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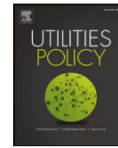
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An object-oriented energy benchmark for the evaluation of the office building stock



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1 An object-oriented energy benchmark for the 2 evaluation of the office building stock

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17 **Abstract:**

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

28 **Keywords:**

29 Energy consumption; energy conservation; building energy benchmark; office
30 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

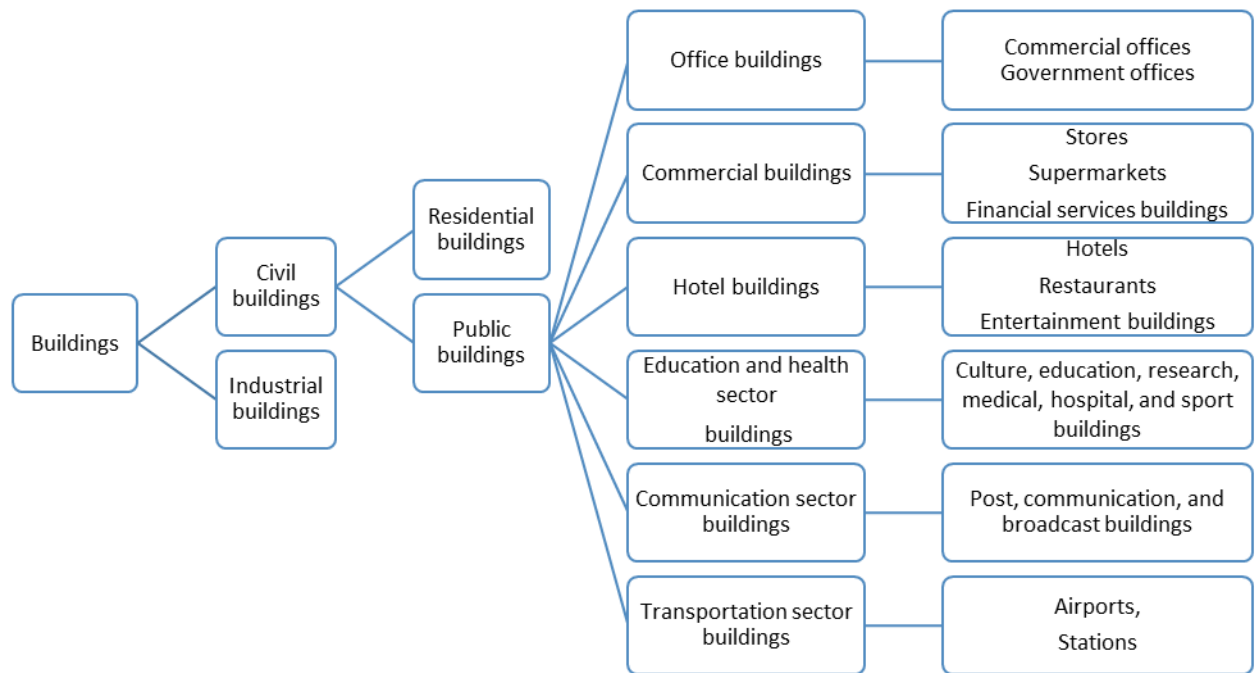
GD	gross building EUI [kWh/m ²]
CDF(x)	cumulative distribution function of the lognormal distribution
r	the planned stock gross floor area increase rate [%]
S	building energy saving percentage compared to baseline year energy consumption [%]
SA	stock gross floor area in baseline year (gross floor area 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]
<i>Abbreviations and acronyms</i>	
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
<i>Subscripts</i>	
<i>t</i>	<i>t</i> th hour of the year

31

32 1. Introduction

33 China is one of the largest energy consumers in the world. In 2014, China generated
34 24% of the world's electricity while consuming 21.2% of the world's total final
35 consumption and emitting 28.2% of the world's CO₂ emissions from fuel combustion
36 (IEA, 2016). The total energy consumption of construction and operation in the
37 Chinese building sector accounts for 36% of the total energy consumption in China
38 (THUBERC, 2016). Building energy consumption associated carbon emission has
39 drawn major concern nationally and internationally. China has a distinctive building
40 classification system with buildings classified into two major groups: civil and

41 industrial. Civil buildings are divided into residential buildings and public buildings.
 42 The public buildings are further classified into office, commercial and hotel buildings
 43 along with buildings in major sectors such as education, health, communication and
 44 transportation (see *Figure 1*).



45

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

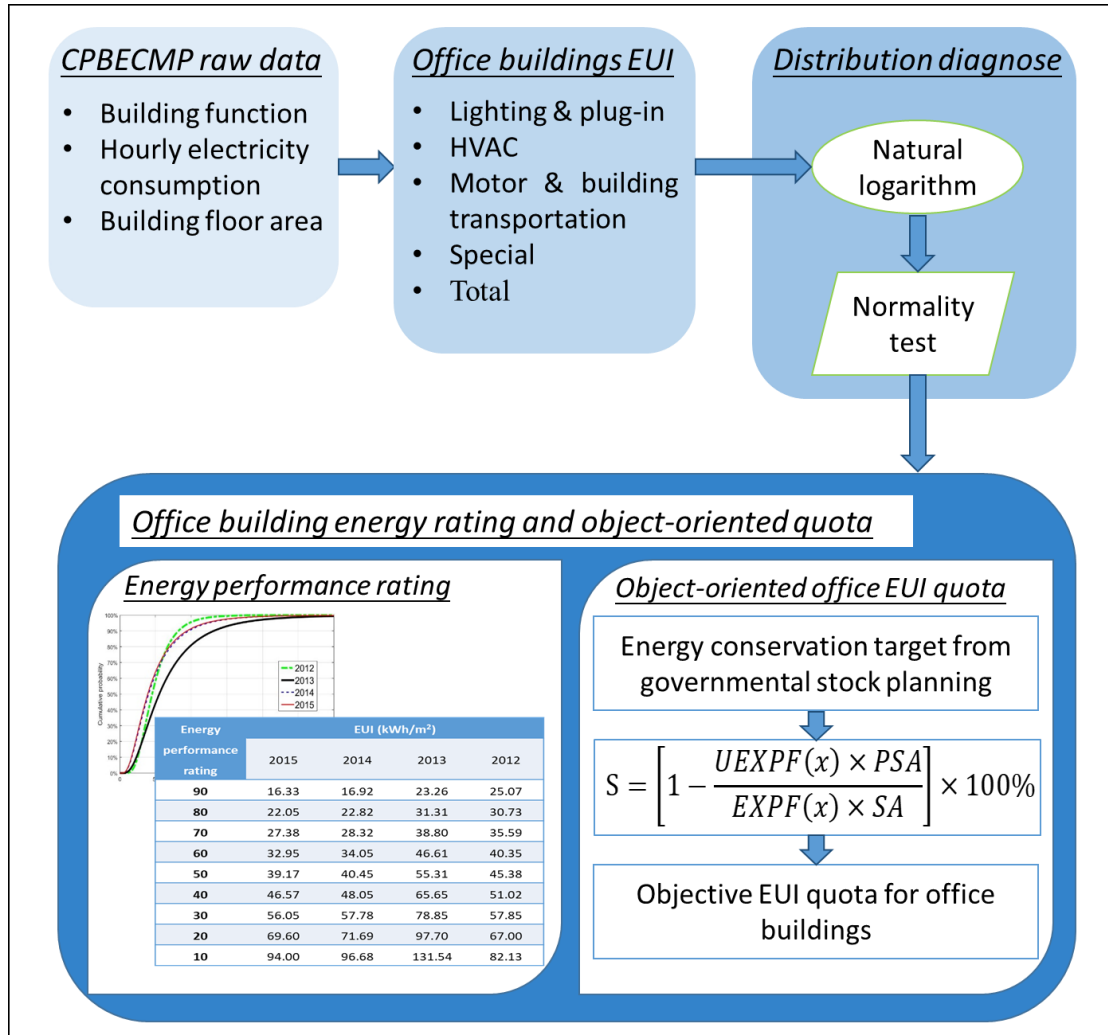
47 A nationwide large-scale investigation into energy efficiency of buildings carried out
 48 over ten years ago recognized that government offices and large-scale public
 49 buildings were to be the key focus of China’s energy efficiency reform (Liang *et al.*,
 50 2007). Public buildings are more energy intensive compared to residential buildings.
 51 Especially, the energy use intensity (EUI) of large-scale public buildings (those with
 52 more than 20,000m² floor area) is 10 to 20 times higher than that of urban residential
 53 buildings (MOHURD, 2014). According to the study by Tsinghua University Building
 54 Energy Research Center (THUBERC, 2016), in 2014 energy consumed within public

55 buildings accounted for more than 27% of total energy consumption in buildings.
56 China has set an ambitious target of reducing carbon dioxide emissions by 60% to
57 65% per unit of GDP based on the 2005 baseline by 2030 (Department of Climate
58 Change, 2015). The public building sector, with its enormous potential for energy
59 saving and emission reduction, has been targeted for energy conservation in order to
60 achieve the national goal (MOHURD, 2017). Legislation had recommended
61 compulsory compliance with building standards and codes for the new buildings (Yao
62 *et al.*, 2005). However, this posed great challenges for the existing buildings, 95% of
63 which were "highly-energy-consuming" (Xu *et al.*, 2009). Therefore, building
64 retrofitting strategies, including improvement of building envelope performance;
65 application of renewable technologies; improvement of the efficiency of energy
66 systems; and intelligent operation and energy management, were to be considered by
67 central and local authorities to achieve the carbon-reduction targets while maintaining
68 a comfortable and sustainable built environment. In practice, two questions remain:
69 What is the distribution of energy performance in the current building stock? How can
70 the decision-makers evaluate and rank the energy performance of buildings within the
71 stock to identify, prioritize, and target buildings for retrofitting? Energy benchmark is
72 a useful measure for understanding and enhancing building performance.

73 The aim of this research is to develop an object-oriented energy benchmarking
74 method which could be used for the evaluation of energy performance in the building
75 stock and for deciding on actions for improvement. Using this new method, local
76 authorities will be able to set up realistic and scientifically-sound energy benchmarks

77 to reduce carbon emissions from buildings and minimize their environmental impact.

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



79 *Figure 2 Framework of this paper*

80 **2. Literature review**

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

84 2.1 Building energy performance data

85 To set a reasonable building energy benchmark for a group of buildings sharing the
86 same function, a detailed analysis of building energy performance is needed. No
87 matter what methodology is used, adequate, valid, and reliable data are essential. The
88 data sources for building energy consumption are twofold: actual performance data
89 collected by surveying or monitoring and simulation data generated from computer
90 models. The computer simulation software can be used to calculate building energy
91 consumption (Boyano *et al.*, 2013; Gao *et al.*, 2014; Pomponi *et al.*, 2015; Xu *et al.*,
92 2013; Yao *et al.*, 2016a), but a performance gap exists between predicted or simulated
93 energy use and actual energy use (Burman *et al.*, 2014; Burman *et al.*, 2012; de Wilde,
94 2014; Menezes *et al.*, 2012; Salehi *et al.*, 2015; Wilde and Jones, 2014). Onsite
95 measured data is favored for the evaluation of the actual energy performance of
96 buildings.

97 First conducted in 1979, the Energy Information Administration (EIA) in the United
98 States continuously carries out national surveys and collects information including
99 energy-related building characteristics and energy usage data for commercial
100 buildings, the Commercial Buildings Energy Consumption Survey (CBECS) (EIA,
101 2015). A similar survey, the Survey of Commercial and Institutional Energy Use
102 (SCIEU), is carried out in Canada. This survey collects data on types and quantities of
103 energy (such as electricity and natural gas) consumed by business and institutional
104 buildings in Canada (Natural Resources Canada, 2016). The first SCIEU was
105 conducted in 2010 as a combination of two previous energy-use surveys: the

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

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

126 The Ministry of Housing and Urban-Rural Development (MOHURD) started a
127 scheme of data collection for the large-scale energy consumption of public buildings

128 in 2007 to build up a national data system. The system collects both basic building
129 information (including name, year of completion, function, and floor area) and energy
130 consumption information (CABR, 2011; Ding *et al.*, 2009). A total of 33 provinces
131 or municipalities have set up online public building energy consumption monitoring
132 platforms that provide yearly monitored building energy consumption reports to
133 MOHURD (MOHURD, 2015b).

134 *2.2 Building energy benchmarks and quotas*

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

142 Based on the American commercial and residential building energy consumption
143 survey data, *ASHRAE Standard 100* (ASHRAE, 2015) provides building energy
144 targets for 48 commercial and five residential building types, the energy target was set
145 as the lower quartile value of energy use by each building type. Moreover, ASHRAE's
146 Building Energy Quotient project applied the *Standard 100* methodology to determine
147 the building energy rating (ASHRAE, 2016). The other popular building energy
148 benchmark in the United States and Canada is the Energy Star rating, which allocates

149 a score from 1-100 to indicate building energy performance against their counterparts.

150 A building having achieved a score of 50 is ranked as an average level of energy

151 performance, while 75 or higher signifies top performance and is eligible for Energy

152 Star certification (ENERGY STAR, 2016a). In the United Kingdom, the publication of

153 *Energy Consumption Guide 19-Energy Use in Offices* sets the benchmark for typical

154 and good practice office buildings based on the median and lower quartile values of

155 the collected mid-1990s data (Best Practice Programme, 2000). CIBSE TM46 (CIBSE,

156 2008) provides an updated operational building energy benchmark for Display Energy

157 Certificates; these annual electricity and fossil-fuel benchmarks for whole buildings

158 are available for 29 building categories. The CIBSE Guide F provides a detailed

159 end-use benchmark for buildings with different building functions(CIBSE, 2012). In

160 the EU, due to the implementation of the European Directive on Energy Performance

161 of Buildings (EPBD) 2002/91/EC and the recast version 2010/31/EU, EU countries

162 are required to receive building energy performance certification(BPIE, 2014). EU

163 member states are required to ensure that energy performance certificates issued for 1)

164 buildings or building units that are constructed, sold or rented out to a new tenant; and

165 2) buildings where a total useful floor area over 250 m² is occupied by a public

166 authority and frequently visited by the public(EU, 2010). The national building

167 benchmarking is based on the situation of an individual country's own national energy

168 consumption. Germany updated the Energy Saving Ordinance (EnEV) to include

169 building energy certificates based on EPBD(BBSR, 2013). In Australia, the National

170 Australian Built Environment Rating System (NABERS) has been used for rating-

171 energy efficiency, water usage, waste management, and indoor environment quality of
172 buildings. The building types it covers include offices, shopping centers, hotels, data
173 centers, and homes. This star rating can have three different scopes: base building,
174 tenancy, and whole building. While three stars represent average performance, six
175 stars represent market-leading performance(NABERS, 2017). New Zealand generated
176 a New Zealand energy efficiency rating system for office buildings, called
177 NABERSNZ, which follows the same approach as NABERS but adapted for New
178 Zealand situations(NABERSNZ, 2017). In Singapore, the Building and Construction
179 Authority data are based on that collected from Building Energy Submission System
180 (BESS). It provides an annual building energy benchmarking report containing
181 national building energy benchmarks for seven commercial building categories for
182 four different functions. The four quartile values are used for benchmarking(BCA,
183 2016).

184 In China, during the design process for public buildings, designers can set up a
185 reference building which matches all the requirements indicated in the *Design*
186 *Standard for Energy Efficiency of Public Buildings*(MOHURD, 2015a). The
187 calculated building energy consumption of the reference building can be used as an
188 energy benchmark for the permitted maximum energy consumption. There is no fixed
189 standard benchmark building to be considered in the design process(MOHURD,
190 2015a), which could cause confusion for building designers aiming to meet energy
191 efficiency targets.

192 Studying building energy benchmarking has attracted many researchers in recent

193 decades. Based on 30 randomly selected supermarkets in Hong Kong, Chung *et al.*
194 (2006) provided a percentile table (from 10 to 90 percentiles) for benchmarking these
195 buildings using an empirical cumulative distribution of the normalized EUI. Zhao *et al.*
196 *al.* (2012) studied building energy quota determination methods for public buildings
197 in China and compared the pros and cons of different central tendency measures
198 including arithmetic mean, geometric mean, median, and mode. As a result, a new
199 statistical index, the 'comprehensive application of mode and percentage rank,' has
200 been claimed as the best index for energy consumption quotas. But there is no
201 convincing solid evidence of the premium quality of this new index compared to other
202 indices. Xin *et al.* (2012) established energy consumption quotas for four-star and
203 five-star luxury hotel buildings in China's Hainan province using statistical methods.
204 Here, the mean index of total energy consumption, the mean of EUIs, the quadratic
205 average of EUIs, the median of EUIs, the 60th percentile of EUIs, the 75th percentile of
206 EUIs, and the mode of EUIs are all considered. Consequently, a building EUI range
207 quota using the maximum and minimum values of all above-mentioned indices was
208 recommended for application during the initial quota implementation stage with the
209 mode of the EUIs to be the final quota after a further implementation of the quota
210 system. Ma *et al.* (2017) studied the building energy consumption of government
211 offices, general offices, and school and hospital buildings in northern China. The
212 selected energy performance benchmarks were the average, lower quartile value,
213 median value, and upper quartile value. In the first Chinese Building Energy
214 Consumption Standard(MOHURD, 2016), the energy benchmark system suggested

215 the mean and lower quartile values as the constraint and recommended indicators.

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

232 **3. Methodology**

233 In the 13th Five-Year-Plan period (from 2016 to 2020), the Chongqing municipality
234 aims to retrofit 3.5×10^6 m² of existing buildings (Chongqing Municipal Commission
235 of Urban-Rural Development, 2016). This study takes the Chongqing office building

236 sector as a case study for the development of a large-scale building energy
237 performance evaluation method and benchmarking model because Chongqing
238 municipality holds one of the central government's 33 energy monitoring platforms.
239 Chongqing's public-building energy-consumption monitoring platform (CPBECMP)
240 was established in 2012 by the Chongqing Municipal Commission of Urban-Rural
241 Development to collect real-time energy consumption data (electricity consumption
242 mainly)(Li *et al.*, 2016). The information covers categories of energy consumption
243 and building information including the name of the building, its location, number of
244 floors, function, gross floor area (GFA), air-conditioned floor area, heated floor area,
245 type of HVAC system, and the number of occupiers. Electricity is the main energy
246 source in Chinese public buildings(Cheng *et al.*, 2013), providing 93.4% of the energy
247 used in government office buildings and large-scale public buildings, followed by
248 5.3% natural gas and 1.1% artificial gas in the Hot Summer and Cold Winter (HSCW)
249 zone in which Chongqing is located (Liu *et al.*, 2013).

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

256 3.1. The building EUI calculation

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

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

268
269 Based on the fact that all studied buildings are located in the same city, the weather
270 conditions do not vary from one building to another in terms of calculating annual
271 EUIs for the same year. So no weather correction factor is required. The annual
272 building EUIs are calculated and analyzed in section 4.2 to show the existing levels of
273 energy consumption in office buildings.

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

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

275 Equation 2,

276
$$d = \ln D \quad (2)$$

277 *3.2. Shapiro–Wilk test*

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

282 The null hypothesis H_0 : the natural logarithm of EUI is normally distributed;

283 The alternative hypothesis H_a : the natural logarithm of EUI is not normally
284 distributed.

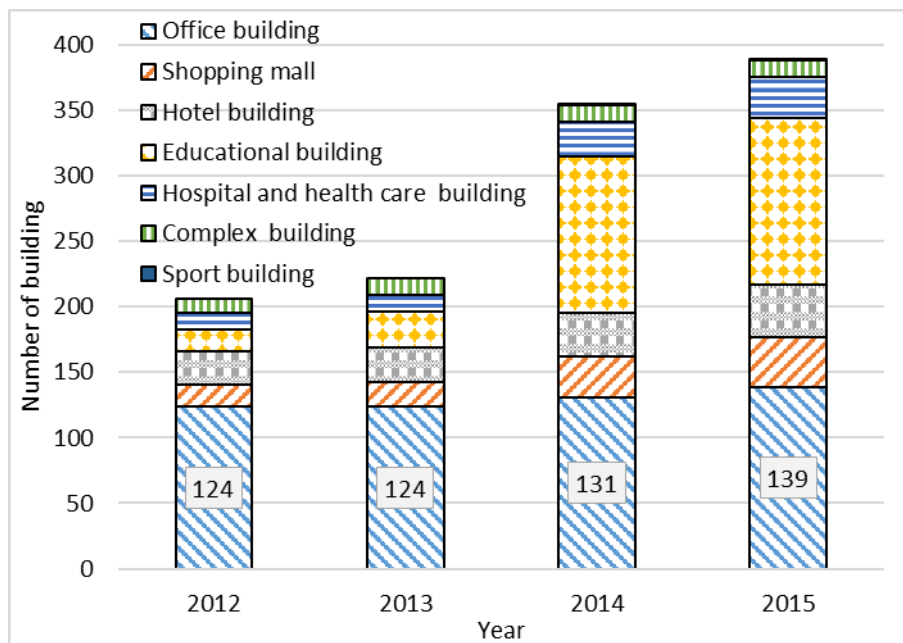
285 The most commonly used significance level ($\alpha=0.05$) is adopted in these tests, which
286 indicates that the level of confidence for the Shapiro–Wilk test results is 95%. If the
287 p-value, an index to assess statistical significance (Wasserstein and Lazar, 2016), is
288 greater than the significance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

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

294 **4. The Chongqing public building energy consumption monitoring platform**

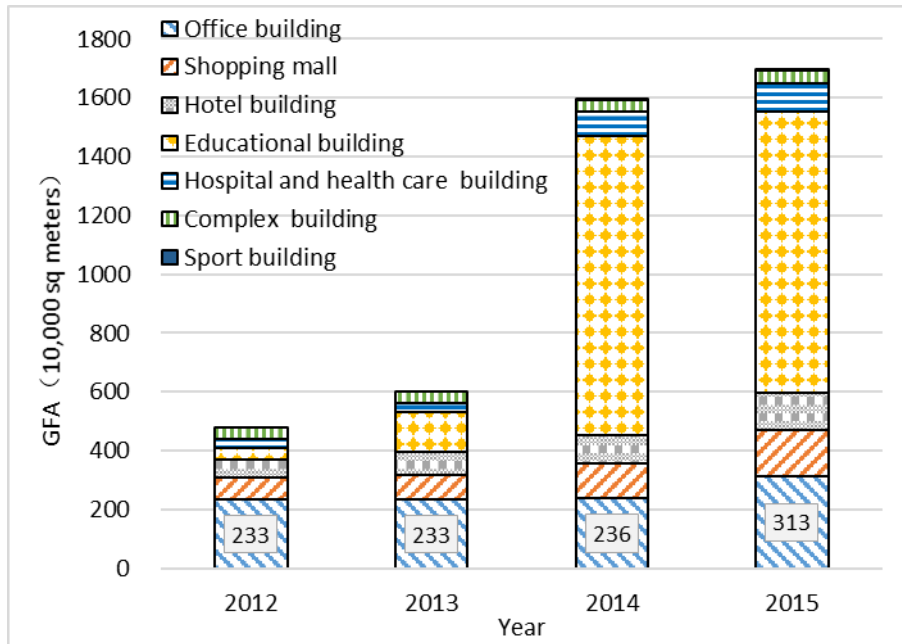
295 *4.1. General information on the platform*

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



304

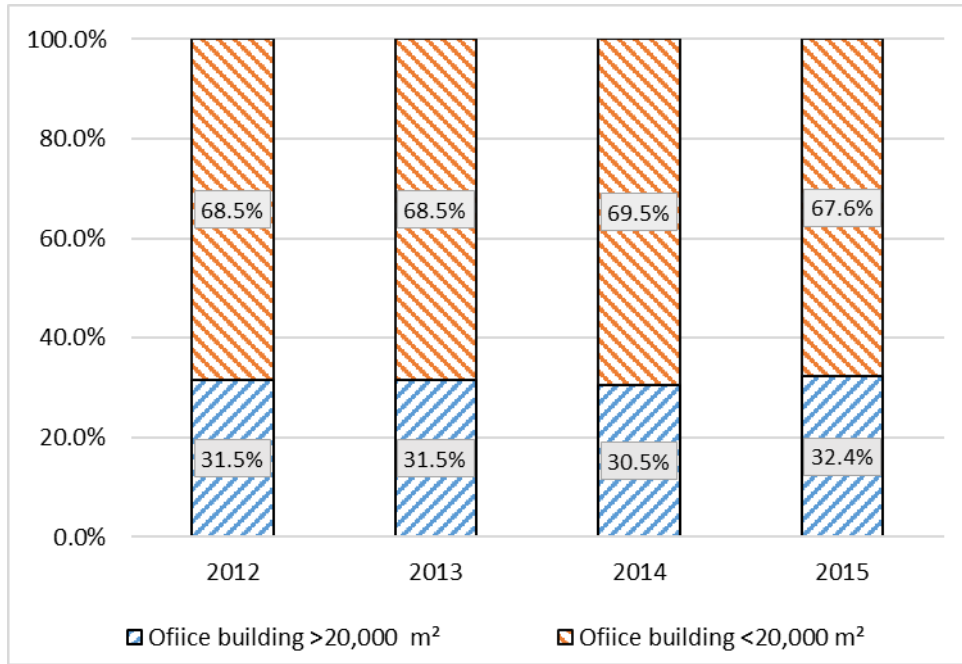
305 *Figure 3: The number of buildings in CPBECMP*



306

307 *Figure 4: The GFA of buildings in CPBECMP*

308 Figure 5 shows the floor area distribution of office buildings. We can see that office
 309 buildings with a GFA less than 20,000 m² account for more than 65% of those in
 310 CPBECMP, while the percentage for the office buildings larger than 20,000m²
 311 (large-scale office buildings) is about 30% of the total number.

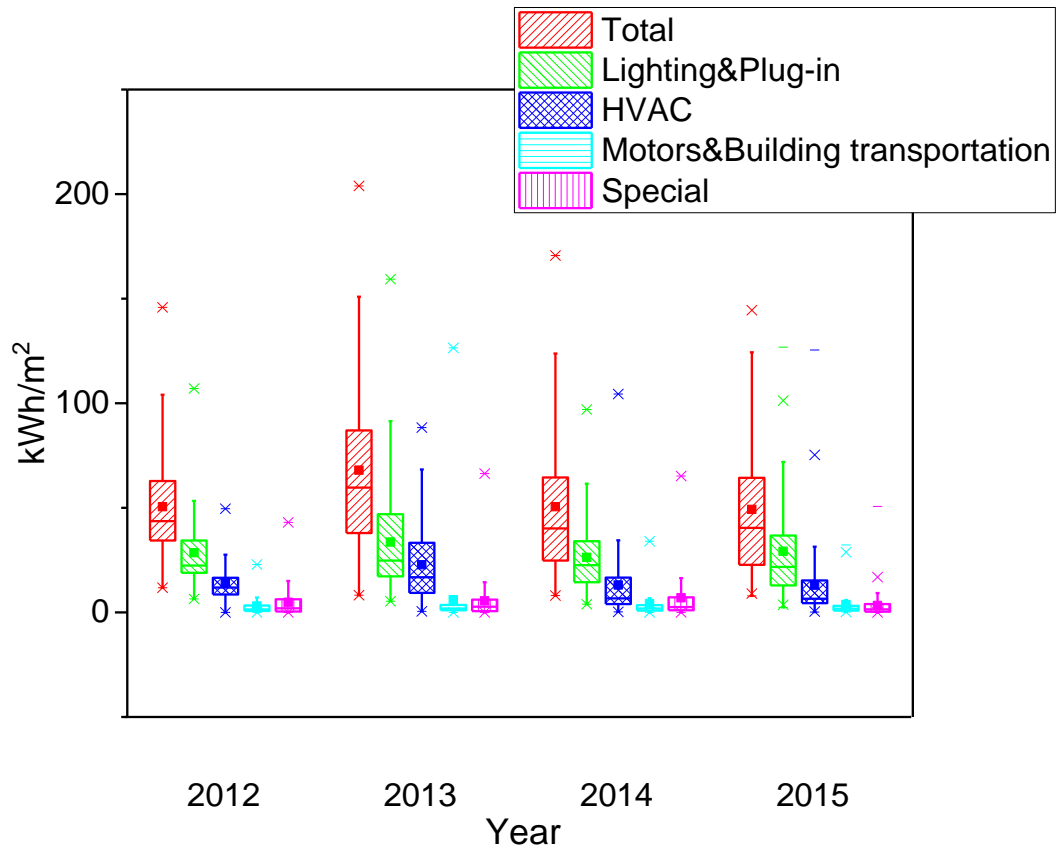


312

313 *Figure 5: The GFA distribution of office buildings in CPBECMP*

314 *4.2. The building energy consumption data*

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



324

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

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

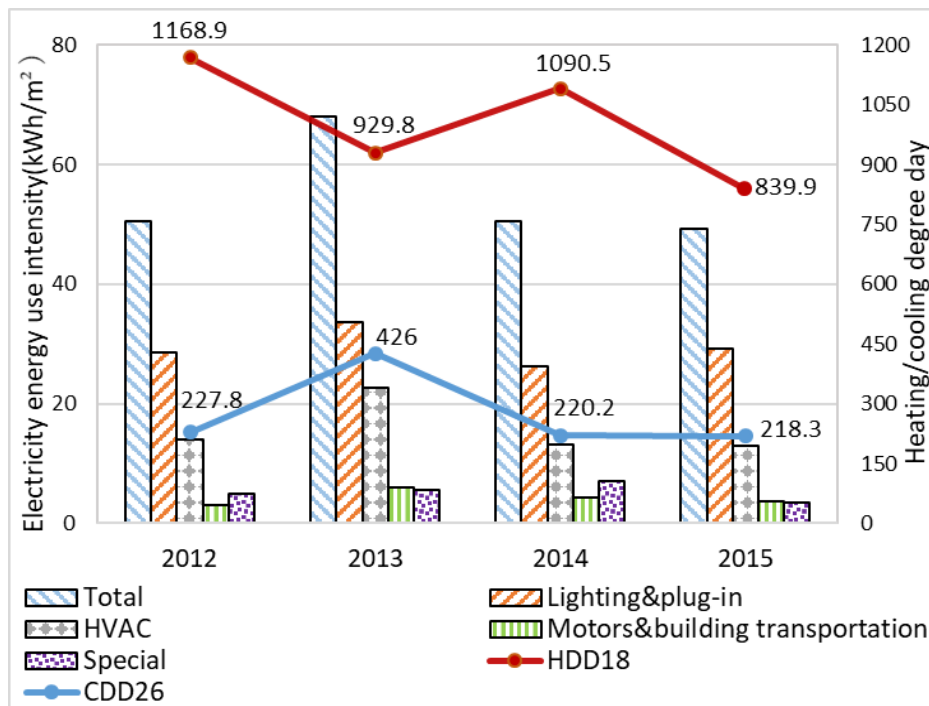
Year	Energy consumption sector	EUI (kWh/m ²)			The average percentage of total energy consumption (%)
		Lower quartile value	Median	Mean	
2012	Total	34.38	43.67	50.47	100.00%
	Lighting & plug-in	18.89	22.43	28.52	56.50%
	HVAC	8.54	11.89	14.08	27.90%

	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%

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

332 Based on the measured climate parameters from the China Meteorological Data
333 Service Center from 2012 to 2015(CMDC, 2017), the heating degree day (HDD) and

334 cooling degree day (CDD) of Chongqing are calculated based on 18° C and 26° C
 335 respectively. The average EUIs of every sub-system, along with the HDD and CDD of
 336 that year, are shown in Figure 7. From the figure, we can see that, on one hand, years
 337 2012, 2014 and 2015 have quite comparable energy consumption in total EUI as well
 338 as for every sub-system with similar CDDs regardless of the gap between their HDDs.
 339 This indicates that office building energy consumption is not sensitive to HDD
 340 variation. On the other hand, 2013 had a relatively higher total EUI. Apart from
 341 higher lighting and plug-in EUI, HVAC EUI is higher due to the higher CDD in 2013.
 342 The higher EUI of the lighting and plug-in contributes more internal heat gains which
 343 further increase the cooling load.



344
 345 *Figure 7: Office building average EUIs and heating and cooling degree days in*
 346 *different years*

347 As indicated in Table 1, the median electricity EUIs of office buildings in Chongqing

348 range between 40.17 and 59.66kWh/m². According to Liu *et al.* (2013), electricity
 349 usage in office buildings accounts for 93.4% of total energy consumption. Adopting
 350 this percentage, the building gross energy consumption will be its electricity
 351 consumption divided by 0.934, as shown in Equation 3. Thus, the median gross EUI
 352 for office buildings in Chongqing are between 43.01 and 63.88kWh/m².

353
$$GD=D/0.934 \quad (3)$$

354 Compared with the EUI benchmarks in other countries and regions of the world
 355 (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 \geq 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.

356 *Table 2*), the EUI in Chongqing offices is much lower. The only exception is private
357 offices without central air-conditioning in Hong Kong, which have a slightly lower
358 EUI. But EMSD Hong Kong states clearly that the index given is not a representative
359 value and can only be used for reference. A majority of the benchmark data shown are
360 given by national median values, without taking into account climate variations. To
361 solve this problem, ASHRAE used a simulated representative building to extrapolate
362 the median EUI to different climate zones across the whole US by applying climate
363 zone ratios. The lower quartile value of energy use was derived and used as the
364 building energy consumption target (ASHRAE, 2015). According to the ASHRAE
365 climate zone classification, Chongqing is located in climate zone 3A, which is defined
366 as ‘warm humid’ (ASHRAE, 2013). The building energy consumption targets for US
367 office buildings in climate zone 3A are 163.93kWh/m² (52kBtu/ft²) for government
368 offices, 132.40kWh/m² (42kBtu/ft²) for professional offices, and 151.32kWh/m²

369 (48kBtu/ft²) for mixed-use offices (ASHRAE, 2015). This reveals that the median
 370 gross EUI in Chongqing office buildings is even lower than the American energy
 371 consumption target for office buildings. This is mainly because China has a wider
 372 temperature range of indoor thermal comfort according to the Chinese building
 373 thermal design standard compared to the developed countries (Li *et al.*, 2014; Zhou *et*
 374 *al.*, 2017). A nationwide field study from Li *et al.* (2014) revealed that the indoor
 375 temperature for public and residential buildings in south China where Chongqing
 376 located varies between 5° C to 35° 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 \geq 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.

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

378 In the Chinese recommended *Standard for Energy Consumption of Buildings GB/T*

379 *51161-2016* (MOHURD, 2016), the office-building energy-consumption benchmark

380 has been established for the Hot Summer and Cold Winter (HSCW) zone where

381 Chongqing is located. The benchmark includes two indices: a *constraint* indicator and

382 a *recommended* indicator. For building energy performance, their annual EUI should

383 not exceed the constraint indicator but attempt to achieve the recommended indicator.

384 The building type of office buildings has been further divided into the sub-stock Type

385 A and Type B based on the possibility of using natural ventilation to maintain a

386 comfortable indoor thermal environment. Buildings with no access to natural

387 ventilation and totally depending on mechanical ventilation as well as HVAC systems

388 for indoor temperature control are regarded as Type B, otherwise Type A.

389 The requirements in this standard for office buildings are listed in

Standard for Energy Consumption of Buildings				CPBECMP	
GB/T 51161-2016				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

390 *Table 3*; the constraint indicators as the mean values for Type A and B government
391 office buildings are 70 and 90kWh/m² and 85 and 110kWh/m² for general office
392 buildings, respectively. The mean gross EUI of office buildings in Chongqing is from
393 52.72 to 72.76kWh/m². We conclude that the overall energy performance of office
394 buildings in Chongqing satisfies the Standard GB/T 51161-2016. The gross EUI of
395 72.76 kWh/m² in 2013 is higher than that required in the Standard, but the CDD of
396 426 in 2013 was much higher than the reference CDD of 241(Chongqing Minicipal
397 Commission of Urnam-Rural Development, 2010).

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

function	type	kWh/m ²	kWh/m ²	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

398 *Table 3: The office-building energy-consumption benchmark indicators from GB/T*
399 *51161-2016 and the CPBECMP office building performance*

400 **5. Building energy performance distribution and rating**

401 *5.1. Normality test results*

402 The Shapiro–Wilk test was applied to the natural logarithm of the total EUI of office
403 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

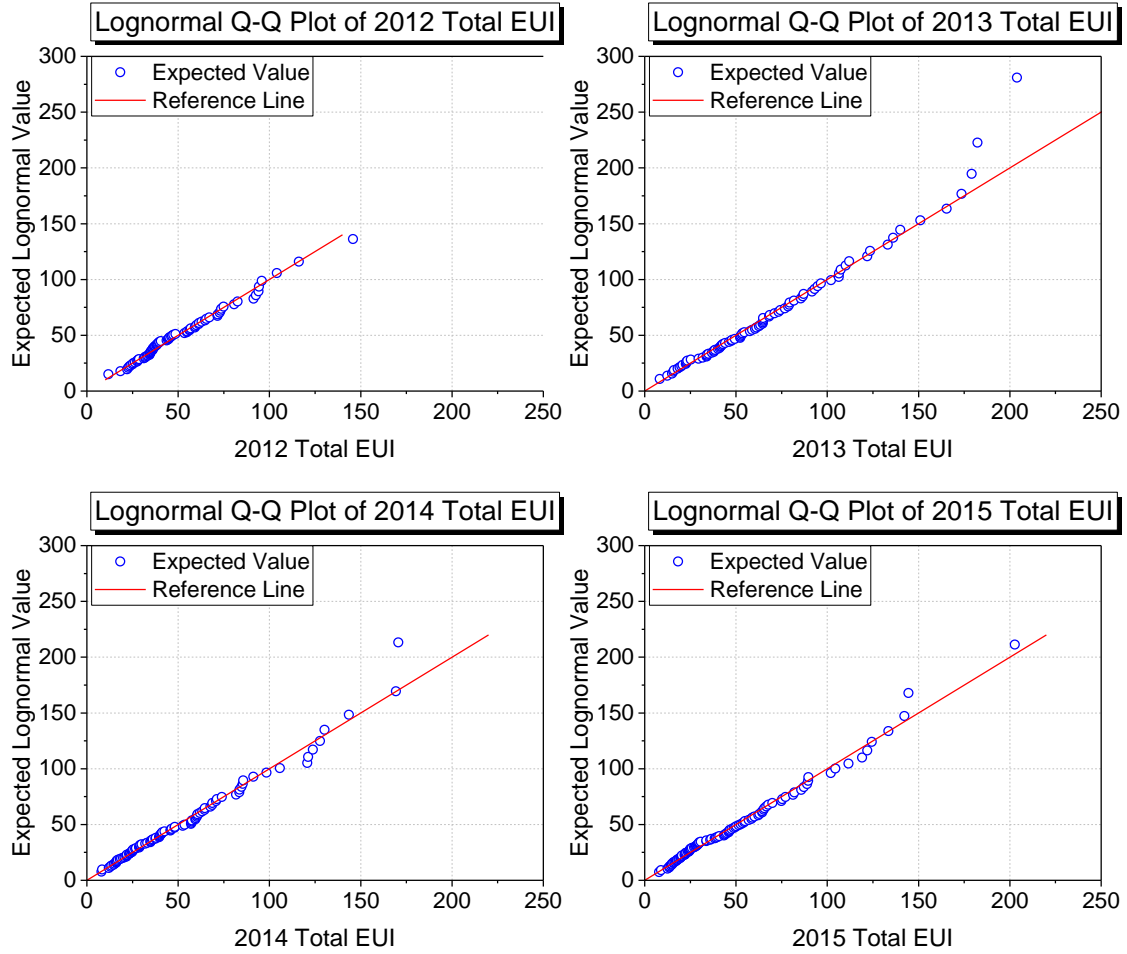
404 *Table 4. The annual total EUIs of Chongqing office buildings all passed the test*
405 *(p>0.05), which indicates that the normal distribution hypothesis can be accepted.*

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

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

407 To further assess if the total EUI follows the lognormal distribution, the
408 quantile-quantile (q-q) graphical plot technique is used and plotted in Figure 8. A
409 45-degree reference line is also plotted as $y=x$. The X-Axis represents the observed
410 value of total EUI while the Y-axis represents the expected lognormal distribution
411 values at the same quantiles as x. From the findings, we can see that all the data points
412 fall approximately along the reference line for year 2012, 2014 and 2015, which
413 confirms that the office building EUI has the same distribution as the lognormal
414 distribution. For the year 2013, even though only one data point which is a bit far
415 away from the reference line, the vast majority of the data points are very close to
416 reference line. Therefore, 2013 total EUI data is lognormal distributed as well.



417

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

419 As the natural logarithm of the building EUIs has passed the normality test, the

420 building EUIs are proved to follow the lognormal distribution. The probability density

421 function and cumulative distribution function for lognormal distribution are shown in

422 Equations 4 and 5.

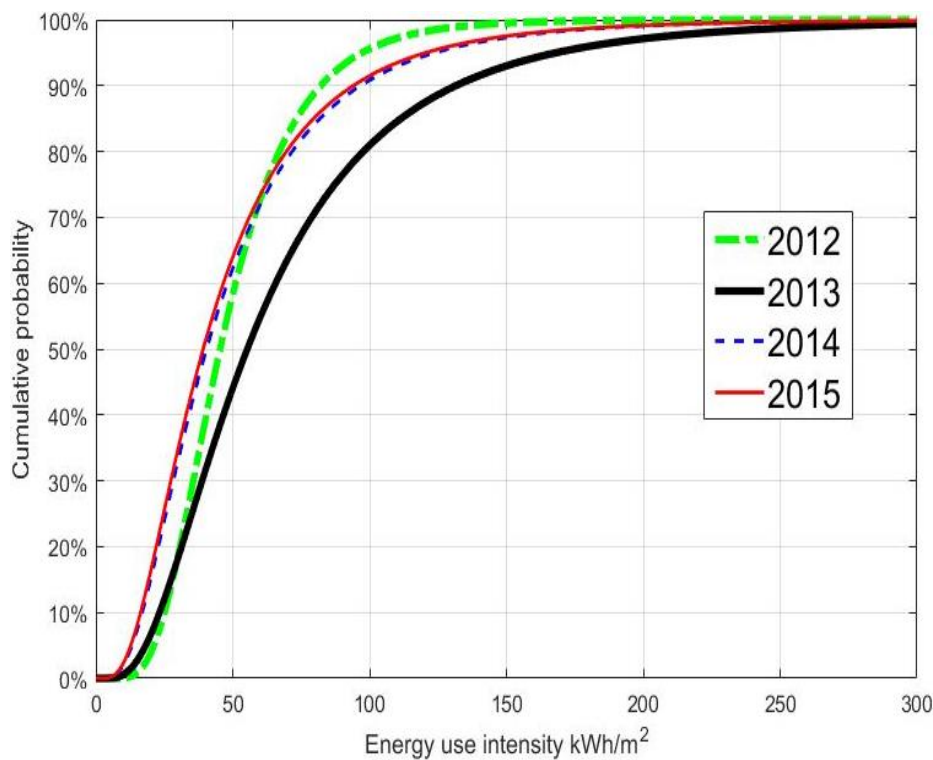
$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right], \quad x > 0 \quad (4)$$

423

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

424

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



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

435 5.2. Building energy-performance rating

436 The lower quartile value, median, and mean for the whole building as well as

437 sub-systems is shown in *Table 1* and can act as benchmarking indices for the
438 evaluation of building energy performance and the performance of individual
439 sub-systems in office buildings in Chongqing. Moreover, based on the cumulative
440 probability function of the annual EUI for office buildings, the building
441 energy-performance rating uses a 1-100 scale established by the cumulative probability
442 level. *Table 5* shows the rating scale for office buildings for different years. An energy
443 consumption rating of 90 indicates that, from an energy consumption standpoint, the
444 building performs better than 90% of buildings of the same type, while a rating of 10
445 indicates the building performs better than only 10% of office buildings in the stock.
446 The energy rating can be used as an indicator to diagnose the energy consumption of
447 an individual office building relative to the whole stock. Based on the average carbon
448 dioxide emission factor of 0.5257kgCO₂/kWh for China's central region power grid
449 where the electricity supply for whole Chongqing city came from the reference
450 (NCSC, 2014), the carbon dioxide emission intensities corresponding to different
451 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

452 *Table 5: The annual EUI rating of office buildings and the corresponding CO₂*
453 *emissions*

454 **6. The object-oriented EUI quota determination model**

455 6.1 The model

456 According to the State Council of the People's Republic of China, for buildings
457 occupied by public authorities, EUI in 2020 should be 10% less than in 2015(SCC,
458 2016). As noted by Yang *et al.* (2016), *applying a uniform EUI reduction rate was not*
459 *equitable to all the buildings, as the high-performance buildings were already*
460 *consuming less energy. It was therefore more difficult for such energy efficient*
461 *buildings to meet the targets, as they had little potential for further energy saving. A*
462 *reasonable energy reduction target should be set at the stock level as a total reduction*
463 *target.*

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

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

467

468 If considering setting a mandatory objective maximum EUI (v) for all office buildings,

469 those with higher EUIs will be required to reduce to, or below, the EUI target.
 470 Assuming all buildings with a lower total EUI are not changing their energy
 471 consumption while all those with a higher total EUI are reducing to the target EUI
 472 value, the updated mean EUI value of the building stock can then be calculated from
 473 Equation 7.

$$\begin{aligned}
 UEXPF(x) &= \int_0^v xf(x)dx + \int_v^{+\infty} vf(x)dx \\
 &= \exp\left(\mu + \frac{\sigma^2}{2}\right) \Phi\left(\frac{\ln v - \mu - \sigma^2}{\sigma}\right) + v - v\Phi\left(\frac{\ln v - \mu}{\sigma}\right) \quad (7)
 \end{aligned}$$

474
 475 With the aforementioned calculation formula for the mean EUI value of the base year
 476 and the updated mean EUI value after the mandatory maximum target EUI being
 477 applied, the stock total energy consumption can be calculated by multiplying the stock
 478 mean EUI by the stock GFA. The energy-saving percentage by applying the target
 479 EUI is measured by the energy consumption reduction divided by the stock energy
 480 consumption for the base year, as shown in Equation 8. The stock GFA variation can
 481 be modified by using the planned stock GFA increase rate r , with $r = PSA / SA$. This
 482 planned stock GFA increase rate should come from the city-level office for stock
 483 development planning.

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

484

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

485

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

495 A Matlab program had been coded for the object-oriented EUI quota determination
 496 model based on Equation 8. To work out the office building EUI quota under a stock
 497 energy-saving percentage goal, the required input information includes the mean
 498 value, the standard deviation value of the natural logarithm of office building EUI,
 499 and the planned increase in stock GFA. The mean and standard deviation values can
 500 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

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

512 6.2 Example of applying the model

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

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

Energy saving percentage goal	The annual EUI quota (kWh/m ²) 521
5%	116.9
10%	87.1
15%	71.0
20%	60.0
25%	51.8

522 As the building energy consumption quota being determined by the object-oriented
 523 model, the energy performance of office buildings can be evaluated based on the
 524 quota. Assuming the energy-saving goal for year 2017 is 10% reduction compared to
 525 year 2015, the office EUI quota is 87.1 kWh/m². If an office building operating total
 526 EUI is over 87.1 kWh/m² in 2015, retrofitting actions should be taken to improve
 527 building energy efficiency.

528 Office building retrofit measures found in the literature(Dong *et al.*, 2014; Guo *et al.*,
 529 2008; Liu *et al.*, 2009; Yao *et al.*, 2016b) including;

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

535 unit, fan efficiency);

536 • Improving building control systems (HVAC system control optimization, external
537 shading control, maximum daylight usage control, etc.);

538 • Applying advanced energy-saving technologies (hybrid ventilation, night
539 ventilation, heat recovery);

540 • Improving the building management services and raising users' energy saving
541 conscious.

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

550 **7. Conclusions**

551 This paper presents the actual operational energy consumption data of office buildings
552 collected from the Chongqing public-building energy-consumption monitoring
553 platform (CPBECMP) between 2012 and 2015. An understanding of the energy
554 consumption profiles in office buildings in Chongqing was obtained. Statistical

555 analysis using Shapiro–Wilk normality tests was applied to identify the EUI
556 distributions, which is essential to the development of the office energy-performance
557 benchmark rating and object-oriented EUI quota determination model. In this study,
558 commonly-used, statistically-based indices for building energy consumption
559 benchmarking, including lower quartile value, median, and mean, and percentile
560 tables (from 10 to 90 percentiles) of building EUI have been presented for the office
561 building stock in Chongqing. The object-oriented EUI quota determination model has
562 also been developed. The building benchmark and object-oriented quota model are
563 practical tools for local authorities to evaluate building energy consumption and make
564 decisions on building energy retrofit. The method of establishing energy benchmarks
565 can be applied to any other building stock once the monitored energy consumption
566 data are available.

567 The key conclusions drawn from our study are as follows:

- 568 • The median gross EUI for office building in Chongqing are from 43.01 to
569 63.88kWh/m², which are much lower than that for developed countries. This is
570 mainly because China has a wider temperature range of indoor thermal
571 comfort according to the Chinese building thermal design standard compared
572 to the developed countries. This situation affects the electricity used for
573 heating and cooling;
- 574 • The annual EUIs of office buildings follow lognormal distribution; therefore,
575 the energy-performance rating can be generated based on the cumulative

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

578 • The object-oriented EUI quota determination model can perform projected
579 energy-saving target analysis that will be useful to the local authorities,
580 including utility service providers, to determine which building need to go
581 through energy conservation retrofit process to meet the stock
582 carbon-reduction target. Government subsidies, as well as policies involving
583 economic and administrative penalties, should be carefully considered and
584 operated to activate the object-oriented EUI quota in building management;

585 • The application of the annual EUI rating and object-oriented EUI quota can
586 contribute greatly to carbon reduction and sustainable built-environment
587 development by proving scientifically sound benchmarks to evaluate
588 Chongqing office-building operational performance.

589 • This research focused on the office buildings in Chongqing, but the statistical
590 analysis and object-oriented EUI quota determination model construction
591 process can be easily adapted to different building stocks in other cities based
592 on the collected energy consumption data.

593 • We recommend the Energy Certificate Display mechanism for office buildings
594 in China as well as open access to the database of public buildings.

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

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

602

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608

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