Performance-Based Building System Evaluation for DOE Energy Asset Score

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ABSTRACT

The Commercial Building Energy Asset Score, being developed by Pacific Northwest National Laboratory for the Department of Energy (DOE), aims to help building owners evaluate overall building energy efficiency under typical operation and occupancy conditions, defined by building use type. The Asset Scoring tool, a web-based application, consists of a simplified user interface built on a centralized simulation engine—EnergyPlus. The tool analyzes the as-built physical characteristics (including building envelope, the mechanical and electrical systems), pinpoints building systems with potential for efficiency improvement , and identifies cost-effective retrofit opportunities. A pilot project with more than 100 buildings revealed that use of whole building Energy Use index (EUI) could not adequately examine efficiency and performance of individual building systems. A building with a well-insulated envelope and low-efficiency HVAC equipment could, theoretically, use the same amount of energy as a building with a poorly insulated envelope and high-efficiency HVAC equipment. For two buildings with the same energy Asset Score (based on source EUI), the system-level evaluations can give tool users insight into the system-level performance and identify building components that need greater attention. Hence, a performance-based system evaluation method has been developed to analyze individual building components pertaining to the building envelope, lighting, heating, cooling, and service hot water systems, as well as their interactions. A prescriptive approach for evaluating building components, though simple to use, is often limited to single variable input comparisons. A simulation-based performance approach has been selected as the primary system evaluation method due to the multivariate nature of most systems examined by the Asset Scoring tool. The performance approach compares the energy use of a building system with that of baselines. The baseline values are determined using the DOE Commercial Building Models (Thornton et. al 2011). A series of performance ranges for different building use types are developed from the highest and lowest energy use obtained by modeling the prototype buildings available for similar use types, typically with the ASHRAE Standard 90.1-2004 model defining the lower limit performance and the 90.1-2010 model defining the higher limit. A building system is ranked by being compared to the predefined performance ranges. For example, a system falling within the range is considered "good." This methodology allows a high level of flexibility and considers a building as an integrated system.

INTRODUCTION

The U.S. Department of Energy (DOE) is developing a voluntary national scoring system for commercial buildings to help building owners and managers assess a building's energy-related systems independent of how they are operated. The goal of the system is to facilitate cost-effective investment in energy efficiency improvements of commercial buildings. The system, known as the Commercial Building Energy Asset Score, will allow building owners and managers to compare their building infrastructure against peers and track building upgrades over time. The system will also help other building

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stakeholders (e.g., building investors, tenants, financiers, and appraisers) understand the relative efficiency of different buildings in a way that is independent from operations and occupancy. The physical characteristics evaluated include the building envelope as well as the mechanical and electrical systems,. The Asset Score is generated by simulating building performance under a standard set of typical operating and occupancy conditions. By focusing only on a building's physical characteristics and removing occupancy and operational variations, the system allows consistent comparisons between differently operated buildings.

The Asset Scoring tool is a web-based evaluation tool. The tool is built on a centralized modeling engine to reduce the implementation cost and increase standardization compared with an approach that requires users to build their own energy models. With this tool, users can enter building information online to obtain a standard Asset Score Report and feedback on areas and options for energy efficiency improvements. A standard Asset Score Report includes four sections—(1) scores (current score and potential score after all recommended upgrades are made) based on source energy use intensities (EUIs), (2) building system evaluations, (3) a list of improvement areas and options, and (4) building assets (a detailed list of building characteristics that contribute to a building's Asset Score) (Wang et al, 2013).

This paper discusses the methodology used for the building system evaluation, which separately characterizes the building's envelope, lighting system, heating and cooling systems, and service hot water system. System evaluation is intended to help users assess all individual assets of the building. For two buildings with the same Asset Score but different characteristics, system evaluation can help identify the unique problems and potentials of the individual buildings.

PERFORMANCE-BASED EVALUATION

Although the whole building EUI indicates the overall building efficiency as an integrated system, it is inadequate to fully understand the individual effect of building subsystems. A building with a well-insulated envelope and low-efficiency HVAC equipment could, use the same amount of energy as a building with a poorly insulated envelope and high-efficiency HVAC equipment. System evaluations are provided separately for the building envelope (roof, walls, windows, floor), lighting, heating, cooling, and service hot water systems. This information can provide insight into the specific energy using components of a building. Both prescriptive and performance approaches have been used in energy standards to design and evaluate building systems. The prescriptive approach specifies some minimum acceptable construction or system standards, such as minimum R-value (or maximum U-factor) for building envelope components or required equipment efficiencies for mechanical systems. A prescriptive approach is easy to use, especially for building or system designers; however, for existing system evaluations, a prescriptive approach can be restrictive, for several reasons.

First, a prescriptive approach is generally limited to single variable component comparisons. More complex systems with multiple components and/or different configurations need to be modeled to understand how the different characteristics operate in concert. For example, a chiller's efficiency is defined both by its design condition coefficient of performance (COP) and the part-load performance curves of its compressor. Second, it is difficult to compare different HVAC systems using a prescriptive approach. For example in ASHRAE Standard 90.1-2010 Table 6.8.1A provides cooling efficiency metrics for packaged equipment in terms of energy efficiency ratio (EER) and integrated energy efficiency ratio (IEER). These ratings are inclusive of energy used by the compressor, the condenser fan, and the system supply fan, thus representing the cooling energy use of the system in its entirety. In contrast Table 6.8.1.C provides cooling efficiency metrics for water cooled chillers in terms of kW/ton and Integrated Part Load Value (IPLV). This represents only the compressor energy use. To account for the energy use of the chilled water cooling system as a whole, you would need to include energy used by the cooling tower (regulated partly by Table 6.8.1G), the system supply fan (regulated by Table 6.5.3.1.1A) and the chilled and condenser water pumps (unregulated by Standard 90.1). It is apparent that it is not possible to compare these two systems based on their prescriptive efficiency metrics only. Third, a prescriptive approach isolates a system from the evaluated building. For example, a building with less insulation may force its HVAC system to handle more extreme operating conditions and use more energy than a building with the same HVAC system but a more efficient envelope.

Due to the multivariate nature of most systems examined by the Asset Scoring tool and considering the appropriate level of data that can be collected by users, a model-based performance approach is selected as the primary system evaluation method for envelope, lighting, HVAC, and service hot water systems. A performance approach compares the source energy use of a building or system with that of a baseline or reference design. It allows a high level flexibility and considers a building as an integrated system. Source energy is used to account for the generation and transmission loss of different fuel types. The following metrics are used as indicators of system performance (Table 1).

Table 1. Performance indicators for building systems

Building Systems	Performance Indicators	Calculation Methods*	Evaluations
Window	kBtu/ft²-yr [W/m2-yr]	= Annual heat transfer through windows / total window area	Higher value indicates more heat transfer through the envelope components, and therefore represents poor thermal performance
Wall	kBtu/ft²-yr [W/m2-yr]	=Annual heat trasnfer through walls / total wall area	
Window + Wall	kBtu/ft²-yr [W/m2-yr]	= Annual heat transfer through walls and windows / total wall plus window area (account for window-wall ratio)	
Roof	kBtu/ft²-yr [W/m2-yr]	= Annual heat transfer through roof / total roof area	
Floor	kBtu/ft²-yr [W/m2-yr]	= Annual heat transfer through floor / total floor area	
Lighting System	kBtu/ft²-yr [W/m2-yr]	= Annual lighting energy use / total floor area	Higher value indicates more lighting energy use, and therefore represents low-efficiency lighting system
Heating System	Heating System Performance Ratio (H-SPR)	= Annual heating load / annual heating system energy use	Lower value indicates more energy use to meet the load, and therefore represents low-efficiency system
Cooling System	Cooling System Performance Ratio (C-SPR)	= Annual cooling load / annual cooling system energy use	
Overall HVAC System	Total System Performance Ratio (T-SPR)	= Heating and cooling load / HVAC system energy use	
Service Hot Water System	Hot water System Performance Ratio (HW-SPR)	= Hot water energy load / hot water use	

* Source energy is used in the above calculations.

Building Envelope

For the envelope assessment, the heating and cooling loads through the envelope are extracted from the energy model. The loads are divided by the exterior surface area of the particular envelope component being examined (thermal boundary) to calculate the annual building loads per unit area of the component (measured in kBtu/ft2-yr).

$$Performance\ Index_{walls} = \frac{Annual\ heating\ load\ through\ walls + Annual\ cooling\ load\ through\ walls\ (kBtu)[\mathrm{W}]}{Total\ exterior\ wall\ area\ (ft2)[\mathrm{m}^2]} \quad (1)$$

A higher value indicates more heat transfer through the envelope and therefore reflects poor thermal performance. This method goes beyond the typical prescriptive standards, which simply use assembly U-values, because it reflects the overall effect of the envelope on the heating and cooling loads, considering such factors as orientation, layout, shading, surfaces reflectance and other factors that affect non-conductive heat transfer properties. This evaluation method is applied to windows, walls, combination of windows and walls (to account for window-to-wall ratio), roofs, and floors to separately evaluate their performances. Because thermal resistance is usually much lower for windows than it is for walls, a building envelope with well-insulated walls and windows may not have good overall performance if the window-wall ratio is high.

The Asset Score tool uses the EnergyPlus engine for whole building simulation and a technical barrier to implementing this performance based approach for envelope evaluations is the complexity involved in reporting heating and cooling loads through envelope components (windows, walls, roof, floor) in the current version of EnergyPlus. However, EnergyPlus is expected to provide a simplified output function in the near future.

Lighting System

For the lighting system assessment, the lighting EUI is used. A higher value indicates more lighting energy use based on the standard assumptions of operating schedules and therefore it represents a less efficient lighting system. Compared to lighting power density (W/ft^2), which only considers installed lighting load, lighting EUI (kBtu/ft^2) includes the effects of lighting controls and daylighting controls in the building, thus considering all component of the system together.

$$Performance\ Index_{lighting} = \frac{Annual\ Lighting\ Energy\ (kBtu)[\mathrm{W}]}{Total\ Building\ Area\ (ft2)[\mathrm{m}^2]} \qquad (2)$$

HVAC Systems

For the HVAC systems, a metric called System Performance Ratio (SPR) is used. It is defined as the ratio of annual system load to the annual system energy consumption, similar to a whole system COP. A higher value indicates less heating and cooling energy use to meet the loads, and therefore represents a more efficient HVAC system. This metric provides single evaluation criteria which addresses all components of a HVAC system, including mechanical ventilation, equipment full and part load performance and distribution system effectiveness. Standard system efficiency ratings (such as seasonal energy efficiency ratio, COP, kW/ton used in Standard 90.1 Tables 6.8.1A through K) usually address a single component within a system and fail to account for all system inefficiencies that may be present within a building as well as their interaction with building loads and ventilation requirements. System efficiency ratings are also based on prescribed rating conditions that may not reflect actual building conditions. This analysis methodology differs from the HVAC Power Density approach (Kavanaugh et. al 2006), which evaluates HVAC systems based on HVAC equipment power density, similar to the lighting power density allowance in ASHRAE 90.1 standards. HVAC power density (HvacPD) is defined in terms of electric power input for the entire system per unit area. The allowances are based on peak load demand hence part load efficiencies, impact of system controls and similar factors aren't reflected in this metric.

Cooling system performance ratio (C-SPR), heating system performance ratio (H-SPR), and total system performance ratio (T-SPR) are separately calculated to provide a discrete evaluation of the heating, cooling, and integrated HVAC systems. Baseline ranges for evaluating HVAC equipment performance are developed specific to a building type and climate zone to account for inherent differences between HVAC systems. For example, a building in a heating-dominated climate needs a more efficient heating system to achieve a good overall performance compared to a building in a cooling-dominated climate because cooling systems for most system types have higher efficiency ratings than heating systems; for example, a 90.1 2004 air cooled chiller would have a COP of 2.8 whereas a gas-fired furnace would have an AFUE of 78%. This aspect is accounted for through reference ranges for each climate zone. The sections below discuss the development of reference ranges for HVAC system evaluation. The proposed approach considers energy used by all individual components that comprise the HVAC system.

Fan and pump energy is assigned to either cooling or heating energy use, based on the mode of operation of the system while the fan or pump is running. Multi-zone reheat systems (such as standard Variable Air Volume (VAV)) pose a challenge in that it is not simple to assign fan energy to either heating or cooling for a system that provides both simultaneously. For each simulation time-step, the supply fan energy use is split between the zones served by the multi-zone system based on the ratio of total system air flow to each zone, hence for an AHU serving perimeter and core zones, the fan energy use is split into heating or cooling in accordance to the end-use condition for each zone.. The coil conditions are evaluated to identify whether the zone is in heating or cooling mode and fan energy use is assigned accordingly. Table 3 lists each applicable scenario and the end use to which fan energy use is assigned.

Table 3. Methodology for Splitting Fan Energy Use for Heating and Cooling

Case	Zone Mode	Fan Energy Consumption
Case 1	$E_{Reheat\ Coilx} = 0$ (Evaluated for each zone)	Cooling (For $Zone_x$)
Case 2	$E_{Reheat\ Coilx} > 0$ (Evaluated for Each Zone)	Heating (For $Zone_x$)

$E_{Reheat\ Coil1\ldots n}$ = Reheat coil energy consumption

Energy use of all system components including pumps and heat rejection systems are included in calculations for a complete heating, cooling or total system evaluation. Hence, the total heating energy use includes coil energy consumption including preheat, reheat, primary and/or supplementary heating coils ($E_{Heating}$), fan energy consumption during heating mode ($E_{Fan_{Heating}}$) and pump energy consumption in the case of hydronic systems ($E_{Pump_{Heating}}$). The total cooling energy use includes coil energy consumption, for cooling and dehumidification ($E_{Cooling}$), fan energy consumption during cooling mode ($E_{Fan_{Cooling}}$), and pump and heat rejection energy use in the case of hydronic systems ($E_{Pump_{Cooling}}$ and $E_{Heat\_Rejection}$).

To determine the base annual heating, cooling, and total loads for each building, the simulation uses a special HVAC system type available in EnergyPlus called the Ideal Loads system. This system calculates the load for each zone in the building and supplies heating or cooling air to meet the set-points at a system efficiency of 100% based on the specifications of the system. This system includes options for humidity control, outdoor air, economizer, demand controlled ventilation, and heat recovery. The supply air flow rate is varied between zero and the maximum in order to satisfy the zone heating or cooling load, zone humidity controls, outdoor air requirements. In order to credit buildings that use economizers or heat recovery to reduce energy consumption, economizer and heat recovery are ignored in base load determination but included in annual energy consumption, thereby resulting in higher system efficiency.

$$System\ Performace\ Ratio_{heating} = \frac{Ideal\ annual\ heating\ load\ \ (kBtu)[W]}{\left(E_{Heating}\ + E_{Fan_{Heating}} + E_{Pump_{Heating}}\right)(kBtu)[W]} \quad (3)$$

$$System\ Performance\ Ratio_{Cooling} = \frac{Ideal\ annual\ cooling\ load\ (kBtu)[W]}{\left(E_{Cooling}\ + E_{Fan_{Cooling}} + E_{Pump_{Cooling}}\ + E_{Heat_{Rejection}}\right)(kBtu)[W]} \quad (4)$$

$$System\ Performance\ Ratio_{Total} = \frac{(Ideal\ annual\ heating\ load + Ideal\ annual\ cooling\ load)\ (kBtu)[W]}{\left(E_{Cooling}\ + E_{Heating} + E_{Fans} + E_{Pumps} + E_{Heat_{Rejection}}\right)(kBtu)[W]} \quad (5)$$

Service Hot Water Systems

Service hot water systems are evaluated using the ratio of the energy delivered in the form of hot water to energy input to the water heater. A higher value indicates that less energy is used to deliver a unit of hot water, and therefore represents a more efficient hot water system. The hot water SPR accounts for a decrease in efficiency due to thermal efficiency, jacket losses, etc. The efficiency is calculated using water density (ϱ), flow-rate at each hot water using fixture (v_{enduse}), specific heat of water (C_p) and the difference between the target water temperature at each end-use (T_{enduse}) and water mains temperature (T_{mains}).

$$System\ Performance\ Ratio_{hot\ water\ system} = \frac{\sum[\rho \times v_{enduse} \times C_p \times (T_{enduse} - T_{mains})]\ (kBtu)[W]}{[E_{WaterHeater} + E_{WaterHeater\_Pumps}](kBtu)[W]} \quad (6)$$

The flow-rate and temperature information is gathered from the EnergyPlus objects used to model water-use equipment. EnergyPlus uses a correlation between outdoor air temperature and water mains temperature to generate water temperature profiles during simulation which can be captured during output.

BASELINE DEVELOPMENT METHODOLOGY

Reference values are generated to evaluate system performance indicators. The "reference range" is hence defined as the calculated annual SPR for heating, cooling and total system performance for each building type and climate zone, with the lower end defined by Standard 90.1 2004 compliant prototype buildings and the upper end defined by Standard 90.1 2010 compliant prototype buildings. Source energy is used in the calculation of the metric, to account for the generation and transmission losses of different fuel types. If a system's performance is within the reference range, its performance is considered "Good." A value below the range indicates the system is "Fair" and a value above the range indicates the system is "Superior".

Prototype buildings compliant with ASHRAE Standard 90.1-2004 and 2010 are used to generate the reference ranges. These prototypes were originally developed for DOE to assess the relative improvement of sequential versions of ASHRAE Standard 90.1. They represent 80% of the commercial building floor area in the United States for new construction, including both commercial buildings and mid- to high-rise residential buildings (Thornton et al. 2011). The HVAC systems in each prototype were selected based on standard "good design practice" for each that building type. The characteristics of the prototype buildings are well documented and the models are readily available online (Thornton et al. 2011). Table 4 lists the specifications of the three prototype buildings evaluated for four climate zones and three ASHRAE Standards. The prototype models were selected for this work to provide consistency, transparency and an industry accepted baseline for the performance indicator comparison.

Table 4. Prototype Building Characteristics

	Small Office Prototype	Medium Office Prototype	Large Office Prototype
Envelope Characteristics			
- Exterior Walls	Wood framed walls	Steel framed walls	Masonry Walls
- Exterior Roof	Attic roof with wood joist	Built-up roof	Built-up roof
- Foundation	Slab-on-grade floors	Slab-on-grade floors	Basement
- Window-to-Wall Ratio	24% South, 19% All other	33% WWR	40% WWR
Interior Loads			
- Interior Lighting	Based on Standard 90.1	Based on Standard 90.1	Based on Standard 90.1
- Equipment Loads	0.75 W/ ft^2 [8.07 W/m^2]	0.75 W/ ft^2 [8.07 W/m^2]	0.75 W/ ft^2 [8.07 W/m^2]
HVAC System			
- Heating	Air source heat pump; supplemental gas furnace	Gas Furnace	Gas fired boiler
- Cooling	Air source heat pump	Packaged direct expansion	Two water cooled chillers
- Fan Systems	Constant volume fans	Variable air volume	Variable air volume
- Ventilation Requirements*	ASHRAE 62.1 1999	ASHRAE 62.1 2004	ASHRAE 62.1 2004

*Standard 90.1 2004 refers to ASHRAE 62.1 1999 for outdoor air requirements. 90.1 2010 refers to ASHRAE 62.1 2004 for outdoor air requirements

Since the reference range is building type specific, and is based on the prototype HVAC system type, the HVAC system type in a rated building will influence the efficiency rating of that building. For example, small office buildings (≤ 5,000 ft^2) typically use packaged single zone HVAC equipment with direct expansion cooling. If a rated small office building incorporates a more efficient water cooled chiller or ground source heat pump, the cooling system performance is likely to be rated as "superior". This is likely even if the water-cooled chiller or heat pump "just meets" the Standard 90.1 efficiency requirements, as that system is expected to use less cooling energy than the reference packaged direct expansion system. Hence, the ranges developed based on the prototype buildings are specific to building type and based on the most commonly used system for a building of that size and function. Table 5 shows the impact of including all system components in the calculation of the annual SPR as against a single component evaluation of coils or equipment..

Table 5. SPR Calculations: Climate Zone 5A

Description	Small Office Climate Zone 5A		Large Office Climate Zone 5A	
	2004	2010	2004	2010
Ideal Loads (kBtu/ft^2-yr) [kWh/m^2-yr]				
Annual Heating Load	7.79 [24.56]	5.70 [17.99]	6.23 [19.64]	4.57 [14.4]
Annual Cooling Load	10.56 [33.30]	9.23 [29.12]	15.94[50.27]	14.47[45.62]
Heating Energy Consumption (kBtu/ft^2-yr) [kWh/m^2-y				
Coil/Equipment Energy Use	5.81 [18.34]	3.14 [9.92]	14.3 [45.08]	7.86 [24.79]
Fans (during heating)	1.52 [4.79]	1.08 [3.41]	0.64 [2.01]	0.51 [1.6]
Hot water pumps	0 [0]	0 [0]	0.4 [1.25]	0.32 [0.99]
Cooling Energy Consumption (kBtu/ft^2-yr) [kWh/m^2-yr]				
Coil/Equipment Energy Use	4.49 [14.16]	3.12 [9.83]	3.18 [10.01]	2.40 [7.58]
Fan (During Cooling)	2.96 [9.34]	2.72 [8.57]	1.28 [4.03]	1.01 [3.2]
Pumps (CHW and CW Pumps)	0 [0]	0 [0]	0.76 [2.41]	0.35 [1.09]
Heat Rejection	0 [0]	0 [0]	0.85 [2.67]	0.38 [1.2]
Heating Efficiency for Coil/Equipment Energy only	1.34	1.82	0.44	0.58
Cooling Efficiency for Coil/Equipment Energy only	2.35	2.96	5.02	6.02
System Efficiency for Coil/Equipment Energy only	1.78	2.39	1.27	1.85
SPR- Heating (Site)	1.06	1.35	0.41	0.53
SPR- Cooling (Site)	1.42	1.58	2.63	3.49
SPR- Total System (Site)	1.24	1.49	1.04	1.48

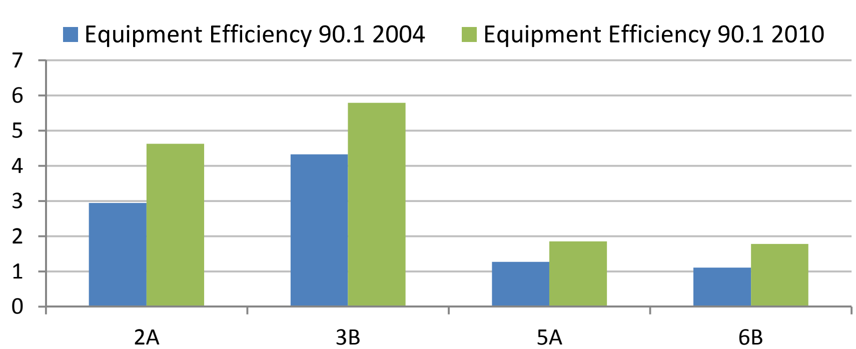

Figure 1: Equipment Efficiency (Site) for Large Office Prototype: Variation Across Climate Zones

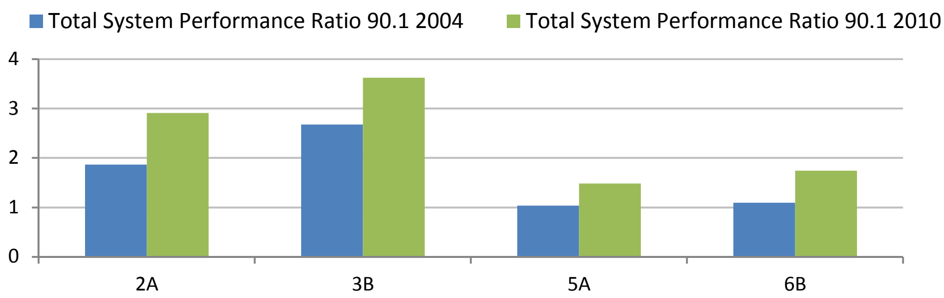

Figure 2: SPR (Site) for Large Office Prototype: Variation across Climate Zones

SYSTEM PERFORMANCE RATIO: KEY CHARACTERISTICS

System performance ratio allowances evaluate the entire system including the building envelope, building design elements, efficiency and configuration of HVAC equipment as well as internal loads and controls. This evaluation metric provides the following benefits:

- Standard operation assumptions are used in the calculation of this metric, to avoid additional penalty or credit due to operating conditions.
- Reference ranges are based on annual energy use and account for integrated building system performance.
- All building sub-systems, including building envelope, design characteristics, internal loads, all components of HVAC system and control strategies, are evaluated as a whole to provide a ranking 'Fair', 'Good' or 'Superior'. This approach overcomes the limitations of an individual component based evaluation.
- Differences in climate and dominant systems are accounted for by generating climate-zone and building type specific reference ranges.

CONCLUSION

While the Asset Score of a building as determined by DOE's Asset Scoring tool does a good job identifying a building's energy efficiency under typical operation and occupancy conditions, it does not identify the relative efficiencies and interaction between each of the building system components like building envelope, HVAC and lighting and electrical systems. Component level efficiency metrics such as those prescribed by ASHRAE Standard 90.1 (i.e., EER, IPLV, COP, annual fuel utilization efficiency, etc.) do not fill this gap, as they do not consider component interactions, nor do they represent the efficiency of a building system as a whole. The system level efficiency evaluation proposed for the Asset Scoring tool is meant to bridge the gap between individual component performance and the whole building integrated system performance. Rating the annualized efficiency of each system as determined by a comparison against a building type specific baseline, identifies the opportunities for improvement, and enables decision makers to focus time and effort on systems with the most potential for improvement.

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