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Research Paper

Benchmark analysis of electricity consumption for complex campus buildings in China

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HIGHLIGHTS

- Subentry electricity consumption is considered for campus building benchmarks.
- New methods of electricity benchmarking for complex campus buildings are proposed.
- A rating system is established based on new benchmarks.

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ABSTRACT

Publicising the energy consumption of buildings is an effective way to promote building energy efficiency in colleges and universities. The aim of this study is to propose a method for developing electricity benchmarks for complex campus buildings. This study uses various statistical methods to determine such benchmarks. The determination of new electricity benchmarks includes the following steps: (a) determination of the factors influencing electricity consumption, (b) standardisation of indicators, and (c) calculation and correction of the electricity benchmarks. Thirteen complex buildings from the hot summer and cold winter zone of China were selected as samples to illustrate the standardisation process. The total electricity and subentry electricity benchmarks are determined based on multiple linear regression analyses. Multi-factor analyses of variance were used to identify the categorical factors that have significant influences on electricity consumption and on the correction of benchmarks. Finally, a rating system for the evaluation of electricity consumption was also established that applied the corrected electricity benchmarks.

1. Introduction

Buildings with increased energy consumption account for more than 95% of existing buildings in China. During the 13th Five-Year Plan period, the contribution of the energy consumption in buildings with respect to the total energy consumption continued to rise [1]. In China, there is a rapid development in higher education institutions currently that has caused an abrupt increase in energy use accompanied by low levels of campus facility operations [2]. Educational buildings account for approximately 34% of the total number of public buildings, while the energy consumption of educational buildings accounts for 39.33% of the total energy consumption of public buildings [3]. The number of college campus buildings accounts for more than 85% of the total number of buildings for educational use [1]. The annual total energy consumption of universities and colleges is approximately 30 million tons of standard coal. Despite the fact that this indicator has declined somewhat, the per capita energy consumption of campus buildings is four times as large as that of Chinese residential buildings [4]. Therefore, it is important to manage the energy consumption on college campuses.

Complex buildings are building types with diversified utility functions. The main functions of complex campus buildings include the execution of scientific research and provision of office space. They are characterised by overloaded schedules, increased electricity consumption, diversified electricity types, and higher electricity consumption per gross floor area (GFA) compared to other office buildings. Thus, it is important to consider schemes to reduce the electricity consumption of campus complex buildings.

Benchmarking and rating building energy performance is extensively recognised as a reasonable method for improving energy efficiency. To date, research and analyses of building energy

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Nomenclature

GFA	Gross floor area, (m^2)
EUI_T	annual total electricity consumption indicator per gross floor area, ($kWh/m^2 \cdot a$)
EUI_{AC}	annual HVAC terminal electricity consumption indicator per gross floor area, ($kWh/m^2 \cdot a$)
EUI_{norm}	normalised annual electricity consumption indicator per gross floor area, ($kWh/m^2 \cdot a$)
$EUI_{LR,\ norm}$	normalised annual lighting and indoor equipment electricity consumption indicator per gross floor area, ($kWh/m^2 \cdot a$)
$EUI_{PS,\ norm}$	normalised annual power system electricity consumption indicator per gross floor area, ($kWh/m^2 \cdot a$)
VRV	variable refrigerant volume system
CC	correction coefficient
CC_{FC}	fan-coil unit system correction coefficient
SA	scientific research office area, (m^2)
EUI	annual electricity consumption indicator per gross floor area, ($kWh/(m^2 \cdot a)$)
EUI_{LR}	annual lighting and indoor equipment electricity consumption indicator per gross floor area, ($kWh/(m^2 \cdot a)$)
EUI_{PS}	annual power system electricity consumption indicator per gross floor area, ($kWh/m^2 \cdot a$)
$EUI_{T,\ norm}$	normalised annual total electricity consumption indicator per gross floor area, ($kWh/m^2 \cdot a$)
$EUI_{AC,\ norm}$	normalised annual HVAC terminal electricity consumption indicator, ($kWh/m^2 \cdot a$)
SAC	split air-conditioning system
FCU	fan-coil unit system
CC_{SAC}	split type air-conditioning system correction coefficient
CC_{VRV}	variable refrigerant volume air-conditioning system correction coefficient
LA	laboratory area, (m^2)

benchmark systems have attracted considerable attention, and numerous studies have developed a series of reasonable energy benchmarks using various methods. Chung [5] classified these systems into various methodologies, based on the existing literature on benchmarking systems: simple normalisation (Simple), ordinary least squares (OLS), data envelopment analysis (DEA), stochastic frontier analysis (SFA), the model-based method (Simulation), and artificial neural networks (ANNs).

Linear regression analysis has been extensively used in benchmarking energy consumption. Jing et al. [6] studied the energy performance of 30 commercial office buildings in Hong Kong, and used multiple linear regression analyses to predict building energy consumption. Wang et al. [7] developed a benchmarking method using multi-variate linear regression analyses with principal component analysis. Wang [8] studied the energy performance of over 60 school buildings in Taiwan and applied multiple regression analyses to predict energy consumption. Lee [9] used multiple linear regression and data envelopment analyses to examine the effectiveness of energy management. Borgstein et al. [10] provided an energy consumption benchmark using a simple linear regression analysis, while thermal simulation of building performance was used to validate the results. Wu et al. [11] established a benchmark for hotel buildings, and stepwise linear regression was applied to hotel energy consumption data. Sharp [12] used stepwise linear regression modelling to identify high-level energy consumption buildings, and the model was applied to office, commercial, and campus buildings.

Other statistical methods, such as DEA, ANNs, and decision tree (DT) methods, have also been used to develop energy benchmarks. Srivastav et al. [13] presented an approach based on Gaussian mixture regression (GMR) for modelling building energy use with parameterised and locally adaptive uncertainty quantification. Lee et al. [14] divided the overall energy efficiency into scale factors and management factors using data envelopment analyses. Lee et al. [15] proposed a multiple attribute decision making approach to rank the energy performance of buildings. Hernandez et al. [16] developed benchmarks for schools in Ireland, and the benchmark data were used to propose a unified approach for developing asset and operational ratings. Park et al. [17] developed an energy benchmark for improving the operational rating system of office buildings using various data-mining techniques, such as correlation analyses, DT analyses, and analysis of variance (ANOVA). Jeong et al. [18] developed integrated energy benchmarks for three evaluation criteria in multi-family housing units that used district heating, and a process model using data-mining techniques was proposed to develop the energy benchmark. Hong et al. [19] improved the comparability of benchmarking energy performance of schools by assessing the impact of intrinsic features, such as built form and occupancy. Multi-variate analyses have also been carried out using ANN to assess the impact of various building characteristics on energy use. Gao [20] developed a new methodology for building energy performance benchmarking based on an intelligent clustering algorithm. AlFaris et al. [21] used the normalised energy utilisation index to analyse the energy data of 19 hotel buildings to differentiate between usual and best practice energy performance.

In addition, some studies on factors affecting energy consumption have been conducted. Lu et al. [22] collected detailed information and energy consumption data for 27 hotel buildings in Hainan, and analysed the energy consumption characteristics. Results indicated that factors affecting electricity utilisation include the electricity percentage, number of guestrooms, and window types. Chung et al. [23] studied factors affecting energy use at different levels of private office buildings. Relevant factors included age, occupancy, climate, people, and energy end-use factors.

These studies all had one common feature: the benchmarks of the total energy or electricity consumption of a building were created without a detailed analysis of sub-entry electricity consumption. Sub-entry electricity consumption usually includes lighting and indoor equipment electricity consumption, HVAC system electricity consumption, and power system electricity consumption. The total electricity consumption reflects the overall electricity consumption status of the building, while the sub-entry electricity consumption reflects the building's electricity use details and electricity demand. Through comparisons with similar buildings, sub-entry electricity consumption can assist with the detection of energy-saving and the mining energy-saving potential, and it is conducive to management energy-saving and behavioural energy-saving patterns.

To bridge this gap, sub-entry electricity consumption is taken into account in this study. Total electricity and sub-entry electricity consumptions are considered, and their benchmarks are explored comprehensively. Buildings are also rated with respect to these benchmarks. The main task of this study is to propose a method to develop electricity energy consumption benchmarks.

To explore rational and reliable electricity benchmarks, this study is carried out as follows:(a) The data, including basic building information and actual real-time electricity consumption, are collected, (b) factors affecting electricity consumption are determined, and benchmarks for total EUI and sub-entry EUI are