TSPR: The Total System Performance Ratio as a Metric for HVAC System Efficiency

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ABSTRACT

North American energy codes do not typically discriminate between high-performing and poorly-performing HVAC system types, thereby perpetuating the installation of systems with high energy consumption and carbon emissions. The problem is compounded in the US by federal preemption rules, prohibiting state and local energy codes from mandating more efficient equipment than is defined in federal standards. In addition, the lack of a total system efficiency metric for HVAC effectively blocks an eventual transition to a performance-based code structure. To surmount this problem, the City of Seattle and Pacific Northwest National Laboratory have developed the Total System Performance Ratio (TSPR) as a proposed amendment to the 2018 Washington State Energy Code. The TSPR is a ratio that compares the annual space heating and cooling load of a building to the annual energy consumed by the building's entire HVAC system. In the TSPR, target ratios for several building types are calculated in relation to those of the HVAC systems judged to be the most appropriate for each building type, so installation of the lowest-performing HVAC system types will be severely constrained, while exceptional design flexibility will still be provided. With financial support from the Carbon Neutral Cities Alliance, a calculation software tool has been developed as a module of the US DOE Asset Score tool, using simplified building energy modeling. Taken together with whole-system evaluation options for lighting and building envelope systems, a whole-system HVAC performance evaluation would create a path for a transition away from prescriptive-based and towards performance-based codes.

Introduction

North American energy codes are for the most part derivatives of one of the two model energy codes; ASHRAE Standard 90.1 or the International Energy Conservation Code (ASHRAE 2016, ICC 2018). These codes have generally developed as a collection of "prescriptive" standards for individual construction elements such as fan efficiency, boiler thermal efficiency, envelope component U-factors, and maximum lighting power allowances. Almost every category of building material, equipment, or control that impacts energy consumption is governed by at least one energy code section. However, such prescriptive codes do not typically require the use of the most efficient or cost-effective systems – any assembly of elements that individually comply with their respective standards is equally acceptable, ignoring the interactions between different combinations of components. The result is that energy performance can vary significantly based on HVAC system type and component choices even if each component minimally meets code. In many cases, systems are selected solely on the basis of lowest construction cost or the local construction norms, resulting in buildings that, while fully code-compliant, can be highly inefficient.

Each of the model energy codes also provides a "whole building performance path," in which the simulated energy performance of a proposed building is compared with that of a virtual building of the same proportions in which most elements are set at the minimum performance allowed by code. Using this "code minimum" building as a baseline, designers can trade the improved performance of some elements for sub-standard performance of others. This approach allows design flexibility and optimization of the entire building as a complete system, considering the unique physical and operational characteristics and location of a particular building. However, as with the prescriptive path, there are a number of drawbacks to whole building performance. First, real-world buildings always contain some elements that exceed code minimums, whereas the performance path baseline buildings do not. Therefore, the performance path could potentially result in buildings that use more energy than typical prescriptively-designed buildings. In addition, the performance path does not differentiate between long-lived aspects such as the building envelope quality or HVAC system type, and shorter-lived components such as lighting controls or individual pieces of equipment. So, while the tradeoffs allowed via the performance path may result in equivalent building energy use at year one, it may be inferior over the total life of the building (Thornton et al. 2015, Jonlin et al. 2016). Finally, energy modeling is an expensive and time-consuming process, performed by specialists and not easily verified by building officials responsible for enforcing code compliance.

Interior lighting is one example of a system that is treated differently by energy codes. Each building is assigned an overall lighting power allowance based on its size and occupancy, with the designer then given the freedom to provide any configuration of lighting within that power allowance. This system encourages the use of higher-performance fixtures, without specifically prohibiting any particular fixture types. As lighting technology has become more efficient (evolving from incandescent to fluorescent to LED), those allowances are correspondingly reduced in the codes.

An equivalent code compliance method for HVAC systems, an "HVAC power density" (similar to a lighting power allowance) has been explored by Kavanaugh (Kavanaugh et al. 2006). Input power density thresholds for HVAC equipment in Btu/hr-ft^2 are established by building type and climate zone. The primary flaw with such a concept is that HVAC system capacities must be sized to accommodate winter and summer extremes, whereas actual HVAC systems typically operate under part load conditions for most hours of the year. As a result, the annual energy impact that is based primarily on efficiency at part load conditions is ignored by the HVAC power density approach, which is based on peak energy use that occurs only a few hours a year. Another issue is that HVAC system power density is influenced by the building heating and cooling loads as well as the performance of the HVAC system itself. A heavily insulated and tightly-sealed building envelope with good solar protection at the fenestration will of course generate significantly lower heating and cooling loads compared to a poorly-designed or poorly-constructed building envelope. A building with fewer computers and other heat-generating equipment will also demand less cooling. An optimal metric for evaluating HVAC system performance should therefore be independent of the building loads.

A more promising metric for evaluating an HVAC system would therefore be one that measures the amount of energy required to deliver each unit of heating and cooling to the building over the course of a typical year, normalized for the loads imposed internally by occupancy and externally through the envelope. Systems using less overall energy each year to meet the building's annual thermal and ventilation loads would be judged to be more efficient. An upper limit of energy use could then be codified for any individual building, such that it would be difficult for the poorer-performing systems to meet code. Ideally such a calculation would also be much simpler than standard whole building performance energy modeling.

This then is the genesis of the HVAC *Total System Performance Ratio* – the TSPR, which has been developed as a proposed amendment to the Washington State Energy Code.

Total System Performance Ratio

Definition

As described above, the TSPR is a ratio of the annual heating and cooling provided for a building, to the energy consumed in generating and distributing that building's heating, cooling and ventilation. The calculation is performed using whole building simulation similar to whole building performance energy modeling, but in a simplified manner as discussed below.

The simplest representation of energy consumed by the HVAC system would use site energy (energy consumed at the site); however, that approach fails to consider the upstream impacts of generation and distribution losses and does not correspond well with greenhouse gas and other emissions. Instead, Washington State Energy Code stakeholders, following policy recommendations by the Washington State Department of Commerce have embraced the use of an energy cost metric for this proposal that includes both the state average utility price for energy and a social cost of carbon (WSDC 2014). Using this approach, the costs for natural gas and electricity are shown in Table 1.

Table 1. Energy Cost used for TSPR Calculations

Cost Category	Natural Gas (therm)	Electricity (kWh)
Base utility cost/unit	$0.8180	$0.0856
Carbon ton/unit	0.0053115	0.0004118
Carbon $/ton	$64	$64
Carbon $/unit	$0.340	$0.026
Total $/unit	$1.158	$0.112

TSPR is calculated as the ratio of the sum of a building's annual heating and cooling load in thousands of Btu to the sum of the annual cost in dollars of energy consumed by the building HVAC systems. A larger TSPR indicates a lower heating and cooling energy cost to meet the loads, and therefore represents a more efficient HVAC system. This metric provides a single evaluation criteria which addresses all components of the HVAC systems used to move heat and air into, out of, and within a building. It includes distribution system effectiveness and considers both full and part load performance. This differs from standard system efficiency ratings (such as seasonal energy efficiency ratio, coefficient of performance, or kilowatt hours per ton) that usually address a single component within a system and fail to account for all the system inefficiencies that may be present within a building as well as their interaction with building loads and ventilation requirements. In addition, such component efficiency ratings are based on standard rating conditions that may not reflect actual building conditions and the climate of the building site.

To calculate the TSPR, annual energy costs of all system components, including auxiliary components, are included in calculations for a complete HVAC system evaluation. Hence, the total HVAC energy cost includes fuel-fired and electric heating coils, direct expansion cooling coils, boilers, chillers, heat rejection, energy recovery, and distribution system fans and pumps. The total electricity and gas costs are calculated as shown in equations (1) and (2).

(1) $Electricity\ Cost_{Total} = \left(E_{Heating-elec} + E_{Cooling} + E_{Fan} + E_{Pump} + E_{Heat_{Rejection}}\right)[kWh] \times \$0.112/kWh$

(2) $Gas\ Cost_{Total} = \left(E_{Heating-gas}\right)[Therm] \times \$1.158/therm$

Where,

$E_{Heating-elec}$	=	Heating electric energy consumption (kWh)
$E_{Cooling}$	=	Cooling electric energy consumption (kWh)
E_{Fan}	=	Fan electric energy consumption (kWh)
E_{Pump}	=	Pump electric energy consumption (kWh)
$E_{Heat\ Rejection}$	=	Heat rejection energy consumption (kWh)
$E_{Heat\ Recovery}$	=	Heat recovery energy consumption (kWh)
$E_{Heating-gas}$	=	Heating gas energy consumption (therm)

To determine the annual heating, cooling, and total loads for each building, the simulation uses a special HVAC system type available in DOE's *EnergyPlus* software called the Ideal Loads system (DOE 2018A). 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 setpoints for temperature and humidity control, and outdoor air quantity, so it truly represents the complete load on the HVAC system. Thus, the TSPR is calculated according to equation (3).

(3) $Total\ System\ Performance\ Ratio = \frac{(Ideal\ annual\ heating\ load + Ideal\ annual\ cooling\ load)\ (kBtu)}{(ElectricityCost_{Total} + Gas\ Cost_{Total})\ (\$)}$

Implementing the TSPR Approach in the Washington State Energy Code

The following sections describe how the TSPR would be applied in the Washington State Energy Code. Code change proposals for the 2018 edition of this code, including this proposal to incorporate the TSPR, will be considered by the Washington State Building Code Council during the summer and fall of 2018, for a revised code that will take effect in July of 2020.

Establishing a Reference Building Design HVAC System

To comply with this new provision , the TSPR of a proposed building design would need to be greater than the TSPR for a standard reference building (baseline) design. The baseline design TSPR is determined using the same building model as the proposed building design, but replacing the HVAC system with one that is determined to be based on good quality, energy-efficient design practice and compliant with the prescriptive HVAC requirements of the code. This approach places a great deal of importance on the selection of the appropriate HVAC system type. Unlike most other energy codes, the Washington State Energy Code already places some prescriptive system type requirements on certain occupancies (WSEC 2015). Offices, education facilities, schools, libraries, and fire stations are not permitted to use standard variable air volume reheat systems or other system types that combine space conditioning with delivery and treatment of outdoor air, and instead must separate space conditioning systems from outdoor air conditioning systems or meet the requirements for a highly efficient Advanced VAV system. Because of this, the first implementation of TSPR in the WSEC is being proposed to apply to office, education and retail occupancies. Together, these three building types represent approximately 37% of new construction starts in Washington State for non-residential buildings (Jarnagin, Banyopadhyay, 2010).

To establish the details of the standard reference design HVAC system for each of three building types, a stakeholders group was established that included, in addition to the authors, mechanical engineers, energy modelers, energy code developers, and code enforcement officials working in Washington State. There are a number of commonalities between the three baseline building systems chosen by this group. They each include a space conditioning heat pump system with a fan that cycles on and off to meet loads and a separate dedicated outdoor air system (DOAS) that includes sensible heat recovery. Additional details about the baseline systems are provided in Table 2.

Modeling the Proposed and Reference Building Design

The proposed building will be required to be modeled in accordance with rules proposed for the 2018 Washington State Energy Code. These include a simplified modeling approach for the building geometry, envelope construction, interior loads, HVAC system specifications, etc. For example, a single lighting power density can input for the entire building or for each block. Blocks as defined by the Washington State Energy Code are a geometric concept used in energy simulation representing a whole building or a portion of a building with the same use type served by the same HVAC system type. Building envelope component thermal characteristics are described by a U-factor input only, with the simulation assuming standard construction characteristics. HVAC system parameters such as coefficient of performance for heat pumps and variable air volume terminal damper minimums are input based on weighted averages by block for similar systems or components. The intent is to reduce the level of effort associated with developing an energy model for the proposed building design by limiting the parameters that can be entered for the proposed building to a standard set of inputs which would be applicable to all buildings pursuing compliance through the TSPR path. It references ASHRAE Standard 90.1 Appendix C for default values related to basic modelling assumptions such as schedules of operation, plug loads, ventilation loads, equipment performance and operation, etc., providing reliable and consistent default values for the baseline and proposed designs (ASHRAE 2016). The reference building model will be that same as the proposed design except that the HVAC systems will be modified as previously described. Any simulation tool used to demonstrate compliance with the TSPR approach would be required to implement these simplifications for the proposed building design and automatically generate the baseline building design.

Table 2. Standard Reference Design HVAC Systems[1]

Parameter	Building type			
	Large office[2]	Small office[2]	Retail	School
System type	WSHP	ASHP	ASHP	ASHP
Fan control[3]	Cycle on load	Cycle on load	Cycle on load	Cycle on load
Space condition fan power (W/cfm)	0.528	0.528	0.522	0.528
Heating/cooling sizing factor[4]	1.25/1.15	1.25/1.15	1.25/1.15	1.25/1.15
Supplemental heating availability	NA	<40°F OA	<40°F OA	<40°F OA
Modeled cooling COP (Net of fan)[5]	4.46	3.83	4.25	3.83
Modeled heating COP (Net of fan)[5]	4.61	3.81	3.57	3.81
Cooling source	DX	DX	DX	DX
Heat source	Heat Pump	Heat Pump	Heat Pump	Heat Pump
Outside air economizer	No	No	Yes	Yes
Occupied ventilation source[6]	DOAS	DOAS	DOAS	DOAS
DOAS fan power (W/cfm)	0.979	0.979	0.873	0.887
DOAS temperature control[7, 8]	Bypass	Wild	Bypass	Bypass
ERV efficiency (sensible only)	70%	70%	70%	70%
WSHP loop heat rejection	Cooling tower[9]	NA	NA	NA
WSHP loop heat source	Gas boiler[10]	NA	NA	NA
WSHP loop temperature control[11]	65°F to 85°F	NA	NA	NA
WSHP circulation pump W/gpm[12]	16	NA	NA	NA
WSHP loop pumping control[13]	Variable flow	NA	NA	NA

[1] ASHP = air source heat pump; COP = coefficient of performance; DOAS = dedicated outdoor air system; DX = direct expansion; HP = heat pump; VSD = variable speed drive; WSHP = water source heat pump.

[2] Offices <50,000 ft^2 use "Small Office" parameters; otherwise use "Large Office" parameters.

[3] Space conditioning system shall cycle on to meet heating and cooling setpoint. One space conditioning system is modeled in each zone. Conditioning system fan operation is not necessary for ventilation delivery.

[4] The equipment capacities (i.e. system coil capacities) for the *standard reference design* building design shall be based on design day sizing runs and shall be oversized by 15% for cooling and 25% for heating.

[5] COPs shown do not include fan energy use. See 90.1 appendix G (G3.1.2.1) for separation of fan from COP in packaged equipment where efficiency ratings includes fan energy (e.g., SEER, EER, HSPF, COP).

[6] Airflow equal to the outside air ventilation requirements is supplied and exhausted through a separate DOAS system including a supply fan, exhaust fan, and sensible only heat exchanger. No additional heating or cooling shall be provided by DOAS. A single DOAS system provided for each *block*. The DOAS supply and return fans run when HVAC system is scheduled to operate in accordance with ASHRAE Standard 90.1 Appendix C.

[7] "Wild" DOAS control indicates no active control of the supply air temperature leaving the DOAS system. Temperature will fluctuate based only on entering and leaving conditions and the effectiveness of ERV.

[8] "Bypass" DOAS control includes modulating dampers to bypass ERV with the intent to maintain supply air temperature at a maximum of the lower of 60 deg. F. and outside temperature when outside air is below 75°F. Once outside air is above 75°F bypass dampers will be fully closed.

[9] Includes a single axial fan cooling tower with variable-speed fans at 38.3 gpm per/hp, sized for an approach of 10°F and a range of 10°F.

[10] Includes a single natural draft boiler with 80% E_t.

[11] Loop controlled to maintain loop temperature entering heat pumps between 65°F and 85°F.

[12] Pump motor input power shall be 16 W/gpm.

[13] Variable flow with variable speed drive pump and 2-way valves at each heat pump. Fluid flow shutoff at each heat pump when compressor cycles off.

Implementation of the TSPR Approach in Asset Score Tool

While any simulation approach that follows the rules proposed for the Washington State Energy Code to calculate the TSPR could be used, PNNL has developed a new module to be used with the U.S. Department of Energy's Building Asset Score Tool (DOE 2018B). Without such a simulation tool with simplified inputs, compliance with the TSPR code requirement would be unduly burdensome for both design teams and building officials, and the design teams would likely be forced into use of detailed energy modeling, similar to that used for the whole-building performance path. It is estimated that a 50,000 ft^2 project will require 4-5 hours to conduct a TSPR analysis, compared to 75-100 hours for a full whole building performance analysis.[1]

The Building Energy Asset Score Tool (Asset Score Tool), developed by PNNL for the U.S. Department of Energy (DOE), is a web-based tool to help building owners and managers assess the efficiency of a building's energy-related systems and to encourage investment in cost-effective improvements (Wang 2015). Asset Score Tool uses EnergyPlus and OpenStudio to develop a whole building energy model of a building and provides an assessment of building systems based on the specified building characteristics (EnergyPlus 2018, OpenStudio 2018). The TSPR approach is being implemented within the Asset Score tool, which would allow users to define their proposed building design in the tool in accordance with the ruleset proposed for the 2018 WSEC and would automatically generate the standard reference design following the rules defined in the code.

Asset Score Tool Workflow

The Asset Score Tool is modular in design for clean separation of functionalities, easier testing, and development. The core components of the Asset Scoring Tool application are functionally separated into the following five subsystems: (i) User Interface that allows a user to define the properties of the proposed building (ii) Asset Score Application that translates all user inputs into the Asset Score schema, (iii) Analytical Engine that identifies the TMY3 weather file based on the building zip code, (iv) Modeling Engine that runs an EnergyPlus simulation via OpenStudio, and (v) Report Generator that post-processes the analysis results (Wang 2015).

Figure 1 shows the Asset Score Tool structure. The User Interface allows a user to define the properties of the proposed building. Following the rules proposed for the WSEC, a user can create a geometric representation of the proposed building using one or more 'blocks'. Blocks can be used to represent a whole building or a portion of a building with the same use type served by the same HVAC system type. Building envelope is defined using the predefined construction assemblies for exterior roof, above grade and below grade walls, exterior and slab-on-grade floors. A user is required to specify the assembly U-values, F-Factors and C-Factors as applicable. The tool uses standard operation schedules, plug loads and ventilation rates, as defined by ASHRAE 90.1-2016 Appendix C. Lighting power density and HVAC systems are defined by the user for each block.

[1] Cost of complete whole building performance path energy modeling based on informal discussions with three energy modeling consultants working in Washington State.

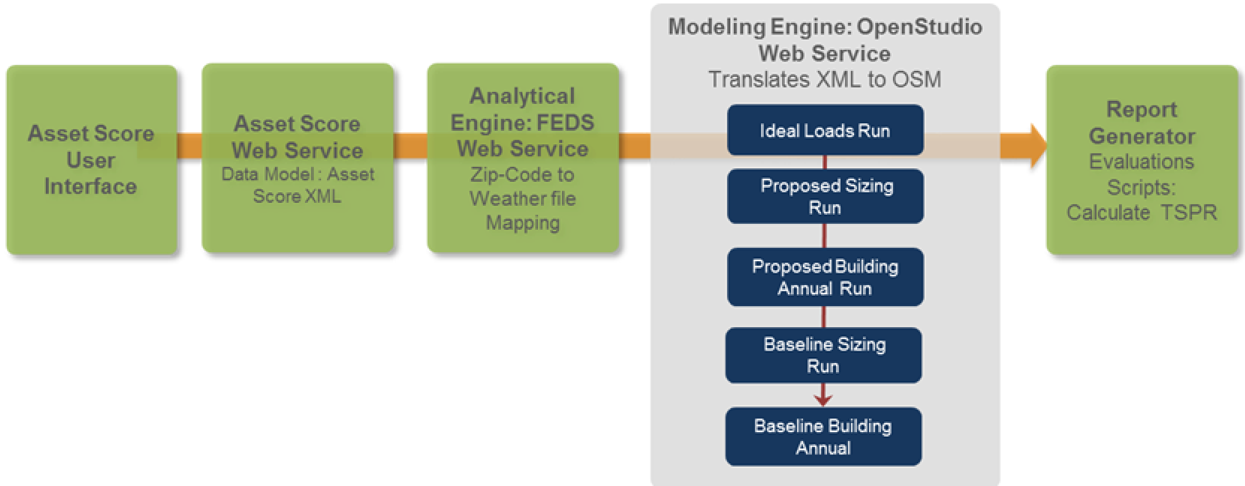

Figure 1. Asset Score Tool Components for TSPR Analysis

These inputs are saved in the Asset Score web application which translates all user inputs into an XML file using the Asset Score data model. The Modeling Engine receives the Asset Score XML which is translated to the proposed building model. The modeling engine translates the XML model to an OpenStudio model and runs the ideal loads –run, sizing run and annual run –for the proposed building. The baseline building is automatically generated based on the proposed building design. It is identical to the proposed building in terms of its geometry, envelope construction and internal loads. However, the HVAC system for each of the blocks in the proposed building are replaced with the HVAC system as defined in the standard reference design. Sizing and annual runs are carried out for the baseline building. The simulation outputs from the Modeling Engine are sent to the Report Generator, which calculates the TSPR for the proposed and baseline building. The tool generates a PDF report which documents the calculated TSPR for the baseline and proposed buildings and all model inputs defined by the user in the user interface.

Asset Score Tool simplifies the modeling process for the proposed building by providing a simplified approach for defining the building geometry and assigning attributes such as envelope properties, lighting power density, HVAC system attributes etc. to the building, and by including defaults for schedules, setpoints, and loads. The automated generation of the baseline building reduces the onerous burden associated with manually modeling the baseline building and this standardized approach used for generating the baseline building ensures fewer errors and inconsistencies. This approach is effective is reducing the cost associated with the energy modeling and compliance process, reducing the errors that could be encountered in detailed energy model and consequently this process has the potential to streamline the compliance verification process since the building official has fewer inputs to verify.

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Conclusions

For the first time, the TSPR gives the energy code a metric and a minimum standard for the overall efficiency of a building's HVAC system, without prescribing the technical means of achieving that level of efficiency. The stringency of TSPR thresholds can be set initially to eliminate only the least efficient systems from consideration, and can then be strengthened over future code cycles to require progressively higher-performing systems. This will shift the focus of code compliance from that of simply conforming to the separate provisions, to that of designing complete integrated systems that interact in a manner that provides the highest levels of efficiency.

The guidelines and procedures proposed for the 2018 version of the WSEC facilitates a standard implementation approach for complying with the TSPR metric. The asset score tool implements these procedures, simplifies the input of the proposed building design, and automates the process of creating the reference building design. This reduces the burden associated with verification of performance-based compliance results, allowing for large scale implementation and broad adoption of the TSPR approach.

While initially developed for a few common building types subject to the WSEC, the TSPR approach could be applied to any code or building energy standard with customized TSPR calculations. When combined with the whole-building evaluation procedures already available for lighting and for building envelope systems, the TSPR has the potential to move energy codes closer to enacting a building performance standard that is based on hard performance targets, without requiring resource intensive whole building performance path modeling.

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