A New Simple HVAC Energy Performance Metric: Climate and Occupant Preference-Adjusted

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ABSTRACT

Penetration of smart home devices such as thermostats, metering devices opened the door for new building energy performance rating reflecting actual operation and maintenance (O&M) and energy service (e.g., comfort requirements) dimensions in their calculation. Existing metrics either focus solely on building asset efficiency or require modeling processes that reflect actual operating and service conditions, limiting their practical application across diverse stakeholders who prefer simple energy performance indices (EnPI). This prospective paper proposes a new simple EnPI that accounts for HVAC systems that incorporates both O&M and energy service dimensions by integrating climate data and occupant preferences into its calculations. Using the Residential Energy Consumption Survey (RECS) data, we demonstrated the implications of this new EnPI, especially compared with the conventional rating approach. In the end, this study will become a new addition to the suite of EnPIs and contribute to a comprehensive understanding of building energy performance.

INTRODUCTION

Building operations are being increasingly digitized in the modern era through adoptions of smart sensing and metering technologies such as smart thermostats, smart meters, smart plugs, and even smart electric panels. These devices have become more affordable and technically simple to install, allowing residents to easily gather Heating, Ventilation, and Ai-Conditioning (HVAC) operational data, indoor environmental data, and circuit-level energy data According to the Residential Consumption Survey (RECS) data (U.S. Energy Information Administration n.d.), the adoption rates of these technologies have increased noticeably, as shown in Figure 1 (next page).

This digitization trend in buildings presents opportunities to enable a broader range of data-driven performance rating methods beyond the two common types of building energy performance indices (EnPIs): (1) asset rating and (2) operational rating. Asset rating, based on simulated energy performance, accounts only for the efficiency of engineering systems (i.e., building assets) and often fails to capture the variability observed in operational rating (Fairey and Goldstein 2016). As a result, asset rating is often used during the design phase but is less applicable during building maintenance and operational, which represents the longest phase in a building's life cycle. Also, its reliance on simulated performance introduces a risk of misrepresenting real-world energy use and occupant behavior.

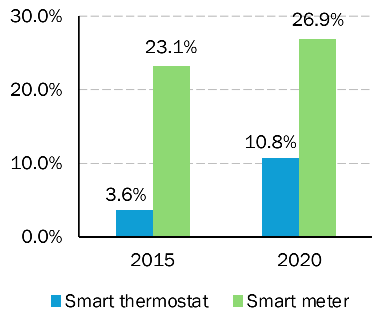

Figure 1. Adoption rates of smart thermostats and smart meters reported in RECS.

On the other hand, operational rating (Equation (1)) covers all three dimensions in its calculation (Figure 2). However, its reliance on energy bills introduces another tweak to performance calculation due to wide adoption of time-of-use (TOU) rates – an electricity pricing structure where the cost of electricity varies depending on the time of day you use it – in the U.S. (Zhao et al. 2017) and its comprehensiveness makes it difficult to identify each dimension's specific contribution to the observed energy use. To address these issues of asset and operational rating approaches effectively, Goldstein and Eley (2014) proposed operation and maintenance (O&M) rating and Energy Service Index, but these metrics require a building energy modeling process using actual operation and service conditions – additional efforts required for rating.

$$Operation\ EnPI = \frac{EP_{RB,AEB}}{EP_{BB,AEB}} \quad (1)$$

where $EP_{RB,AEB}$: the energy performance of the rated building determined from the utility bills and $EP_{BB,AEB}$: the energy performance of the baseline building with the same conditioned floor space as the rated building, but adjusted for the operating conditions of the rated building.

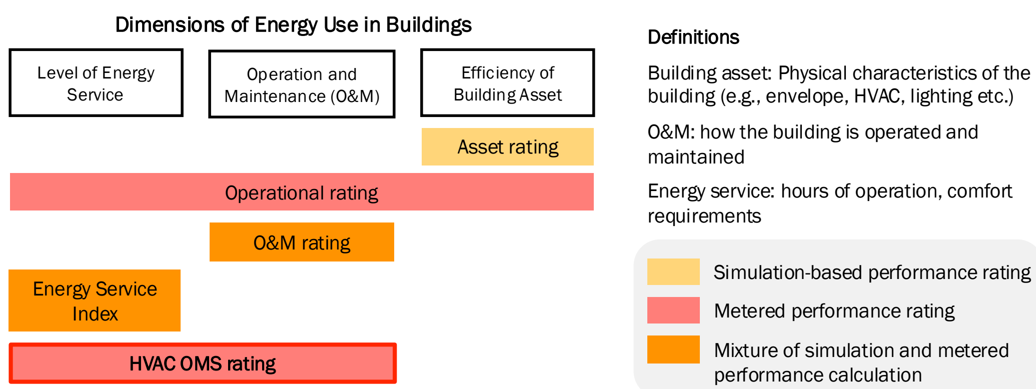

Figure 2. Relationship of EnPIs to the dimensions of building energy performance

The objective of this prospective research paper is to introduce a new simple metric, named HVAC Operation, Maintenance, and Service (OMS) index, which accounts for 'energy service' and 'O&M' dimensions in HVAC. HVAC handles half of end use in U.S. commercial buildings (U.S. Energy Information Administration 2023) and 31% of electricity consumption in residential buildings (U.S. Energy Information Administration 2023). Also, efficiency of HVAC equipment is well established through diverse metrics such as coefficient of performance (COP), energy efficiency ratio (EER). However, based on our extensive literature review, little research efforts have been made to introduce a metric that quantitatively explains two critical dimensions in HVAC energy performance.

METHODOLOGY

As noted by Goldstein and Almaguer (2013), simple EnPIs are often preferred across all stakeholders and the HVAC OMS index aims to introduce a handful of input parameters (Table 1) that are readily collectable through existing smart sensing and metering technologies. For the proposed HVAC OMS index, the variables (Table 1) were selected through the authors' extensive literature review and experiences in HVAC energy performance. Also, these variables can be readily obtained using currently available smart sensing and metering technology.

Table 1. Input variables for HVAC OMS index

Variable	Abbreviation	Unit	Explanation
Heating and cooling degree days	HDD and CDD	Kelvin·days	A measure of how cold/hot the temperature was on a given day. The base temperature is often 65°F.
Thermostat setpoints	S_H: Heating setpoint S_C: Cooling setpoint	°F	Typical user-defined heating and cooling setpoints.
Floor area	A	ft^2	The (energy-consuming) gross floor area in the building
Energy use for space heating and cooling	L_H: Heating Load L_C: Cooling Load	Btu	Energy consumption derived from space heating and air-conditioning equipment

With these variables, the HVAC OMS index can be calculated through Equations (2) to (3). Equation (2) normalizes the heating load by heating degree days (climate) and typical heating setpoint during occupancy by the household. The heating setpoint gets adjusted by 65°F, following a similar approach to HDD calculations. This part accounts for the O&M and energy service dimensions (See our perspectives on this part in the Conclusion section). This equation can be applied to cooling load as well. Equation (3) is the summation of normalized cooling and heating loads of a household.

$$NL_{H,i} = \frac{\frac{L_{H,i}}{A}}{HDD_i(\varepsilon + |65 - S_{H,i}|)} \quad (2)$$

$$HVAC\ OMS_i = NL_{H,i} + NL_{C,i} \quad (3)$$

where i is the household and ε is the constant value that prevents division by zero (e.g., 1°F).

To demonstrate the example results of this HVAC OMS index, we conducted purposive sampling from the 2020 RECS data – a national representative sample of 123.5 million housing units (U.S. Energy Information Administration n.d.) – using the HDD and CDD values to separate climate groups (cold and hot), as shown in Table 2, and shared the results in the following section.

Table 2. Grouping criteria using HDD and CDD values.

	Group #1 (Cold)	Group #2 (Hot)
HDD	> 10,859 (the 75 percentile)	Not applicable
CDD	Not applicable	> 3,291 (the 75 percentile)
Sample number	75	1271

In addition, we used the conventional energy performance metrics, especially energy use intensity (EUI), which is one of the widely used metrics for building energy performance across asset and operational rating approaches, for comparison. EUI accounts for annual energy consumption divided by the total building floor area.

RESULTS

As shown in Figure 3 and Table 3, EUI and HVAC OMS values revealed different results and patterns across homes.

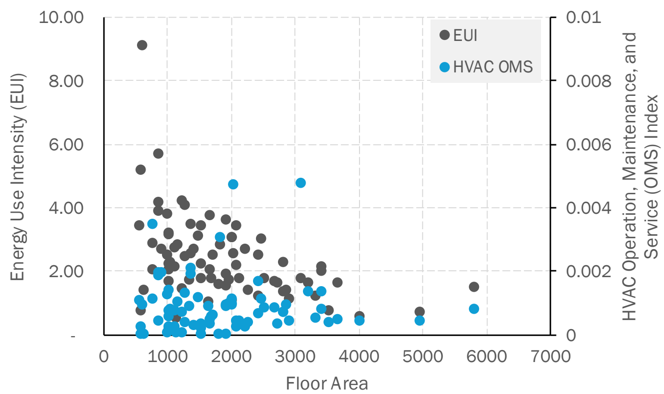

Figure 3. Group #1 (Cold): EUI and HVAC OMS values

Table 3. Pearson correlation coefficients between HVAC OMS and EUI values

	Group #1 (Cold)	Group #2 (Hot)
Correlation coefficient	0.14	0.36

Both indices can be complementary to each other. For example, among four homes that had less than 600ft^2 (Table 4), Home #4 maintained a lower temperature setpoint (65°F), compared to other homes (74°F). Consequently, this home had low EUI and HVAC OMS values. In contrast, the remaining three homes revealed very different EUI and HVAC OMS values. Home #2 had the second highest L_H and HVAC OMS values but highest EUI value. This means that utility rates or energy sources that this home utilized were somehow much more expensive than other homes or other equipment (lighting or plug loads) might have contributed significantly than HVAC.

Table 4. Inputs and results from example homes from Group #1 (Cold).

	HDD	S_H	A	L_H	Total energy bill	EUI	HVAC OMS
Home #1	12,437	74	560	21,246	2,935	5.24	3.05×10^{-4}
Home #2	10,913	74	580	61,618	5,299	9.14	9.74×10^{-4}
Home #3	14,658	74	540	89,420	1,867	3.46	1.13×10^{-3}
Home #4	11,231	65	560	433	457	0.82	6.88×10^{-5}

CONCLUSION

The ongoing digitization of buildings via smart sensing and energy metering technologies presents new opportunities to collect and leverage real-world, measured data. This prospective study shared the preliminary results for a new EnPI that leverages established technologies to help energy managers make informed decisions by offering a new prospective on building energy performance. The proposed HVAC OMS index assesses HVAC energy performance with an emphasis on O&M and energy service dimensions. Another notable advantage is its simplicity, requiring minimal effort for data collection and calculation. Consequently, this metric can be readily implemented across buildings to provide a detailed interpretability opportunity.

As for the future study, we intend to incorporate other EnPIs such as operating rating, O&M index, and energy service index by establishing the baseline by analyzing the RECS data statistically and modeling with actual operational data. Also, we will employ actually measured data from buildings using energy metering technology – beyond the 2020 RECS data – to further demonstrate the pros and cons of this proposed HVAC OMS EnPI.

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