System-level Key Performance Indicators (KPIs) for Building Performance Evaluation

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ABSTRACT

Quantifying building energy performance is essential for achieving high-efficiency goals for both new and existing buildings. Currently, building energy performance is usually represented either at the whole building level such as site or source energy use intensity (EUI), or at the equipment/component level such as EER/SEER for packaged DX equipment, chiller COP, fan efficiency, boiler AFUE or thermal efficiency. Although those metrics provide some insights into how the whole building or individual equipment/component performs, there lack system-level key performance indicators (KPIs) to represent system-level performance. Building systems are usually complicated and interconnected, identifying KPIs at the system level is critical to have a deep understanding of energy performance and operational efficiencies of building systems. System-level KPIs can be used for performance benchmarking and diagnostics. Moreover, current building energy standards (such as ASHRAE 90.1, ASHRAE 189.1, and California Title 24) do not have a system performance compliance path. A well-defined and validated set of system-level KPIs can be potentially used as a system performance compliance path. This study developed a suite of system-level KPIs and showcased their applications. The KPIs cover major building energy systems, including indoor lighting, outdoor lighting, cooling, heating, ventilation, air distribution, water distribution, service hot water, and miscellaneous energy loads. The rationales of KPIs definitions and structures are discussed. To showcase the use of the KPIs, typical KPI values are derived via simulations of the DOE reference large-sized office building models. Future work includes extending the KPIs for other building types, as well as compiling KPIs from measured data of real buildings, which forms a valuable dataset for system performance benchmarking and diagnostics.

INTRODUCTION

Improving energy efficiency in the building sector has gained increasing attention from both research and practice worlds over the years. Efforts for designing and constructing energy-efficient buildings as well as retrofitting existing buildings for higher efficiency have accelerated. Quantifying building energy performance is essential for achieving high-efficiency goals for both new and existing buildings. For new buildings, measurable building energy performance targets are crucial for plan, design, construction, and commissioning. For existing buildings, quantifying building energy performance is centric and the basis of many fault detection and diagnostics (FDD), retro-commissioning, and measurement and verification applications.

The most common approach to assess building energy performance is at the whole building level. Through whole-building benchmarking, performance indicators such as annual site energy use intensity (EUI) of a building is compared to a benchmarking dataset of similar buildings from either real buildings or simulated results. This approach

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is usually simple and effective since it requires very few inputs and provides relatively accurate evaluations [Wang et al. 2012]. But given the complexity of the built environment, the whole-building level approach becomes insufficient in many circumstances when the site EUI cannot capture the uncertain factors such as system operations, mixed-use types, and dynamic occupant behaviors. Mills et al. [2008] stated the importance of system and component level metrics which allows users to identify, screen, and prioritize potential efficiency improvements. Therefore, building energy performance assessment at multiple levels [Field et al. 1997] becomes necessary. Multiple-level assessment starts from the whole building level to the system level and ends at the component level. The performance of each level is quantifiable via a set of key performance indicators (KPIs). Whole-building level KPIs such as site and source energy consumption and EUI are widely used in different scenarios including building energy benchmarking and retrofit analysis. There are also plenty of performance indicators at the component level such as EER/SEER for packaged DX equipment, HSPF for air source heat pump, COP for chillers, fan efficiency, and boiler AFUE or thermal efficiency. Those performance indicators are clearly defined and widely accepted by the building industry. Some of the applications include equipment performance rating, component-level FDD, and building standard compliance checking [ASHRAE, 2016].

On the contrary, the availability and application of performance indicators at the system level are still very limited. Figure 1 shows the gap of system-level KPIs in evaluating building performance. There is a handful of researchers trying to address this issue by defining and promoting system-level KPIs. Harris and Higgins [2012] describe New Buildings Institute's investigation of metered KPI for commercial building energy use. Their results use data from two office buildings outfitted with system-level metering to calculate KPIs. They found that calculated system-level KPIs can reveal superior or inferior performance of certain aspects of design, operations and occupant behaviors. Pérez-Lombard et al. [2011] proposed a set of energy efficiency indicators for HVAC system at global, service, sub-system, and equipment levels. Liao et al. [2018] defined and showcased the whole-building load to energy ratio (LER) to cooling and heating efficiency. Deru et al. [2005] developed a procedure to measure the indoor lighting energy performance. However, the definitions of KPIs in those studies are siloed and only have limited coverage of the building systems. Also, the data for system-level performance evaluation was not typically readily available [Lazarova-Molnar and Mohamed, 2016]. In recent years, the growing availability of smart sensors and meters make it possible to monitor building systems continuously. Therefore, this study aims to develop a suite of system-level KPIs and showcase their potential applications. The KPIs cover major building energy systems, including indoor lighting, outdoor lighting, cooling, heating, ventilation, air distribution, water distribution, service hot water, and miscellaneous energy loads (MELs).

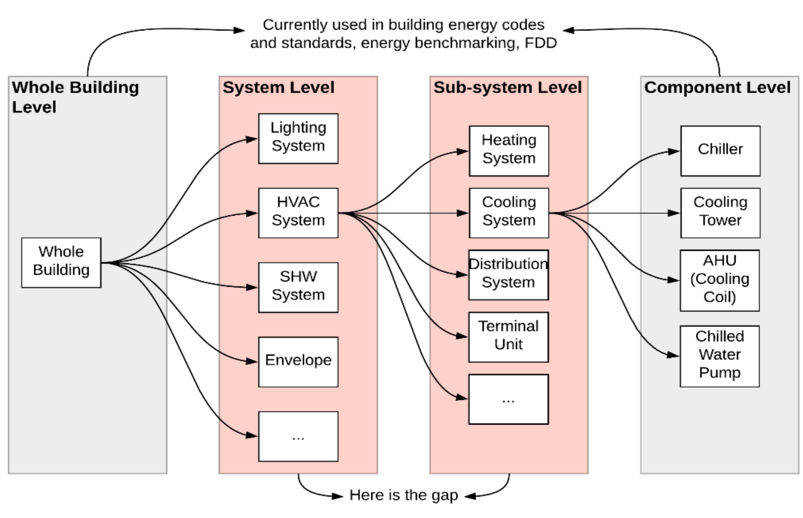

Figure 1. The lack of system-level KPIs

This paper first summarizes the methodology of developing a set of system-level KPIs for building performance evaluation. The paper then presents several examples of the system-level KPIs of large office buildings. Typical values of the KPIs generated from batch EnergyPlus simulations considering three ASHRAE 90.1 vintages, and five U.S. climate zones are also presented. Finally, potential applications of the KPIs in FDD and building energy benchmarking, as well as future work are discussed.

METHODOLOGY

A clear definition of building systems is the prerequisite of defining the system-level KPIs. In this paper, a system refers to an aggregation of individual equipment and distribution network (e.g., pipes and ducts) that delivers a particular building service (e.g., lighting, heating, cooling, ventilation, service hot water, and miscellaneous equipment). Instead of evaluating performance at the equipment level, the system-level KPIs aims to indicate a system's overall performance by taking into account all equipment in that system. Moreover, the system-level KPIs should reflect the system performance from different perspectives such as the amount of energy consumed, the peak demand to the grid, and the impact to the built environment by the system. Therefore, when determining the KPIs, one must consider how the KPIs can represent system performance including the following criteria:

Energy Use: Energy use related KPIs evaluate how efficient a building system is in delivering the service with a certain amount of energy consumption. The common types of energy use related KPIs are energy use intensity (EUI) and energy efficiency (EE). EUI represents the cumulative energy consumption as a function of normalizing factor (e.g., annual lighting energy consumption/building floor area). EE indicates the ratio of served energy to the consumed consumption (e.g., delivered cooling energy/consumed electricity).

Power Demand: Power demand is another critical metric which has a high impact on building operations and utility structure. It is directly related to the maximum service generation and transportation capacity. The KPIs defined aim to enable the evaluation of building systems' peak demands with a higher resolution.

Responsiveness to Control: Control strategies or technologies are usually hard to evaluate via whole building or component performance. System-level KPIs provide opportunities to pinpoint control issues in individual systems. For example, the average weekday's lighting energy consumption during summer should be less than that of winter if daylighting controls work effectively since summer has more daylight than winter.

Responsiveness to Service Demand: Consumption should be correlated to real demand. System-level KPIs can help identify whether the system is functioning at reasonable efficiency. For example, cooling system total energy consumption should be correlated to outdoor air temperature. The ratio between service hot water (SHW) consumption to occupant count informs whether the SHW system works properly. The ventilation rate should correlate to occupant count if it is a demand-controlled ventilation system.

Aggregation Level: KPIs with different aggregation levels can be used for different purposes. For example, the hourly cooling system EUI can be used to track system performance change and identify control issues. And the annual cooling system EUI can be used to assess the overall cooling system efficiency.

Value Type: KPIs with different types of values can be applied in different scenarios. A single-value KPI such as annual heating system EUI indicates the overall energy performance of the heating system. On the other hand, a serial-value KPI indicates the change patterns of system performance. The monthly heating energy EUI before and after a heating system renovation could be used for measurement and verification purposes.

In addition to the criteria stated above, other important aspects such as the common issues and improvement opportunities behind an abnormal KPI value, the sensor/meter needed to calculate the KPIs, and the parameters needed to derive the KPIs in EnergyPlus, are also included. Table 1 shows the structure of the system-level KPIs tables.

Table 1. Structure of the System-level KPI Tables

Column	Meaning
System	System name
Sub-system	Sub-system name
KPI	KPI's name (This field can be a unit or a profile type.)
Definition	The KPI definition
Impact Category	KPI's main impact category. It can be energy (energy efficiency, energy use intensity), peak demand or power, water usage, air quality, and thermal comfort. 'Energy | EE' stands for energy efficiency, 'Energy | EUI' stands for energy use intensity.
Value Type	A KPI value can be a single value (e.g., annual EUI) or serial values (e.g., monthly values, load shape or profile)
Aggregation Level	Sensor/meter reading time interval (hourly, daily, monthly, annual)
Common Issues	Common system deficiency or faults associated with abnormal KPI value or trend
Improvement Opportunities	Improvement opportunities corresponding to the common issues
Sensor/Meter	Required sensors and meters to provide data for calculating the KPI
EnergyPlus Parameters	Corresponding output meters or variables in EnergyPlus to represent or calculate the KPIs

SHOWCASE OF SYSTEM-LEVEL KPIs

A total of 43 KPIs for large-sized office buildings are identified which are grouped into four main system types and 11 sub-system types. Four main system types are lighting system, MELs, HVAC, and SHW. Although the KPIs defined in this project originate from the large-sized office building type, the structured table format allows further development to cover more building and system types holistically. Figure 2 and Figure 3 show the example KPIs for lighting system, cooling system, and heating system. KPIs for other systems are organized in the same format.

System	Sub-system	KPI	Definition	Impact Catrgory	Value Type	Time Interval	Sensor/Meter	EnergyPlus Parameters
MELs	Occupant-related MELs	W/ft2	Energy demand of the system per person and floor area.	Demand | Power	Single Value	Multiple (hourly, monthly, annual)	Electricity meter for MEL	Output:Variable,*,Electric Equipment Electric Power,hourly; !- Zone Average [W]
		kWh/(ft2*yr)	Annual energy consumption per person	Energy |EUI	Single Value	Annual	Electricity meter for MEL	Output:Meter,InteriorEquipment:Electricity,hourly; !- [J]
		Usage Profile	The percentages of four status - active, idle, sleep, and off.	Energy | EE	Distribution	Annual	Electricity meter for MEL	NA
	Non-occupant-related MELs	W/ft2	Energy demand of the system per person and floor area.	Demand | Power	Single Value	Multiple (hourly, monthly, annual)	Electricity meter for MEL	Output:Variable,*,Electric Equipment Electric Power,hourly; !- Zone Average [W]
		kWh/(ft2*yr)	Annual energy consumption per person	Energy |EUI	Single Value	Annual	Electricity meter for MEL	Output:Meter,InteriorEquipment:Electricity,hourly; !- [J]
		Usage Profile	The percentages of four status - active, idle, sleep, and off.	Energy |EE	Distribution	Annual	Electricity meter for MEL	NA

Figure 2. Example table of MEL system KPIs (partial)

System	Sub-system	KPI	Definition	Impact Catrgory	Value Type	Time Interval	Sensor/Meter	EnergyPlus Parameters
HVAC System	Cooling System	W/ft2	Cooling system demand per floor area	Demand | Power	Serial	Multiple (daily, weekly, seasonal, annual)	Electricity meters for chiller, chiled water pumps, and cooling towers (If applicable)	Output:Variable,*,Plant Supply Side Cooling Demand Rate,hourly; !- HVAC Average [W]
		kWh/kWh	Cooling system consumption per delivered cooling energy	Energy | EE	Single	Multiple (daily, weekly, seasonal, annual)	Electricity meters for chiller, chiled water pumps, and cooling towers (If applicable)	Varied by system types
		kW/ton	Cooling system power demand per delivered tooling tonnage	Demand | Power	Single	Annual	Electricity meters for chiller, chiled water pumps, and cooling towers (If applicable)	Varied by system types
		kWh/ft2	Cooling system energy use intensity	Energy | EUI	Single	Annual	Electricity meters for chiller, chiled water pumps, and cooling towers (If applicable)	Output:Meter,Cooling:Electricity,hourly; !- [J]
		kWh/(ft2*CDD)	Cooling system energy use intensity bormalized by cooling degree days	Energy | EUI	Single /Serial	Multiple (daily, weekly, seasonal, annual)	Electricity meters for chiller, chiled water pumps, and cooling towers (If applicable)	Output:Meter,Cooling:Electricity,hourly; !- [J]
		ton-hour/kWh	Energy efficiency of a central cooling plant, including energy use of chillers, chilled-water pumps, cooling towers, and condenser-water pumps (for water-cooled chillers). The KPI is calculated as the ratio of ton-hour of delivered cooling energy to kWh of consumed electricity of all central plant equipment.	Energy | EE	Single /Serial	Multiple (hourly, monthly, annual)	Electricity meters for chiller, chiled water pumps, and cooling towers (If applicable)	Output:Meter,Electricity:Plant,hourly; !- [J]; Output:Meter,Gas:Plant,hourly; !- [J]; Output:Meter,Pumps:Electricity,hourly; !- [J]

Figure 3. Example table of cooling system KPIs (partial)

Energy simulations are good virtual sources of building system sensor and meter data. Therefore, a set of building energy simulation is conducted to obtain typical values of the system-level KPIs. The energy simulation used DOE's reference large-sized office building models with EnergyPlus as the simulation engine. To investigate the KPI variations across different locations and building code versions. Five climate zones (Miami - 1A, Houston - 2A, San Francisco - 3C, Chicago - 5A, Burlington - 6A) and three ASHRAE 90.1 Vintages (90.1-2004, 90.1-2010, and 90.1-2013) are used in the batch simulations. As discussed before, KPIs can be single-value and/or serial-value, Figure 4 shows examples of single-value KPIs. Single-value KPIs indicate the overall performance of a system or sub-system and are often aggregated to monthly, seasonal, or annual level. They can be used for benchmarking at multiple levels.

System	Sub-system	KPI	Impact Category	Vintage	Miami (1A)	Houston (2A)	San Francisco (3C)	Chicago (5A)	Burlington (6A)
Lighting System	Indoor Lighting System	kWh/(ft2*yr)	Energy | EUI	ASHRAE 90.1-2004	2.9	2.9	2.9	2.9	2.9
Lighting System	Indoor Lighting System	kWh/(ft2*yr)	Energy | EUI	ASHRAE 90.1-2010	2.1	2.2	2.1	2.1	2.1
Lighting System	Indoor Lighting System	kWh/(ft2*yr)	Energy | EUI	ASHRAE 90.1-2013	1.9	1.9	1.9	1.9	1.9
Lighting System	Indoor Lighting System	W/ft2	Demand | Power	ASHRAE 90.1-2004	0.28	0.28	0.28	0.28	0.28
Lighting System	Indoor Lighting System	W/ft2	Demand | Power	ASHRAE 90.1-2010	0.23	0.23	0.23	0.23	0.23
Lighting System	Indoor Lighting System	W/ft2	Demand | Power	ASHRAE 90.1-2013	0.20	0.20	0.21	0.21	0.21
Lighting System	Indoor Lighting System	kWh/(person*yr)	Energy | EE	ASHRAE 90.1-2004	587.7	587.7	587.7	587.7	587.7
Lighting System	Indoor Lighting System	kWh/(person*yr)	Energy | EE	ASHRAE 90.1-2010	439.2	442.5	436.6	434.1	435.0
Lighting System	Indoor Lighting System	kWh/(person*yr)	Energy | EE	ASHRAE 90.1-2013	389.3	389.8	390.8	390.1	390.7
Lighting System	Indoor Lighting System	kWh/(FTE_Occupied Hours)	Energy | EE	ASHRAE 90.1-2004	584.6	584.6	584.6	584.6	584.6
Lighting System	Indoor Lighting System	kWh/(FTE_Occupied Hours)	Energy | EE	ASHRAE 90.1-2010	436.9	440.2	434.4	431.8	432.7
Lighting System	Indoor Lighting System	kWh/(FTE_Occupied Hours)	Energy | EE	ASHRAE 90.1-2013	387.2	387.7	388.7	388.1	388.6
MEL System	-	kWh/(ft2*yr)	Energy | EUI	ASHRAE 90.1-2004	11.6	11.6	11.6	11.6	11.6
MEL System	-	kWh/(ft2*yr)	Energy | EUI	ASHRAE 90.1-2010	11.3	11.3	11.3	11.3	11.3
MEL System	-	kWh/(ft2*yr)	Energy | EUI	ASHRAE 90.1-2013	11.3	11.3	11.3	11.3	11.3
MEL System	-	kWh/(person*yr)	Energy | EE	ASHRAE 90.1-2004	2377.9	2377.9	2377.9	2377.9	2377.9
MEL System	-	kWh/(person*yr)	Energy | EE	ASHRAE 90.1-2010	2318.7	2318.7	2318.7	2318.7	2318.7
MEL System	-	kWh/(person*yr)	Energy | EE	ASHRAE 90.1-2013	2316.5	2316.5	2316.5	2316.5	2316.5
HVAC System	-	kWh/ft2	Energy | EUI	ASHRAE 90.1-2010	3.3	3.1	2.0	3.0	3.0
HVAC System	-	kWh/ft2	Energy | EUI	ASHRAE 90.1-2013	3.5	3.1	1.9	3.0	2.9
HVAC System	Heating System	BTU/(ft2*HDD)	Energy | EUI	ASHRAE 90.1-2004	4.5	5.1	2.0	4.4	4.5
HVAC System	Heating System	BTU/(ft2*HDD)	Energy | EUI	ASHRAE 90.1-2010	1.5	1.3	0.2	2.5	2.6
HVAC System	Heating System	BTU/(ft2*HDD)	Energy | EUI	ASHRAE 90.1-2013	0.3	1.5	0.2	2.9	3.0
HVAC System	Cooling System	kWh/ft2	Energy | EUI	ASHRAE 90.1-2004	5.7	4.6	1.9	2.6	2.3
HVAC System	Cooling System	kWh/ft2	Energy | EUI	ASHRAE 90.1-2010	4.7	3.7	0.8	1.6	1.2
HVAC System	Cooling System	kWh/ft2	Energy | EUI	ASHRAE 90.1-2013	4.0	3.2	0.8	1.5	1.1
HVAC System	Air Distribution System	W/cfm	Demand | Power	ASHRAE 90.1-2004	0.44	0.43	0.42	0.42	0.41
HVAC System	Air Distribution System	W/cfm	Demand | Power	ASHRAE 90.1-2010	0.42	0.41	0.42	0.41	0.41
HVAC System	Air Distribution System	W/cfm	Demand | Power	ASHRAE 90.1-2013	0.41	0.40	0.40	0.42	0.42
HVAC System	Ventilation	cfm/ft2	Air quality	ASHRAE 90.1-2004	0.12	0.11	0.14	0.09	0.09
HVAC System	Ventilation	cfm/ft2	Air quality	ASHRAE 90.1-2010	0.07	0.09	0.12	0.10	0.10
HVAC System	Ventilation	cfm/ft2	Air quality	ASHRAE 90.1-2013	0.09	0.08	0.10	0.10	0.10
SHW	-	gallon/person	Energy | EE	ASHRAE 90.1-2004	0.0022	0.0022	0.0022	0.0022	0.0022
SHW	-	gallon/person	Energy | EE	ASHRAE 90.1-2010	0.0022	0.0022	0.0022	0.0022	0.0022
SHW	-	gallon/person	Energy | EE	ASHRAE 90.1-2013	0.0022	0.0022	0.0022	0.0022	0.0022
SHW	-	W/gpm	Demand | Power	ASHRAE 90.1-2004	8.06	8.06	8.06	8.06	8.06
SHW	-	W/gpm	Demand | Power	ASHRAE 90.1-2010	8.06	8.06	8.06	8.06	8.06
SHW	-	W/gpm	Demand | Power	ASHRAE 90.1-2013	8.06	8.06	8.06	8.06	8.06

Figure 4. Typical values of system-level KPIs (partial)

In addition to single-value KPIs, serial-value KPIs show the change of system performance over a certain period. Those KPIs can be used to track system performance fluctuation, detect abnormal patterns, and compare system performance change before and after system modification/update. Depending on the application, the time intervals of serial-value KPIs can vary from sub-hourly to monthly.

POTENTIAL APPLICATIONS

System-level performance diagnostics. Traditional component-level FDD provides insights into how a specific component works, but building systems are complicated and interconnected. The operation of specific equipment may be influenced by other equipment. For instance, air handling unit (AHU) supply air fan operations are related to VAV terminal units. The lighting system, MEL system, and ventilation system performance can be all linked to the occupant-based control system. System-level KPIs provide a new perspective to evaluate the building performance, which considers the performance of the equipment in the system as a whole part. System-level KPI values help track the system performance and identify abnormal operating conditions.

System-level performance benchmarking. Another potential application is the performance benchmarking at the system level. Building energy performance benchmarking will have a higher accuracy with appropriate system-level KPIs. For example, Figure 5 shows two system-level energy performance benchmarking scenarios with different

KPIs. The KPI values are derived from the simulations with DOE's reference large-sized office buildings in five different locations with three ASHRAE 90.1 vintages. Scenario 1 uses the annual cooling EUI which indicates that the building in San Francisco has the lowest cooling EUI among five locations. However, scenario 2 shows that San Francisco has the highest cooling EUI normalized by cooling degree days (CDD). The KPI in scenario 2 captures the impact of weather condition on the building's cooling system, which indicates the potentials of cooling energy savings with air economizers added to old buildings.

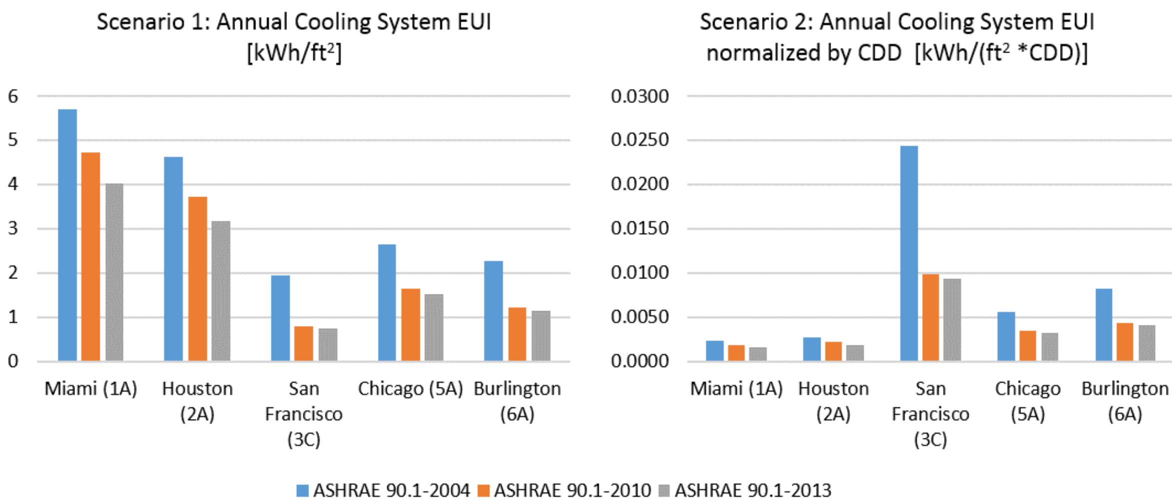

Figure 5. System-level performance benchmarking comparison between two KPIs

Engineering reference. There are a bunch of efficiency metrics for the whole building and individual equipment. Common sources are engineering handbooks, building standards, and manufacturer brochures, but there lacks such reference for system level performance. So, one potential application of the system-level KPIs would be engineering reference. The engineering reference should cover typical values or ranges of system-level KPIs in buildings under different operational conditions such as different vintages, different building types, and different climate zones.

DISCUSSION

This project starts an effort to define KPIs at the building system level. Three potential applications were discussed. The KPIs in this project are defined for office buildings. Typical KPIs are derived via energy simulations instead of real measurements. Further development and applications of system-level KPIs are of future interests:

Develop a KPI database. A database of system-level KPI values can be derived from simulation results of DOE's reference building models covering diverse use types, vintages, and climates. The KPI database can be validated and reinforced with measurement of real buildings systems.

Integrate the system-level KPIs with FDD tools. Further study is needed to explore how the system-level KPIs can be used to assist FDD of energy systems in buildings.

Customize KPIs for specific building types. The system-level KPIs are building specific. For example, in hospital buildings, system performance is closely related to the number of patient beds and room use types. In laboratory buildings, system performance is affected by the type of activities and equipment. In sports facilities and theaters, system performance is related to the types and frequencies of events. Therefore, specific KPIs are needed to describe the system performance.

Integrate the system-level KPIs with DOE's Building Performance Database (BPD). DOE's BPD is the nation's largest dataset with energy-related information for commercial and residential buildings. It provides straightforward energy data visualization and comparison functions. However, the energy-related metrics in BPD are mostly at the whole building level. Adding system-level KPIs to BPD could take advantage and expand its existing functions. An underline challenge is the availability of data to determine the system-level KPIs.

Integrate the system-level KPIs into building energy codes and standards, as well as utility incentives/rebate for new and existing buildings programs. Building energy codes and standards such as ASHRAE 90.1, ASHRAE 189.1, and California Title 24 do not have a system performance compliance path, except ASHRAE 90.1 has a tradeoff method for the building envelope performance compliance. A well-defined and validated set of system-level KPIs can be potentially used as a system performance compliance path. Utilities can also reference the system-level KPIs to design their incentives and rebates programs for existing and new buildings.

CONCLUSION

A suite of system-level KPIs are developed in this study, which covers four main end-use systems in large office buildings including lighting system, MELs system, HVAC system, and SHW system. Each main system category contains several sub-systems. This paper discussed the considerations when selecting and defining the KPIs. The KPI tables list part of a complete set of 43 KPIs, their explanations, their primary impact categories, and the sensor/meter data needed to calculate the KPIs. This study also showcases examples of some KPIs derived from energy simulations, and discussed their potential applications: system-level performance diagnosis, system-level performance benchmarking, and engineering reference. Future development is needed to expand the coverage of the system-level KPIs and promote related applications.

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