-we-score-grade.pdf.

NREL. 2011. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*. Golden, Colorado: National Renewable Energy Laboratory. NREL/TP-5500-46861. http://www.nrel.gov/docs/fy11osti/46861.pdf.

PNNL. 2014. *Facility Energy Decision System User's Guide, Release 7.0*. Richland, Washington: Pacific Northwest National Laboratory. PNNL-107079. http://www.pnl.gov/feds/pdfs/FEDS_7-0_user_guide.pdf.

Rosenberg, M., R. Hart, J. Zhang, and R. Athalye. 2015. *Roadmap for the Future of Commercial Energy Codes*. Richland, WA: Pacific Northwest National Laboratory. PNNL-24009. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24009.pdf.

Sanyal, J., J. New, R. E. Edwards, and L. Parker. 2014. "Calibrating Building Energy Models Using Supercomputer Trained Machine Learning Agents." *Concurrency and Computation Practice and Experience* 26 (13): 2122–2133. doi:10.1002/cpe.3267.

Stationery Office Dublin. 2006. *European Communities (Energy Performance ff Buildings) Regulations 2006*. S.I. No. 666 of 2006. Dublin: Government Publications Office, Sun Alliance House. http://www.seai.ie/Your_Building/BER/EPBD/SI_666_EPBD.pdf.

Thorne, J., and C. Egan. 2002. *An Evaluation of the Federal Trade Commission's EnergyGuide Appliance Label: Final Report and Recommendations*. Report Number A021. Washington, DC: American Council for an Energy-Efficient Economy.

Thornton, B. A., M. Rosenberg, E. E. Richman, W. Wang, Y. Xie, J. Zhang, H. Cho, V. V. Mendon, R. A. Athalye, and B. Liu. 2011. *Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010*. Richland, WA: Pacific Northwest National Laboratory. PNNL-20405.

Turner, C., and M. Frankel. 2008. *Energy Performance of LEED for New Construction Buildings*. Vancouver, WA: New Buildings Institute.

Wang, N., S. Goel, and A. Makhmalbaf. 2013. *Commercial Building Energy Asset Score System: Program Overview and Technical Protocol (Version 1.1)*. Richland, WA: Pacific Northwest National Laboratory. PNNL-22045.

Wang, N., S. Goel, V. Srivastava, and A. Makhmalbaf. 2015. *Building Energy Asset Score Program Overview and Technical Protocol (Version 1.2)*. Richland, WA: Pacific Northwest National Laboratory. PNNL-22045.

USGBC. 2009. *LEED 2009 for New Construction and Major Renovations Rating System with Alternative Compliance Paths for Projects Outside the U.S.* Washington, DC: U.S. Green Building Council.