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A multi-level energy performance diagnosis method for energy information poor buildings

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ABSTRACT

A thorough assessment and diagnosis is critical for understating and enhancing building energy performance while most buildings cannot provide sufficient energy use data for a detailed diagnosis. This paper presents a multi-level energy performance diagnosis method for energy information-poor buildings where very limited energy use data are available. A simplified monthly energy performance calculation method based on basic energy balances within a building is developed. It provides sufficient energy performance data of a building at multiple levels (i.e., building, system and component levels) while only requiring monthly energy bill data and few in-situ measurements of the HVAC system. The energy performance level then can be determined by comparing the estimated performance data with the benchmark data. A customized benchmarking method using the "relative performance factor" is proposed to indicate the relative difference between the current performance and the expected performance, and to estimate the energy saving potentials. The developed multi-level energy performance calculation method is validated in a super high-rise building in Hong Kong. A case study on illustrating how to apply the proposed diagnosis method for identifying the poor performance areas and the causes behind as well as estimating the energy saving potentials is also presented.

1. Introduction

The building sector has been the largest energy consumer in most countries. For instance, buildings account for about 40% of the total energy consumption in the EU (European Union) and over 90% of the total electric energy consumption in Hong Kong [1,2]. Excessive amounts of energy are often wasted in existing buildings because they often fail to operate as intended. Theoretical studies and field investigations demonstrated that energy saving potentials of the most investigated buildings can reach up to 20%–50% of the total consumption [3]. Improving energy efficiency in buildings is a major priority worldwide [4]. Building energy performance assessment and diagnosis, which can help to identify the amount of energy waste, the degree of efficiency deterioration and the probable causes behind, plays an important role in improving building energy efficiency and reducing building energy consumption.

Many studies on the development and application of energy performance assessment and diagnosis methods can be found in the existing literature. Hernandez et al. developed energy performance benchmarks and building energy ratings for non-domestic buildings in Irish [5]. Chung et al. performed a study on benchmarking energy efficiency in commercial buildings using the multiple regression analysis [6]. A method for assessing building energy efficiency using both simulation and experiment approaches has been developed by Pisello et al. [7]. Lee and Yik developed simplified models for use in the assessment of HK-BEAM (Building Environmental Assessment Method) as an alternative to the detailed simulation method [8]. Participants of Energy Performance of Buildings Directive (EPBD) in EU have developed various energy certification methods for compulsory assessment of new and existing buildings [9,10]. The IEA (International Energy Agency) also has launched two Annex projects (Annex 46 and Annex 53) to promote the energy efficiency of existing buildings by developing and applying appropriate energy performance assessment methods for different types of buildings [11].

Methods for building energy benchmarking and assessment can be categorized into white box method, gray box method and black box method [12]. A white box method is also termed as first principle based method, which begins with a description of the building system or component of interest and defines the building being

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modeled according to its physical description. These models may be described as either simplified or sophisticated, depending on the complexity and scope of the mathematical model. Sophisticated models, such as DOE-2 and EnergyPlus, generally require a large number of inputs and as a result are often difficult to calibrate. Simplified models, such as SBEM (Simplified Building Energy Model) and modified bin method, generally require fewer inputs and as a result are easier to calibrate [13]. On the contrast, a black box method uses data fitting techniques rather than physical knowledge, therefore requires a pre-selected statistical model and training data [12]. ANN (Artificial neural network method) and SVM (support vector machine method) are examples of black box method [14]. A gray box method has the features of white box and black box models, which combines both physical knowledge of the system and data fitting techniques to derive a useful energy model. RC network models and Degree-day methods are typical examples of gray box method [15,16].

Energy performance assessment schemes and methods are established mainly for two purposes: energy classification and energy performance diagnosis [9]. Energy classification is often used by regulators as a "macroscopic level of performance assessment for a group of buildings", which aims to distinguish buildings with different energy performance levels and encourage owners to improve energy efficiencies of their buildings [17]. Typical energy classification programs include whole building benchmarking tools, building certification methods and environmental assessment schemes [9,18]. Energy Star and Cal-Arch are two well-established whole-building benchmarking tools in USA [19,20]. In addition to aforementioned energy performance certification methods developed by EPBD participants, similar certification and rating systems can also found in US including the ASHRAE's bEQ (Building Energy Quotient) program and the DOE AR (energy asset rating) program [21,22]. Typical environmental assessment schemes include Leadership in Energy and Environmental Design (LEED) in USA [23], Building Research Establishment Environmental Assessment Method (BREEAM) in UK [24] and HK-BEAM (Building Environmental Assessment Method) in Hong Kong [25].

Energy performance diagnosis is usually used by building owners as a performance inspection tool, which aims to identify faults and poor energy performance areas and causes in a building so that useful information and recommendations can be provided for fixing these faults and problems. Energy performance diagnosis can be conducted in a building at different levels. According to the inspection scope and examination details in a building, all diagnosis methods can be categorized as whole building diagnosis, system level diagnosis and multi-level diagnosis. Whole building diagnosis, which typically only addresses the overall performance of a building and does not require large amounts of information regarding the operation of the building, is the most commonly used diagnosis method in practice. Shao and Claridge proposed a quality control method using "Energy Balance Load" for verifying whole-building energy-use data [26]. Different from the HB (heat balance) method for load calculation [27],"Energy Balance Load" is a parameter derived from the first law of thermodynamics based on a whole-building energy analysis, which is mainly used to detect building level faulty energy use data [28]. PACRAT (Performance And Continuous Re-commissioning Analysis Tool), the WBD (Whole Building Diagnostician), and the ABCAT (Automated Building Commissioning Analysis Tool) are three well-recognized whole building diagnosis tools [13]. These tools can help identify a building with poor energy performance (e.g., the measured building consumption is larger than the predicted data) or faculty energy data while they are difficult to explain the performance and identify the causes of poor performance. For provided a more detailed diagnosis, a system level diagnosis that can make clear the energy performance of each individual system is necessary. Lee et al. proposed a method for assessing the energy performance of a complex building at system level, by which the energy consumption of main central systems are calculated using a bottom-up estimation method [29]. Yan and Wang proposed a simplified method for assessing the energy performance at the building and system levels [30]. This method can effectively break down the energy bill data into three individual systems without using sub-meters. In addition, building cooling load is also included in the assessment, which can help to differentiate whether a high level of energy use in a building is caused by intensive cooling demands or by inefficient cooling systems.

The most detailed diagnosis method is multi-level diagnosis, which extends the examination of energy performance from building level to system, subsystem and/or component levels, and consequently can provide the most useful performance information and the most specific and targeted recommendations for enhancing the performance. For example, Field et al. proposed a hierarchical performance tree comprised of various energy performance indices of different types of end-use for assessing the building energy performance at multiple levels [31]. The detailed end use data can be either provided by sub-meter systems or calculated based on detailed usage information such as the rated power, the usage time and the usage factor through in-site surveys. This method has also been adopted by Energy Assessment and Reporting Methodology-Office Assessment Method (EARM-OAM), which is a progressively detailed multi-level assessment method, consisting of three stages, i.e. initial stage, intermediate stage and advance stage [32]. More detailed and useful information about the energy performance can be provided when more time and efforts are increasingly taken for data survey and monitoring stage by stage.

However, the current studies or applications of multi-level assessment and diagnosis are still very limited due to the problematic availability of energy use information in most existing buildings [33]. A detailed diagnosis is usually dependent on sufficient energy use data (e.g., end-use data) and/or detailed energy performance data. Energy use data are the most important information for understanding the energy performance of building energy systems. Most existing buildings are energy information-poor buildings in which very few or even no sub-meters are installed [34]. As a result, only the total energy use data of the whole building are available from monthly energy bills. Without the detailed energy use and performance data of individual systems, the energy performance could not be diagnosed at system level, not to mention at component level. Installing a comprehensive sub-metering system is a possible solution while it is usually considered as too expensive for practical applications [35]. Using calibrated simulation tools might be, in principle, the most powerful methods by providing abundant and detailed outputs. However, even though a simulation tool is carefully calibrated at the whole building level (i.e., the simulated energy use of whole building fits well with the utility bill data), the reliability and accuracy at system and end-use level still cannot be guaranteed [9]. In addition, the use of calibrated-simulation usually needs to spent much time and efforts to collect a large number of performance data and system parameters, which is also not cost-effective in practice, particularly in buildings with poor data availability.

In order to resolve the dilemma that most buildings need a detailed diagnosis while few buildings can provide sufficient energy use data, this paper therefore presents a multi-level diagnosis method specially for energy information poor buildings (i.e., buildings with limited energy use data). This method can assess and diagnose energy performance of a building at different levels and then provide sufficient information for decision making even though there are very limited energy use data available in the building. A simplified energy performance calculation method is developed to estimate the energy performance at building level, system level, subsystem and component levels based on monthly electricity bill data and little in-situ measurement data. This calculation method is based on two types of energy balance (i.e., the electricity consumption balance and cooling energy balance) developed in previous study [30] and is improved and extended by using component-level HVAC models (i.e. chiller, pump and fan models) to calculate the most informative data for a detailed diagnosis. A top-down diagnosis approach is proposed for identifying the locations and causes of poor performance from the building level to system and component levels. A customized benchmarking method using the "relative performance factor" is proposed to indicate the relative difference between the current performance and the expected performance. Particularly for the HVAC system, three "relative performance factors" are introduced to examine the energy performance of the HVAC system from different aspects and to estimate energy saving potentials. A case study is conducted in a high-rise building in Hong Kong to validate the improved multi-level energy performance calculation method and to demonstrate the application of the proposed diagnosis method in real buildings.

2. Outline of the diagnosis method

In this section, the scope of energy performance examination, the framework of the energy performance calculation method and the general procedures for energy performance diagnosis are outlined as follows.

2.1. What to be examined in a building?

The proposed energy performance diagnosis method can examine the energy performance at three levels (i.e., building, system and subsystem/component level) using a top-down approach, as shown in Fig. 1. It uses high-level performance indicators to reason the possible low-level causes of degradation. At the building level, the total energy consumption (or EUI) is used to examine the overall energy performance of the whole building.

At the system level, all building energy consumers are divided into three systems, which are the heating, ventilation and air-conditioning (HVAC) system, "internal-consumers" (i.e., the equipment in air-conditioned area such as lighting and office appliances) and "other-consumers" (e.g., the equipment in non-air-conditioned area such as lifts, fire and security systems). The energy consumptions of these three systems can be estimated using the proposed energy performance calculation method. For "internal-consumers" and "other-consumers", the energy performance is evaluated by comparing the estimated energy consumptions (or EUI) with the benchmark data from similar buildings. For the HVAC system, in addition to the energy consumption data, the cooling load and overall energy efficiency of the system are provided to examine the performance at demand side and supply side respectively.

At the component level, the performances of main components of the HVAC system are further examined in detail. At the demand side, the contributions of different heat gains are analyzed to identify the largest cooling load components and the possible measures for reducing cooling load. At the supply side, the energy performances of chillers, pumps and fans are analyzed to identify the inefficient equipment and the causes behind the inefficiencies.

2.2. How to obtain sufficient performance data with limited energy information?

The most important and difficult job for a multi-level diagnosis is how to obtain sufficient energy performance data when only limited energy use information is available. Fig. 2 presents the framework of the proposed simplified method for calculating the energy performance of a building at different levels. Considering the limited data availability of energy information-poor buildings, only easy-to-obtain information is required as inputs that mainly include the monthly electricity bills, general building design data, weather condition data and very limited design and operation data of HVAC systems. All required information, except the weather data that may need to be provided by a local observatory, could be obtained from the already available documents or supplemented by short-term field measurements. The outputs from the calculation include the individual energy consumption of three systems (i.e., the HVAC system, "internal-consumers" and "other-consumers"), the building cooling load, and the energy efficiency of the HVAC system and main subsystems/components. All energy performance data are calculated on a monthly basis. The development of the calculation method will be presented in Section 3.

2.3. How to diagnose building energy performance?

Once the current energy performance of the concerned building is determined, the problems at different levels can be diagnosed by comparing the current energy performance data with the expected data at the same level, as shown in Fig. 3. The expected

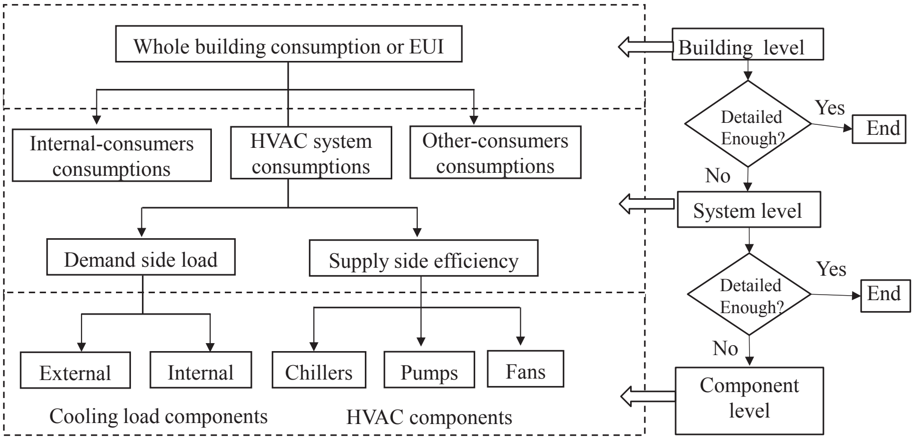

Fig. 1. Top-down approach for multi-level diagnosis.

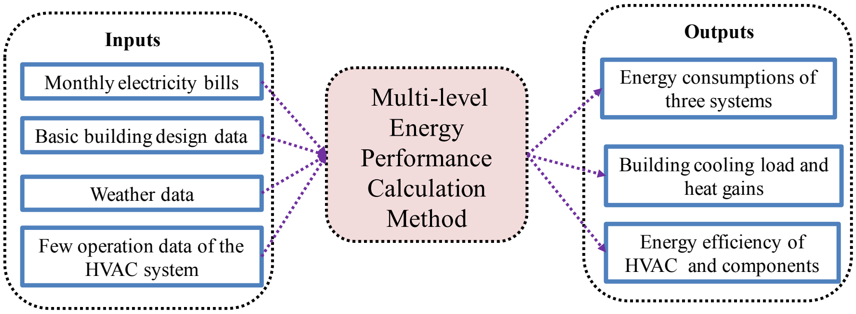

Fig. 2. Framework of the multi-level energy performance calculation.

performance can either be the generic benchmarks referring to similar buildings (i.e., the peer buildings) or the customized benchmarks calculated using the self-reference models. The poor performance areas are detected when the current performance data are worse than the expected data (i.e., benchmark data). The causes of poor performance can be identified when the lower level performance are analyzed based on reasoning. The energy saving potential is usually considered as the difference between the current performance and the expected performance after energy saving measures are adopted.

3. Improved multi-level energy performance calculation method

The authors have developed a simplified method for calculating the energy performance at building and system level [30]. However, the performance data at component level that are the most informative data for diagnosing performance problems cannot be provided yet. In this work we expand the previous method (i.e., the system level energy performance calculation) to be a multi-level energy performance calculation method by newly developing or selecting three component-level HVAC models.

3.1. Brief introduction of the previous study

The simplified energy performance calculation method is based on two basic energy balances and the interactions among different systems. The first balance is the electricity energy consumption balance at the whole building level in Eq. (1), which is mainly used to break down the total energy consumption into the individual consumption of three systems.

$$E_{Building} = E_{HVAC} + E_{Internal} + E_{Others} \tag{1}$$

where, $E_{Building}$ is the total energy consumption of the whole building, which is given by the monthly energy bills. E_{HVAC}, $E_{Internal}$ and E_{Others} are the monthly energy consumption of the HVAC system, “internal-consumers” and “other-consumers” respectively.

The second balance is the cooling energy balance between the demand side and supply side of the HVAC system when the intended indoor temperature is maintained. This balance is mainly

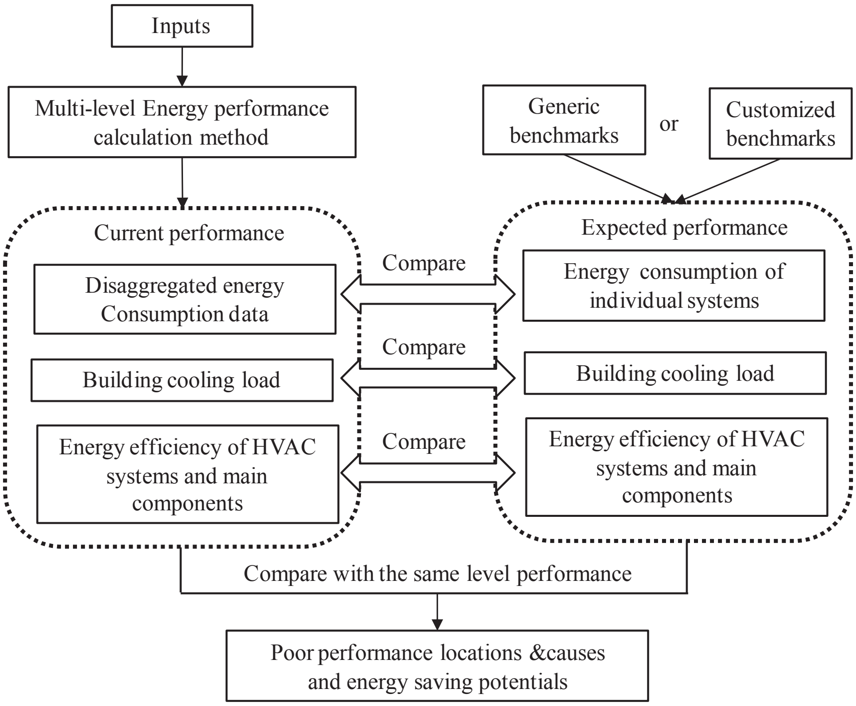

Fig. 3. Flowchart of the multi-level energy performance diagnosis.

used for determining the cooling load and the energy performance of the HVAC system.

$$CL_{Demand} = CL_{Supply} \tag{2}$$

where, CL_{Demand} and CL_{Supply} are the monthly cooling load calculated at the demand side and supply side respectively. The demand side cooling load is determined by all heat gains and can be estimated using Eq. (3).

$$CL_{Demand} = Q_{\mathrm{Electricty-Indept}} + (E_{Internal} + \alpha \cdot E_{HVAC})_{\mathrm{Electricity-Dept}} \tag{3}$$

where, $Q_{Electricty\_Indep}$ represents the heat gains that are independent on the electricity usage, including the heat gain through the envelope, the heat gain due to the fresh air and released by occupants, which can be calculated with given inputs. The details for these heat gain calculation can be found in ASHRAE Handbooks [36]. Other heat gains heavily depend on the electricity use, including the heat gain released by “internal” equipment and some HVAC equipment. The heat gain released by “internal-consumers” can be considered to equal their energy consumptions in most occasions. The heat gain released by the HVAC system is mainly contributed by the cooling delivery equipment (i.e. chilled water pumps and AHU (air handling unit) fans), which is determined by the energy ratio (i.e. α) of the cooling delivery system to the entire HVAC system.

On the other hand, the building cooling load can also be calculated from the supply side of the HVAC system using Eq. (4).

$$CL_{Supply} = E_{HVAC} \times SCOP \tag{4}$$

where, *SCOP* is short for “system coefficient of performance”, which is the overall energy efficiency of the entire HVAC system.

The individual energy consumption of three systems, building cooling load and energy efficiency of the HVAC system are connected as described by two energy balances in Fig. 4. Based on these interactive relations, an optimization algorithm using the “trial-and-error” method was developed to calculate these energy performance data. The schematic of this optimization algorithm is shown in Fig. 5. The main trial variables during the “trial-and-error” process are the electricity consumption of the three consumers. The values of E_{HVAC}, $E_{Internal}$ and E_{Others} are unknown while the sum of them is constrained to be equal to the total electricity consumption. Different trials of consumption data can generate different CL_{Demand} and CL_{Supply}. In most cases, the generated CL_{Demand} and CL_{Supply} do not equal. Only when the trials of consumption equal or approach to the true consumptions, the cooling energy balance can be achieved. In other words, the system consumptions are determined when the cooling balance residuals between the demand side and supply side are zero or minimized.

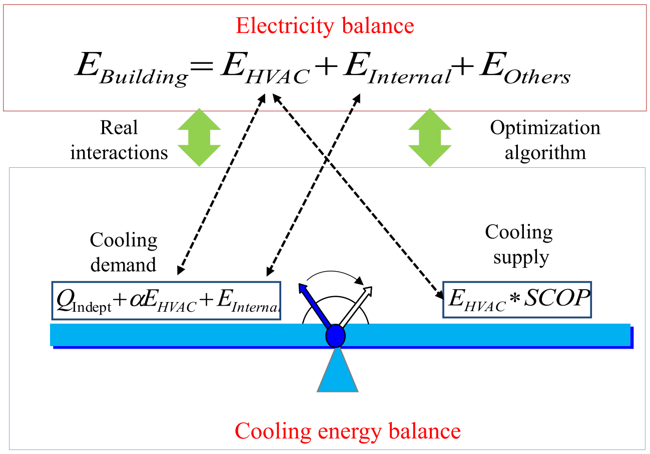

Fig. 4. Interaction of systems described by energy balances.

It is worth noting that even though both the electricity balance and the cooling balance are achieved, it does not ensure that the “exactly true” consumptions are identified. Because some trial consumptions even having no physical meaning (e.g., with minus values) may also be included, since there are three variables but only two balance equations as constraints in each cooling month. In order to identify the “exactly true” consumptions from “possible true” consumptions, the energy usage characteristics of three systems are considered as realistic constrains. For example, the monthly variations of $E_{Internal}$ and E_{Others} are usually very limited, which can used to eliminate those “possible true” consumptions with relative large variations. More details about the optimization algorithm and the energy performance calculation can be referred to [30].

3.2. Development of component-level HVAC models

SCOP and α are two important parameters for determining the cooling energy balance of the HVAC system and consequently affecting the calculation results of the proposed method. In the previous study, *SCOP* and α are estimated using two system-level regression models in which the entire HVAC system is viewed as a whole and the performance is considered to be only determined by the part load ratio of chiller while other factors are missing. As a result, the energy performance can only be examined at the system level while the performance at component level cannot be provided. By contrast, in this study, *SCOP* and α are calculated using the component-level HVAC models by which the energy performance of both the entire HVAC system and individual components can be provided for detailed diagnosis.

The definitions of *SCOP* and α are presented in Eq. (5) and Eq. (6), respectively.

$$SCOP = \frac{CL_{Supply}}{E_{HVAC}} = \frac{CL_{Supply}}{E_{Chiller} + E_{Pump} + E_{Fan}} \tag{5}$$

$$\alpha = \frac{E_{Delivery}}{E_{HVAC}} = \frac{E_{CHW} + E_{PAU} + E_{AHU}}{E_{Chiller} + E_{Pump} + E_{Fan}} \tag{6}$$

where, $E_{chiller}$, E_{Pump} and E_{Fan} are the energy consumption of chillers, pumps and fans respectively. $E_{Delivery}$ is the energy consumption of cooling energy delivery systems including chilled water pumps, air handling unit (AHU) and primary air-handling unit (PAU) fans. E_{CHW}, E_{PAU}, and E_{AHU} are the energy consumption of chilled water pumps, PAU and AHU fans respectively.

The energy consumption of chillers can be calculated through cooling load divided by chiller *COP* (i.e., CL_{Supply}/COP). Considering different influences of internal and external factors, chiller coefficient of performance (COP) can be described as a combined product of ideal efficiency (temperature dependent) and internal efficiency (*PLR* dependent) [37]. An empirical model is proposed to calculate the *COP* of electrical chillers under different operating conditions, as shown in Eq. (7). This model is the combination of a physically based Carnot-factor for the temperature dependency and a third order polynomial for the part load dependency. In this model, the impact of working temperatures and part load ratio can be separated clearly, which can be used to explain how the chiller performance is affected.

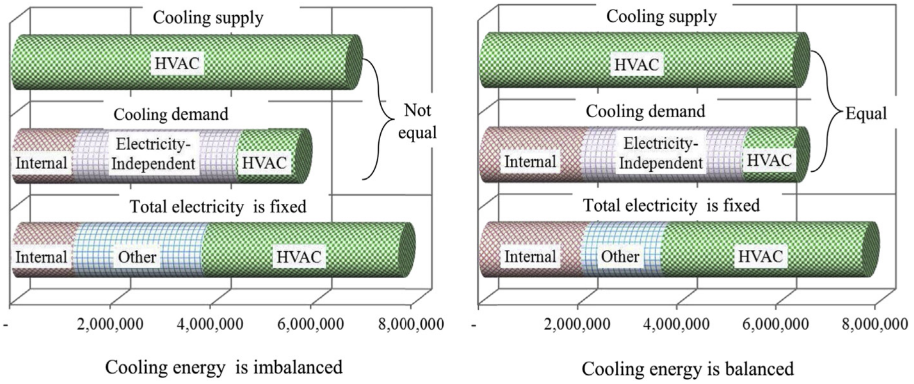

Fig. 5. Schematic of the “trial-and-error” method for searching the best trial variables.

$$COP = \frac{273.15 + T_{Eva}}{T_{Con} - T_{Eva}} \times \left(C_0 + C_1 \cdot PLR + C_2 \cdot PLR^2 + C_3 \cdot PLR^3\right) \tag{7}$$

where, T_{Eva} and T_{Con} are evaporating and condensing temperature (°C), respectively; C_0–C_3 are the correlation coefficients that can be identified from chiller catalogs or field measurement data. PLR is the part-load ratio, which reflects the deviation degrees of partial load operating conditions from the full load conditions. For engineering application, PLR can be simply defined as the ratio of the actual cooling load (CL_{Supply}) to the available cooling capacity ($CL_{Available}$) as shown in Eq. (8).

$$PLR = \frac{CL_{Supply}}{CL_{Available}} = \frac{CL_{Supply}}{N_{Chiller} \cdot CL_{Nominal}} \tag{8}$$

where, $CL_{Nominal}$ is the nominal cooling capacity of each chiller, and $N_{Chiller}$ is the number of operating chillers. This equation is based on the assumption that identical chillers are used in the same building, which is very common in practice.

The calculation methods for constant speed and variable speed pumps and fans are different. For constant speed pumps (fans), the energy consumption can be considered as constant (equal to the rated power). For variable speed pumps (fans), the performance varies greatly under different load conditions. It is very difficult to calculate the accurate power consumption since many aspects such as the equipment characteristics, installation characteristics, speed and pressure differential can influence the power consumption. However, for pumps (or fans) that are already installed in a building, use of flow rate alone often results in sufficiently accurate power models when the system configurations, set points and control sequences remain unchanged [38]. In this study, two simplified variable speed pump and fan models presented in Ref. [39] are selected to calculate the part-load power consumption as a function of part load flows, as shown in Eq. (9) and Eq. (10).

$$E_{Pump} = \dot{E}_{Pump,\ Rated} \times \left(C_0 + C_1 \cdot PLR_{Flow} + C_2 \cdot PLR_{Flow}^2 + C_3 \cdot PLR_{Flow}^3\right) \times t_m \tag{9}$$

$$E_{Fan} = \dot{E}_{Fan,\ Rated} \times \left(C_0 + C_1 \cdot PLR_{Flow} + C_2 \cdot PLR_{Flow}^2 + C_3 \cdot PLR_{Flow}^3\right) \times t_m \tag{10}$$

where, $\dot{E}_{Pump,\ Rated}$ and $\dot{E}_{Fan,\ Rated}$ are the rated input power of the pumps and fans respectively. t_m is the working hours of the concerned month. The coefficients C_0–C_3 can be identified from the catalogs or short-term in-site measurements. The factor PLR_{Flow}, is defined as the ratio between the actual volumetric flow ($\dot{V}_{Actual}$) and the rated flow ($\dot{V}_{Rated.}$), as described in Eq. (11).

$$PLR_{Flow} = \frac{\dot{V}_{Actual}}{\dot{V}_{Rated.}} = PLR \cdot \frac{\Delta T_{Design}}{\Delta T_{Actual}} \tag{11}$$

where, $\triangle T_{Design}$ and $\triangle T_{Actual}$ are the design and actual temperature differences between return and supply of the delivered chilled water by pumps and cooled air by fans.

4. Validation of the improved method

The system level energy performance calculation has been validated in two different types of buildings with different operation modes and different climates in the previous study [30]. The improved multiple-level energy performance calculation method is further validated using the data in a super high-rise commercial building in Hong Kong.

4.1. Building and HVAC system descriptions

This building is an information rich building, in which sufficient energy use data and HVAC performance data are recorded in detail. An advanced sub-metering system with more than 300 power meters is installed to monitor the individual energy consumptions of systems and main components. Almost all the important operation variables of the HVAC system, such as pressures, temperatures, flow rate, as well as operating status and control signals of key points are monitored by the BMS. Such a big number of power meters and BMS sensors provide sufficient data for validating the measurements and the developed method, although very few measurements are actually required for inputs. More information about this building can be seen in detail in Appendix “A”. The general information of the building is presented in Table A.1. The outdoor weather conditions and envelope parameters are shown in Tables A.2 and A.3, respectively.

A simplified diagram of the water side HVAC system is shown in Fig. 6, in which six identical centrifugal chillers with the capacity of 7230 kW each are used to supply cooling. Each chiller is associated with one condenser water pump (constant speed) and one primary chilled water pump (constant speed). Secondary chilled water pumps are variable speed pumps. The design temperature difference of the chilled water system is 6 °C. The heat generated from

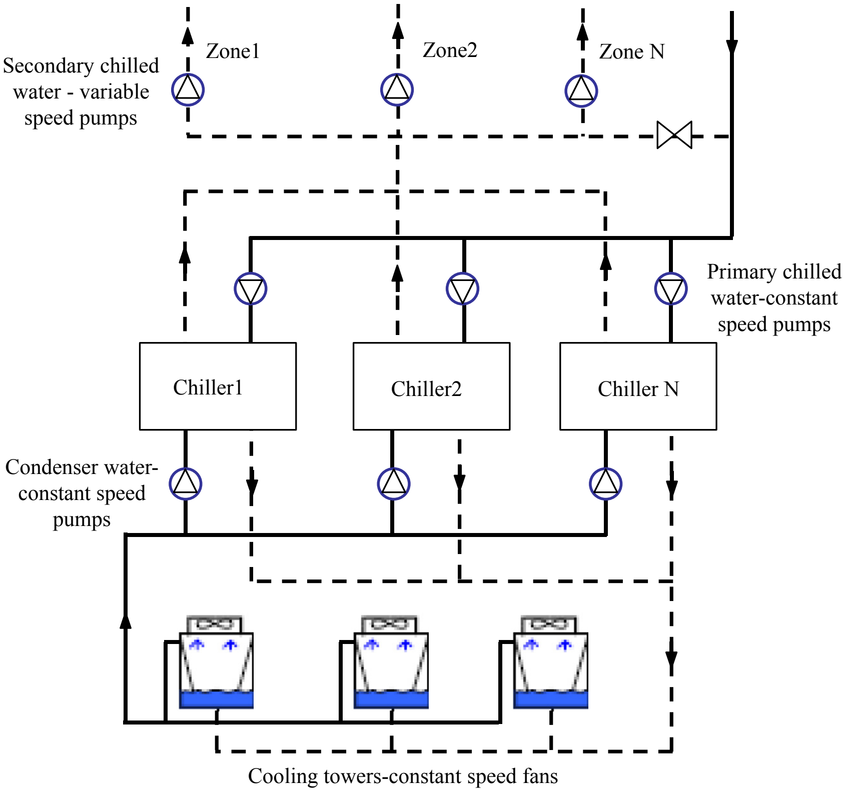

Fig. 6. Schematic of the HVAC system in water side.

the chiller condensers is rejected by evaporative water cooling towers. According to the operating rules of this central chilled water system, the running number of chillers, condenser water and primary chilled water pumps are the same while the number of cooling towers is double this number.

The schematic of the air delivery system is shown in Fig. 7, which consists of 152 AHUs and 16 PAUs. The fresh air is delivered to each AHU through the shaft in the core by PAUs (primary air units). The fans of PAUs are constant speed. AHUs equipped with variable frequency drives (VFDs) are used to handle the mixture of the fresh air and recycled air from rooms. The temperature difference between the supply and return air is designed as 9 °C.

The specifications of main components of the HVAC system including chillers, condenser water pumps, primary and secondary chilled water pumps as well as the fans of PAUs, AHUs and cooling towers are summarized in Table A.4 in Appendix “A”.

4.2. Inputs for energy performance calculation

All required energy use and system operation data are summarized in Table A.5 in Appendix “A”. The total electricity consumption of the whole building in each month is provided from the monthly electricity bills. The “electricity-independent heat gains” is the sum of heat gains from the envelope, outdoor fresh air and occupants. The monthly average operating data of the HVAC system, such as the evaporating (T_{Eva}) and condensing temperature (T_{Con}), the number of chillers in operation, and the temperature difference ($\triangle T_{Water}$) of the secondary chilled water system, are monitored by the BMS. The actual temperature differences ($\triangle T_{Air}$) of various AHUs are not available. Herein, the average value is assumed to be the design value (i.e., 9 °C). Given the number of chillers operating and the operating rules of the central chilled water system mentioned above, the actual number of operating condenser water pumps, primary chilled water pumps and cooling towers can also be determined.

For the concerned HVAC system, the coefficients for the chiller model in Eq. (7) are identified using the catalog data as shown in Table A.6. The coefficients of the variable speed pump (i.e.,

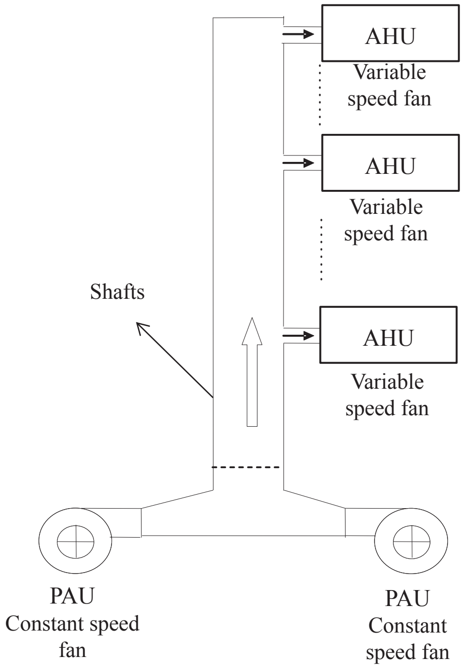

Fig. 7. Schematic of the HVAC systems in air side.

secondary chilled water pumps) and the variable speed fan (i.e., AHU fans) models in Eq. (9) and Eq. (10), respectively, are identified using the field measurement data monitored by the BMS during two typical operating days. The identified coefficients of three component models are presented in Table 1. All models are identified using the polynomial fitting method in Microsoft Excel and the regression performances are shown in Fig.A.1–Fig.A.3 in Appendix ”A”.

4.3. Validation results

The validation involves comparisons of energy performance data calculated using the developed method (denoted as “Cal.”) with that from BMS monitored data (denoted as the “Meas.”) at the same level. Except for the building level consumption, which is given as inputs, the comparison results at system level and component level are presented as follows.

4.3.1. Energy consumption of three systems

The total energy consumption is disaggregated into the individual energy consumption of three energy systems. The comparison between the calculated and the measured monthly energy consumption of three systems is presented in Fig. 8. It can be observed that calculated data agree well with the data monitored by the sub-metering systems in most months. Except that the calculation errors in September and October are relative large, the calculation errors for three systems in other months are less than 10%. The annual average errors of the HVAC system, the “internal-consumers” and “other-consumers” are 2.2%, −3.9% and −6.4% respectively.

4.3.2. Energy performance of the entire HVAC system

The validation results of the energy performance indicators at the HVAC system level are presented in Table 2. The calculation errors of the *CL* (cooling load), *SCOP* and α in all months are within the range of ±15%. The annual average errors of the HVAC performance data are all less than 3%, which indicates that the developed method can estimate the HVAC performances with a satisfactory accuracy. It is worth noting that many energy performance indicators in this paper, such as the *CL*, *SCOP* and α as well as the *COP* and *PLR* of the chiller, cannot be measured directly. The term of “measured” means that the data used for computing these indicators are the actual measured or monitored data.

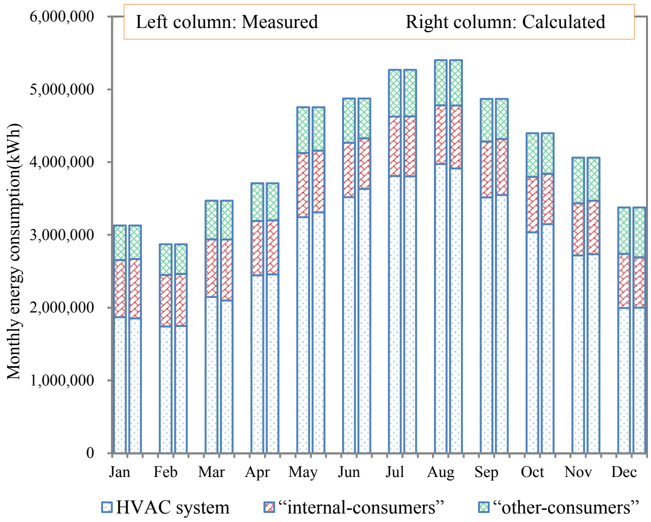

Fig. 8. Comparison of measured and calculated energy consumption of three systems.

Table 2
Comparison of energy performance of the entire HVAC system.

	CL (10^6 kWh)			SCOP			α		
	Meas.	Cal.	Error	Meas.	Cal.	Error	Meas.	Cal.	Error
Jan	3.09	2.93	−5.1%	1.65	1.55	−6.2%	47.1%	48.1%	2.1%
Feb	2.76	2.78	0.5%	1.59	1.58	−0.7%	45.8%	45.6%	−0.5%
Mar	3.59	3.32	−7.4%	1.67	1.61	−3.8%	42.1%	44.5%	5.9%
Apr	4.97	4.90	−1.3%	2.04	1.95	−4.1%	38.2%	42.5%	11.4%
May	7.15	7.35	2.9%	2.20	2.18	−1.0%	36.9%	36.1%	−2.2%
Jun	7.88	7.87	−0.1%	2.24	2.21	−1.3%	35.1%	34.2%	−2.5%
Jul	8.73	8.71	−0.2%	2.29	2.25	−1.6%	34.5%	32.6%	−5.6%
Aug	9.18	9.53	3.7%	2.31	2.42	4.5%	35.9%	34.0%	−5.3%
Sep	8.11	8.99	10.8%	2.31	2.41	4.4%	35.5%	34.4%	−3.2%
Oct	6.31	7.03	11.5%	2.08	2.20	5.7%	37.7%	37.8%	0.3%
Nov	5.75	5.75	0.1%	2.12	2.06	−2.5%	39.0%	39.5%	1.4%
Dec	3.48	3.38	−3.1%	1.75	1.65	−5.6%	46.3%	46.9%	1.2%
Ave	5.92	6.05	2.2%	2.02	2.01	−0.7%	38.4%	38.2%	−0.4%

4.3.3. Energy performance of individual components

By including the HVAC component models in the calculation, the energy consumption of main components and key energy performance indicators (e.g., *COP* and *PLR*) of chillers can be calculated. The energy performance validation results of chillers, pumps and fans are summarized in Table 3, Figs. 9 and 10, respectively. Chillers are the largest energy consumers in the HVAC system and therefore the accuracy of the chiller performance calculation plays the greatest role in determining the overall accuracy of the whole method. From the comparison results presented in Table 3, the calculated energy consumption, *COP* and *PLR* agree well with the “measured” data.

The energy consumption comparisons of three pump systems are presented in Fig. 9. Acceptable results are achieved for the CWP (condenser water pumps) and the CHWP-Primary (primary chilled water pumps), which are constant speed pumps. However, for the

Table 1
Identified coefficients for three component models.

Model	Identified coefficients				Fitting performance (R^2)
	C_0	C_1	C_2	C_3	
Chiller model in Eq. (7)	0.0198	0.6901	0.4478	−0.3522	0.9998
Pump model in Eq. (9)	0	2.4102	−3.6338	2.2513	0.9557
Fan model in Eq. (10)	0	0	0.9364	−0.1797	0.8727

Table 3
Comparison of energy performance of chillers.

	Energy consumption (10^6 kWh)			*COP*			*PLR*		
	Meas.	Cal.	Error	Meas.	Cal.	Error	Meas.	Cal.	Error
Jan	0.65	0.63	−3.5%	4.77	4.69	−1.6%	40.6%	37.8%	−7.1%
Feb	0.62	0.62	0.6%	4.46	4.46	−0.1%	36.6%	36.2%	−1.3%
Mar	0.85	0.74	−12.9%	4.23	4.49	6.3%	41.6%	38.2%	−8.2%
Apr	1.09	0.98	−9.4%	4.58	4.98	8.9%	51.2%	49.3%	−3.7%
May	1.53	1.56	1.4%	4.66	4.73	1.4%	55.7%	55.9%	0.3%
Jun	1.70	1.71	0.2%	4.62	4.61	−0.3%	59.3%	58.7%	−1.2%
Jul	1.84	1.92	4.2%	4.74	4.54	−4.2%	59.3%	57.7%	−2.8%
Aug	1.91	1.93	0.8%	4.81	4.95	2.8%	64.2%	64.7%	0.9%
Sep	1.70	1.82	7.0%	4.76	4.93	3.6%	59.1%	62.6%	6.0%
Oct	1.34	1.45	8.2%	4.70	4.84	3.0%	54.0%	58.6%	8.5%
Nov	1.20	1.19	−0.5%	4.79	4.81	0.6%	54.5%	53.2%	−2.4%
Dec	0.72	0.73	1.4%	4.86	4.65	−4.4%	43.1%	40.8%	−5.4%
Ave	1.26	1.27	0.8%	4.66	4.72	1.3%	51.6%	51.1%	−0.9%

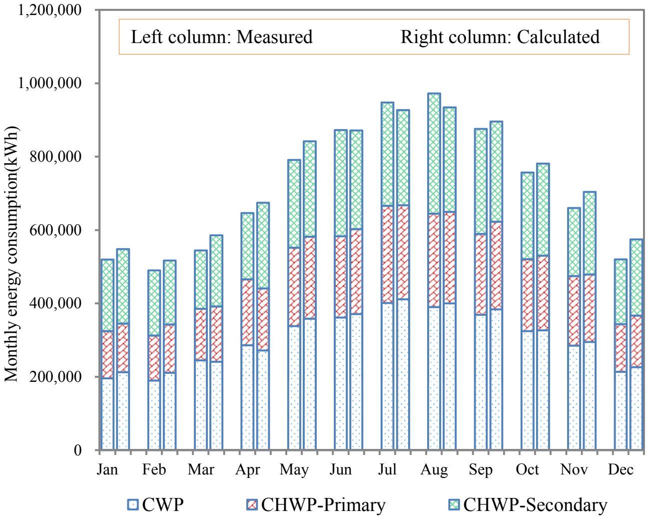

Fig. 9. Comparison of measured and calculated energy consumption of three types of pumps.

CHWP-Secondary (secondary chiller water pumps), which are variable speed pumps, large errors (e.g., ≥20%) are observed in some months. This indicates that the energy performance of the variable speed pumps is more difficult to predict than that of the constant speed pumps.

The energy consumption comparisons of three types of fans are presented in Fig. 10. Compared with other HVAC components, the energy performance of fans are the most difficult to predict. Relative deviations (i.e., errors) between the calculated and measured consumption are observed beyond the range of ±10% in many months. Particularly for the PAU fans, the actually measured energy consumption varies significantly in different months while the calculated energy consumption is estimated based on the nearly constant rated power and operating hours, which causes large errors (e.g., ≥ ±20%) in some months. Fortunately, the negative effect of relative large errors of fan systems on the calculation of other components and the HVAC system are still limited because the energy consumption of fans is relatively small.

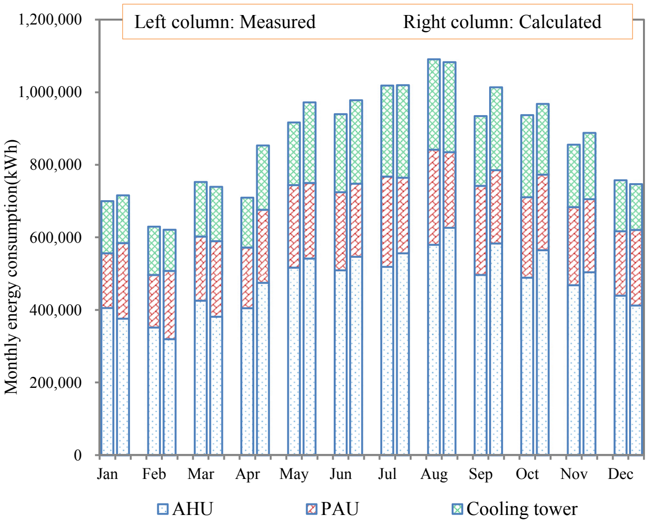

Fig. 10. Comparison of measured and calculated energy consumption of three types of fans.

5. Energy performance diagnosis benchmarks

Once the multi-level energy performances of the concerned building are estimated, corresponding benchmarks should be established for diagnosis. Two approaches are usually used to generate the energy performance benchmarks for building performance assessment and diagnosis. One approach is to use the average or the typical performance of the similar buildings as benchmarks, i.e., generic benchmarks. The other approach is to use a self-reference building model to calculate the expected energy performance as benchmarks, i.e., customized benchmarks. These two approaches have different applicable characteristics in practice and both are combined to assess and diagnose the building energy performance in this paper.

5.1. Generic benchmarks

The generic energy performance benchmarks, which represent the typical performance of similar buildings, are usually established by statistical analysis of a representative energy performance database covering a significant number of buildings. In the last decades, more and more countries and regions have set up their own building energy databases that could provide useful information for establishing generic energy performance benchmarks [6,29,40]. These benchmarks may include the energy consumption data of the whole building, the energy consumption of typical building energy systems, and the energy consumption and/or energy efficiency of subsystems or components.

It is worth noting that building energy performance is affected by various interactive factors such as building design, climate, system operation and occupant behavior. Each building is unique with different characteristics. Not all affecting factors are considered when establishing the generic benchmarks, which may cause the comparison to be unfair sometimes.

5.2. Customized benchmarks

The energy performance benchmarks can also be calculated using the self-reference models that enable the benchmarks to be customized realistically by considering more affecting factors. In this study, a concept of “relative performance factor” is proposed to indicate the relative difference between the current energy performance and the expected energy performance. Both the current and the expected energy performance data are calculated using the same method while their operating conditions are different. The current energy performance data are based on the actual operating conditions that may include some faults. The expected energy performance data are based on the expected operating conditions, i.e., the fault-free conditions. As a result, the impact of faults can be determined more accurately since the impact of calculation error or model uncertainty can be offset.

Three “relative performance factors” are introduced to examine the energy performance of the HVAC system from different aspects. The “relative performance factor” of the cooling load (ε_{CL}) and the “relative performance factor” of the overall energy efficiency (ε_{SCOP}) are used to assess the performance of the demand side and supply side, as shown in Eq. (12) and Eq. (13) respectively.

$$\varepsilon_{CL} = \frac{CL_{Expected}}{CL_{Current}} \tag{12}$$

$$\varepsilon_{SCOP} = \frac{SCOP_{Current}}{SCOP_{Expected}} \tag{13}$$

where, $CL_{Current}$ and $CL_{Expected}$ are the current and expected building cooling load respectively. $SCOP_{Current}$ and $SCOP_{Expected}$ represent the current and expected *SCOP* of the HVAC system respectively.

The "relative performance factor" of the entire HVAC system can be used to indicate the energy saving potential of the system, which is defined in Eq. (14).

$$\varepsilon_{HVAC} = \frac{E_{Expected,\ HVAC}}{E_{Current,\ HVAC}} \tag{14}$$

where, $E_{Current,\ HVAC}$ and $E_{Expected,\ HVAC}$ are the current and the expected energy consumption of the HVAC system respectively. Considering that the energy consumption of the HVAC system is determined by the cooling load and *SCOP*, ε_{HVAC} can be derived as shown below in Eq. (15).

$$\varepsilon_{HVAC} = \frac{(CL_{Expected}/SCOP_{Expected})}{(CL_{Current}/SCOP_{Current})} = \varepsilon_{CL} \times \varepsilon_{SCOP} \tag{15}$$

From Eq. (15), it clearly shows that the energy saving of a HVAC system can be realized by reducing the building cooling load and improving the energy efficiency of the HVAC system. The electrical energy saving potential of the HVAC system can be considered as (1-ε_{HVAC}).

6. Diagnosis case study in a real building

In this section, a case study is presented to illustrate how to apply the proposed multi-level energy performance diagnosis method to identify the poor performance areas and the causes behind as well as to estimate the energy saving potential in real buildings. The diagnosis process is conducted in the same building as introduced in Section 4. Although this building is information rich where sufficient energy performance data are recorded by BMS and sub-metering systems, the energy performance data for diagnosis are calculated using the proposed multi-level energy performance calculation.

6.1. Building level performance

At the building level, the annual total electricity consumption is used to examine the overall energy performance of the whole building. The total energy consumption is about 52.9 million kWh based on the actual energy bills. Given the total floor area is 321,000 m^2, the building level energy use intensity (EUI) is calculated as 164.8 kWh/m^2. Although it is a complex commercial building, the majority (over 95% of the floor area) of this building is used as offices. As a result, the comparison criteria from office buildings are selected for this building. Lam et al. investigated the electricity use characteristics of 20 air-conditioned office buildings in Hong Kong [41]. The investigation results shown that the average EUI of those buildings is 270 kWh/m^2. Taking this value as the generic benchmark for office buildings in Hong Kong, the overall energy performance of this building can be considered as excellent.

Generally, when the overall energy performance of a building is evaluated to be energy efficient, the diagnosis towards the low-level performance is not necessary. However, as a complete example of multi-level energy performance assessment and diagnosis, the examination at the system level and component level are continued.

6.2. System level performance

The current energy consumptions of the HVAC system, "internal-consumers" and "other-consumers" are disaggregated from the energy bill data. By comparing with the benchmarks of the similar buildings in Hong Kong [29], the energy performance of these three individual systems can be determined. As shown in Table 4, the current EUI of the "internal-consumers" and "other-consumers" calculated using the proposed method are much less than the benchmark values of similar buildings. However, the current EUI of the HVAC system is higher than the benchmark value. This indicates that the "internal-consumers" (including the lighting and office equipment) and "other-consumers" (including the lifts and miscellaneous equipment) are very energy efficient while the energy performance of the HVAC system is not so good. The energy consumption of the HVAC system is expected to be reduced by 5.2% when compared with similar HVAC systems in Hong Kong.

6.3. Component level performance

For diagnosing the energy performance and estimating the energy saving of the HVAC system, the energy performance of individual subsystems/components and the contribution of different heat gains to the building cooling load are analyzed separately.

6.3.1. Chiller performance analysis

As shown in Eq. (7), chiller *COP* is determined by the working temperatures and the *PLR* (part load ratio). The evaporating temperature (T_{Eva}) and condensing temperature (T_{Con}) are difficult to change while the *PLR* values can be changed by controlling the running number (n) of chillers. According to the chiller control logic, the *PLR* should be not less than 55%. Otherwise, the chiller number should be reduced to the minimum number (i.e., at least one chiller is running). However, the current *PLR* on monthly average is less than 55% in most months, particularly in winter months, as shown in Table 5. This indicates that the chiller sequence is not controlled as well as intended.

If the monthly average *PLR* in winter months can be improved to be 55% by properly implementing the optimal control sequence, the chiller COP is expected to increase significantly. The expected COP based on the expected running number is calculated using the identified chiller model. As shown in Fig. 11, the improvement of COP in winter months through the proper control sequence can be up to 30%~50%. In addition, the reduction of the number of chillers operating can help reduce the number of associated pieces of equipment also operating including primary chilled water pumps, condenser water pumps and cooling tower fans.

6.3.2. Pump performance analysis

The energy consumption of constant speed pumps can be reduced by reducing the number in operating while the energy consumption of variable speed pumps can be reduced by reducing the chilled water flow rate.

According to the "locked" relationship between chillers, primary chilled water pumps and condenser water pumps, the optimal control sequence of the chillers can also help reduce the number of associated pumps in operation. The expected energy consumption of primary chilled water pumps and condenser water pumps are

Table 4
Energy use intensity (EUI) of three systems.

Systems	Current EUI (kWh/m^2)	Benchmark EUI [29]. (kWh/m^2)
HVAC system	138.4	131.5
"Internal-consumers"	28.8	71.9
Others-consumers	20.9	37.6

*1: EUI of the HVAC system is calculated using the air-conditioned area; *2: EUIs of "internal-consumers" and others-consumers are calculated using the gross area.

Table 5
Current and expected parameters for chiller *COP* calculation.

	T_{Con} (°C)	T_{Eva} (°C)	Current value		Expected value	
			PLR	*n*	*PLR*	*n*
Jan	24.4	5.1	37.8%	1.41	53.5%	1.00
Feb	24.5	5.0	36.2%	1.55	55.0%	1.02
Mar	25.3	4.9	38.2%	1.60	55.0%	1.11
Apr	28.6	4.8	49.3%	1.87	55.0%	1.67
May	33.0	4.6	55.9%	2.38	55.9%	2.38
Jun	35.1	4.5	58.7%	2.55	58.7%	2.55
Jul	35.1	4.5	57.7%	2.74	57.7%	2.74
Aug	35.7	4.3	64.7%	2.66	64.7%	2.66
Sep	34.9	4.4	62.6%	2.64	62.6%	2.64
Oct	33.7	4.6	58.6%	2.17	58.6%	2.17
Nov	31.2	4.6	53.2%	2.03	55.0%	1.96
Dec	25.9	4.9	40.8%	1.50	55.0%	1.12

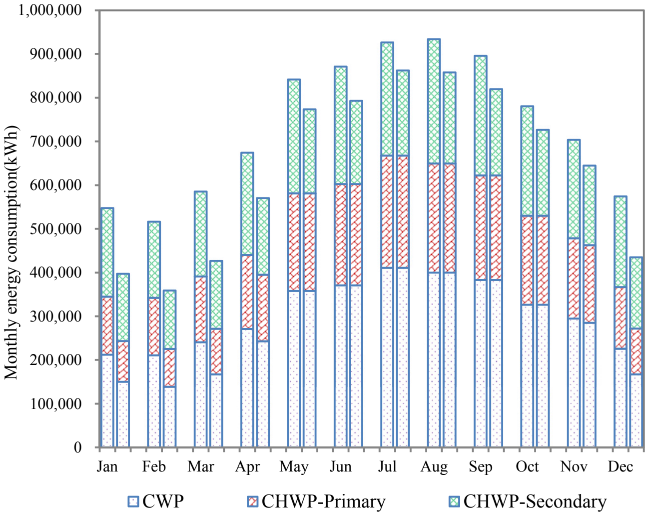

Fig. 12. Comparison of the current and expected pump consumptions.

calculated based on the expected running numbers and rated powers. The energy consumption of secondary chilled water pumps is considered to be only affected by the chilled water flow rate as discussed in Section 3.2. The current values of temperature difference of chilled water range from 3.0 °C to 3.9 °C in all months as shown in Table A5, which are lower than the design value (i.e., 6 °C) or the commonly acceptable value (i.e., 5 °C) in practice. Through a preliminary analysis, this low temperature difference problem may be caused by the deficit flow (i.e., the flow direction in the balancing pipe is from the return pipe to the supply pipe) and the overestimated pressure-differential set point of the pumps. If proper solutions are implemented, the temperature difference is expected to be increased at least to the commonly acceptable value (i.e., 5 °C). Based on this assumption, the expected energy consumption of secondary chilled water pumps is calculated.

The current and expected energy consumptions of all pumps are presented in Fig. 12. The annual energy consumption of all pumps is expected to be reduced 13.4% by reducing the number of constant speed pumps in operating and increasing the temperature difference of the chilled water.

6.3.3. Fan performance analysis

The current and expected energy consumptions of all fans are presented in Fig. 13. The energy consumption of cooling tower fans and PAU fans can be reduced by reducing the number in operation and/or their running hours. According to the “locked” relationship between chillers and cooling tower fans aforementioned, the expected number of operating cooling towers is reduced proportionally to the reduction in the number of chillers operating.

The main function of PAUs is to supply sufficient fresh air to occupants. The current fresh air rate is constant regardless of the fact that the actual occupant number is usually less than the design value. A demand-controlled ventilation (DCV) strategy, which can properly control the fresh air rate according to the actual number of occupants and still maintain the acceptable indoor air quality (IAQ), is proposed by the building operators to reduce the ventilation rate. This control strategy has been tested in typical floors and results show that the average fresh air rate can be reduced 30% by switching off some of PAU fans during the partially occupied periods. When this DCV strategy is applied to all other floors, the total fresh air rate can be reduced by 30% of the current value. The energy consumption of PAU fans is expected to be reduced by 30% accordingly.

The energy performance of AHU fans is not analyzed in the diagnosis process since the temperature differences ($\triangle T_{Air}$) of various AHUs are not available. The current energy consumption is estimated based on the assumption that the actual temperature differences are equal to the design values.

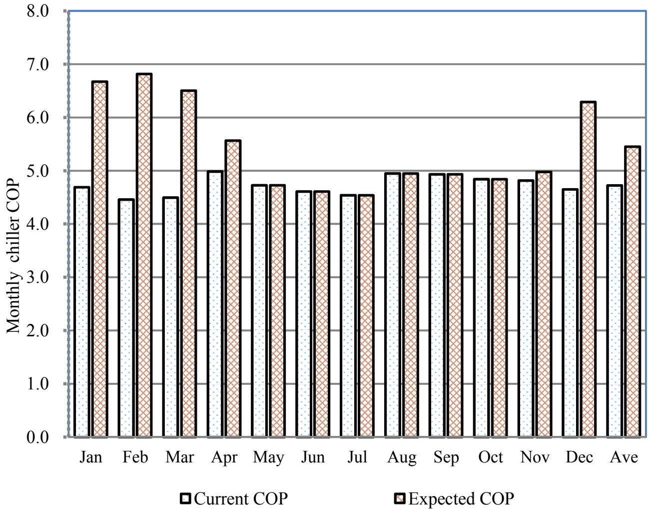

Fig. 11. Comparison of the current and expected chiller *COP*.

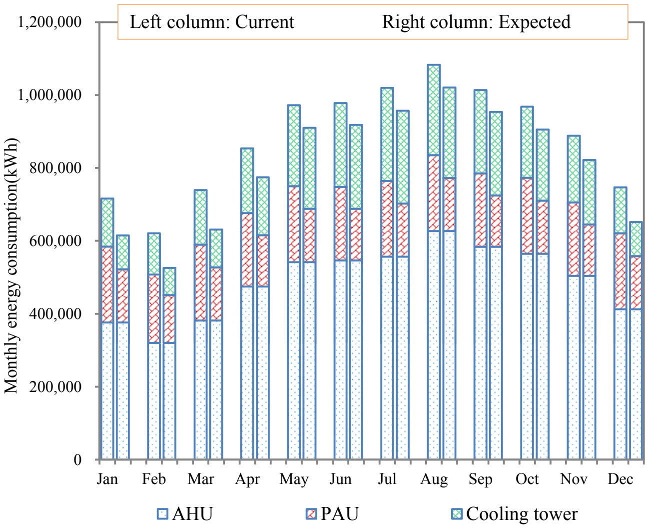

Fig. 13. Comparison of the current and expected fan consumptions.

6.3.4. *"Relative performance factor" of the overall energy efficiency*

The overall energy efficiency of the entire HVAC system is expected to be improved as the energy performances of all subsystems are enhanced. When the expected energy consumptions of all components are provided, the expected *SCOP* can be calculated using Eq. (5). The comparison between the current *SCOP* and the expected *SCOP* is shown in Fig. 14. The annual average value of the current *SCOP* and the expected *SCOP* are 1.98 and 2.22, respectively. According to Eq. (13), the "relative performance factor" of the overall energy efficiency (ε_{SCOP}) is calculated to be 89.3%, which means the overall energy efficiency of the HVAC system is expected to be improved by 10.7% if the energy performances of subsystems are enhanced as aforementioned.

6.3.5. *"Relative performance factor" of cooling load*

In this building, the cooling load consists of five different components (or heat gains). The percentage of each cooling load component is shown in Fig. 15. The largest cooling load component is the fresh air ventilation load, which contributes 32% of the total cooling load. This part of load can be reduced by reducing the unnecessary fresh air rate when the number of occupants is less than the design number. The second largest cooling load is contributed by the envelope. Increasing the indoor temperature set point can reduce this part of the cooling load since the current indoor temperature (23 °C) is relatively low. The cooling load contribution from the HVAC system components is also significant, which can be reduced by improving the energy performance of PAU, AHU and chilled water pumps. The cooling load contribution from the occupants is hardly alterable. The cooling load contribution from the "internal-consumers" is already very small due to the efficient operation of the lighting and office equipment.

The comparison between the current cooling load and expected cooling load is shown in Fig. 16. The current and expected annual cooling loads are 7.29×10^7 kWh and 6.38×10^7 kWh, respectively. According to Eq. (12), the "relative performance factor" of the cooling load (ε_{CL}) is calculated to be 87.6%, which indicates that the building cooling load is expected to be reduced by 12.4%. The reduction of building cooling load is expected from three aspects: reducing 30% of the current fresh air rate by implementing DCV strategy, increasing indoor temperature set point from 23 °C to 25 °C, and reducing the energy consumption of cooling delivery systems by improving their energy efficiencies.

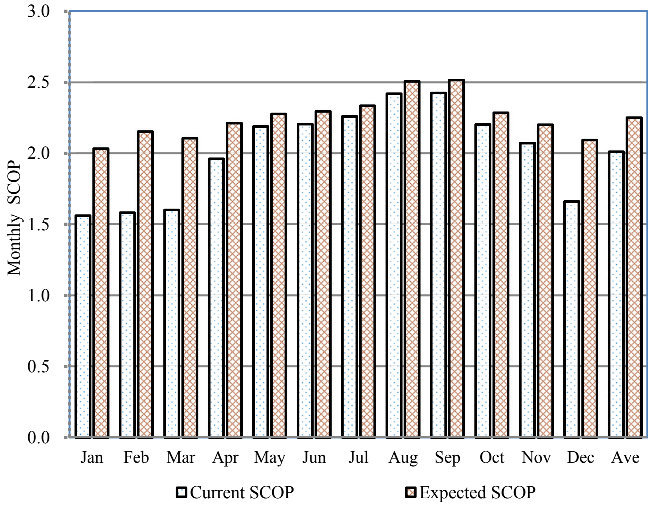

Fig. 14. Comparison of the current and expected *SCOP.*

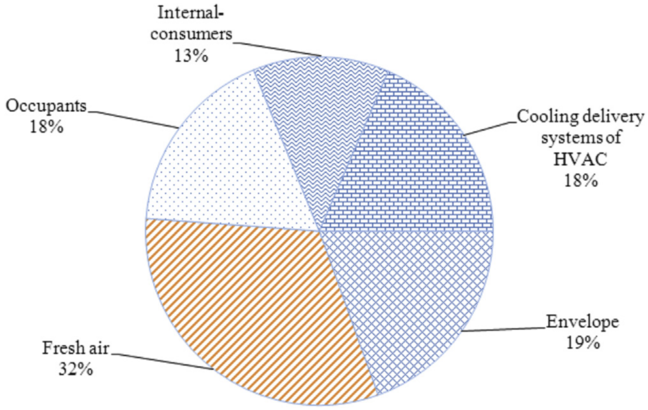

Fig. 15. Current percentages of different building cooling load components.

6.3.6. *"Relative performance factor" of the whole HVAC system*

The overall energy performance and the energy saving potential of the whole HVAC system can be indicated by the "relative performance factor" of the HVAC system (ε_{HVAC}). For the concerned HVAC system, the value of ε_{HVAC} is calculated to be 78.2% using Eq. (15), which indicates that the electrical energy consumption of the HVAC system is expected to be reduced by 21.8% if all energy saving measures on both the supply and the demand side are adopted.

7. Conclusions

This paper presented a systematic method for assessing and diagnosing the multi-level energy performance of a building with very limited energy use information. The development, validation and application of the proposed simplified energy performance calculation method for a thorough diagnosis of a building at different levels are provided. The concluding remarks from this study are as follows.

(1) Limited availability of energy use data is a realistic obstacle for building performance diagnosis. It is very common that no sub-meters are installed in a building and no reliable and continuous energy measurement data can be provided from the BMS due to aging problems and poor quality maintenance. The developed energy performance calculation method requires very limited energy use data and a few short-term field measurements while providing reliable and sufficient information for examining the energy performance of different systems and components. Such features are very

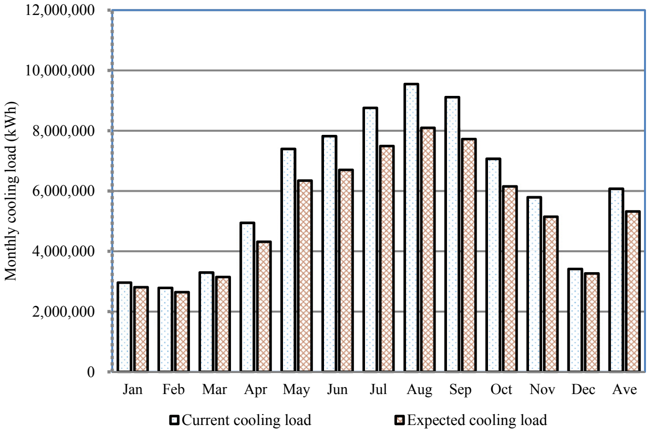

Fig. 16. Comparison of the current and expected building cooling load.

useful for the practical application in existing buildings, particularly in old buildings where the energy data availability is often problematic.

(2) Multi-level assessment is necessary for detecting the poor performances, identifying the causes and recommending energy saving measures. In the presented case study, the overall energy performance of the concerned building can be considered as excellent when it is evaluated using the building level performance indicators. However, this does not mean all systems are operating efficiently. The energy performance of the HVAC system is detected to be not good enough when the examination is extended to the system level. The causes of the unsatisfactory performance of the HVAC system are identified when the energy performances of subsystems and components are analyzed. The efforts for improving the energy performance can also be recommended in the focused areas.

(3) Customized benchmarks might be more suitable for energy performance assessment and diagnosis than generic benchmarks. The building design and usage conditions are usually very different and the energy performance expectations vary significantly among different building owners. More influential factors can be considered and more realistic performance can be expected when using the customized benchmarks. For example, the energy saving potential of the concerned HVAC system is estimated to be 21.8% when considering all feasible improvement measures in this building. However, the potential is only 5.2% when using the generic benchmarks. Additionally, using customized benchmarks can help reduce the negative impact from calculation error or model uncertainty.

(4) The proposed chiller performance model can estimate chiller COP with a satisfactory accuracy and independently identify the impacts of operating temperatures and part load ratios. This is very useful for identifying problems with chiller sequence control.

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Appendix A. Information of the concerned building

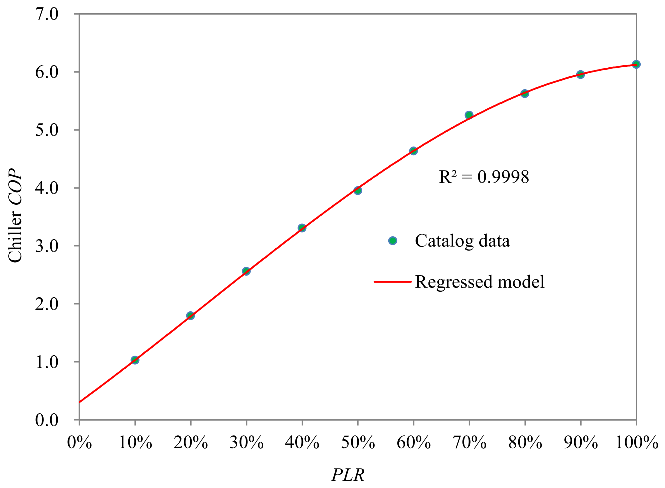

Fig. A.1. Performance of the identified chiller model using catalog data.

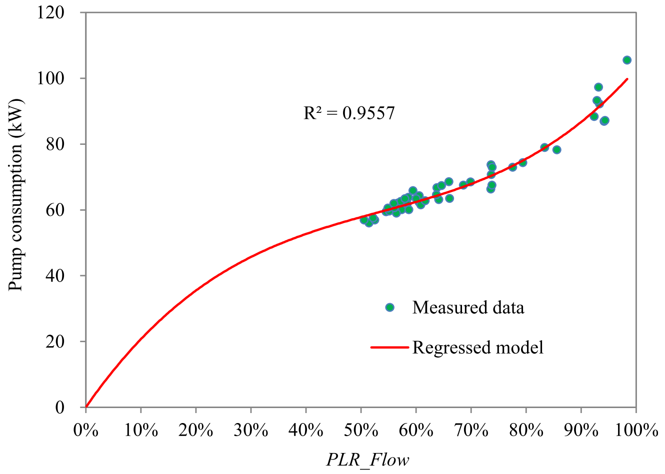

Fig. A.2. Performance of the identified variable speed (secondary) pump model using field data.

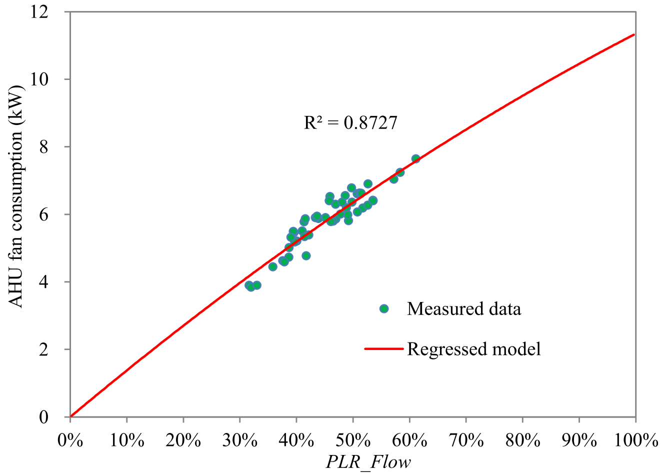

Fig. A.3. Performance of the identified variable speed fan (AHU) model using field data.

Table A.1
General information of the validation building.

Climate	Subtropical
Gross area	321,000 m^2
Air-conditioning area	267,000 m^2
Height	490 m
Indoor parameters	23 °C/60%
Ventilation rate	10 L/s/person
Occupants number	18,000
Occupancy period	24 h

Table A.2
Monthly average outdoor weather data.

Month	Temperature (°C)	RH	Global radiation (kWh/m^2)
Jan	14.4	74%	98
Feb	17.5	82%	89
Mar	18.7	79%	103
Apr	23.0	85%	143
May	27.1	84%	137
Jun	29.5	85%	129
Jul	29.7	86%	159
Aug	30.3	87%	171
Sep	29.4	87%	129
Oct	29.6	80%	113
Nov	25.8	75%	95
Dec	18.3	65%	109

Table A.3
Envelope parameters of the validation building.

Envelope		Net area (m^2)	U-factor ($W/(m^2K)$)	Absorptance or SHGC
Wall	East	12,730	$U_{Wall} = 1.66$	$\alpha_S = 0.9$
	South	12,881		
	West	12,891		
	North	12,501		
	Roof	11,622		
Window	East	14,853	$U_{Win} = 1.06$	$SHGC = 0.29$
	South	14,828		
	West	14,572		
	North	14,758		
	Skylight	3473		

Table A.4
Specifications of the HVAC system.

Components		Number	Flow rate	Speed type	Pressure	Power
Chiller		6	345 (L/s)	Variable	–	1180 (kW)
Pump	Primary chilled water pump	6	345 (L/s)	Constant	316 (kPa)	126 (kW)
	Secondary chilled water pump	12	207 (L/s)	Variable	303 (kPa)	76 (kW)
	Condenser water pump	6	410 (L/s)	Constant	416 (kPa)	202 (kW)
Fan	AHU fan	152	6.5 (m^3/s)	Variable	1800 Pa	15 (kW)
	PAU fan	16	40 (m^3/s)	Constant	350 Pa	17.5 (kW)
	Cooling tower fan	12	200 (L/s) for water; 127 (m^3/s) for air	Constant	–	55 (kW)

Table A.5
Required operating data for energy performance modeling.

	Total consumption of the whole building (10^6 kWh)	Sum of “electricity-independent heat gains” (10^6 kWh)	$N_{Chiller}$	T_{Con} (°C)	T_{Eva} (°C)	ΔT_{Water} (°C)
Jan	3.13	1.22	1.41	24.4	5.1	3.0
Feb	2.87	1.26	1.55	24.5	5.0	3.2
Mar	3.47	1.52	1.60	25.3	4.9	3.3
Apr	3.71	3.12	1.87	28.6	4.8	3.3
May	4.75	5.31	2.38	33.0	4.6	3.5
Jun	4.87	5.88	2.55	35.1	4.5	3.6
Jul	5.27	6.65	2.74	35.1	4.5	3.7
Aug	5.40	7.31	2.66	35.7	4.3	3.9
Sep	4.87	7.04	2.64	34.9	4.4	3.8
Oct	4.40	5.15	2.17	33.7	4.6	3.8
Nov	4.06	3.94	2.03	31.2	4.6	3.7
Dec	3.37	1.75	1.50	25.9	4.9	3.2

Table A.6
Catalog data for chiller modeling identification.

PLR	Cooling capacity (kW)	Power input (kW)	Teva,out (°C)	Tcond,in (°C)	COP
100%	7230	1180	7	32	6.13
90%	6507	1094	7	32	5.95
80%	5784	1029	7	32	5.62
70%	5061	964	7	32	5.25
60%	4338	936	7	32	4.63
50%	3615	915	7	32	3.95
40%	2892	875	7	32	3.31
30%	2169	848	7	32	2.56
20%	1446	807	7	32	1.79
10%	723	704	7	32	1.03

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