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Benchmarking energy performance for cooling in large commercial buildings☆

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ABSTRACT

Urban development rapidly increases the total area and the energy consumption of large commercial buildings. Accordingly, the total energy consumption is the focus of numerous energy saving studies. An optimal benchmarking system provides a recommended energy consumption level for each building as well as identifying and prioritizing challenges to energy saving in each building. Based on detailed sub-metering system data and building operational data, this paper presents a simplified energy consumption benchmarking method for air-conditioning systems that cool large commercial buildings. Firstly, a multi-level benchmarking index system is established. Next, the energy performance data of eight large shopping centers in China validates the simplified benchmarking method and finally, the energy performance data of the participating shopping centers is analyzed under the present method. Our data focus on the energy saving potential, as well as informing improvement strategies for building energy performance, that can be used for efficient energy benchmarking process for cooling in large-scale commercial buildings.

1. Introduction

1.1. Backgrounds

Between 2000 and 2012, the worldwide building energy consumption increased from 102 to 120 EJ, which accounted for more than 30% of total final energy consumption across all economic sectors [1]. During the same period, the building energy consumption in China grew by 37%. Under current consumption trends, this figure is predicted to increase another 70% by 2050 [2]. In 2013, to respond to this issue, the Chinese government announced a “Total Energy Use Control” plan as well as publishing the Energy Development, “Twelfth Five Year Plan”, which mandated a ceiling for energy usage and stronger control of total energy [3]. However, in more recent years, urbanization and overall economic development have significantly improved across China, resulting in a substantial increase in commercial floor space and energy consumption in large-scale commercial buildings. The large-scale commercial buildings consume 200–400 kWh/(m^2·a), 4–8 times more than the ordinary public buildings [4], which has raised concern about the energy consumption requirements for these types of buildings. Therefore, the establishment of a benchmarking method is necessary to enable scientific evaluation of large-scale commercial building energy performance and inform efficient energy consumption strategies.

1.2. Literature review

Building energy benchmarking compares the actual energy performance of similar buildings [5,6]. Considerable researches have investigated building energy benchmarking methods using a variety of classification techniques [7–9]. Wang et al. [7] reviewed and then classified energy performance assessment methods into three categories: calculation-based, measurement-based and hybrid methods. Kinney and Piette [8] classified benchmarking methods into four types: statistical methods, points-based rating systems, simulation methods as well as hierarchical and end-use metrics. Li et al. [9] categorized energy benchmarking methods as black-box, gray-box and white-box. The black box-method uses data fitting techniques rather than physical knowledge. This corresponds to statistical methods per Kinney’s classification which includes regression, artificial neural networking, data envelopment analysis, and other mathematical methods [10–14]. The most commonly used black-box method is the regression method [15–19], which is based on a large sample data size. This method achieves rapid evaluation of building energy consumption through the

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Nomenclature

A	Area, m^2
e	Solar radiation absorption factor of the exterior surface
E	Accumulated electricity consumption, kWh
c_p	Specific heat capacity of water, kJ/(kg·°C)
CE_{supply}	Cooling energy supplied by the air-conditioning system, kWh
CL_{demand}	Cooling demand, kWh
g	Water flow rate, m^3/h
G	Airflow rate, m^3/h
h	Air enthalpy value, kJ/kg
j	Total cooling hours
n	Number of occupants per hour
q	Cooling load from building envelop, W
q_0	Total heat released by an adult, W
Q	Cooling load, kWh
$SHGC$	Solar heat gain coefficient
SR	Solar radiation intensity, W/m^2
t	Chilled water temperature, °C
T	Air temperature, °C
U	Heat transfer coefficient, W/(m^2·K)
V	Building volume, m^3
WWR	Window to wall ratio

Greek symbols

∂_{out}	Convective heat transfer coefficient of the exterior surface, W/(m^2·K)
ε	Building shape factor
η	Correction factor of the motor installation position
η_m	Electrical efficiency of fans and pumps
ρ	Water density, kg/m^3
φ	Percentage of adult male, adult woman and children.
$\triangle\tau$	Time interval, hour

Subscript

lighting and equip	Lighting and equipment
exf	Exfiltration
fan	Terminal system
i	Orientation, which represents east, west, south, north and the horizontal plane (i.e., roof)
in	Indoor air
inf	Infiltration
inlet	Inlet chilled water
l	The number of chillers
ma	Mechanical fresh airflow
me	Mechanical exhausted airflow
out	Outdoor air
outlet	Outlet chilled water
pump,c	Condensate water pumps
pump,ch	Chilled water pumps
r	Refrigeration system
total	Total fresh outdoor air
tower	Cooling tower
wall	Exterior wall
win	Exterior window

input of finite parameters. However, the reliability of this model is highly dependent on sample data accuracy which makes it fundamentally unusable in real-world applications. The white-box method is based on physical principles whereby constraints are embedded into the modelling of building components. The most common white-box method is the detailed simulation method [20–22] in which the built-in simulation software is very detailed; as such, it is able to provide accurate benchmarking results. Moreover, the input parameters can be used to analyze different working conditions as well as comparing the influence of different factors on energy consumption. Here, a disadvantage is that each building must be separately modeled, which is a complex and a nonreplicable process. The gray-box method combines both physical knowledge and data-fitting techniques to derive a model that typically utilizes Bayesian and RC networks for air-conditioning loads. The Bayesian networks can only be applied in the buildings with a similar building usage pattern and energy consumption profile, while RC networks are only applicable in heating and cooling load calculations [9].

Given that the type and proportion of both business and operational conditions in each building significantly vary, each building must set individual energy consumption targets. While all three methods can be used to benchmark building energy consumption, only the results obtained by the white-box method reflect the actual management level for each target building as well as guiding further energy saving strategies. In general, calculations are simplified to promote efficiency. Yan et al. [23] proposed a simplified assessment method to calculate cooling loads in existing buildings. They used an optimization algorithm to disaggregate total building energy consumption into per-user consumption, i.e., air-conditioning consumers, internal consumers and other consumers. However, the assessment only occurred at the main system level and it did not provide an evaluation criterion.

1.3. Purpose of the paper

The energy consumed by an air-conditioning system usually accounts for 50% of total energy consumption of a building [24]; as such, air-conditioning has the greatest potential for energy reduction. Therefore, this paper presents a simplified method for benchmarking the energy consumption of air-conditioning systems that cool large commercial buildings. A multi-level benchmarking index system of energy consumption is established using simplified calculation formulas based on fundamental principles. The benchmark provides recommended energy consumption levels for each building, which represents the average building energy performance within the same type of buildings in China. Then, the building operation and management level can be evaluated from the deviation between the actual value and recommended value as well as the energy-saving potential. A field test validates the reliability of the calculation method by providing actual operational data from sample buildings. The energy performance of the cooling systems in eight large shopping centers is evaluated using the index system, and then the energy saving potential is analyzed.

2. Methodology

The energy performance of an air-conditioning system in a building is determined by the cooling demand of the building and the energy efficiency of the air-conditioning system. The cooling demand indicates the cooling load of a building under controlled conditions and the energy efficiency describes the operational level of the air-conditioning system and the related devices. As such, benchmarking the cooling energy performance of a commercial building follows these steps: benchmark cooling energy; rate energy efficiency; and benchmark energy consumption. The following subsections describe the calculation methods.