Lai, J. and Lu, M. (2019), Analysis and benchmarking of carbon emissions of commercial buildings, Energy and Buildings, Vol. 199, pp. 445-454. https://doi.org/10.1016/j.enbuild.2019.07.012

Analysis and benchmarking of carbon emissions of commercial buildings

Abstract: Carbon emission, a holistic environmental performance indicator that reflects the level to which resources are used for buildings, has not been studied as widely as energy use. Commercial buildings, especially the existing ones, utilize substantial operating resources, but empirical carbon studies on such buildings, as compared with the counterparts on new buildings, are limited. To contribute knowledge about factors that affect the carbon emission level of existing commercial buildings and establish meticulous benchmarks for gauging and comparing their environmental performance, a study was conducted on 32 buildings in Hong Kong. Through face-to-face meetings with the buildings' representatives, reliable monthly data over a period of six years were collected. Analyzing the data revealed that carbon emission level is more significantly correlated with total floor area than age or common floor area of the buildings. Benchmarking charts, constructed based on the buildings' normalized carbon emission levels, enable comparisons to be made between the environmental performances of peer buildings in different ranges of age and scale. The finding that small buildings generally produced more carbon emissions than the large ones is important information for policy-makers and facility managers in prioritizing environmental conversation measures for implementation in existing buildings.

Keywords: Benchmark, building, carbon, energy, facility management, policy

1. Introduction

Over the past few decades, global warming and climate change have attracted worldwide attention. Excessive greenhouse gas (GHG) emissions (also known as carbon emissions) due to human activities are proved to be the main causes for global warming and many other environmental issues (IPCC, 2007). According to the Intergovernmental Panel on Climate Change (IPCC), the building sector accounts for more than one third of global total energy use and 19% of energy-related carbon emission (IPCC, 2014). Enhancing building energy efficiency and curbing building carbon emissions, therefore, have become a priority among the environmental conservation efforts of many governments and organizations.

In uplifting building energy efficiency, there are regulatory and voluntary approaches (Lee and Yik, 2004). In most places, especially the developed countries such as the United Kingdom (UK) and Germany in Europe, the United States (US) and Canada in America, Japan and Singapore in Asia, and Australia, regulations on building energy efficiency are already in place. Voluntary schemes that promote building environmental performance have also been developed in various countries (e.g. Building Research Establishment Environmental Assessment Method (BREEAM) in the UK and the Leadership in Energy and Environmental Design (LEED) in the US) and cities (e.g. BEAM Plus in Hong Kong). The Energy Efficiency Registration Scheme for Buildings, for instance, is a voluntary scheme dedicated for encouraging buildings in Hong Kong to outperform the statutory requirements of the Buildings Energy Efficiency Ordinance (EMSD, 2018a; 2018b).

Intended for governing carbon emission, mandatory schemes have been introduced across the globe. As reviewed earlier (Lai, 2014), examples of such schemes are: the UK GHG Reporting System, the US GHG Reporting Program, the GHG Emission Reporting Scheme in Canada, the National Greenhouse and Energy Reporting System (Australia), and the Mandatory GHG Accounting and Reporting System in Japan. In parallel, various standards have been developed to facilitate carbon reduction, including those providing guidelines on life cycle energy management (ISO 14040, 2006), sustainable building construction (ISO 21931, 2010) and carbon reduction for existing buildings (ISO 16745, 2017). Yet reporting of carbon emissions, even in metropolises (e.g. Hong Kong) where the energy use and hence carbon emission is significant, remains a voluntary action of individual building owners.

Compared with energy use, carbon emission can better reflect the holistic environmental performance of buildings. According to the Greenhouse Gas Protocol (WBCSD & WBI, 2004), carbon emissions to be quantified should include direct emissions (e.g. due to on-site fuel combustion) and indirect emissions (e.g. due to consumption of electricity purchased from power company). To reveal the environmental performance of a building, in any case, a detailed carbon audit, through a rigorous process of data collection and analysis, is needed.

For buildings, the operation and maintenance stage accounts for over 80% of total carbon emission throughout their lifecycle, whereas the remaining 10%~20% are due to the other stages (e.g. material production, construction, demolition). The proportion of carbon emission due to building construction and demolition, around 0%~2%, is comparatively less (Ramesh *et al.*, 2010; Martínez-Rocamora *et al.*, 2017; Wu *et al.*, 2012). In fact, commercial buildings have been well recognized as the major type of buildings causing carbon emissions (U.S. EIA, 2018a; EMSD, 2018c). In Hong Kong, for example, commercial buildings consume 43% of the total energy, which is about twice of that of the residential building sector (EMSD, 2018c). But since carbon audits on buildings are often confronted with the difficulties of getting voluminous and reliable data (Lai *et al*., 2012), in-depth empirical studies that probe into the real carbon emissions of buildings and analyze factors affecting the emissions have been limited. Benchmarking studies, which enable comparative evaluation of the carbon emissions between commercial buildings in the same peer group, are even rare. Aimed at filling these research gaps, a study, as reported in the following, was conducted on 32 commercial buildings in Hong Kong - an Asian metropolis with a recent carbon intensity of 5.7 tonnes per capita.

The ensuing section presents the literature review conducted for the study, including the past studies on building energy - a main contributor to carbon emission. This part of the review covers the approaches and models used in those past studies and, particularly, how they developed energy benchmarks. The remainder of the review comprises two areas: (i) energy and carbon benchmarking tools made available by governments and environmental organizations; and (ii) past studies that investigated the carbon emissions of existing commercial buildings. Then, the data acquisition method for the current study and how the data were analyzed are described. The findings, including carbon emission levels of the buildings studied and their correlations with the buildings' parameters, are analyzed and discussed. After showing the carbon emission benchmarking results of the buildings, the conclusions drawn from the study are given.

2. Literature Review

2.1 Benchmarking tools

There are various energy benchmarking tools around the world. Among the well-known ones is Energy Star initiated by the United States Environmental Protection Agency. Developed based on the method of Sharp (1996), Energy Star has been adopted in Canada and the US for building energy benchmarking (Chung *et al.*, 2006; Kinney & Piette, 2002; Energy Star, 2018; Natural Resources Canada, 2018). In Australia, the online benchmarking tool "Calculating Cool" is recommended by the government for building managers to benchmark the energy efficiency of heating ventilation and air-conditioning (HVAC) systems (Calculating Cool, 2018). In Singapore, there was a tool called e-Energy Benchmarking System (Chung *et al*., 2006); the tool available now is the Building Energy Submission System (BESS) operated by the Building and Construction Authority (BCA) of Singapore (BCA, 2018). Based on the data collected from BESS, BCA published the Building Benchmarking Report annually (BCA, 2017). In the UK, the Chartered Institution of Building Services Engineers (CIBSE) released energy benchmarking guidelines (e.g. CIBSE TM 46) for the building sector and industries (CIBSE, 2007; 2016). Such CIBSE Guidelines have been adopted by national organizations and agencies, such as the National Energy Foundation, to benchmark building energy efficiency (National Energy Foundation, 2018).

In some cases, an integrated system allows benchmarking both energy consumption and carbon emission. One such example is the US Energy Star system. Usually adopted for energy benchmarking purposes, it is an online system that incorporates GHG emission benchmarking (Department of Energy and Environment of D.C., 2018; New York City Government, 2018).

Besides governments, some organizations committed to environmental protection also provide online tools for carbon benchmarking. For instance, Carbon Footprint Ltd, based in the UK, provides an online tool to support customers to reduce carbon emissions for complying with related regulations and ISO/British standards (Carbon Footprint, 2018a). The tool is free for the public to calculate building carbon emission or total carbon footprint, e.g. including the carbon emission due to transportation (Carbon Footprint, 2018b). It also contains carbon emission reports from buildings of various types (e.g. hospitals, retails), which enable users to benchmark their own buildings with the reported buildings in addition to uploading voluntarily the emission information of their own buildings (Carbon Footprint, 2018c).

For emission sources such as computers and printers in buildings, which belong to the Information and Communication Technology (ICT) sector, there are bespoke benchmarking tools. For instance, ICT Footprint, ECO_2 Clouds, Sustainability Assessment Framework (SASF), etc. are projects funded by the European Commission (EU) that aim at carbon reduction, and most of them offer free-accessed online assessment tools for carbon emission (ICT Footprint, 2018a; 2018b). In particular, the ICT Footprint assessment reports show detailed carbon emission benchmarking charts where the assessed buildings can be benchmarked with all users, users in the same sector, and so on (ICT Footprint, 2018b). Moreover, the Green Grid is a non-profit association that has developed multiple metrics and fact sheets for carbon emission and benchmarking in the ICT sector (The Green Grid, 2018a). The metrics and fact sheets, which are open to the public, have been widely employed by governments and organizations for carbon emission benchmarking. For example, the "Carbon Usage Effectiveness (CUE)" metric was adopted by Singapore's National Environment Agency for benchmarking the carbon emissions of 23 data centers (The Green Grid, 2018b; NEA, 2012).

In Hong Kong, the Electrical and Mechanical Services Department (EMSD) provides a series of online benchmarking tools for various building types such as residential, office, hospital, factory, etc. (EMSD, 2018d; 2018e), yet such tools are for benchmarking energy consumption rather than carbon emission. Besides, the Environment Bureau of Hong Kong, in collaboration with the City University of Hong Kong, has introduced an online carbon audit toolkit for individuals and organizations (Climate Ready, 2018). In accordance with the Environmental, Social and Governance Reporting Guide (called as ESG Guide), carbon emissions of listed companies in Hong Kong can be accessed at the website of Carbon Footprint Repository, which has been made available by the Environmental Protection Department since 2012 (Carbon Footprint Repository, 2018a; 2018b).

2.2 Benchmarking methods

Studies on building energy have been carried out in many parts of the world. For instance, Martin (2013) presented a case study of a commercial building in Cape Town, South Africa. Shahrestani *et al*. (2013) researched on office buildings in England and Wales. Borgstein & Lamberts (2014) established energy benchmarks with data collected from 1890 bank branches across Brazil. In China, Jiang *et al.* (2014) explored a new energy performance based benchmarking method for addressing energy saving measures for buildings. Based on the data collected from 1072 office buildings, Park *et al.* (2016) established a new energy benchmark for office buildings in South Korea. Recently, the study of Khoshbakht *et al.* (2018) established energy benchmark values for higher education campuses in Australia.

In the previous benchmarking studies, various approaches or methods were used. The study of Chung *et al*. (2006), for example, illustrated a benchmarking approach with the use of multiple regression analysis. Using also regression analyses, the studies of Priyadarsini *et al*. (2009) and Lai (2016a) were on hotel buildings in Singapore and Hong Kong, respectively. By means of multiple linear regression, Summerfield *et al.* (2010) developed two models for benchmarking energy efficiency in the UK residential sector and Wang (2012) established two models for predicting energy consumption of hotel buildings in Taiwan. Besides, Chung (2012) developed a fuzzy linear regression method to deal with fuzzy data such as occupant behavior when normalizing the energy use intensities of commercial buildings. Gao & Malkawi (2014) introduced a new methodology for building energy benchmarking based on intelligent clustering algorithm (machine learning). Other methods such as support vector regression, decision tree and Bayesian network have also been adopted to benchmark the energy use of buildings (Li *et al.*, 2014).

Benchmarking models for building energy efficiency are mainly developed based on energy-efficiency indicators such as energy use intensity (Chung *et al.*, 2006) or referred to as energy utilization index (EMSD, 2018d), with both of them abbreviated as EUI (i.e. total energy consumption per unit floor area). Through correlation analysis or Principle Component Analysis (PCA), dominant factors (e.g. climatic condition, building area, etc.) can be identified for normalizing building energy consumptions (Chung *et al.*, 2006; Chung, 2012; Lai, 2016a). EUIs computed on this basis, in turn, can be taken for making fair comparisons between the energy consumptions of buildings with, for example, different scales.

By calculating EUI percentiles (10^{th} percentile, 20^{th} percentile, etc.) of the buildings being studied, benchmark tables can be established (Chung *et al.*, 2006). Whereas energy benchmarking can be made by referring to the maximum, minimum and average values of EUI (Chung & Hui, 2009; Khoshbakht *et al.*, 2018) or merely the average EUI value (Li *et al.*, 2018), Lai (2016a) constructed EUI percentile charts for benchmarking purposes.

2.3 Studies on carbon emissions of existing buildings

Through the literature search process for the current study, a number of studies that investigated the amounts of carbon emissions of existing buildings were identified. Such studies, in the recent decade, were conducted in different continents: those in Asia (Bağcı, 2009; Jiang & Tovey, 2010; Wu *et al*., 2010; Lai, 2015; Huang *et al*., 2015; Garg *et al*., 2017; Jing *et al.*, 2017; Ye *et al.*, 2018) are the majority group; the others include those in Europe (Wallhagen *et al*., 2011; Acha *et al.*, 2018) and Australia (Braslavsky *et al.*, 2015). Table 1 shows, in chronological order, a summary of the studies, covering their location, number of buildings sampled, building type, EUI and carbon emission level. In these studies, the carbon emissions were typically quantified by multiplying the amounts of resources used (e.g. energy) by the corresponding carbon emission factors. While the units of the carbon emissions quantified in these studies were not identical, they were converted into a common unit (kg/m^2/year) for easy comparison, as shown in the last column of Table 1.

Table 1. Studies on carbon emissions of existing buildings

Study	Location	Sample size	Building type	EUI	Carbon emission (unit used in the study)	Carbon emission (kg/m^2/year)
Bağcı, 2009	Hong Kong	1	Office	9,902 MWh/year (330 kWh/m^2/year)	About 8,216 tons/year	273.8 kg/m^2/year
Jiang & Tovey, 2010	Beijing, China	5	Commercial	173 kWh/m^2/year	178 kg/m^2/year	178 kg/m^2/year
Jiang & Tovey, 2010	Shanghai, China	4	Commercial	132 kWh/m^2/year	119 kg/m^2/year	119 kg/m^2/year
Wu *et al.*, 2010	Singapore	29	Hotel	427 kWh/m^2/year	221.8 kg/m^2/year	221.8 kg/m^2/year
Wallhagen *et al.*, 2011	Sweden	1	Office	100 kWh/m^2/year	2.7 kg/m^2/year	2.7 kg/m^2/year
Lai, 2015	Hong Kong	3	Hotel	N.A.	0.014~0.024 t/m^2/month	168~288 kg/m^2/year
Braslavsky *et al.*, 2015	Sydney, Australia	1	Shopping center	2,937 MWh/m^2/year	2,899 tons/building/year	52.7 kg/m^2/year
Huang *et al*., 2015	Taiwan	58	Hotel	277 kWh/m^2/year	132 kg/m^2/year	132 kg/m^2/year
Garg *et al.*, 2017	Gujarat, India	197	Commercial	98~181 kWh/m^2/year	0.98 kg CO_2/kWh	96~177 kg/m^2/year
Jing *et al.*, 2017	Hong Kong	30	Office	236 kWh/m^2/year	0.19 ton/m^2/year	190 kg/m^2/year
Acha *et al.*, 2018	Bristol, UK	1	Commercial	1,107 kWh/m^2/year	250 kg/m^2/year	250 kg/m^2/year

Ye *et al.*, 2018	China	362	Office	N.A.	1.19 x 10^6 kg/building/year	73.45 kg/m^2/year

Apparently, the highest carbon emission levels were found with the studies in the UK and Hong Kong (as high as 288 kg/m^2/year), while the lowest one (2.7 kg/m^2/year) was revealed by a study in Sweden. Note should be taken that the latter study, same as the one in Australia, was on a single building. In order to be more representative, studies with a larger sample of buildings are preferred, provided that the data collected had undergone a rigorous quality-check process before they were taken for analysis (e.g. Lai, 2015).

Different from office and other kinds of commercial buildings, hotels operate on a non-stop basis, with their carbon emission levels generally on the high side (Wu *et al.*, 2010; Lai, 2015; Huang *et al*., 2015). Whereas the studies of Bağcı (2009), Wallhagen *et al*.(2011), Jing *et al*. (2017) and Ye *et al.* (2018) were all on office buildings, the levels of carbon emission revealed vary from 2.7 kg/m^2/year to 273.8 kg/m^2/year. Likewise, the studies of Jiang & Tovey (2010), Garg *et al*. (2017) and Acha *et al*. (2018), although focusing on the same building type - commercial, the range of carbon emissions found is from 96 kg/m^2/year to 250 kg/m^2/year. After all, the buildings studied (Table 1) are different in, for example, locality, hence climate, which could be some factors contributory to the difference in their carbon emission levels.

The above review shows that over the past decade, the volume of research on carbon emissions has grown. Those focused on embodied carbon emissions, for example, are: Simonen *et al.* (2017) and Chastas *et al.* (2018). Lai (2015) burrowed into the carbon footprints of hotels in Hong Kong; Wu *et al.* (2010) and Huang *et al.* (2015) benchmarked carbon emissions of hotels in Singapore and Taiwan, respectively. Jeong *et al.* (2018) developed a carbon emission benchmark for residential buildings in South Korea, and the study of Han & Ji (2016) was on industrial carbon emission in Beijing of China. When compared with the counterpart on building energy use, research on carbon emissions of existing buildings remains scanty.

3. Method and Data

With the support of four major stakeholder organizations of existing buildings in Hong Kong, namely, Hong Kong Green Building Council, Building Services Operation and Maintenance Executives Society, Greater China Institute of Property Management, and Hong Kong Institute of Facility Management, a survey was distributed to facility management (FM) professionals working on commercial buildings (Lai, 2016b). Subsequent to the survey, the study team contacted the respondents who indicated interest to participate in a further part of the study - detailed carbon audits of buildings.

In view of the large volume of data needed and the need of accurate data for the audits, the study team held face-to-face meetings with the participants, during which a set of electronic templates tailored for collecting the data were explained and then provided to the participants. After such meetings, the templates completed by the participants were subject to quality checks. Then, follow-up meetings were held with the participants to clarify the irregularities found and solicit the missing data. The study covered commercial buildings that contained mainly office and retail premises. Data of the buildings including their age, number of storeys and floor area (as investigated in Chung *et al*., 2006) and longitudinal data of energy and other carbon-emitting resources consumptions were collected. Such longitudinal data cover a period of six years or, for buildings aged below six, the entire period over which they have been operated.

The method used to quantify the carbon emissions of the buildings followed that of Lai (2015), which was established based on the guidelines of the Environmental Protection Department & Electrical and Mechanical Services Department (2010). The carbon emissions quantified, according to the classification of the Greenhouse Gas Protocol (WBCSD & WBI, 2004), fall into three scopes. Scope 1 emissions, due to on-site direct fuel combustion (EM_A^D), were calculated by Eq. (1). Scope 2 emissions, due to consumption of purchased electricity (EM_{GHG}^E), were determined using Eq. (2). Emissions due to electricity used for processing fresh water and sewage (EM_{GHG}^{SS}), belonging to scope 3, were computed by Eq. (3).

$$EM_A^D = \sum_{f=1}^{f=F} \sum_{t=1}^{t=T} A_{f,t} \times F_{(f)A} \times G_{(A)} \qquad (1)$$

$$EM_{GHG}^E = \sum_{t=1}^{t=T} A_{(E)t} \times F_{(E)t} \qquad (2)$$

$$EM_{GHG}^{SS} = A_{(W)} \times (F_{(W)} + F_{(D)}) \qquad (3)$$

Where

$A_{(E)t}$ = amount of electricity used (kWh) in the t^{th} period

$A_{f,t}$ = amount of fuel f consumed in the t^{th} period (L)

$A_{(W)}$ = amount of water consumed (m^3)

$F_{(D)}$ = emission factor of processing sewage (kg CO_2-e/m^3)

$F_{(E)t}$ = emission factor (kg CO_2-e/kWh) of electricity used in the t^{th} period (kg CO_2-e/kWh)

$F_{(f)A}$ = emission factor of gas A (e.g. CO_2, CH_4, N_2O) for fuel f (g/L)

$F_{(W)}$ = emission factor of processing fresh water (kg CO_2-e/m^3)

$G_{(A)}$ = global warming potential of gas A

Since the buildings were located across various districts of Hong Kong where the electricity was supplied by two different companies (China Light & Power Hong Kong Limited (CLP) and The Hongkong Electric Company Limited (HEC)), the emission factors of electricity consumed ($F_{(E)t}$) by each building, which vary from year to year, were retrieved from the record figures published by the respective electricity supplier. As regards the emission factors of processing fresh water ($F_{(W)}$) and sewage ($F_{(D)}$), they were determined by multiplying the territory-wide default value (0.7 kg/kWh) of purchased electricity by the respective amount of electricity used per unit volume of water or sewage processed (in kWh/m^3) - figures published by the Water Supplies Department and the Drainage Services Department, respectively. The fuel consumed by the sampled buildings for on-site direct combustion is diesel oil; the corresponding emission factors ($F_{(f)A}$) of the gases (CO_2, CH_4, N_2O) emitted are 2.614 kg/L, 0.0239 g/L and 0.0074 g/L, and their global warming potentials ($G_{(A)}$) are 1, 21 and 310, respectively (Environmental Protection Department & Electrical and Mechanical Services Department, 2010).

For each building, its monthly carbon emission was quantified and, for each of the six years covered, the monthly emission amounts were summed to become the respective annual emission. To smooth out any fluctuations that may arise from, for example, building renovation work, the annual carbon emissions were averaged over the six-year period. Using such averaged values, descriptive statistics: mean, minimum, maximum and standard deviation of carbon emissions, including those due to consumption of the main operating resources (i.e. electricity, water), were computed. This set of descriptive statistics was also computed for electricity consumption given that the latter, as revealed in earlier studies (e.g. Lai, 2015), is a major contributor to carbon emission. Afterwards, correlation analyses were carried out for two purposes: first, identify whether there existed any relationship between the characteristics (e.g. age, area) of the buildings and their carbon emissions; second, identify an appropriate parameter for normalizing the carbon emissions so as to enable fair comparisons to be made between the normalized carbon emissions of the buildings. Finally, benchmark percentile values were calculated for total carbon emissions, normalized carbon emissions and normalized electricity consumptions of the buildings. By grouping such carbon emissions and electricity consumptions into bin values, their cumulative frequency distribution curves were constructed, which serve as benchmarking charts for assessing the environmental performance of the buildings.

4. Results and Discussion

4.1 Building characteristics

Data of 32 buildings were collected. Referring to the main usage of these sampled buildings, 13 of them were retail buildings, 5 were office buildings, and 13 accommodated a mix of retail and office premises. The remaining sample, whose data were without sufficient details, was eventually excluded from analysis. Like many commercial buildings in Hong Kong, 26 of the sampled buildings were built with car parking spaces. For the 29 buildings with full data of their characteristics provided, a summary of their statistics was worked out, as shown in Table 2. On average, the buildings were 21 years old (standard deviation: S.D. = 8.6) and the oldest one had been operated for 36 years (Table 2). Data of internal floor area (IFA), measured in total for each building, were in the range between 4,569 m^2 and 135,284 m^2 (average: 38,442 m^2). When measuring only the buildings' common areas which include the parts operated and maintained by the landlord such as car park, corridors, lobbies and staircases, the IFA varies from 330 m^2 to 52,911 m^2.

Table 2 Building characteristics

	mean	min	max	S.D.
Age (year)	21	6	36	8.6
Number of floors	17	2	46	13.2
Total IFA (m^2)	38,442	4,569	135,284	29,455
Common IFA (m^2)	14,883	330	52,911	12,077

4.2 Energy consumption and carbon emission

The emission factors used in calculating the carbon emissions over the six-year period are summarized in Table 3. The factors in respect of processing sewage were between 0.17 kg CO_2-e/m^3 and 0.18 kg CO_2-e/m^3, while the counterpart of processing fresh water varied from 0.41 kg CO_2-e/m^3 to 0.44 kg CO_2-e/m^3. For electricity purchased from the two power companies (i.e. CLP and HEC), their emission factors were between 0.54 kg CO_2-e/kWh and 0.79 kg CO_2-e/kWh.

Table 3 Emission factors

Year	2010	2011	2012	2013	2014	2015
Processing sewage ($F_{(D)}$) (kg CO_2-e/m^3)	0.17	0.17	0.17	0.17	0.17	0.18
Processing fresh water ($F_{(W)}$) (kg CO_2-e/m^3)	0.41	0.42	0.44	0.41	0.40	0.41
Electricity used - CLP ($F_{(E)t}$) (kg CO_2-e/kWh)	0.54	0.59	0.58	0.63	0.64	0.54
Electricity used - HEC ($F_{(E)t}$) (kg CO_2-e/kWh)	0.79	0.79	0.79	0.78	0.79	0.78

Given that the buildings were different in size, their total carbon emissions vary: the largest annual emission level (10,598 tonnes $CO_{2\text{-}e}$) was about four times the mean level (2,788 tonnes $CO_{2\text{-}e}$), while the minimum level was 238 tonnes $CO_{2\text{-}e}$ (Table 4). On average, around 98% of the total carbon emission was due to consumption of electricity. The amount of this dominant source of building energy use, among the sampled buildings, was as high as 18,011 MWh per year. In contrast, the proportion of carbon emission due to water consumption out of the total carbon emission was minimal.

Table 4 Annual energy consumption and carbon emission

	mean	min	max	S.D.
Total carbon emission (tonne)	2,788	238	10,598	2,802
Carbon emission due to electricity consumption (tonne)	2,723	237.9	10,548	2,743
Carbon emission due to water consumption (tonne)	8.4	0.04	46.4	12.1
Amount of electricity consumed ($A_{(E)t}$) (MWh)	4,439	396	18,011	4,638
Amount of water consumed $A_{(W)}$ (m^3)	12,334	59.8	79,189	17,645
Amount of fuel (diesel oil) consumed ($A_{f,t}$) (L)	367.5	28.0	1,032	324.3

4.3 Correlation analysis and normalization

Of the sampled buildings, 29 of them provided the full set of data that allowed investigations into the relations between factors that may affect the amounts of carbon emission or energy consumption of the buildings. Such factors, including age and floor area, were selected for analysis based on two propositions: (i) the older the building, the poorer the condition it is (hence higher carbon emission and energy consumption); and (ii) the bigger the building, the more energy it consumes (hence higher carbon emission). For the purpose of such investigations, the SPSS software was used to conduct a series of Pearson correlation analyses. The analysis results, namely, the correlation coefficients (*r*) pertaining to different pairs of the parameters investigated, are summarized in a matrix (Table 5).

Table 5 Correlation coefficients matrix

	Building age	Total IFA	Common IFA	Electricity consumption	Total carbon emission	Emission due to electricity consumption	Emission due to water consumption
Building age	1						
Total IFA	0.110	1					
Common IFA	-0.056	0.798**	1				
Electricity consumption	-0.015	0.808**	0.782**	1			
Total carbon emission	-0.006	0.823**	0.782**	0.993**	1		
Emission due to electricity consumption	-0.006	0.824**	0.778**	0.993**	0.999**	1	

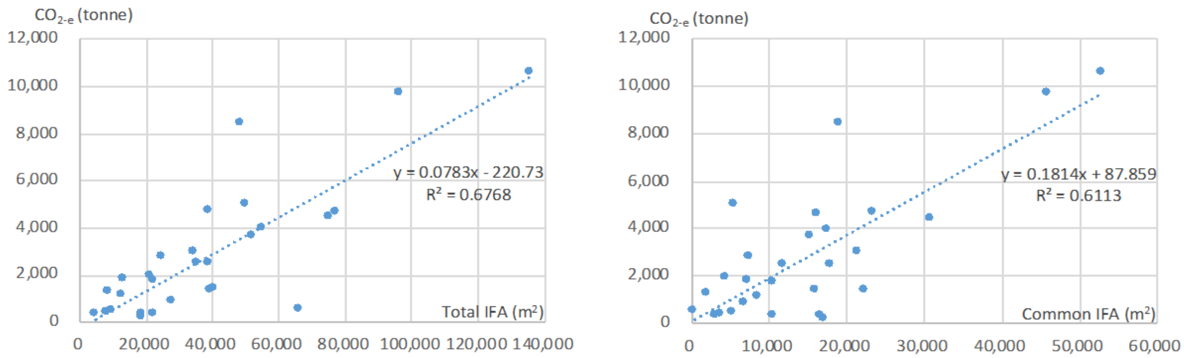
Emission due to water consumption	0.058	0.481**	0.323	0.546**	0.599**	0.591**	1

** Correlation is significant at the 0.01 level (2-tailed).

The results show that building age is the only parameter that exhibits no significant correlations with all the other parameters. While not significantly correlated with building age or carbon emission due to water consumption, common IFA had significant positive correlations with carbon emission due to electricity consumption (0.778), total carbon emission (0.782), electricity consumption (0.782), and total IFA (0.798). From the rest of the results, strongly positive correlations were found, particularly between: (i) total IFA and carbon emission due to electricity consumption (0.824); (ii) electricity consumption and total carbon emission (0.993); (iii) electricity consumption and carbon emission due to electricity consumption (0.993); and (iv) total carbon emission and carbon emission due to electricity consumption (0.999).

Logically, a larger building, with more facilities and more end users, has a higher total energy consumption and hence more carbon emission than a smaller building; and vice versa. Therefore, comparing the environmental performance of the sampled buildings by their raw energy consumptions or raw carbon emissions would not be fair. Instead, their normalized energy consumption or carbon emission levels are needed for comparison purposes. As building age was not significantly correlated with any of the electricity consumption or carbon emission parameters in Table 5, it was not a suitable normalization factor. The other two physical parameters, total IFA and common IFA, were found to have significant correlations with the remaining parameters investigated. In selecting which of these two parameters as the normalization factor, the first step was to inspect their Pearson correlation coefficients summarized in Table 5. The inspection results were that across the board, the correlation coefficients associated with total IFA (r = 0.481 to 0.824) are higher than the counterparts of common IFA (r = 0.323 to 0.782). In a further step, two scatter diagrams as shown in Fig. 1 were plotted. They illustrate that the goodness of fit of the trend line between total carbon emission and total IFA (R^2 = 0.6768) is higher than that between total carbon emission and common IFA (R^2 = 0.6113). The results of the two steps both support that total IFA is a more suitable normalization factor. In fact, the Electrical and Mechanical Services Department also defines energy utilization index (EUI) as the total energy consumption of the central building services installations in a building for a specific period divided by the total IFA of the building (EMSD, 2018f).

For each building, the total carbon emission was normalized by the total IFA of the building. The results of such normalized total carbon emissions, plotted against building age, are shown in Fig. 2. On average, the normalized annual total carbon emission was 71.7 kg/m^2, and the minimum and maximum values were 8.2 kg/m^2 and 173.8 kg/m^2, respectively. From the plot, no clear pattern between normalized carbon emission and building age can be observed.



(a) (b)

Fig. 1 Total carbon emission against (a) total IFA and (b) common IFA

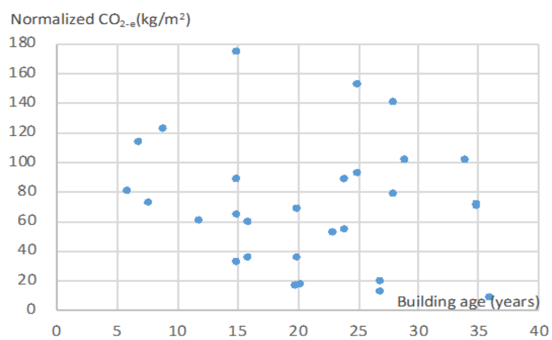


Fig. 2 Total carbon emission normalized by total IFA against building age

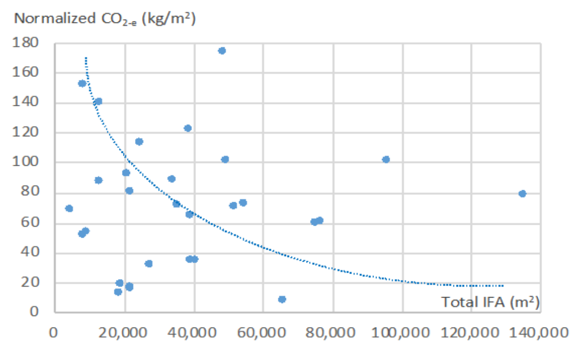


Fig. 3 Total carbon emission normalized by total IFA against total IFA

Plotting the buildings' normalized annual total carbon emissions against their total IFA (Fig. 3) shows a declining trend with increase in building scale. This suggests that for bigger buildings with larger-scale of central building facilities such as chiller plant, pumping system, etc., it is more likely that the facilities could be operated in an optimized manner, thereby producing less carbon emission.

Given the earlier finding that the major portion of carbon emissions of the buildings was due to electricity consumption, a scatter plot of EUI against total IFA was prepared (Fig. 4(a)). It shows that, similar to the observation in Fig. 3, there is a downward trend of EUI when total IFA increases. To further show whether there exists any pattern between normalized electricity consumption and building height, Fig. 4(b), which is a scatter plot of the EUIs of the buildings against their number of storeys, was worked out. Again, a downward trend was observed – the taller the building, the lower the normalized electricity consumption. These two observations concur with the previous findings that large buildings tend to have better energy performance than small buildings (Kahn *et al*., 2014; BCA, 2017), and tall buildings perform better than short buildings in terms of energy consumption (Liu *et al*., 2017). Note that as the height of a building increases, the cooling or heating energy use intensity due to internal loads (e.g. people, equipment) may remain constant but the energy consumption for artificial lighting decreases – premises at the upper floors have more daylight than those at the lower floors (Liu *et al.*, 2017).

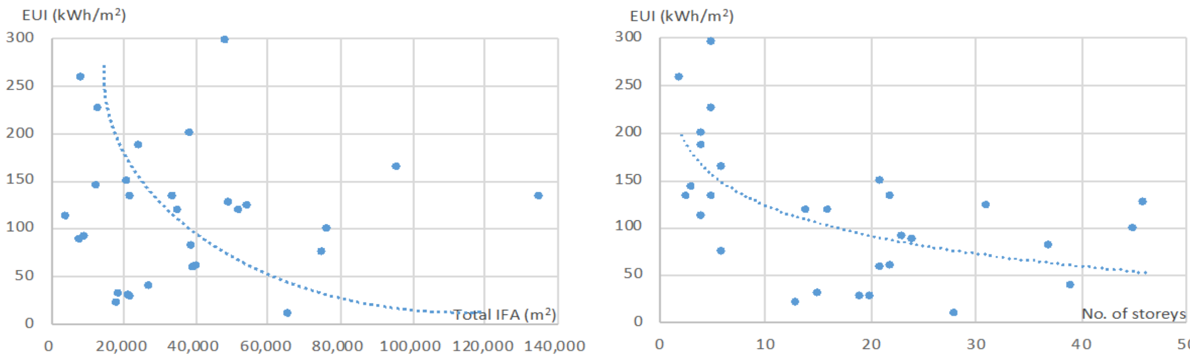


Fig. 4 EUI against (a) total IFA and (b) building height

4.4 Benchmarking

To enable benchmarking the environmental performance of the buildings, percentiles of annual total carbon emission, normalized annual electricity consumption (i.e. EUI) and normalized annual total carbon emission of the buildings were calculated based on the usable data of 30 sampled buildings. The results summarized in Table 6, when compared to those of the previous studies, are more elaborate - not only the benchmark value of every 10th percentile but also those of the quartiles (25th and 75th) are tabulated, thereby allowing more detailed performance comparisons.

Ranging from 238 tonnes/year to 10,598 tonnes/year, the median value of annual total carbon emission was 1,801 tonnes/year. The first and third quartiles of normalized annual total carbon emission were 35.1 kg/m^2/year and 91.4 kg/m^2/year, respectively. The normalized annual electricity consumptions of the buildings, as per their EUIs, varied from 10.4 kWh/m^2/year to 296.3 kWh/m^2/year, and the median was 115.7 kWh/m^2/year. Compared with the results of the past studies in Hong Kong (Jing *et al*, 2017), Beijing (Jiang & Tovey, 2010), Shanghai (Jiang & Tovey, 2010), several cities in China (Ye *et al*, 2018) and India (Garg *et al*, 2017), the normalized annual total carbon emissions and EUIs of the present study are lower, meaning that the buildings investigated are more environmentally friendly. Nevertheless, the wide range of EUIs found from the present study may be ascribed to the fact that the samples include a mix of office and retail buildings. This is a point that warrants further investigations in future.

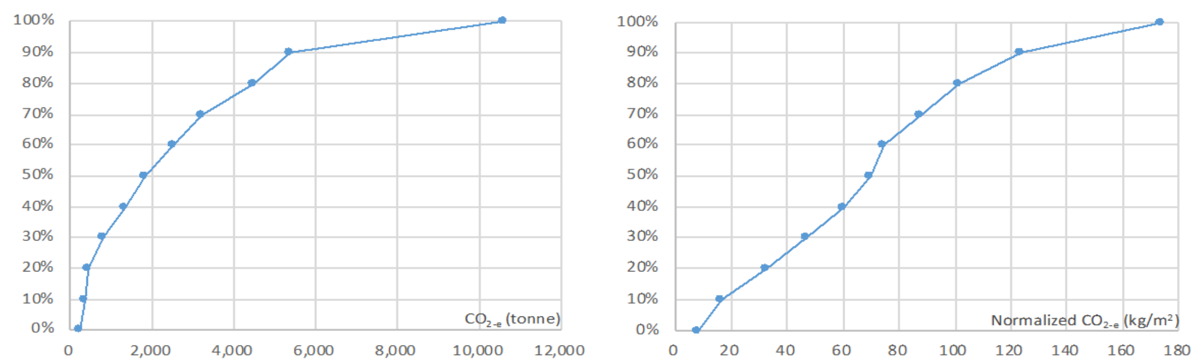
Table 5 Benchmarks of carbon emission and EUI

Percentile	Total carbon emission (tonne $CO_{2\text{-}e}$/year)	Normalized total carbon emission (kg $CO_{2\text{-}e}$/m^2/year)	EUI (kWh/m^2/year)
0	238	8.2	10.4

Lai, J. and Lu, M. (2019), Analysis and benchmarking of carbon emissions of commercial buildings, Energy and Buildings, Vol. 199, pp. 445-454. https://doi.org/10.1016/j.enbuild.2019.07.012

10%	359	16.8	28.4
20%	422	32.7	52.4
25%	514	35.1	58.6
30%	783	46.8	70.4
40%	1,340	60.0	90.0
50%	1,801	69.6	115.7
60%	2,512	74.8	124.6
70%	3,204	87.9	133.1
75%	3,900	91.4	141.3
80%	4,487	101.2	149.4
90%	5,366	123.8	202.2
100%	10,598	173.8	296.3

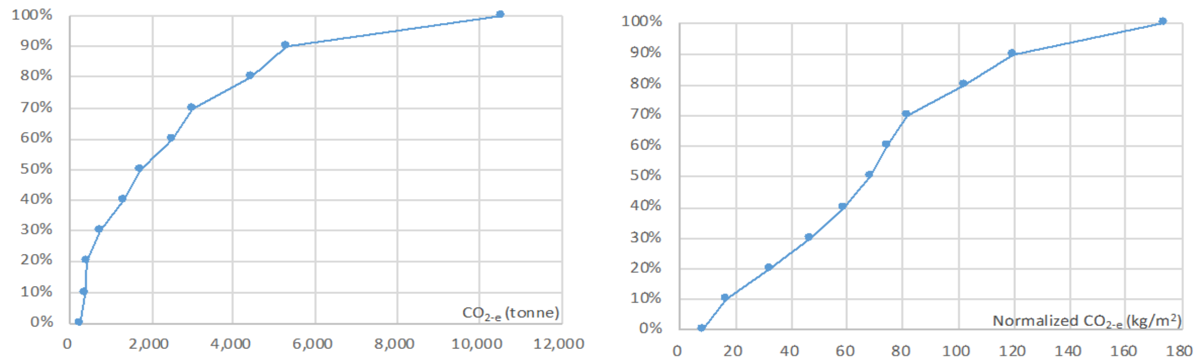
A cumulative percentile plot of annual total carbon emissions was made. Referring to Fig. 5(a), the line chart indicates that before the 90th percentile, the increment in carbon emission across each 10th percentile was rather gradual. From the 90th percentile to the 100th percentile, the increment accelerates. A similar pattern of line chart is observed from Fig. 5(b), which was plotted based on the normalized annual total carbon emissions. In this case, nevertheless, the acceleration of the increment in normalized carbon emission started earlier - at the 80th percentile. On the basis of these observations, there are two interpretations. First, there was a higher concentration of buildings in the low range of total carbon emission, and the same occurred with normalized total carbon emission. Second, for buildings with environmental performance worse than that of the majority (80% to 90%), they require a much larger effort to reduce their carbon emission before they can reach a higher rank in environmental performance.



(a) (b)

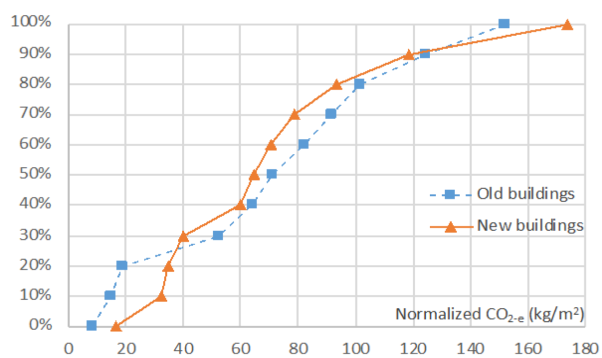
Fig. 5 Benchmarking charts for (a) total carbon emission and (b) total carbon emission normalized by total IFA

Given that electricity consumption represents the major source of carbon emission of the building, benchmarking charts for carbon emission due to electricity consumption and normalized carbon emission due to electricity consumption were made. Fig. 6(a) and (b), exhibiting a pattern of line chart similar to those for total carbon emissions (Fig. 5(a) and (b)), are useful for benchmarking carbon emissions due to electricity consumptions.



(a) (b)

Fig. 6 Benchmarking charts for carbon emission due to electricity: (a) raw emission and (b) emission normalized by total IFA



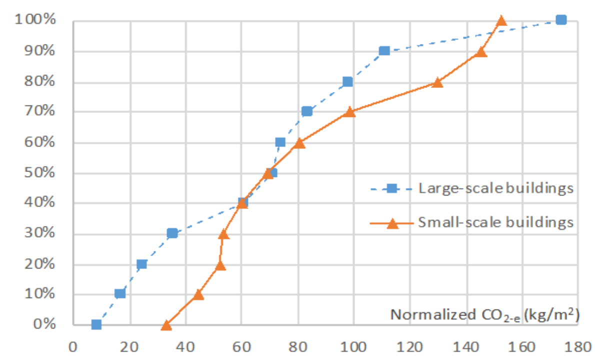


Fig 7 Benchmarking chart for new and old buildings

Fig.8 Benchmarking chart for large-scale and small-scale buildings

The median age of the 30 sampled buildings was 21 years; it serves as a dividing line between new and old buildings. On this basis, two benchmarking charts were made for new and old buildings, respectively (Fig. 7). The majority of the line chart pertaining to the old buildings lie below that of the new buildings. This indicates that most samples of the old buildings generated more carbon emissions per unit building area. Nevertheless, the maximum annual carbon emission level of the new buildings was 173.8 kg/m^2, which is higher than that of the old buildings (152.2 kg/m^2).

The buildings are not only different in age, but also in scale. Although there are no official classifications for different scales of commercial buildings in Hong Kong, the figure that demarcates the scale of an office building or a retail building in Singapore is 15,000 m^2 (BCA, 2017). With this figure taken to segregate the sampled buildings into two groups – small-scale and large-scale, two line charts were made for benchmarking normalized total carbon emission (Fig. 8). Almost all parts of the distribution line for the former group (small-scale) are below the counterparts of the large-scale buildings. This shows that the small-scale buildings, in general, generated more carbon emission per unit building area. Yet, the two distribution lines almost overlap between the 40th and 50th percentiles. This observation implies that the carbon emission levels of the two groups of buildings in that range are similar.

5. Conclusions

Over the years, a plethora of studies have been undertaken on building energy use. Yet carbon emission, which serves as a more comprehensive environmental performance indicator for buildings, has not been widely studied. As such, there remains insufficient understanding of what factors that are influential to the carbon emissions of existing buildings, especially commercial buildings that utilize substantial operating resources. In addressing this research gap, the study reported above, through a rigorous data collection and analysis process, revealed the carbon emission level of real-world commercial buildings and showed that the emission level is more significantly correlated with total floor area than age or common floor area of the buildings.

Tools for benchmarking building energy and carbon emission have been increasingly developed by governments and environmental organizations. But meticulous benchmark values and benchmarking charts that are established from research using reliable, longitudinal data collected via face-to-face meetings with facility managers, like the results illustrated above, are unprecedented. The benchmarking charts, with subdivided categories for different building age and building scale, enable performance comparisons to be made between peer buildings.

It was found that in consistent with the principle of economies of scale, the large buildings, when compared with the small buildings, produced less carbon emissions per unit floor area. On the basis of this finding, small buildings should be given priority and more attention when policy-makers such as authorities and building owners implement environmental conversation measures.

Following the methodology of this study, further research can be conducted in the future to cover more samples of existing commercial buildings and more types of carbon-intensive buildings (e.g. hospitals). Effects of building characteristics (e.g. storey height, building volume) on carbon emissions should also be studied. When more findings of this kind are made available, governments and stakeholders alike will be more able to evaluate the environmental performance of existing buildings in the pursuit of a sustainable built environment.

Acknowledgement:

This work was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 152095/15E).

References:

Acha, S., Mariaud, A., Shan, N. & Markides, C. N. (2018). Optimal design and operation of distributed low-carbon energy technologies in commercial buildings. *Energy*, 142, 578-591.

Bağcı, B. (2009). Energy saving potential for a high-rise office building. *Intelligent Buildings International*, 1:2, 156-163.

Borgstein, E. H. & Lamberts, R. (2014). Developing energy consumption benchmarks for buildings: Bank branches in Brazil. *Energy and Buildings*, 82, 82-91.

Braslavsky, J. H., Wall, J. R. & Reedman, L. J. (2015). Optimal distributed energy resources and the cost of reduced greenhouse gas emissions in a large retail shopping centre. *Applied Energy*, 155, 120-130.

Building and Construction Authority (BCA). (2017). Building Energy Benchmarking Report 2017. https://www.bca.gov.sg/GreenMark/others/BCA_BEBR_Abridged_FA_2017.pdf

Building and Construction Authority (BCA). (2018). Building Energy Submission System (BESS). https://www.bca.gov.sg/bess/

Calculating Cool. (2018). Calculating Cool. http://www.calculatingcool.com.au/#/start (accessed 15 August 2018)

Carbon Footprint. (2018a). About Us. https://www.carbonfootprint.com/aboutus.html (accessed 15 August 2018)

Carbon Footprint. (2018b). Free Carbon Calculators. https://www.carbonfootprint.com/calculator1.html (accessed 15 August 2018)

Carbon Footprint. (2018c). Carbon & Sustainability Benchmarking. https://www.carbonfootprint.com/carbon_benchmark.html (accessed 15 August 2018)

Carbon Footprint Repository. (2018a). Background. https://www.carbon-footprint.hk/node/53 (accessed 12 September 2018)

Carbon Footprint Repository. (2018b). Carbon Footprint Repository for Listed Companies in Hong Kong. https://www.carbon-footprint.hk/node/87 (accessed 12 September 2018)

Chartered Institution of Building Services Engineers (CIBSE). (2007). CIBSE TM46: Energy Benchmarks. https://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7evAAC (accessed 15 August 2018)

Chartered Institution of Building Services Engineers (CIBSE). (2016). CIBSE GVF2012 Guide F: Energy Efficiency in Buildings. https://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7oTAAS (accessed 15 September 2018)

Chastas, P., Theodosiou, T., Kontoleon, K. J. & Bikas, D. (2018). Normarlising and assessing carbon emissions in the building sector: A review on the embodied CO2 emissions of residential buildings. *Building and Environment*, 130, 212-226.

Chung, W. & Hui, Y. V. (2009). A study of energy efficiency of private office buildings in Hong Kong. *Energy and Buildings*, 41, 696-701.

Chung, W. (2012). Using the fuzzy linear regression method to benchmark the energy efficiency of commercial buildings. *Applied Energy*, 95, 45-49.

Chung, W., Hui, Y. V. & Lam, Y. M. (2006). Benchmarking the energy efficiency of commercial buildings. *Applied Energy*, 83, 1-14.

Climate Ready. (2018a). Carbon Calculators. https://www.climateready.gov.hk/education_centre.php?section=carbon_calculator (accessed 12 September 2018)

Department of Energy and Environment of D.C. (2018). Energy Benchmarking for Washington D.C., http://energybenchmarkingdc.org/#dc/2016?categories[0][field]=report_status&categories[0][values][]=In+Compliance&categories[0][other]=false&layer=energy_star_score&metrics[]=energy_star_score&sort=energy_star_score&order=desc&lat=38.889931&lng=-77.009003&zoom=12 (accessed 12 September 2018)

Electrical and Mechanical Services Department (EMSD). (2018a). Buildings Energy Efficiency Ordinance. https://www.emsd.gov.hk/beeo/en/mibec_beeo.html (accessed 12 September 2018)

Electrical and Mechanical Services Department (EMSD). (2018b). Hong Kong Energy Efficiency Registration Scheme for Buildings. https://www.emsd.gov.hk/filemanager/en/content_723/hkeersb2018_en.pdf (accessed 12 September 2018)

Electrical and Mechanical Services Department (EMSD). (2018c). Hong Kong Energy End-use Data 2018. https://www.emsd.gov.hk/filemanager/en/content_762/HKEEUD2018.pdf (accessed 12 April 2019)

Electrical and Mechanical Services Department (EMSD). (2018d). Energy Utilization Indexes and Benchmarks for Residential, Commercial and Transport Sectors. http://ecib.emsd.gov.hk/en/index.htm (accessed 12 September 2018)

Electrical and Mechanical Services Department (EMSD). (2018e). Online Benchmarking Tools. http://ecib.emsd.gov.hk/en/subgroup_cmc.asp (accessed 12 September 2018)

Electrical and Mechanical Services Department (EMSD). (2018f). Code of Practice for Building Energy Audit. https://www.emsd.gov.hk/beeo/en/pee/EAC_2018.pdf (accessed 12 September 2018)

Energy Star. (2018). Energy Star. https://www.energystar.gov/about/origins_mission/energy_star_overview/about_energy_star_commercial_buildings (accessed 12 September 2018)

Environmental Protection Department & Electrical and Mechanical Services Department (2010), Guidelines to Account for and Report on Greenhouse Gas Emissions and Removals for Buildings (Commercial, Residential or Institutional Purposes) in Hong Kong, Hong Kong Government.

Gao, X. & Malkawi, A. (2014). A new methodology for building energy performance benchmarking: An approach based on intelligent clustering algorithm. *Energy and Buildings*, 84, 607-616.

Garg, A., Maheshwari, J., Shukla, P. R. & Rawal, R. (2017). Energy appliance transformation in commercial buildings in India under alternate policy scenarios. *Energy*, 140, 952-965.

Han, M. & Ji, X. (2016). Alternative industrial carbon emissions benchmark based on input-output analysis. *Frontiers of Earth Science*, 10, 731-739.

Huang, K. T., Wang, J. C. & Wang, Y. C. (2015). Analysis and benchmarking of greenhouse gas emissions of luxury hotels. *International Journal of Hospitality Management*, 51, 56-66.

ICT Footprint. (2018a). Related tools & Services. https://ictfootprint.eu/en/related-tools-services?field_means_proposed_tid%5B%5D=75 (accessed 12 September 2018)

ICT Footprint. (2018b). Self-Assessment Tool. http://sat-o.ictfootprint.eu/Pages/Home.aspx (accessed 12 September 2018)

Intergovernmental Panel on Climate Change (IPCC). (2007). Changes in Atmospheric Constituents and in Radiative Forcing. Geneva, Switzerland.

Intergovernmental Panel on Climate Change (IPCC). (2014). Climate Change 2014 Mitigation of Climate Change (Fifth Report), https://www.ipcc.ch/report/ar5/wg3/ (accessed 16 August 2018)

International Organization for Standardization (ISO). (2006). ISO 14040 Environmental management - Life cycle assessment - Principles and framework

International Organization for Standardization (ISO). (2010). ISO 21931 Sustainability in building construction -- Framework for methods of assessment of the environmental performance of construction works

International Organization for Standardization (ISO). (2017). ISO 16745 Sustainability in buildings and civil engineering works — Carbon metric of an existing building during use stage

Jeong, K., Hong, T. & Kim, J. (2018). Development of a CO_2 emission benchmark for achieving the national CO_2 emission reduction target by 2030. *Energy and Buildings*, 158, 86-94.

Jiang, M. P. & Tovey, K. (2010). Overcoming barriers to implementation of carbon reduction strategies in large commercial buildings in China. Building and Environment, 45, 856-864.

Jiang, P., Chen, Y., Dong, W. & Huang, B. (2014). Promoting low carbon sustainability through benchmarking the energy performance in public buildings in China. *Urban Climate*, 10, 92-104.

Jing, R., Wang, M., Zhang, R., Li, N. & Zhao, Y. (2017). A study on energy performance of 30 commercial office buildings in Hong Kong. *Energy and Buildings*, 144, 117-128.

Kahn, M. E., Kok, N. & Quigley, J. M. (2014). Carbon emissions from the commercial building sector: The role of climate, quality, and incentives. *Journal of Public Economics*, 113, 1-12

Khoshbakht, M., Gou, Z. & Dupre, K. 2018. Energy use characteristics and benchmarking for higher education buildings. *Energy and Buildings*, 164, 61-76.

Kinney, S. & Piette, M. A. (2002). Development of California commercial-building energy benchmarking database. In: ACEEE 2002 summer study on energy efficiency in buildings, vol. 7; p. 109–20.

Lai J. H. K. (2014), Mandatory reporting of greenhouse gas emissions from buildings: Stakeholders' opinions in Hong Kong. *Energy Policy*, 75, 278-288.

Lai, J. H. K. (2015). Carbon footprints of hotels: Analysis of three archetypes in Hong Kong. *Sustainable Cities and Society*, 14, 334-341.

Lai, J. H. K. (2016a). Energy use and maintenance costs of upmarket hotels. *International Journal of Hospitality Management*, 56, 33-43.

Lai, J. H. K. (2016b). Operating resources and carbon footprints of commercial buildings: a study in Hong Kong. *IFMA 2016 Academic & Research Conference*, San Diego, US, 5-7 October 2016, pp.1-8.

Lai, J. H. K., Yik, F. W.H. & Man, C. S. (2012). Carbon audit: a literature review and an empirical study on a hotel. *Facilities*, 30(9), 417 - 431

Lee, W. L. & Yik, F. W. H. (2004). Regulatory and voluntary approaches for enhancing building energy efficiency. *Progress in Energy and Combustion Science*, 30(5), 477-499.

Li, Z., Han, Y. & Xu, P. (2014). Methods for benchmarking building energy consumption against its past or intended performance: An overview. *Applied Energy,* 124, 325-334

Li, X., Yao, R., Li, Q., Ding, Y. & Li, B. (2018). An object-oriented energy benchmark for the evaluation of the office building stock. *Utilities Policy*, 51, 1-11.

Liu, L., Wu, D., Li, X., Hou, S., Liu, C. & Jones, P. (2017). Effect of geometric factors on the energy performance of high-rise office towers in Tianjin, China. *Building Simulation*, 10, 625-641.

Martin, C. (2013). Generating low-cost national energy benchmarks: A case study in commercial buildings in Cape Town, South Africa. *Energy and Buildings*, 64, 26-31.

Martínez-Rocamora, A., Solís-Guzmán, J. & Marrero, M. (2017). Ecological footprint of the use and maintenance phase of buildings: Maintenance tasks and final results. *Energy and Buildings*, 155, 339-351.

National Energy Foundation. (2018). Benchmarking. http://www.nef.org.uk/service/existing-buildings/performance-measurement/benchmarking (accessed 16 August 2018)

National Environment Agency (NEA). (2012). Data Centre Energy Efficiency Benchmarking. https://www.e2singapore.gov.sg/DATA/0/docs/Resources/NEA%20DC%20Energy%20Benchmarking%20Summary-%20Final%20Report%20(3).pdf (accessed 16 August 2018)

Natural Resources Canada (2018). ENERGY STAR benchmarking for commercial and institutional buildings. http://www.nrcan.gc.ca/energy/efficiency/buildings/energy-benchmarking/3691 (accessed 12 September 2018)

New York City Government (NYC). (2018). NYC Energy and Water Benchmarking. https://serv.cusp.nyu.edu/projects/evt/ (accessed 16 August 2018)

Park, H. S., Lee, E, M., Kang, H., Hong, T. & Jeong, J. (2016). Development of a new energy benchmark for improving the operational rating system of office buildings using various data-mining techniques. *Applied Energy*, 173, 225-237.

Priyadarsini, R., Wu, X.C. & Lee, S.E. (2009). A study on energy performance of hotel buildings in Singapore. *Energy and Buildings*, 41, 1319-1324.

Ramesh, T., Ravi, P., & Shukla, K. K., (2010). Life cycle analysis of buildings: an overview. *Energy and Buildings*. 42, 1592-1600.

Shahrestani, M., Yao, R. & Cook, G. K. (2013). A review of existing building benchmarks and the development of a set of reference office buildings for England and Wales. *Intelligent Buildings International*, 6, 41-64.

Sharp, T. (1996). Energy benchmarking in commercial-office buildings. In: ACEEE 1996 summer study on energy efficiency in buildings, vol. 4; p. 321–9.

Simonen, K., Rodriguez, B. X. & De Wolf, C. (2017). Benchmarking the Embodied Carbon of Buildings. T*echnology, Architecture & Design*, 1, 208-218.

Summerfield, A. J., Lowe, R. J. & Oreszczyn, T. (2010). Two models for benchmarking UK domestic delivered energy. *Building Research & Information*, 38, 12-24.

The Green Grid. (2018a). About Us. https://www.thegreengrid.org/en/about-us (accessed 23 October 2018)

The Green Grid. (2018b). Carbon Usage Effectiveness (CUE): A GREEN GRID Data Center Sustainability Metric. https://www.thegreengrid.org/en/resources/library-and-tools/241-Carbon-Usage-Effectiveness-%28CUE%29%3A-A-Green-Grid-Data-Center-Sustainability-Metric (accessed 23 October 2018)

U.S. Energy Information Administration (U.S. EIA) (2018a). Use of Energy in the United States Explained Energy Use in Commercial Buildings. https://www.eia.gov/energyexplained/index.php?page=us_energy_commercial. (accessed 8th April 2019)

U.S. Energy Information Administration (U.S. EIA) (2018b). How much energy is consumed in U.S. residential and commercial buildings? https://www.eia.gov/tools/faqs/faq.php?id=86&t=1 (accessed 8th April 2019)

Wallhagen, M., Glaumann, M. & Malmqvist, T. (2011). Basic building life cycle calculations to decrease contribution to climate change – Case study on an office building in Sweden. *Building and Environment*, 46, 1863-1871.

Wang, J. C. (2012). A study on the energy performance of hotel buildings in Taiwan. *Energy and Buildings*, 49, 268-275.

World Business Council for Sustainable Development & World Resources Institute (WBCSD & WBI). (2004). The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition). https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf (accessed 23 October 2018)

Wu, X. C., Priyadarsini, R. & Lee, S. E. (2010). Benchmarking energy use and greenhouse gas emissions in Singapore's hotel industry. *Energy Policy*, 38, 4520-4527.

Ye, H., Ren, Q., Shi, L., Song, J., Hu, X., LI, X., Zhang G., Lin, T. & Xue, X. (2018). The role of climate, construction quality, microclimate, and socio-economic conditions on carbon emissions from office buildings in China. *Journal of Cleaner Production*, 171**,** 911-916.