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Three-level Energy Performance Calculation and Assessment Method for Information Poor Buildings

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Abstract

A thorough assessment is critical for understating and enhancing building energy performance. This paper presents a three-level energy performance assessment method for information-poor buildings where very limited energy use data are available. Using this method, the energy performance of a building can be assessed at multiple levels (i.e., building level, system level and component level) based on limited energy use data and few in-situ measurement and/or catalogue data of air-conditioning systems. The core part of this assessment method is a quantitative energy performance calculation method that consists of two basic energy balances, simplified models of air-conditioning components and an optimization algorithm based on the energy balances within buildings. The proposed assessment method is well validated in a high-rise building in Hong Kong by comparing the energy performance data from the proposed method with that from detailed measurements. Results show that this method can estimate the energy performance indicators quantitatively at three levels with acceptable accuracy.

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Keywords: Building energy efficiency; Energy performance assessment; Information poor buildings

1. Introduction

The building sector has been the largest energy consumer in most countries. Excessive amounts of energy are often wasted in existing buildings as buildings often fail to operate as intended. Building energy performance assessment, which can help to identify the amount of energy waste, the degree of efficiency deterioration and the

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probable causes behind, plays an important role in reducing building energy consumption. Many research and industrial efforts can be found in the development and application of quantitative energy performance assessment methods [1]. Most of available methods often address the overall performance at building level using the whole-building assessment methods. However, very few methods consider the assessment at system and component level, although the multi-level assessment results provide more details about energy performance [2].

A more critical issue is that most energy performance assessment methods for existing buildings are based on abundant energy performance data from reliable BMS (building management systems) and/or based on the data from continuous in-situ measurements. Few methods can be used in information-poor buildings wherein very limited energy use and building operation data are available. The BMS of these buildings, if they have one, are generally equipped with insufficient sensors due to financial considerations. Furthermore, many sensors usually are out of order or bear very large errors, owing to limited efforts in calibrating and maintenance. Energy use data are the most important information for understanding the energy performance of building energy systems. For most existing buildings, particularly old buildings, very few or even no sub-meters are installed. As a result, only the total energy use 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 assessed and/or diagnosed at system level, not to mention at component level.

The authors have developed a simplified method for calculating the energy performance at building and system level [3]. 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 extend our previous method to be a multi-level energy performance calculation method by newly developing or selecting three component-level HVAC models. The validation of the multi-level assessment method is also presented.

2. Three-level energy performance assessment method

In order to assess the energy performance of an information poor building at multiple levels, the most important and difficult job is to calculate the energy performance data of each level when only very limited energy use information is available. In this study, a simplified energy performance assessment method based on macroscopic energy balance principles within buildings is developed for estimating the required multi-level energy performance data.

2.1. Energy balance concept

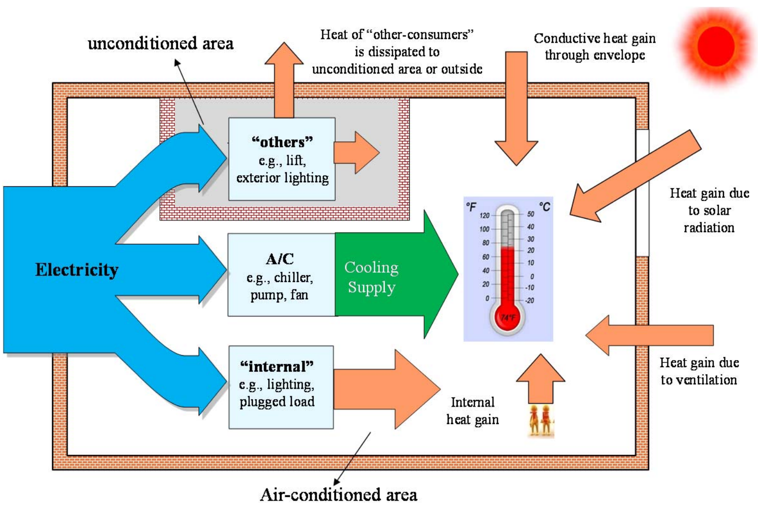

Fig. 1. Energy flows and balances in an air-conditioned building

Figure.1 shows two typical energy flows in an air-conditioned building, which can be used to determine building energy performances. The first is the electricity flow that describes electricity consumption of all end-users in the building. All these end-users are classified into three categories in this study, which are the HVAC system, "internal-consumers" (e.g., lighting system) and "other-consumers" (e.g., lift, outdoor lighting). The second energy flow is the thermal energy flow that describes all heat transfer processes in the building. These heat transfer processes can be classified as the "electricity-dependent" and "electricity-independent". Along the two energy flows, two energy balances can be established. The first energy balance is the electricity consumption balance, i.e., the sum of consumptions of all consumers must equal to the total consumption of the whole building. The second energy balance is the cooling energy balance between the demand side and the supply side of the HVAC system, i.e., the cooling load contributed by various heat gains at the demand side should equal the cooling energy supplied by the HVAC system. All required energy performance data for the assessment can be connected and determined by these two energy balances.

2.2. Building energy balance

The electricity energy consumption balance at building level in Eq. (1) is mainly used to break down the total energy consumption into the individual consumption of three systems. The cooling energy balance in Eq. (2) is mainly used for determining the cooling load and the energy performance of the HVAC system.

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

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

where, $E_{Building}$ is the total energy consumption of building, giving by 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. CL_{Demand} and CL_{Supply} are the monthly cooling load calculated at the demand side and supply side, using Eq. (3) and Eq. (4) respectively.

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

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

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 [4]. 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 fans), which is determined by the energy ratio (i.e. α) of the cooling delivery system to the entire HVAC system. *SCOP* represents the system coefficient of performance of the whole HVAC system.

2.3. HVAC component models

SCOP and α are two important variables for determining the cooling energy balance of the HVAC system, which are defined by Eq. (5) and Eq. (6), respectively.

$$\mathrm{SCOP}=\frac{\mathrm{CL}_{\mathrm{Supply}}}{\mathrm{E}_{\mathrm{HVAC}}}=\frac{\mathrm{CL}_{\mathrm{Supply}}}{\mathrm{E}_{\mathrm{Chiller}}+\mathrm{E}_{\mathrm{Pump}}+\mathrm{E}_{\mathrm{Fan}}} \tag{5}$$

$$\alpha=\frac{\mathrm{E}_{\mathrm{Delivering}}}{\mathrm{E}_{\mathrm{HVAC}}}=\frac{\mathrm{E}_{\mathrm{CHW}}+\mathrm{E}_{\mathrm{PAU}}+\mathrm{E}_{\mathrm{AHU}}}{\mathrm{E}_{\mathrm{Chiller}}+\mathrm{E}_{\mathrm{Pump}}+\mathrm{E}_{\mathrm{Fan}}} \tag{5}$$

where, $E_{chiller}$, E_{Pump} and E_{Fan} represent the energy consumption of all chillers, pumps and fans, respectively. $E_{Delivering}$ represents the energy consumption of cooling energy delivering systems, including the chilled water system, AHU (air handling unit) and PAU (primary air-handling unit) systems. E_{CHW}, E_{PAU}, and E_{AHU} represent the energy consumption of chilled water pumps, PAU and AHU fans, respectively.

In this section, three well-recognized empirical models of main HVAC components are selected from previous studies and configured to estimate the energy performance (i.e., *SCOP* and *α*) of the system and components under different load conditions. The energy consumption of chillers can be calculated through cooling load divided by chiller efficiency (i.e., CL_{Supply}/COP). A regression model is proposed to calculate the chiller *COP* (coefficient of performance) under different working conditions, as shown in Eq. (7).

$$COP=\frac{273.15+T_{Eva}}{T_{Con}-T_{Eva}}\times\left(C_0+C_1\cdot PLR+C_2\cdot PLR^2+C_3\cdot PLR^3\right) \tag{6}$$

where, T_{Eva} and T_{Con} are evaporating and condensing temperature (°C), respectively; C_0 to 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 working conditions from the full load conditions.

It is very common that both constant speed and variable speed pumps (fans) are used in a system. For constant speed pumps (fans), the input power can be considered as constant. For variable speed pumps (fans), it is difficult to calculate the accurate power consumption since many factors influence their power consumptions. However, for pumps (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. In this work, simplified variable speed pump/fan models developed by Brandemuehl [5] are selected to calculate the part-load power consumption as a function of part load flows, as shown in Eq. (8).

$$\dot{E}_{Pump/Fan}=\dot{E}_{Rated}\times(P_0+P_1\cdot PLR_{Flow}+P_2\cdot PLR_{Flow}^2+P_3\cdot PLR_{Flow}^3) \tag{7}$$

where, the factor PLR_{Flow}, is defined as the ratio between the actual volumetric flow and the rated flow. The coefficients P0- P3 can be identified from the catalogs or experimental data.

2.4. Optimization algorithm for solution

The system energy consumption, building cooling load and energy efficiency of the HVAC system are interacted by electricity and cooling balances. Based on these interactive relations, an optimization algorithm using the "trial-and-error" method is developed as shown in Figure 2. The main trial variables are the electricity consumption of the three consumers, i.e., E_{HVAC}, $E_{Internal}$ and E_{Others}. 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 small enough. More details about the optimization algorithm and the energy performance calculation can be referred to our previous study in [3].

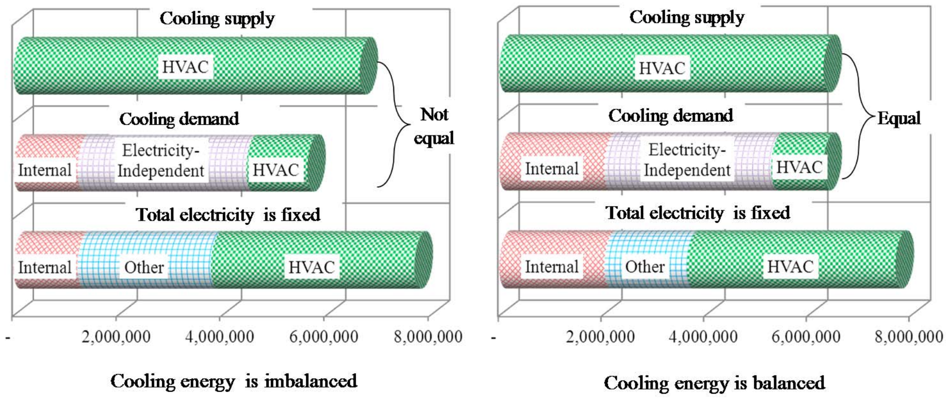

Fig. 2. Schematic of the “trial-and-error” method for searching the best trial variables

3. Validation in a real building

The developed method is validated in a super high-rise building in Hong Kong. This building is an information rich building, in which detailed energy use data and HVAC performance data are well monitored. A 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 are monitored by BMS. Such a big number of power meters and BMS sensors provide sufficient data for validating the proposed method. The validation involves comparisons of the energy performance indicators that calculated using the developed method (denoted as “Calculated” or “Cal.” for short) with that from monitored data (denoted as the “Measured or “Meas.” for short) at the same level.

3.1. Energy consumption of individual systems

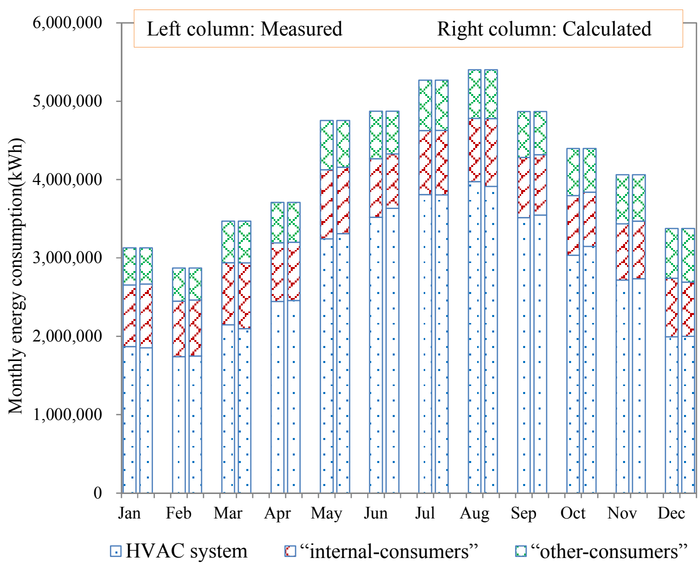

Fig. 3. Comparison of measured and calculated energy consumption of three systems

The comparison between the calculated and the measured monthly energy consumption of three individual systems is presented in Figure.3. 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.

3.2. Energy performance of the HVAC system

The validation results of the HVAC performance indicators are presented in Table 1. The relative errors of cooling load, *SCOP* and α in almost all months are within the range of ±10%.

Table 1. Comparison of energy performance of the HVAC system

	CL (10^6 kWh)			*SCOP*			α		
	Meas.	Cal.	Error	Meas.	Cal.	Error	Meas.	Cal.	Error
Jan	3.09	2.87	-7.1%	1.65	1.50	-9.2%	47.1%	48.1%	2.1%
Feb	2.76	2.73	-1.3%	1.59	1.53	-3.9%	45.8%	45.6%	-0.5%
Mar	3.59	3.29	-8.2%	1.67	1.57	-6.2%	42.1%	44.5%	5.8%
Apr	4.97	4.79	-3.7%	2.04	1.89	-7.3%	38.2%	42.5%	11.4%
May	7.15	7.17	0.3%	2.20	2.10	-4.8%	36.9%	36.1%	-2.2%
Jun	7.88	7.79	-1.2%	2.24	2.14	-4.6%	35.1%	34.2%	-2.5%
Jul	8.73	8.49	-2.8%	2.29	2.16	-5.7%	34.5%	32.6%	-5.6%
Aug	9.18	9.27	0.9%	2.31	2.30	-0.6%	35.9%	34.0%	-5.3%
Sep	8.11	8.60	6.0%	2.31	2.28	-1.3%	35.5%	34.4%	-3.2%
Oct	6.31	6.84	8.5%	2.08	2.11	1.4%	37.7%	37.8%	0.3%
Nov	5.75	5.61	-2.4%	2.12	1.99	-5.9%	39.0%	39.5%	1.4%
Dec	3.48	3.30	-5.4%	1.75	1.59	-8.8%	46.3%	46.9%	1.2%
Ave	5.92	5.90	-0.4%	2.02	1.93	-4.5%	38.4%	38.2%	-0.4%

3.3. Energy performance of HVAC components

Table 2. 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	0.65	-0.2%	4.77	4.44	-6.9%	40.6%	37.8%	-7.1%
Feb	0.62	0.65	4.6%	4.46	4.21	-5.6%	36.6%	36.2%	-1.3%
Mar	0.85	0.77	-8.8%	4.23	4.25	0.6%	41.6%	38.2%	-8.2%
Apr	1.09	1.01	-7.0%	4.58	4.74	3.6%	51.2%	49.3%	-3.7%
May	1.53	1.60	4.5%	4.66	4.47	-4.0%	55.7%	55.9%	0.3%
Jun	1.70	1.80	5.3%	4.62	4.34	-6.1%	59.3%	58.7%	-1.2%
Jul	1.84	1.98	7.6%	4.74	4.28	-9.6%	59.3%	57.7%	-2.8%
Aug	1.91	2.01	5.5%	4.81	4.60	-4.3%	64.2%	64.7%	0.9%
Sep	1.70	1.86	9.4%	4.76	4.61	-3.1%	59.1%	62.6%	6.0%
Oct	1.34	1.50	11.8%	4.70	4.56	-3.0%	54.0%	58.6%	8.5%
Nov	1.20	1.23	2.3%	4.79	4.57	-4.5%	54.5%	53.2%	-2.4%
Dec	0.72	0.75	4.3%	4.86	4.41	-9.3%	43.1%	40.8%	-5.4%
Ave	1.26	1.32	4.3%	4.66	4.46	-4.4%	51.6%	51.1%	-0.9%

Chillers are the largest energy consumers in the HVAC system and therefore the accuracy of chiller performance calculation plays the greatest role in determining the overall accuracy of the whole method. From the comparison results presented in Table 2, the calculated energy consumption, *COP* and *PLR* agree well the "measured" data.

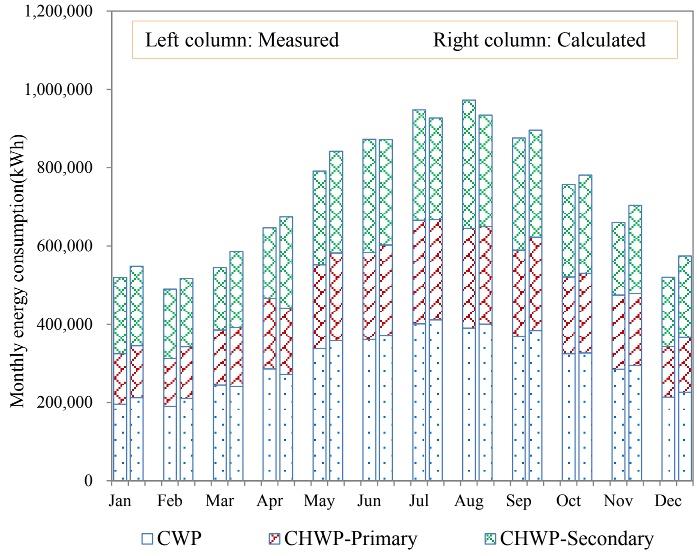

Figure 4. Measured and calculated energy consumption of three types of pumps

The energy consumption comparisons of three pump systems are presented in Figure.4. Acceptable results are achieved for the condenser water pumps and the primary chilled water pumps, which are constant speed pumps. But for the secondary chiller water pumps, which are variable speed pumps, large errors (e.g., $\geqslant$ 15%) are observed in four months. This indicates that the energy performance of the variable speed pumps are more difficult to be predicted than that of the constant speed pumps.

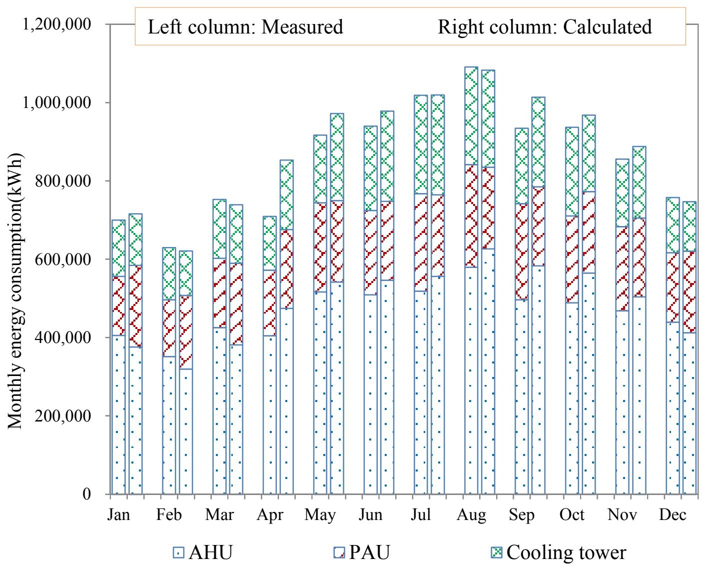

Figure 5. Measured and calculated energy consumption of three types of fans

The energy consumption comparisons of three types of fans are presented in Figure 5. Relative deviations (i.e., errors) between the calculated and measured consumption are observed be-yond the range of ±10% in several months. Particularly for the PAU fans, the actually measured energy consumptions varies significantly in different months while the calculated energy consumption are estimated based the nearly constant rated power and operating hours, which causes large errors (e.g., ⩾±20%). Fortunately, the negative effect of relative large errors of fan systems on the calculation of other components and systems are still limited because the energy consumption of fans are relatively small.

4. Conclusions

A quantitative energy performance calculation method is developed for assessing the energy performance of information-poor buildings at multiple levels using limited energy use information. Through achieving the electricity consumption balance and cooling energy balance in each cooling month, the total energy consumption of the whole building can be disaggregated into the energy consumption of three individual systems. Building cooling load, energy efficiency indicators of the whole HVAC system, and energy consumption and key performance indicators of main components can also be estimated simultaneously. This method requires very limited energy use data and a few short-term field measurements while providing sufficient information for examining the energy performance of different systems and components. Such features are very useful for the practical application in existing buildings, particularly in old buildings where the data availability is often problematic.

The developed multi-level energy performance assessment method is validated in a super high-rise building in Hong Kong. Results show that the developed method can effectively estimate most of the energy performance indicators at different levels with a satisfactory accuracy. Particularly, the relative errors of the energy consumption of three systems, cooling load, *SCOP* and α of the HVAC system, and *COP* and *PLR* of chiller system, as well as the energy consumption of the constant speed pumps, are within the range of ±10% in almost all months. However, it is also observed that the energy consumption of variable speed pumps (e.g., the secondary chilled water pumps) and energy consumption of AHU, PAU and cooling tower fans are more difficult to be estimated. Their relative errors are beyond the range of ±20% in some months.

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