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Article

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Abstract:

Energy benchmarking is useful for understanding and enhancing building performance. The aim of this research is to develop an object-oriented energy benchmarking method for the evaluation of energy performance in buildings. Statistical analysis of the four-year monitored energy consumption data for office buildings was conducted. The results show that the energy use intensity follows the lognormal distribution with the Shapiro–Wilk normality test. Based on the lognormal distribution, the energy rating system for office buildings has been established. An object-oriented energy use intensity quota determination model has been developed. This research provides practical tools that enable decision-makers to evaluate a building's energy performance and determine the energy benchmark.

Keywords:

Energy consumption; energy conservation; building energy benchmark; office building; quota; carbon emissions.

Nomenclature

Symbols

A	building gross floor area [m^2]
d	natural logarithm of the building EUI [kWh/m^2]
D	building EUI [kWh/m^2]
E	hourly electricity consumption [kWh]
EXPF(x)	expectation function of lognormal distribution
f(x)	probability density function of the lognormal distribution

GD	gross building EUI [kWh/m2]
CDF(x)	cumulative distribution function of the lognormal distribution
r	the planned stock gross floor area increase rate [%]
S	building energy saving percentage compared to baseline year energy consumption [%]
SA	stock gross floor area in baseline year (gross floor area for office buildings) [m^2]
UEXPF(x)	updated expectation function of the lognormal distribution
PSA	planned stock gross floor area in the future [m^2]
v	target building EUI [kWh/m^2]
Φ	cumulative distribution function of the standard normal distribution
μ	mean value of the natural logarithm of EUI [kWh/m^2]
σ	standard deviation value of the natural logarithm of EUI [kWh/m^2]

Abbreviations and acronyms

CDD	cooling degree day
EUI	energy use intensity
HDD	heating degree day
HSCW	hot summer and cold winter
HVAC	heating, ventilation and air conditioning
GFA	gross floor area
CPBECMP	Chongqing public building energy consumption monitoring platform

Subscripts

t	t^{th} hour of the year

1. Introduction

China is one of the largest energy consumers in the world. In 2014, China generated 24% of the world's electricity while consuming 21.2% of the world's total final consumption and emitting 28.2% of the world's CO_2 emissions from fuel combustion (IEA, 2016). The total energy consumption of construction and operation in the Chinese building sector accounts for 36% of the total energy consumption in China (THUBERC, 2016). Building energy consumption associated carbon emission has drawn major concern nationally and internationally. China has a distinctive building classification system with buildings classified into two major groups: civil and industrial. Civil buildings are divided into residential buildings and public buildings. The public buildings are further classified into office, commercial and hotel buildings along with buildings in major sectors such as education, health, communication and transportation (see *Figure 1*).

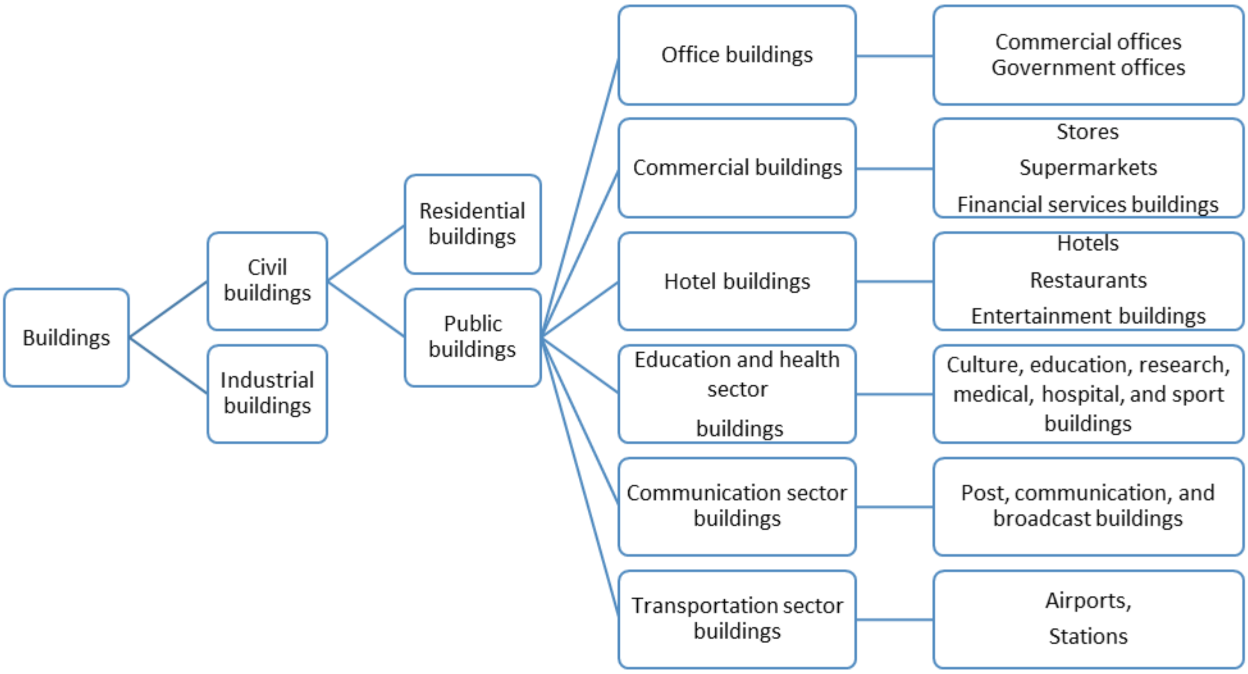

Figure 1: Chinese building classification(Yao et al., 2016b)

A nationwide large-scale investigation into energy efficiency of buildings carried out over ten years ago recognized that government offices and large-scale public buildings were to be the key focus of China's energy efficiency reform (Liang *et al.*, 2007). Public buildings are more energy intensive compared to residential buildings. Especially, the energy use intensity (EUI) of large-scale public buildings (those with more than 20,000m^2 floor area) is 10 to 20 times higher than that of urban residential buildings (MOHURD, 2014). According to the study by Tsinghua University Building Energy Research Center (THUBERC, 2016), in 2014 energy consumed within public buildings accounted for more than 27% of total energy consumption in buildings. China has set an ambitious target of reducing carbon dioxide emissions by 60% to 65% per unit of GDP based on the 2005 baseline by 2030 (Department of Climate Change, 2015). The public building sector, with its enormous potential for energy saving and emission reduction, has been targeted for energy conservation in order to achieve the national goal (MOHURD, 2017). Legislation had recommended compulsory compliance with building standards and codes for the new buildings (Yao *et al.*, 2005). However, this posed great challenges for the existing buildings, 95% of which were "highly-energy-consuming" (Xu *et al.*, 2009). Therefore, building retrofitting strategies, including improvement of building envelope performance; application of renewable technologies; improvement of the efficiency of energy systems; and intelligent operation and energy management, were to be considered by central and local authorities to achieve the carbon-reduction targets while maintaining a comfortable and sustainable built environment. In practice, two questions remain: What is the distribution of energy performance in the current building stock? How can the decision-makers evaluate and rank the energy performance of buildings within the stock to identify, prioritize, and target buildings for retrofitting? Energy benchmark is a useful measure for understanding and enhancing building performance.

The aim of this research is to develop an object-oriented energy benchmarking method which could be used for the evaluation of energy performance in the building stock and for deciding on actions for improvement. Using this new method, local authorities will be able to set up realistic and scientifically-sound energy benchmarks to reduce carbon emissions from buildings and minimize their environmental impact.

The framework of the paper is presented in *Figure 2*.

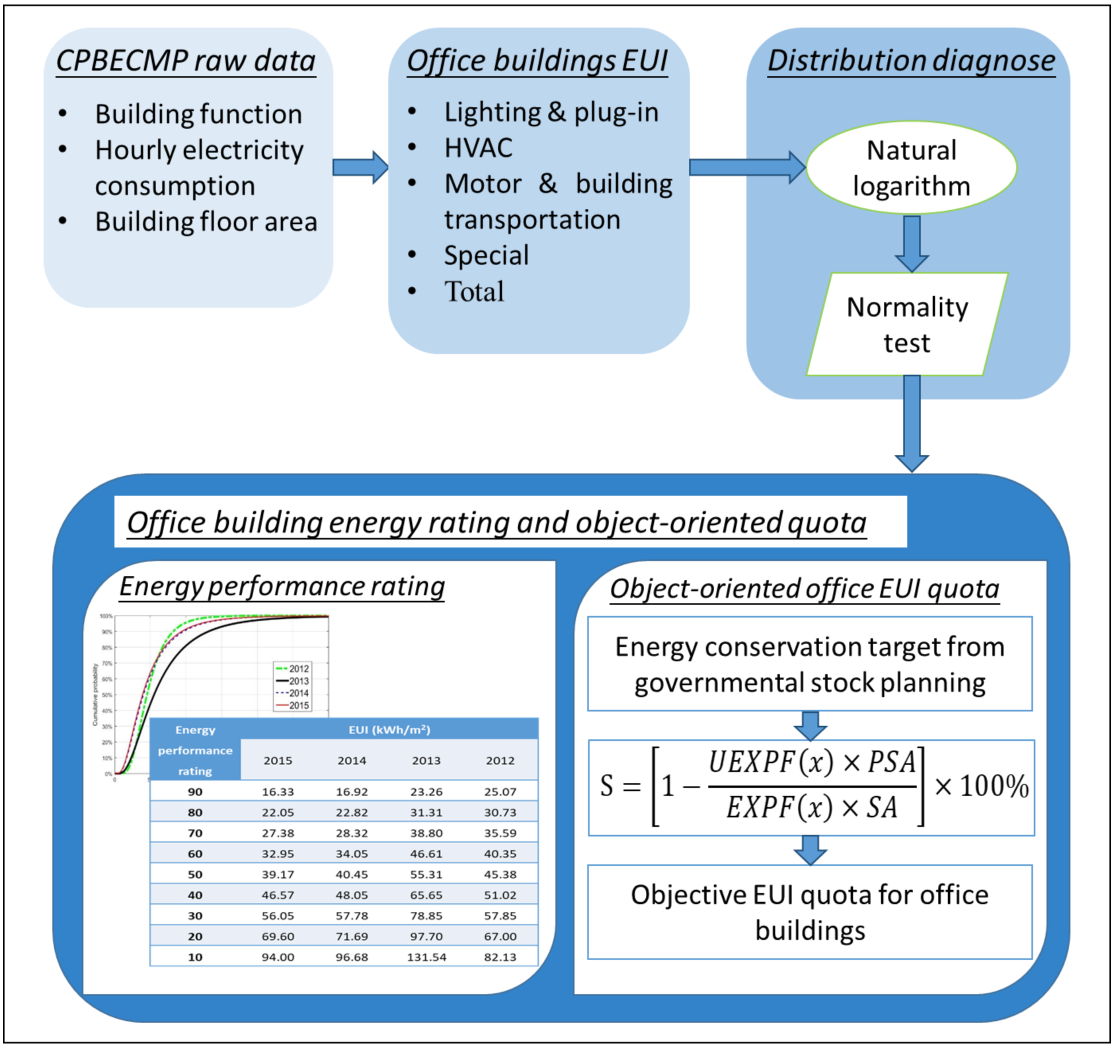

Figure 2 Framework of this paper

2. Literature review

The establishment of realistic benchmarks and quota mechanisms requires two main steps: the collection of energy consumption data and building energy benchmark setting.

2.1 Building energy performance data

To set a reasonable building energy benchmark for a group of buildings sharing the same function, a detailed analysis of building energy performance is needed. No matter what methodology is used, adequate, valid, and reliable data are essential. The data sources for building energy consumption are twofold: actual performance data collected by surveying or monitoring and simulation data generated from computer models. The computer simulation software can be used to calculate building energy consumption (Boyano *et al.*, 2013; Gao *et al.*, 2014; Pomponi *et al.*, 2015; Xu *et al.*, 2013; Yao *et al.*, 2016a), but a performance gap exists between predicted or simulated energy use and actual energy use (Burman *et al.*, 2014; Burman *et al.*, 2012; de Wilde, 2014; Menezes *et al.*, 2012; Salehi *et al.*, 2015; Wilde and Jones, 2014). Onsite measured data is favored for the evaluation of the actual energy performance of buildings.

First conducted in 1979, the Energy Information Administration (EIA) in the United States continuously carries out national surveys and collects information including energy-related building characteristics and energy usage data for commercial buildings, the Commercial Buildings Energy Consumption Survey (CBECS) (EIA, 2015). A similar survey, the Survey of Commercial and Institutional Energy Use (SCIEU), is carried out in Canada. This survey collects data on types and quantities of energy (such as electricity and natural gas) consumed by business and institutional buildings in Canada (Natural Resources Canada, 2016). The first SCIEU was conducted in 2010 as a combination of two previous energy-use surveys: the

Commercial and Institutional Consumption of Energy Survey, started in 2001 (Natural Resources Canada, 2010), and the Commercial and Institutional Building Energy Use Survey, started in 2003 (Natural Resources Canada, 2008). In the United Kingdom, the Department of Energy and Climate Change (DECC) set up the Building Energy Efficiency Survey (BEES) and the National Energy Efficiency Data-Framework (NEED) for the collection of building energy consumption data and energy efficiency analysis (DECC, 2013a, b). In Singapore, after Part IIIB—Environmental Sustainability Measures for Existing Buildings was introduced to the Building Control Act in December 2012, building owners are required to submit their building information and energy consumption data annually to the Building and Construction Authority (BCA) via the Building Energy Submission System (BESS) (BCA, 2017). All of these surveys established databases including actual building energy consumption data for building performance evaluation and energy consumption benchmarking. The establishment of a comprehensive building energy consumption database collected from actual buildings is the most reliable method of obtaining a full picture of the whole building stock. Moreover, it provides a robust reference for property owners and decision-makers to determine building energy benchmarks.

Data on the energy consumption of buildings in China are lacking due to the absence of a monitoring mechanism in the national statistical system (Ding *et al.*, 2009). An urgent need exists to collect these data for statistical analysis (Yang *et al.*, 2007).

The Ministry of Housing and Urban-Rural Development (MOHURD) started a scheme of data collection for the large-scale energy consumption of public buildings in 2007 to build up a national data system. The system collects both basic building information (including name, year of completion, function, and floor area) and energy consumption information (CABR, 2011; Ding *et al.*, 2009). A total of 33 provinces or municipalities have set up online public building energy consumption monitoring platforms that provide yearly monitored building energy consumption reports to MOHURD (MOHURD, 2015b).

2.2 Building energy benchmarks and quotas

According to the definition of the U.S. Department of Energy (DOE), *building energy use benchmarking serves as a mechanism to measure the energy performance of a single building over time, relative to other similar buildings, or to modeled simulations of a reference building built to a specific standard* (DOE, 2016). The establishment of building energy use benchmarks and quotas can be an effective way to reduce energy use. Many countries in the world have their own systems and targets for achieving energy efficiency and reducing carbon emissions.

Based on the American commercial and residential building energy consumption survey data, *ASHRAE Standard 100* (ASHRAE, 2015) provides building energy targets for 48 commercial and five residential building types, the energy target was set as the lower quartile value of energy use by each building type. Moreover, ASHRAE's Building Energy Quotient project applied the *Standard 100* methodology to determine the building energy rating (ASHRAE, 2016). The other popular building energy benchmark in the United States and Canada is the Energy Star rating, which allocates a score from 1-100 to indicate building energy performance against their counterparts. A building having achieved a score of 50 is ranked as an average level of energy performance, while 75 or higher signifies top performance and is eligible for Energy Star certification (ENERGY STAR, 2016a). In the United Kingdom, the publication of *Energy Consumption Guide 19-Energy Use in Offices* sets the benchmark for typical and good practice office buildings based on the median and lower quartile values of the collected mid-1990s data (Best Practice Programme, 2000). CIBSE TM46 (CIBSE, 2008) provides an updated operational building energy benchmark for Display Energy Certificates; these annual electricity and fossil-fuel benchmarks for whole buildings are available for 29 building categories. The CIBSE Guide F provides a detailed end-use benchmark for buildings with different building functions(CIBSE, 2012). In the EU, due to the implementation of the European Directive on Energy Performance of Buildings (EPBD) 2002/91/EC and the recast version 2010/31/EU, EU countries are required to receive building energy performance certification(BPIE, 2014). EU member states are required to ensure that energy performance certificates issued for 1) buildings or building units that are constructed, sold or rented out to a new tenant; and 2) buildings where a total useful floor area over 250 m^2 is occupied by a public authority and frequently visited by the public(EU, 2010). The national building benchmarking is based on the situation of an individual country's own national energy consumption. Germany updated the Energy Saving Ordinance (EnEV) to include building energy certificates based on EPBD(BBSR, 2013). In Australia, the National Australian Built Environment Rating System (NABERS) has been used for rating-energy efficiency, water usage, waste management, and indoor environment quality of buildings. The building types it covers include offices, shopping centers, hotels, data centers, and homes. This star rating can have three different scopes: base building, tenancy, and whole building. While three stars represent average performance, six stars represent market-leading performance(NABERS, 2017). New Zealand generated a New Zealand energy efficiency rating system for office buildings, called NABERSNZ, which follows the same approach as NABERS but adapted for New Zealand situations(NABERSNZ, 2017). In Singapore, the Building and Construction Authority data are based on that collected from Building Energy Submission System (BESS). It provides an annual building energy benchmarking report containing national building energy benchmarks for seven commercial building categories for four different functions. The four quartile values are used for benchmarking(BCA, 2016).

In China, during the design process for public buildings, designers can set up a reference building which matches all the requirements indicated in the *Design Standard for Energy Efficiency of Public Buildings*(MOHURD, 2015a). The calculated building energy consumption of the reference building can be used as an energy benchmark for the permitted maximum energy consumption. There is no fixed standard benchmark building to be considered in the design process(MOHURD, 2015a), which could cause confusion for building designers aiming to meet energy efficiency targets.

Studying building energy benchmarking has attracted many researchers in recent decades. Based on 30 randomly selected supermarkets in Hong Kong, Chung *et al.* (2006) provided a percentile table (from 10 to 90 percentiles) for benchmarking these buildings using an empirical cumulative distribution of the normalized EUI. Zhao *et al.* (2012) studied building energy quota determination methods for public buildings in China and compared the pros and cons of different central tendency measures including arithmetic mean, geometric mean, median, and mode. As a result, a new statistical index, the 'comprehensive application of mode and percentage rank,' has been claimed as the best index for energy consumption quotas. But there is no convincing solid evidence of the premium quality of this new index compared to other indices. Xin *et al.* (2012) established energy consumption quotas for four-start and five-star luxury hotel buildings in China's Hainan province using statistical methods. Here, the mean index of total energy consumption, the mean of EUIs, the quadratic average of EUIs, the median of EUIs, the 60th percentile of EUIs, the 75th percentile of EUIs, and the mode of EUIs are all considered. Consequently, a building EUI range quota using the maximum and minimum values of all above-mentioned indices was recommended for application during the initial quota implementation stage with the mode of the EUIs to be the final quota after a further implementation of the quota system. Ma *et al.* (2017) studied the building energy consumption of government offices, general offices, and school and hospital buildings in northern China. The selected energy performance benchmarks were the average, lower quartile value, median value, and upper quartile value. In the first Chinese Building Energy Consumption Standard(MOHURD, 2016), the energy benchmark system suggested the mean and lower quartile values as the constraint and recommended indicators.

As pointed out by Yang *et al.* (2016), the building energy benchmark or quota derived from the statistical indices like the mean and quartile values does not consider the outcome of the actual energy saving results that the benchmark can achieve for the entire stock. Meanwhile, Yang *et al*. developed a methodology to determine the building energy consumption quota for each individual building using their own historic energy consumption data. However, this kind of tailored individual building benchmark is not suitable for application to a large-scale group of buildings as it needs historic energy consumption data for each individual building to produce the individual benchmark calculation. There is thus a need to develop a practical tool that can be easily applied on a large scale for decision-makers to use in the determination of a savings-targeted building energy benchmark based on the monitored data for energy consumption from representative buildings. The tool is expected to be used by decision-makers of local authorities on each building's energy conservation measures to meet the carbon-reduction target based on the overall stock situation. An understanding of the distribution of energy performance in the current building stock can reveal the achievable energy conservation target.

3. Methodology

In the 13th Five-Year-Plan period (from 2016 to 2020), the Chongqing municipality aims to retrofit $3.5x10^6$ m^2 of existing buildings (Chongqing Municipal Commission of Urban-Rural Development, 2016). This study takes the Chongqing office building sector as a case study for the development of a large-scale building energy performance evaluation method and benchmarking model because Chongqing municipality holds one of the central government’s 33 energy monitoring platforms. Chongqing's public-building energy-consumption monitoring platform (CPBECMP) was established in 2012 by the Chongqing Municipal Commission of Urban-Rural Development to collect real-time energy consumption data (electricity consumption mainly)(Li *et al.*, 2016). The information covers categories of energy consumption and building information including the name of the building, its location, number of floors, function, gross floor area (GFA), air-conditioned floor area, heated floor area, type of HVAC system, and the number of occupiers. Electricity is the main energy source in Chinese public buildings(Cheng *et al.*, 2013), providing 93.4% of the energy used in government office buildings and large-scale public buildings, followed by 5.3% natural gas and 1.1% artificial gas in the Hot Summer and Cold Winter (HSCW) zone in which Chongqing is located (Liu *et al.*, 2013).

For this study, hourly electricity consumption data from 2012 to 2015 were collected from the CPBECMP database, which allowed further analysis of the energy performance of Chongqing office buildings. Building energy usage intensity distribution was identified and statistically tested using the Shapiro–Wilk test. Finally, a Chongqing office building energy consumption benchmark and object-oriented quota model were developed.

3.1. The building EUI calculation

On the CPBECMP, the energy consumption has been divided into four sub-systems: the lighting and plug-in system, the HVAC system, the motors and building transportation system and special systems. The motors and building transportation system refers to all equipment such as the elevators and water supply pumps but excluding fans and pumps in the HVAC system. The special systems section is for uncommon or accessibility functions, such as a data center, laundry room, kitchen, and swimming pool. The building EUI is calculated considering the 'per-unit floor area' to enable a fair comparison between different buildings as it has been proved to be the most suitable index to represent the energy consumption level(Xin *et al.*, 2012). A building's total EUI, as well as the EUI for each sub-system, can be calculated using Equation 1:

$$D = \frac{\sum_{t=1}^{8760} E_t}{A} \qquad (1)\ *$$

Based on the fact that all studied buildings are located in the same city, the weather conditions do not vary from one building to another in terms of calculating annual EUIs for the same year. So no weather correction factor is required. The annual building EUIs are calculated and analyzed in section 4.2 to show the existing levels of energy consumption in office buildings.

The natural logarithm of the EUI for an office building has been calculated using

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* Because 2012 was a leap year, it had 366 days, so the 8760 in Equation 1 became 8784 for 2012 only.

Equation 2,

$$d=\ln D \qquad (2)$$

3.2. Shapiro–Wilk test

The Shapiro–Wilk test is a test of normality in frequentist statistics, according to the study of Ghasemi and Zahediasl (2012), and is a powerful method to check the normal distribution of the natural logarithm of office total EUI. The null and alternative hypotheses for the Shapiro–Wilk test are as follows:

The null hypothesis H0: the natural logarithm of EUI is normally distributed;

The alternative hypothesis Ha: the natural logarithm of EUI is not normally distributed.

The most commonly used significance level (α=0.05) is adopted in these tests, which indicates that the level of confidence for the Shapiro–Wilk test results is 95%. If the p-value, an index to assess statistical significance(Wasserstein and Lazar, 2016), is greater than the significance level α, the null hypothesis cannot be rejected, so it is reasonable to believe that the natural logarithm of EUI (d) is normally distributed.

In this study, the natural logarithm of each annual EUI has been analyzed using the Shapiro–Wilk test. The revealed distribution characteristics provide a deeper understanding of the actual operational energy consumption in office buildings in Chongqing.

4. The Chongqing public building energy consumption monitoring platform

4.1. General information on the platform

The CPBECMP has seven building categories based on the building function: office building, shopping mall, hotel building, educational building, hospital and health-care building, complex building, and sports building. After its establishment in 2012, the CPBECMP had been operating continuously with more public buildings enrolled in the energy monitoring every year. The number of buildings and the gross floor area (GFA) of each building category are presented in Figure 3 and Figure 4. The total number of monitored buildings was 206 with a GFA of $4.79 \times 10^6\ m^2$ in 2012. In 2015, the number of monitored buildings increased to 389 with a GFA of $16.93 \times 10^6\ m^2$.

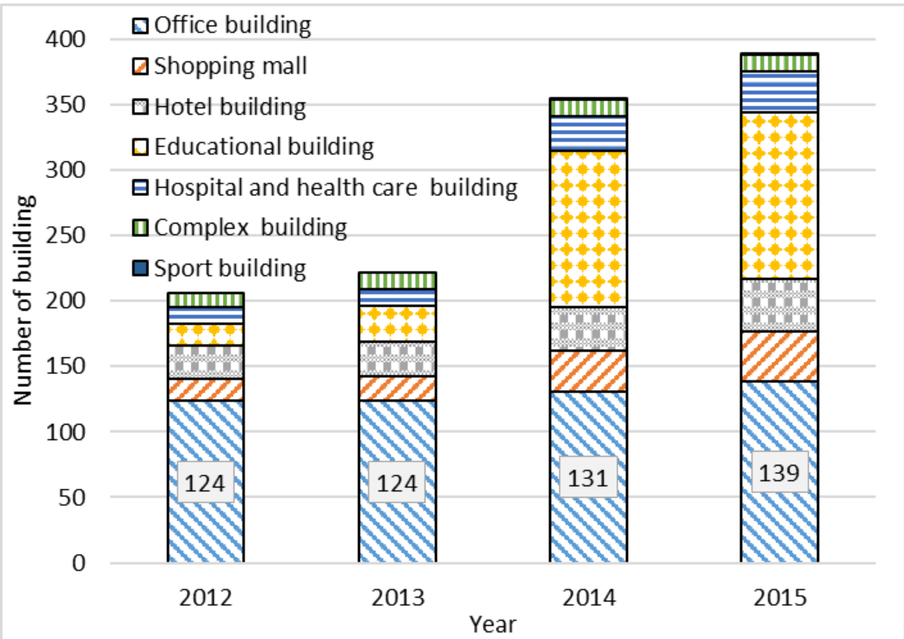

Figure 3: The number of buildings in CPBECMP

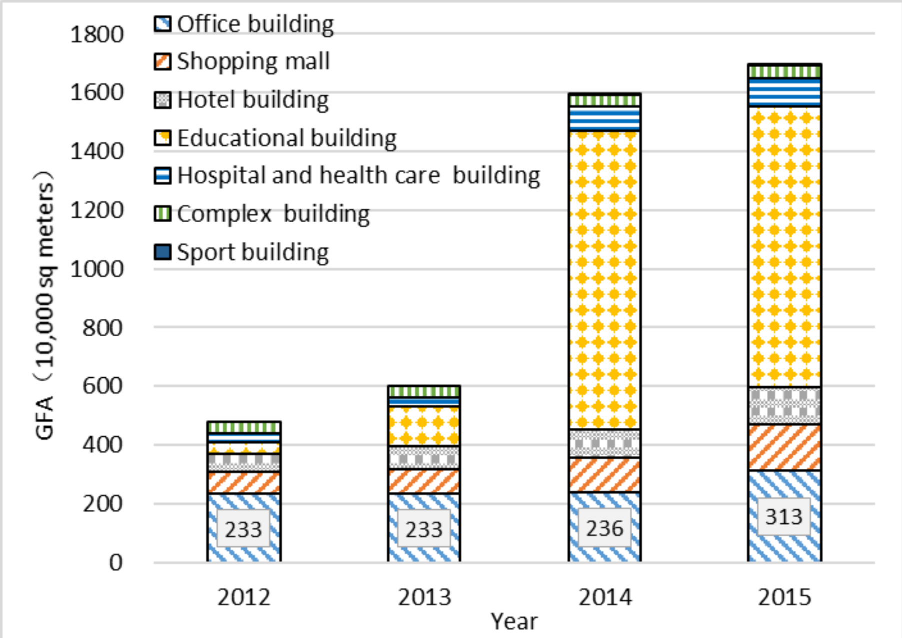

Figure 4: The GFA of buildings in CPBECMP

Figure 5 shows the floor area distribution of office buildings. We can see that office buildings with a GFA less than 20,000 m^2 account for more than 65% of those in CPBECMP, while the percentage for the office buildings larger than 20,000m^2 (large-scale office buildings) is about 30% of the total number.

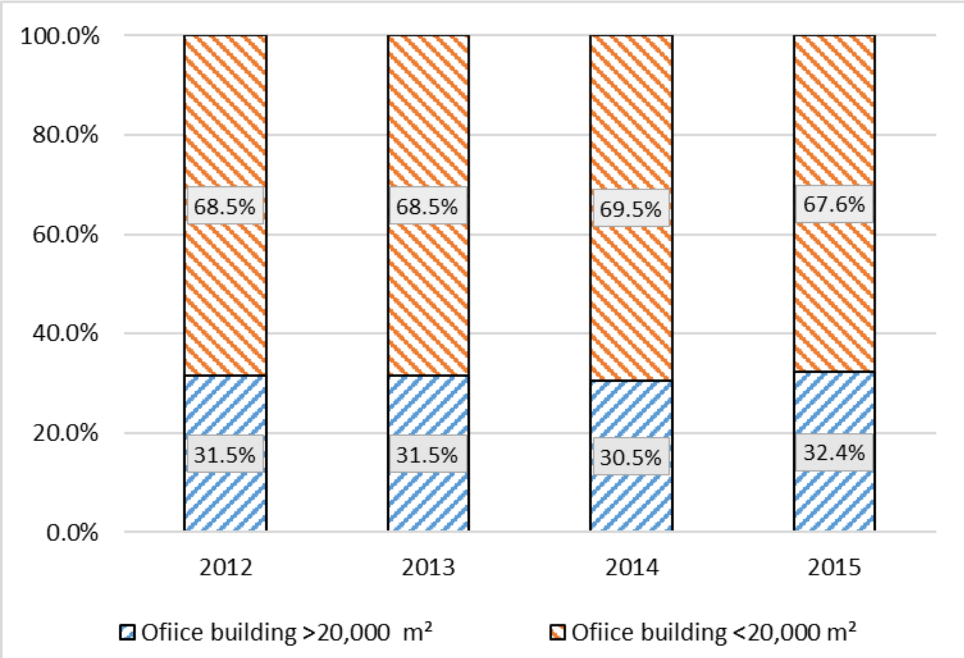

Figure 5: The GFA distribution of office buildings in CPBECMP

4.2. The building energy consumption data

As described in Section 3.1, there are four sub-systems for the energy consumption data provided by the CPBECMP. The box graph of building EUI in total and for different sub-systems is shown in Figure 6. The mean values of the annual total EUI in the Chongqing office building stock are greater than the median value, which indicates the positive skewness of the total building EUI. Moreover, the total energy consumption densities are non-negative, which indicates that they may be lognormal distributed (Limpert *et al.*, 2001). The normality tests for the natural logarithm of building annual EUI are statistically processed and their results are illustrated in section 5.1.

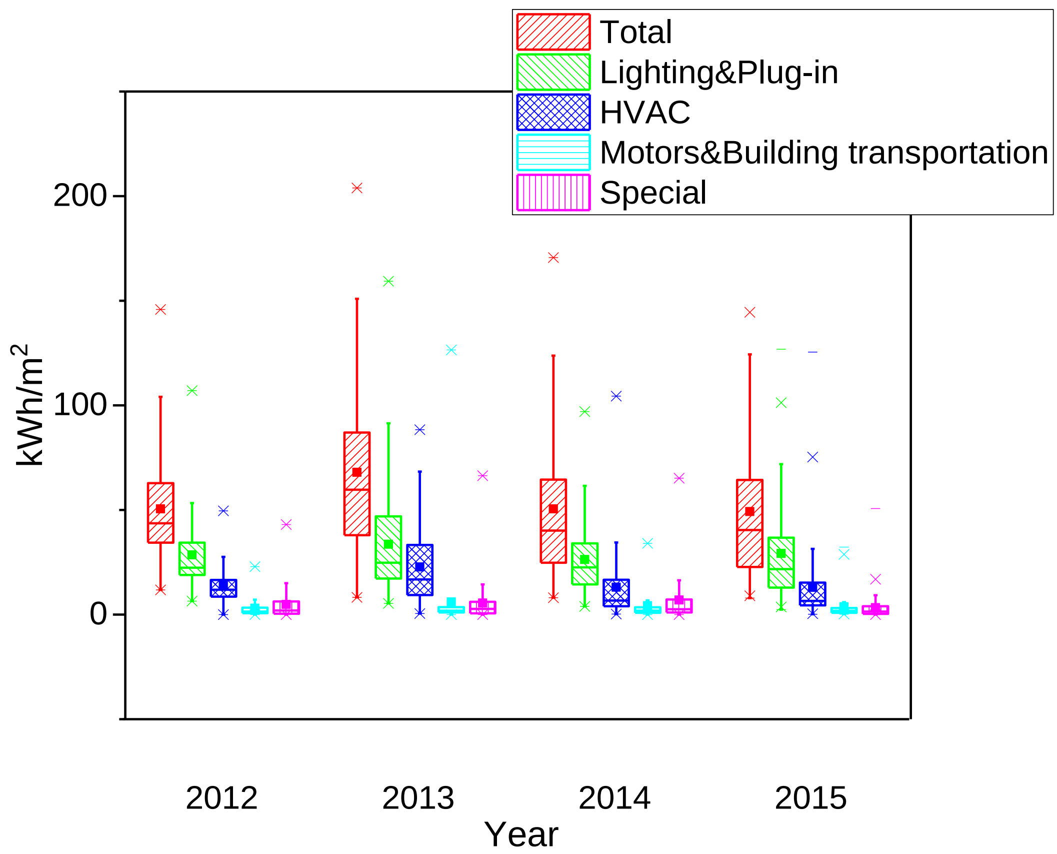

Figure 6: The annual EUIs of office buildings in different years

The lower quartile, median, and mean values for office building energy consumption are shown in Table 1. The average percentage of total energy consumption for the lighting and plug-in system is 49.5% to 59.3% for the four studied years, followed by the HVAC system, which used over 25% of the total energy consumption.

Year	Energy consumption sector	EUI (kWh/m^2)			The average percentage of total energy consumption (%)
		Lower quartile value	Median	Mean	
2012	Total	34.38	43.67	50.47	100.00%
	Lighting & plug-in	18.89	22.43	28.52	56.50%
	HVAC	8.54	11.89	14.08	27.90%

	Motor & building transportation	0.64	1.45	3.03	6.00%
	Special	0.4	1.99	4.84	9.60%
2013	Total	37.91	59.66	67.96	100.00%
	Lighting & plug-in	17.24	24.75	33.63	49.50%
	HVAC	9.36	16.8	22.74	33.50%
	Motors & building transportation	1.05	1.87	6.06	8.90%
	Special	0.56	2.69	5.52	8.10%
2014	Total	24.83	40.17	50.53	100.00%
	Lighting & plug-in	14.41	22.58	26.32	52.10%
	HVAC	4.03	6.73	13.07	25.90%
	Motor & building transportation	0.89	1.84	4.21	8.30%
	Special	1.02	2.51	6.93	13.70%
2015	Total	22.75	40.4	49.24	100.00%
	Lighting & plug-in	12.92	21.73	29.2	59.30%
	HVAC	4.4	6.57	12.96	26.30%
	Motors & building transportation	0.88	1.74	3.73	7.60%
	Special	0.35	1.44	3.35	6.80%

Table 1: The statistical information about annual EUI of office buildings in different years

Based on the measured climate parameters from the China Meteorological Data Service Center from 2012 to 2015(CMDC, 2017), the heating degree day (HDD) and cooling degree day (CDD) of Chongqing are calculated based on 18°C and 26°C respectively. The average EUIs of every sub-system, along with the HDD and CDD of that year, are shown in Figure 7. From the figure, we can see that, on one hand, years 2012, 2014 and 2015 have quite comparable energy consumption in total EUI as well as for every sub-system with similar CDDs regardless of the gap between their HDDs. This indicates that office building energy consumption is not sensitive to HDD variation. On the other hand, 2013 had a relatively higher total EUI. Apart from higher lighting and plug-in EUI, HVAC EUI is higher due to the higher CDD in 2013. The higher EUI of the lighting and plug-in contributes more internal heat gains which further increase the cooling load.

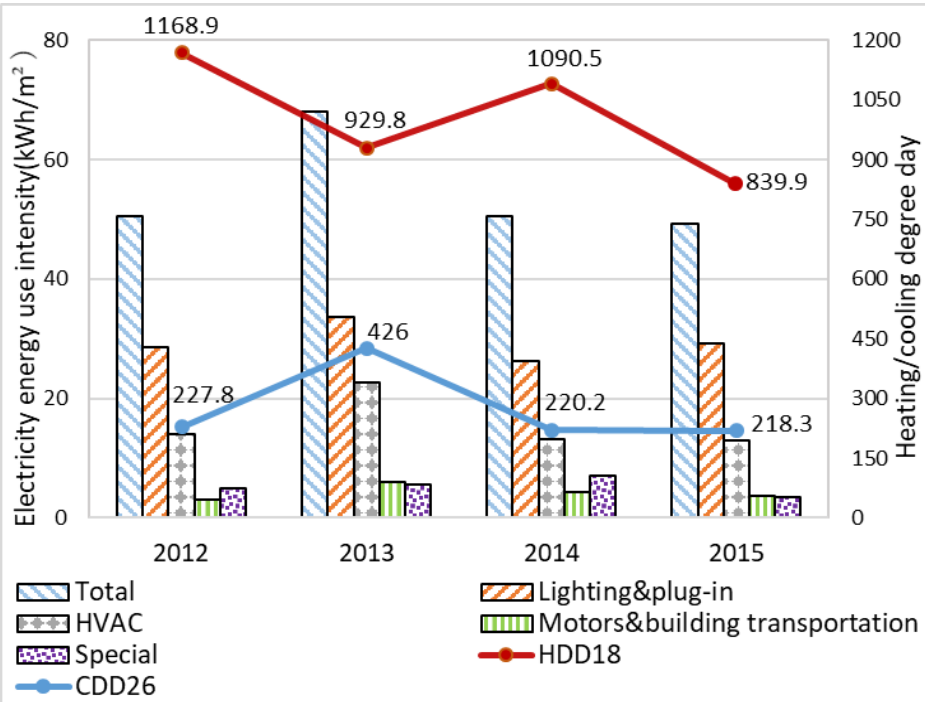

Figure 7: Office building average EUIs and heating and cooling degree days in different years

As indicated in Table 1, the median electricity EUIs of office buildings in Chongqing range between 40.17 and 59.66kWh/m^2. According to Liu *et al.* (2013), electricity usage in office buildings accounts for 93.4% of total energy consumption. Adopting this percentage, the building gross energy consumption will be its electricity consumption divided by 0.934, as shown in Equation 3. Thus, the median gross EUI for office buildings in Chongqing are between 43.01 and 63.88kWh/m^2.

$$GD=D/0.934 \qquad (3)$$

Compared with the EUI benchmarks in other countries and regions of the world (shown in

Countries	Office building energy benchmark (site energy)	Note
Canada (ENERGY STAR, 2016b)	252.8 kWh/m^2 (0.91GJ/m^2)	National median total energy use intensity.
Hong Kong (EMSD, 2016)	279.2 kWh/m^2 (1005 MJ/m^2) Government Office. 132.2 kWh/m^2 (476 MJ/m^2) Private Office with central air-conditioning. 43.1 kWh/m^2 (155 MJ/m^2) Private Office without central air-conditioning.	Total energy use intensity (for reference only, not representative energy consumption levels).
Singapore	213.0 kWh/m^2	National median electricity

(BCA, 2016)	(GFA⩾15,000m^2) 192.0 kWh/m^2 (GFA <15,000m^2)	energy use intensity.
USA (ENERGY STAR, 2016c)	212.3 kWh/m^2 (67.3kBtu/ft^2)	National median total energy use intensity.
UK (CIBSE, 2008)	95.0 kWh/m^2 (weather adjustment considered in benchmark, but not valid for office electricity consumption)	National median electricity energy use intensity.

Table 2), the EUI in Chongqing offices is much lower. The only exception is private offices without central air-conditioning in Hong Kong, which have a slightly lower EUI. But EMSD Hong Kong states clearly that the index given is not a representative value and can only be used for reference. A majority of the benchmark data shown are given by national median values, without taking into account climate variations. To solve this problem, ASHRAE used a simulated representative building to extrapolate the median EUI to different climate zones across the whole US by applying climate zone ratios. The lower quartile value of energy use was derived and used as the building energy consumption target (ASHRAE, 2015). According to the ASHRAE climate zone classification, Chongqing is located in climate zone 3A, which is defined as ‘warm humid’ (ASHRAE, 2013). The building energy consumption targets for US office buildings in climate zone 3A are 163.93kWh/m^2 (52kBtu/ft^2) for government offices, 132.40kWh/m^2 (42kBtu/ft^2) for professional offices, and 151.32kWh/m^2

($48kBtu/ft^2$) for mixed-use offices (ASHRAE, 2015). This reveals that the median gross EUI in Chongqing office buildings is even lower than the American energy consumption target for office buildings. This is mainly because China has a wider temperature range of indoor thermal comfort according to the Chinese building thermal design standard compared to the developed countries (Li *et al.*, 2014; Zhou *et al.*, 2017). A nationwide field study from Li *et al.* (2014) revealed that the indoor temperature for public and residential buildings in south China where Chongqing located varies between 5^{o} C to 35^{o} C.

Countries	Office building energy benchmark (site energy)	Note
Canada (ENERGY STAR, 2016b)	252.8 kWh/m^2 (0.91GJ/m^2)	National median total energy use intensity.
Hong Kong (EMSD, 2016)	279.2 kWh/m^2 (1005 MJ/m^2) Government Office. 132.2 kWh/m^2 (476 MJ/m^2) Private Office with central air-conditioning. 43.1 kWh/m^2 (155 MJ/m^2) Private Office without central air-conditioning.	Total energy use intensity (for reference only, not representative energy consumption levels).
Singapore	213.0 kWh/m^2	National median electricity

(BCA, 2016)	(GFA $\geqslant$ 15,000m^2) 192.0 kWh/m^2 (GFA <15,000m^2)	energy use intensity.
USA (ENERGY STAR, 2016c)	212.3 kWh/m^2 (67.3kBtu/ft^2)	National median total energy use intensity.
UK (CIBSE, 2008)	95.0 kWh/m^2 (weather adjustment considered in benchmark, but not valid for office electricity consumption)	National median electricity energy use intensity.

Table 2: Energy use intensity benchmarks in other countries or regions in the world

In the Chinese recommended *Standard for Energy Consumption of Buildings GB/T 51161-2016* (MOHURD, 2016), the office-building energy-consumption benchmark has been established for the Hot Summer and Cold Winter (HSCW) zone where Chongqing is located. The benchmark includes two indices: a *constraint* indicator and a *recommended* indicator. For building energy performance, their annual EUI should not exceed the constraint indicator but attempt to achieve the recommended indicator. The building type of office buildings has been further divided into the sub-stock Type A and Type B based on the possibility of using natural ventilation to maintain a comfortable indoor thermal environment. Buildings with no access to natural ventilation and totally depending on mechanical ventilation as well as HVAC systems for indoor temperature control are regarded as Type B, otherwise Type A.

The requirements in this standard for office buildings are listed in

Standard for Energy Consumption of Buildings GB/T 51161-2016				CPBECMP office building	
Building function	Building type	Constraint indicator kWh/m^2	Recommended indicator kWh/m^2	Year	Mean gross EUI
Government office buildings.	Type A	70	55	2012	54.04
	Type B	90	65	2013	72.76
General office buildings.	Type A	85	70	2014	54.10
	Type B	110	80	2015	52.72

Table 3; the constraint indicators as the mean values for Type A and B government office buildings are 70 and 90kWh/m^2 and 85 and 110kWh/m^2 for general office buildings, respectively. The mean gross EUI of office buildings in Chongqing is from 52.72 to 72.76kWh/m^2. We conclude that the overall energy performance of office buildings in Chongqing satisfies the Standard GB/T 51161-2016. The gross EUI of 72.76 kWh/m^2 in 2013 is higher than that required in the Standard, but the CDD of 426 in 2013 was much higher than the reference CDD of 241(Chongqing Minicipal Commission of Urnam-Rural Development, 2010).

Standard for Energy Consumption of Buildings GB/T 51161-2016				CPBECMP office building	
Building	Building	Constraint indicator	Recommended indicator	Year	Mean gross

function	type	kWh/m^2	kWh/m^2
Government office buildings.	Type A	70	55
	Type B	90	65
General office buildings.	Type A	85	70
	Type B	110	80

	EUI
2012	54.04
2013	72.76
2014	54.10
2015	52.72

Table 3: The office-building energy-consumption benchmark indicators from GB/T 51161-2016 and the CPBECMP office building performance

5. Building energy performance distribution and rating

5.1. Normality test results

The Shapiro–Wilk test was applied to the natural logarithm of the total EUI of office buildings for the four studied years using SPSS, and the results are presented in

Year	p-value	Mean value	Standard deviation
2012	0.612	3.815	0.463
2013	0.393	4.013	0.676
2014	0.704	3.700	0.680
2015	0.521	3.668	0.683

Table 4. The annual total EUIs of Chongqing office buildings all passed the test ($p>0.05$), which indicates that the normal distribution hypothesis can be accepted.

Year	p-value	Mean value	Standard deviation

2012	0.612	3.815	0.463
2013	0.393	4.013	0.676
2014	0.704	3.700	0.680
2015	0.521	3.668	0.683

Table 4: Results of the of the Shapiro–Wilk tests

To further assess if the total EUI follows the lognormal distribution, the quantile-quantile (q-q) graphical plot technique is used and plotted in Figure 8. A 45-degree reference line is also plotted as y=x. The X-Axis represents the observed value of total EUI while the Y-axis represents the expected lognormal distribution values at the same quantiles as x. From the findings, we can see that all the data points fall approximately along the reference line for year 2012, 2014 and 2015, which confirms that the office building EUI has the same distribution as the lognormal distribution. For the year 2013, even though only one data point which is a bit far away from the reference line, the vast majority of the data points are very close to reference line. Therefore, 2013 total EUI data is lognormal distributed as well.

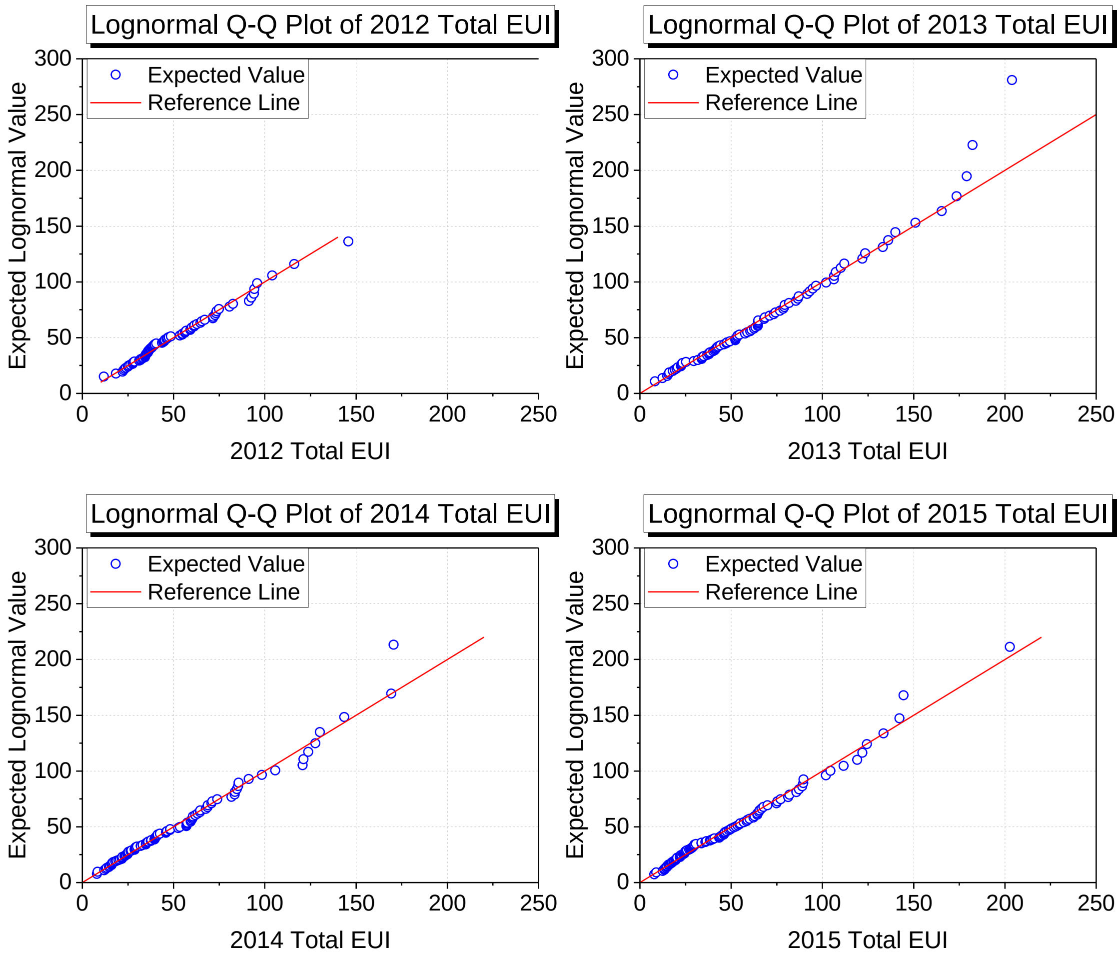

Figure 8: Lognormal Q-Q plots for office total EUI from 2012 to 2015

As the natural logarithm of the building EUIs has passed the normality test, the building EUIs are proved to follow the lognormal distribution. The probability density function and cumulative distribution function for lognormal distribution are shown in Equations 4 and 5.

$$\mathrm{f(x)} = \frac{1}{x\sigma\sqrt{2\pi}} exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right], \qquad x > 0 \quad (4)$$

$$\mathrm{CDF(x)} = \int_0^x f(\xi)d\xi = \Phi\left(\frac{\ln x - \mu}{\sigma}\right) \quad (5)$$

Knowing the lognormal distribution of the EUIs for office buildings for the four study years, their cumulative probability curves for annual EUIs were drawn and presented in **Error! Reference source not found.** using Equation 5 for the lognormal distribution cumulative probability function. The cumulative distribution function provides a way to calculate the exact EUI values at different cumulative probability levels that are relatively independent of the EUIs of office building samples. Furthermore, it is used to generate a building energy performance rating based on monitored data for Chongqing office buildings in section 5.2.

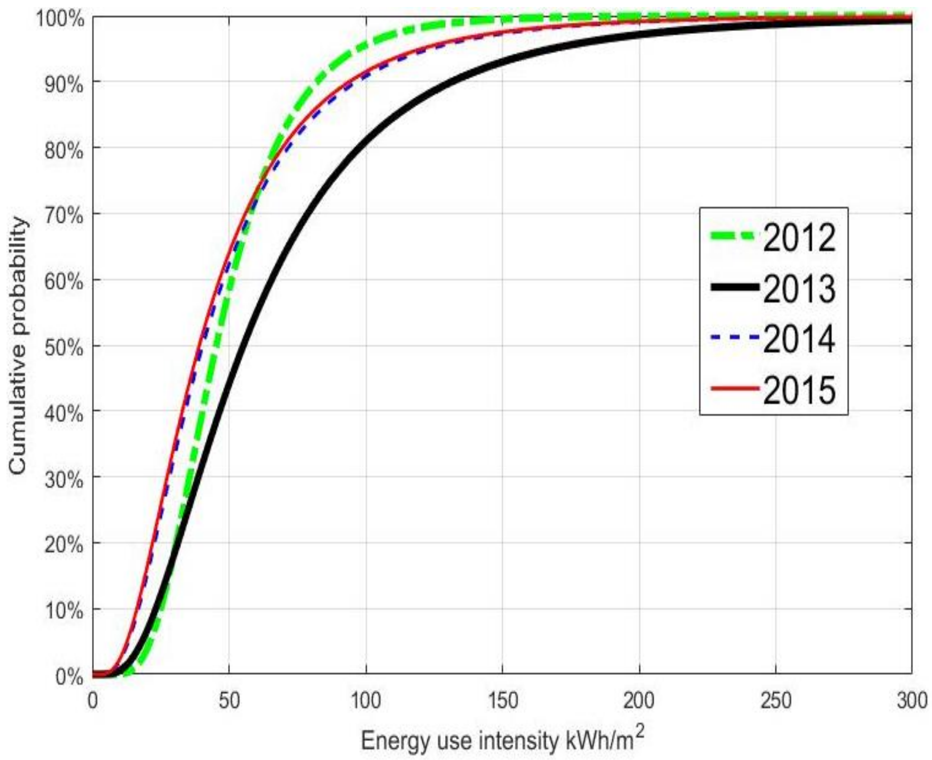

Figure 9: The cumulative probability of annual EUI for office buildings in the four years

5.2. Building energy-performance rating

The lower quartile value, median, and mean for the whole building as well as sub-systems is shown in *Table 1* and can act as benchmarking indices for the evaluation of building energy performance and the performance of individual sub-systems in office buildings in Chongqing. Moreover, based on the cumulative probability function of the annual EUI for office buildings, the building energy-performance rating uses a 1-100 scale established by the cumulative probability level. *Table 5* shows the rating scale for office buildings for different years. An energy consumption rating of 90 indicates that, from an energy consumption standpoint, the building performs better than 90% of buildings of the same type, while a rating of 10 indicates the building performs better than only 10% of office buildings in the stock. The energy rating can be used as an indicator to diagnose the energy consumption of an individual office building relative to the whole stock. Based on the average carbon dioxide emission factor of 0.5257kgCO_2/kWh for China's central region power grid where the electricity supply for whole Chongqing city came from the reference (NCSC, 2014), the carbon dioxide emission intensities corresponding to different building energy performance rankings are presented in *Table 5*.

Energy performance rating	EUI (kWh/m^2)				CO_2 emission (kgCO_2/m^2)			
	2015	2014	2013	2012	2015	2014	2013	2012
90	16.33	16.92	23.26	25.07	8.58	8.89	12.23	13.18
80	22.05	22.82	31.31	30.73	11.59	12.00	16.46	16.15
70	27.38	28.32	38.80	35.59	14.39	14.89	20.40	18.71
60	32.95	34.05	46.61	40.35	17.32	17.90	24.50	21.21
50	39.17	40.45	55.31	45.38	20.59	21.26	29.08	23.86
40	46.57	48.05	65.65	51.02	24.48	25.26	34.51	26.82

30	56.05	57.78	78.85	57.85	29.47	30.37	41.45	30.41
20	69.60	71.69	97.70	67.00	36.59	37.69	51.36	35.22
10	94.00	96.68	131.54	82.13	49.42	50.82	69.15	43.18

Table 5: The annual EUI rating of office buildings and the corresponding CO_2 emissions

6. The object-oriented EUI quota determination model

6.1 The model

According to the State Council of the People's Republic of China, for buildings occupied by public authorities, EUI in 2020 should be 10% less than in 2015(SCC, 2016). As noted by Yang *et al.* (2016), *applying a uniform EUI reduction rate was not equitable to all the buildings, as the high-performance buildings were already consuming less energy. It was therefore more difficult for such energy efficient buildings to meet the targets, as they had little potential for further energy saving.* A reasonable energy reduction target should be set at the stock level as a total reduction target.

Based on the lognormal distribution of total annual EUI, the expectation function of lognormal distribution for calculating the mean EUI value of lognormal distribution is shown on Equation 6.

$$\mathrm{EXPF}(x) = \int_0^{+\infty} x f(x) dx = exp(\mu + \frac{\sigma^2}{2}) \quad (6)$$

If considering setting a mandatory objective maximum EUI (v) for all office buildings, those with higher EUIs will be required to reduce to, or below, the EUI target. Assuming all buildings with a lower total EUI are not changing their energy consumption while all those with a higher total EUI are reducing to the target EUI value, the updated mean EUI value of the building stock can then be calculated from Equation 7.

$$\mathrm{UEXPF}(\mathrm{x}) = \int_{0}^{v} x f(x) dx + \int_{v}^{+\infty} v f(x) dx$$
$$= exp\left(\mu + \frac{\sigma^2}{2}\right) \Phi\left(\frac{\ln v - \mu - \sigma^2}{\sigma}\right) + v - v\Phi\left(\frac{\ln v - \mu}{\sigma}\right) \quad (7)$$

With the aforementioned calculation formula for the mean EUI value of the base year and the updated mean EUI value after the mandatory maximum target EUI being applied, the stock total energy consumption can be calculated by multiplying the stock mean EUI by the stock GFA. The energy-saving percentage by applying the target EUI is measured by the energy consumption reduction divided by the stock energy consumption for the base year, as shown in Equation 8. The stock GFA variation can be modified by using the planned stock GFA increase rate r, with r = PSA / SA. This planned stock GFA increase rate should come from the city-level office for stock development planning.

$$\mathrm{S} = \left[1 - \frac{UEXPF(x) \times PSA}{EXPF(x) \times SA}\right] \times 100\% = \left[1 - \frac{UEXPF(x)}{EXPF(x)} \times r\right] \times 100\%$$

$$= \left\{1 - \left[\Phi\left(\frac{\ln v - \mu - \sigma^2}{\sigma}\right) - \frac{v\Phi\left(\frac{\ln v - \mu}{\sigma}\right)}{\exp\left(\mu + \frac{\sigma^2}{2}\right)} + \frac{v}{\exp(\mu + \frac{\sigma^2}{2})}\right] \times \mathrm{r}\right\} \times 100\% \quad (8)$$

The target EUI which meets the savings target of the energy consumption of the office building stock can be calculated using Equation 8, which can be called the EUI quota determination model. This model can be used to calculate the objective EUI value and is helpful to local authority decision-makers in deciding the building energy quota under a specific energy saving target issued by the government. It means that if the EUI of an office building exceeds the objective EUI value, actions should be taken to reduce energy consumption. With improved operational energy for the poorly-performing buildings, the preset stock energy conservation target can be achieved automatically.

A Matlab program had been coded for the object-oriented EUI quota determination model based on Equation 8. To work out the office building EUI quota under a stock energy-saving percentage goal, the required input information includes the mean value, the standard deviation value of the natural logarithm of office building EUI, and the planned increase in stock GFA. The mean and standard deviation values can be found in

Year	p-value	Mean value	Standard deviation
2012	0.612	3.815	0.463
2013	0.393	4.013	0.676
2014	0.704	3.700	0.680

2015	0.521	3.668	0.683

Table 4, while the energy-saving goal and the planned stock GFA increase rate should be determined by the government and policy makers according to the general plan for Chongqing. This model is an easy-to-use, object-oriented, building energy benchmarking tool for local authority to evaluate office building performance. In order to make the objective EUI quota achievable for the high energy consumption buildings, building retrofitting strategies could be planned, including the improvement of building envelope performance; the application of renewable technologies; the improvement of the efficiency of energy systems; and intelligent operations and energy management. Government subsidies should be considered for those high EUI buildings with building retrofitting for the improvement of energy performance based on the benchmarking provided.

6.2 Example of applying the model

According to THUBERC (2017), office building had already accounting for the biggest portion in public building stock in China, the total floor area for office building should be controlled for no further increase. So the planned office stock GFA increase rate r is assumed to be 1, which indicated a constant office stock GFA. The year 2015 was selected as the baseline year for building energy saving percentage definition. TTable 6 lists some EUI quotas calculated using Equation 8 under different stock energy-saving goals.

Table 6 the annual EUI quotas under different energy-saving percentage goal

Energy saving percentage goal	The annual EUI quota (kWh/m^2)
5%	116.9
10%	87.1
15%	71.0
20%	60.0
25%	51.8

As the building energy consumption quota being determined by the object-oriented model, the energy performance of office buildings can be evaluated based on the quota. Assuming the energy-saving goal for year 2017 is 10% reduction compared to year 2015, the office EUI quota is 87.1 kWh/m^2. If an office building operating total EUI is over 87.1 kWh/m^2 in 2015, retrofitting actions should be taken to improve building energy efficiency.

Office building retrofit measures found in the literature(Dong *et al.*, 2014; Guo *et al.*, 2008; Liu *et al.*, 2009; Yao *et al.*, 2016b) including;

- Improving building envelope insulation (roof, external wall, window, etc.) and airtightness;
- Improving the efficiency of indoor lighting systems and office utilization equipment;
- Improving HVAC facilities and system efficiency (boiler, chillier, air-condition

unit, fan efficiency);

- Improving building control systems (HVAC system control optimization, external shading control, maximum daylight usage control, etc.);
- Appling advanced energy-saving technologies (hybrid ventilation, night ventilation, heat recovery);
- Improving the building management services and raising users’ energy saving conscious.

Office buildings having the same EUI value may have different intensity of energy consumption due to its own energy consumption characteristics. There are no uniform retrofit measures, so each building identified and being proposed to the retrofitting plan should go through energy consumption diagnose and retrofit measure analysis (including reliability analysis, operability analysis and economic analysis), to find the optimum retrofit measure bundle. The Technical code for the retrofitting of public building energy efficiency JGJ176-2009 (MOHURD, 2009) can be referenced to guide the selection of energy conservation retrofit measure.

7. Conclusions

This paper presents the actual operational energy consumption data of office buildings collected from the Chongqing public-building energy-consumption monitoring platform (CPBECMP) between 2012 and 2015. An understanding of the energy consumption profiles in office buildings in Chongqing was obtained. Statistical analysis using Shapiro–Wilk normality tests was applied to identify the EUI distributions, which is essential to the development of the office energy-performance benchmark rating and object-oriented EUI quota determination model. In this study, commonly-used, statistically-based indices for building energy consumption benchmarking, including lower quartile value, median, and mean, and percentile tables (from 10 to 90 percentiles) of building EUI have been presented for the office building stock in Chongqing. The object-oriented EUI quota determination model has also been developed. The building benchmark and object-oriented quota model are practical tools for local authorities to evaluate building energy consumption and make decisions on building energy retrofit. The method of establishing energy benchmarks can be applied to any other building stock once the monitored energy consumption data are available.

The key conclusions drawn from our study are as follows:

- The median gross EUI for office building in Chongqing are from 43.01 to 63.88kWh/m^2, which are much lower than that for developed countries. This is mainly because China has a wider temperature range of indoor thermal comfort according to the Chinese building thermal design standard compared to the developed countries. This situation affects the electricity used for heating and cooling;
- The annual EUIs of office buildings follow lognormal distribution; therefore, the energy-performance rating can be generated based on the cumulative

distribution function of lognormal distribution. The annual EUI rating can identify the high energy consumption buildings;

- The object-oriented EUI quota determination model can perform projected energy-saving target analysis that will be useful to the local authorities, including utility service providers, to determine which building need to go through energy conservation retrofit process to meet the stock carbon-reduction target. Government subsidies, as well as policies involving economic and administrative penalties, should be carefully considered and operated to activate the object-oriented EUI quota in building management;
- The application of the annual EUI rating and object-oriented EUI quota can contribute greatly to carbon reduction and sustainable built-environment development by proving scientifically sound benchmarks to evaluate Chongqing office-building operational performance.
- This research focused on the office buildings in Chongqing, but the statistical analysis and object-oriented EUI quota determination model construction process can be easily adapted to different building stocks in other cities based on the collected energy consumption data.
- We recommend the Energy Certificate Display mechanism for office buildings in China as well as open access to the database of public buildings.

This study also suggests ideas for future research into the roles of thermal management and energy efficiency in the built environment and their effect on electric utilities and capacity needs, particularly in regions with hot summers and cold winters.

Improving building performance could help relieve heating and cooling electricity peak loads. Further studies could focus on how electricity utilities are adapting to the impact of the diversity of thermal comfort demand on electricity consumption in China.

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