The following publication Lai, J. H. K., & Lu, M. (2024). Carbon emission and maintenance cost of commercial buildings: Quantification, analysis and benchmarking. Journal of Cleaner Production, 447, 141459 is available at https://doi.org/10.1016/j.jclepro.2024.141459.

Carbon emission and maintenance cost of commercial buildings: quantification, analysis and benchmarking

Abstract:

Minimizing the carbon emissions of buildings entails effective resources deployment to maintain the buildings and their facilities. Through an environmental-economics lens, a mixed methods research was conducted on 27 commercial buildings, from which reliable and longitudinal data were collected. Considering the different mixes of premises (office, retail and car park) in the buildings and their variability in carbon emission intensity and maintenance cost intensity, a normalization method was developed based on appropriate scaling factors of the premises. Correlation analyses revealed significant correlations between building age and builder's work maintenance cost, as well as between building area and carbon emissions. The finding that the carbon emission intensities of the buildings decreased with capital project costs implies that capital projects, especially energy retrofits, can significantly reduce carbon emissions. Using the benchmarking charts constructed, the buildings - with or without capital projects implemented - were compared in terms of carbon emissions and maintenance costs. Besides contributing insights into future research, the study results hold significance for stakeholders including policy makers, building owners and facilities managers in optimizing maintenance resources for attaining a cleaner built environment.

Keyword: Benchmarking; carbon; commercial building; energy; maintenance cost; scaling factor.

1. Introduction

The global energy consumption and carbon emissions have continued to rise. According to the International Energy Agency (IEA), buildings are responsible for over a third of energy consumption and 19% of energy-related carbon emissions (IEA, 2022). In metropolises, buildings account for more than 60% of citywide total carbon emission: 66% in New York City (NYC, 2022), nearly 68% in London (GLA, 2020), around 72% in Tokyo (TMG, 2022), and over 60% in Hong Kong (EEB, 2023).

Commercial buildings, in fact, are prominent energy consumers that warrant meticulous attention. In Hong Kong, commercial buildings surpassed all other sectors, accounting for 43% of the total energy consumption, which is much more than the proportion (24%) contributed by residential buildings (EMSD, 2023). Similarly, in Singapore, the commercial sector is responsible for 38.6% of the total electricity consumed, which significantly outweighs the residential sector's contribution (14.4%) (EMA, 2023). In China, the carbon emission intensity of commercial buildings is more than double of the national average for buildings (Wang *et al.*, 2023). Although carbon emission has become a hot research topic in recent years, a comprehensive understanding of the carbon emissions emanating from commercial buildings remains elusive (Lu & Lai, 2020).

Over the entire lifespan of a commercial building, the operation and maintenance (O&M) stage accounts for as high as 90% of the building's lifecycle energy use (Sartori & Hestnes, 2007;

Blengini, 2009; Martínez-Rocamora *et al.,* 2017), representing the predominant contributor to carbon emissions (Ramesh *et al*., 2010; de Wilde *et al*., 2011; Lai, 2016; Ma *et al.*, 2017). Hence, it is essential to identify effective measures for minimizing carbon emissions during the O&M stage. But the implementation of such measures entails resource input, i.e. maintenance cost. In this context, gaining an in-depth understanding of the relationship between maintenance cost and carbon emission of commercial buildings assumes paramount significance. Such insights will empower decision-makers to optimize resource allocation while effectively mitigating the buildings' emissions.

In principle, buildings with a higher maintenance cost would have more resources available for the upkeep and improvement of their facilities. On the other hand, a higher maintenance cost could be associated with buildings where the condition of their facilities is poorer, i.e. leading to more energy use and carbon emissions. To date, however, limited research has been undertaken to explore the empirical relationship between carbon emission and maintenance cost of commercial buildings, for reasons such as the dearth of reliable maintenance cost data (Lai & Yik, 2008). Due to the complex mix of premises (e.g. retail, office) in commercial buildings, a robust normalization and benchmarking method (Lai *et al*., 2008) is also lacking.

Despite the above predicaments, the present study was conducted to investigate the nexus between carbon emissions and maintenance costs of commercial buildings. To attain this aim, concomitant research questions are: 1) How to credibly quantify buildings' carbon emissions and maintenance costs? 2) Are there any relationships between the parameters of buildings' carbon emissions and maintenance costs? 3) How to benchmark the buildings' performance in terms of carbon emission and maintenance cost?

With these research questions in mind, the next section of this paper portrays the contextual background of the study by presenting a critical review of the key relevant literature. Then, the data collection methods and analysis methods are elucidated. After presenting the results and discussing the analyzed findings, the paper draws conclusions and proffers recommendations for further research.

2. Contextual background and critical literature review

2.1 Carbon emissions of commercial buildings

Among the limited in-depth empirical research on carbon emission of commercial buildings (Lu & Lai, 2020), Lai & Lu (2019) found that the carbon emission intensity of commercial buildings in Hong Kong ranged from 8.2 to 173.8 kg $CO_{2\text{-}e}/m^2$/year, with an average of 71.7 kg $CO_{2\text{-}e}/m^2$/year. These findings are in line with prior research on carbon emissions in Hong Kong, where the average emission intensity of office buildings was found to be 190 kg/m^2/year and the emission intensities of hotels ranged from 167 to 287 kg/m^2/year (Jing *et al.,* 2017; Lai, 2015). In Singapore, a carbon emission intensity of approximately 221.8 kg $CO_{2\text{-}e}/m^2$/year for its hotels was reported (Wu *et al.,* 2010). Commercial buildings in Beijing, Shanghai and Bristol also exhibited significant carbon emission intensities, which were 178 kg $CO_{2\text{-}e}/m^2$/year, 119 kg $CO_{2\text{-}e}/m^2$/year and 250 kg $CO_{2\text{-}e}/m^2$/year, respectively (Jiang & Tovey, 2010; Acha *et al.,* 2018). It is worth noting that among various types of commercial buildings, hotels, due to their round-the-clock operations, typically recorded higher energy use intensities (EUIs) and carbon emission intensities, whereas the counterparts, e.g., office buildings, are generally lower (BCA, 2018; Lai & Lu, 2019; EMSD, 2022a). Furthermore, building size plays a crucial role in emission performance, as smaller buildings generate higher carbon emissions per unit floor area when compared to the larger ones (BCA, 2018; Lai & Lu, 2019).

In sub-tropical regions, commercial buildings consume large amounts of energy for cooling. According to official statistics (BCA, 2018; EMSD, 2022b), the carbon mitigation efforts undertaken in Hong Kong and Singapore have yielded discernible reductions in EUIs. Legislation and guidance have also been introduced to bolster the carbon reduction culture. For instance, the Hong Kong government promulgated a set of guidelines to assist building managers in measuring the carbon emissions of their buildings (EMSD & EPD, 2010). Moreover, an online building energy benchmarking tool for residential, commercial and transportation sectors has been introduced, which aims to help improve building energy efficiency and reduce building carbon emission (EMSD, 2022a).

The O&M stage of a commercial building bears responsibility for the major part of its total lifecycle carbon emission, while the other lifecycle stages collectively account for 10~20% of the total carbon emission, with the proportion of carbon emission during construction and demolition being around 0~2% (Ramesh *et al.*, 2010; Jiang et *al.,* 2013; Martínez-Rocamora *et al.*, 2017). Carbon emissions during the renovation phase were found to be negligible in comparison to those during the maintenance stage (Rosselló-Batle *et al.,* 2010; Park & Hong, 2011). Hence, it is of utmost importance to devise effective strategies for emission reduction during the O&M stage. In this connection, the imperative lies in a credible quantification of carbon emissions, coupled with a comprehensive exploration of their intricate relationship with maintenance costs.

Furthermore, to enable comparison of carbon emissions and thus identify best practices of carbon mitigation from peer commercial buildings, various studies have ventured into establishing emission benchmarks for different building lifecycle stages. For instance, Simonen *et al.* (2017) formulated benchmarks for carbon emissions arising from extracting and manufacturing building materials, termed embodied carbon emissions. Focusing on the building-in-use stage, Wu *et al.* (2010), Huang *et al.* (2015) and Lai & Lu (2019) conducted benchmarking studies on carbon emissions of buildings in Singapore, Taiwan, and Hong Kong respectively.

2.1 Maintenance costs of commercial buildings

Maintenance costs of buildings can be broadly classified into two categories: the cost for maintaining building services installations (e.g. air-conditioning system, electrical system) and the cost for maintaining builder works (e.g. façade, roof). In each category, the maintenance cost comprises components including expenses associated with routine maintenance activities (i.e., repair and maintenance (R&M) cost), and unanticipated occurrences (e.g., typhoons) or significant financial outlays for works such as retrofits (i.e., capital project cost) (Lai, 2016; Vitiello *et al*., 2019). Examples of routine maintenance activities are: inspection of lifts, repair of faulty control circuits, replacement of malfunctioned lighting, etc. For capital projects that take place occasionally (e.g. once in 15 years), the replacement of chillers and re-roofing are two examples.

When compared to the extensive studies on building energy consumption and energy efficiency, research on building maintenance costs has been relatively less. Nevertheless, some investigations have affirmed the intrinsic connection between maintenance management and energy use (Lewis *et al*., 2011). Recognizing the potential for enhancing energy performance, Farahani et al. (2019) conducted a comparative analysis of three building maintenance and renovation scenarios. Lee *et al.* (2017) explored NABERS-rated buildings and ascertained that those displaying superior environmental performance realized notable O&M cost savings. Lai (2016) analyzed the nexus between energy consumption and maintenance costs across 30 upmarket hotels, revealing that capital project cost outstripped all other components of the maintenance cost. Lai & Yik (2008) unveiled that the cost for maintaining lifts and escalators constitutes a substantial share of the contract costs within the repair and maintenance cost structure for hotels. Given that this study focused exclusively on hotels - a sub-category of commercial buildings, further investigation is needed to determine whether these patterns and links can be broadly applicable to other types of commercial buildings.

Research has demonstrated that building retrofits can mitigate carbon emissions while minimizing maintenance costs from a life-cycle perspective (e.g. Carlson & Pressnail, 2018, Nägeli *et al*., 2019). Nonetheless, further exploration is warranted to optimize the equilibrium between renovation expenses and carbon emission efficiency (Nägeli *et al*., 2019; La Fleur *et al*., 2019; Streicher *et al*., 2020). Given the requirement for new buildings in Europe to be net-zero emission buildings, more and more studies have probed into the gap between the cost-optimal and net-zero emission buildings (Pallis *et al*., 2019a; Pallis *et al*., 2019b). Referring to the German demonstration program 'Energy Optimized Building (EnOB)', Wagner *et al.* (2014) conducted a thorough investigation on commercial buildings within the program, unveiling that compared to conventional buildings, the maintenance costs of these buildings were not elevated while energy use was mitigated.

While routine maintenance cost dominates the total O&M cost, capital projects on installations such as chillers, heat and power systems (e.g. turbines, heat pumps) have the potential to optimize both energy performance and maintenance costs. Lai *et al.* (2009) revealed that the maintenance cost of large chiller plants for commercial buildings can be economized by the scale of the plants. Wen *et al.* (2020) investigated various scenarios of optimally designed Distributed Energy Systems (DESs) and conducted case studies on commercial buildings in Changsha, China. The results showed that all the scenarios yielded substantial energy and O&M cost savings. Whereas cooling poses a primary concern in tropical areas, heating becomes a significant consideration in other regions. Wiryadinata *et al.* (2016) investigated the energy and economic effects of ground-source terminal heat pumps (GTHP) in hotels and motels; the modeling results showed diminished routine maintenance and lifetime capital costs. Based on published data of reference buildings, Rist *et al.* (2017) conducted case studies on an energy system – an economic dispatch of a single micro-gas turbine under combined heat and power (CHP) operation, revealing that this economic dispatch of a micro gas turbine can results in savings in electricity, heating and maintenance cost.

Despite the foregoing efforts on maintenance cost research, empirical data on maintenance cost are inherently sensitive and thus arduous to obtain (Lai *et al.*, 2008; 2009). To tackle this hurdle, Fulcher *et al.* (2022) proposed a mixed philosophical approach that amalgamates both pragmatic and interpretive elements. However, studies that reveal detailed maintenance cost breakdowns of commercial buildings remain limited, let alone research that examines the effect of maintenance cost on carbon emissions of the buildings.

3. Materials and Methods

To plug the above research gap, this empirical study entails reliable data of maintenance costs and carbon emissions. For this purpose, face-to-face interviews were held with facilities management (FM) professionals working on commercial buildings in Hong Kong (Lai & Lu, 2019). The professionals were requested to retrieve their FM records and complete a template that the study team designed for collecting the needed data. Eventually, data of 27 commercial buildings were included in the analysis. The three distinct categories of the data are: i) physical characteristics of the buildings, including age, number of floors, and total internal floor area (IFA); ii) energy consumptions; and iii) maintenance costs. The energy consumption data were retrieved from the monthly electricity bills of the buildings while the maintenance cost data were retrieved from the buildings' annual expenditure accounts by the FM professionals. Both were collected cover a period of six years. As elucidated below, this approach minimizes the impact of yearly fluctuations in carbon emissions or maintenance costs when determine their mean annual values.

3.1 Quantification of carbon emission

The buildings' carbon emissions were quantified with reference to the methodology elucidated in Lai (2015), which was formulated following the guidelines of the government (EMSD & EPD, 2010). This set of guidelines aligns with the Greenhouse Gas Protocol (WBCSD & WRI, 2004). According to the Protocol, carbon emissions fall into three scopes: Scope 1 encompasses emissions from on-site direct fuel combustion; Scope 2 covers emissions due to consumption of purchased electricity; Scope 3 accounts for emissions from using electricity to process fresh water and sewage. Since electricity consumption contributes to more than 90% of the total carbon emission of commercial buildings (Lai & Lu, 2019), the annual carbon emission of each building investigated in the present study (i.e. Scope 2 emission), averaged over the 6-year data period, was calculated by Eq. (1).

$$\bar{E} = \frac{\sum_{t=1}^{t=T} EU_t \times F_t}{T} \tag{1}$$

Where

$\bar{E}$= mean annual carbon emission (kg $CO_{2\text{-}e}$)

EU_t= electricity used in the t^{th} year (kWh)

F_t = emission factor of electricity used in the t^{th} year (kg CO_2-e/kWh)

T = 6, for a data period of six years

The buildings studied are located in various districts of Hong Kong, where the electricity supplies are from two power companies, namely, China Light & Power Hong Kong Limited (https://www.clp.com.hk/en/index) and The Hong Kong Electric Company Limited (https://www.hkelectric.com/). Thus, the emission factors of electricity consumption pertaining to these two companies, which were published in their respective annual reports, were taken to calculate the buildings' carbon emissions.

3.2 Calculation of maintenance cost

The total maintenance cost of each building, encompassing two elements (R&M cost and capital project cost), was calculated using Eq. (2). Each of these elements embraces two sub-categories: building services cost, and builder's work cost. Hence, the R&M cost was calculated by Eq. (3) and the capital project cost was calculated by Eq. (4). Averaging the cost data over the six years (T = 6), the annual total maintenance cost was calculated (Eq. (5)).

$$C_{Total,t} = C_{R\&M,t} + C_{Cap,t} \tag{2}$$

$$C_{R\&M,t} = C_{R\&M\ BS,t} + C_{R\&M\ BW,t} \tag{3}$$

$$C_{Cap,t} = C_{Cap\ BS,t} + C_{Cap\ BW,t} \tag{4}$$

$$\bar{C} = \frac{\sum_{t=1}^{t=T} C_{Total,t}}{T} \tag{5}$$

Where

$\bar{C}$ = mean annual total maintenance cost ($)

$C_{Total,t}$ = total maintenance cost of the t^{th} year ($)

$C_{R\&M,t}$ = repair and maintenance cost of the t^{th} year ($)

$C_{Cap,t}$ = capital project cost of the t^{th} year ($)

$C_{R\&M\ BS,t}$ = cost of building services (within R&M's scope) of the t^{th} year ($)

$C_{R\&M\ BW,t}$ = cost of builder's work (within R&M's scope) of the t^{th} year ($)

$C_{Cap\ BS,t}$ = cost of building services (within capital project's scope) of the t^{th} year ($)

$C_{Cap\ BW,t}$ = cost of builder's work (within capital project's scope) of the t^{th} year ($)

3.3 Scaling factor for normalization of carbon emission

Past studies and statistics reports have shown that the carbon emission intensity of office buildings is generally lower than that of retail buildings (BCA, 2018; Lai & Lu, 2019; EMSD, 2022a), whereas car parks mark the lowest carbon emissions compared to office buildings and retail buildings (Yik *et al.*, 1998). Since the 27 sampled buildings encompass a blend of office, retail and car park premises, it is essential to determine appropriate scaling factors for the different types of premises, enabling the normalization of buildings' carbon emissions and maintenance costs. Using such normalized values, fair and meaningful comparisons or benchmarking of carbon emissions and maintenance costs can be conducted across the buildings.

In the study of Lai *et al.* (2008), the scaling factor for energy use of office premises $(SF_{e,o})$ was 1.00 (i.e. base reference value), and the scaling factor for energy use of retail premises $(SF_{e,r})$ - calculated based on previous survey studies - was found to be 1.48. As regards car parks, they typically exist in commercial buildings, as is the case for all the 27 sampled buildings in this study. Car parks exhibit significantly lower energy use than office and retail premises (Yik *et al.*, 1998); although past research has mostly excluded car park emissions from their analyses, it is necessary to include the energy use and hence carbon emission of car parks in the overall carbon audit of the sampled buildings.

The detailed energy audit of Yik *et al.* (1998) found that the energy consumption of car parks was primarily for lighting and ventilation, rendering it relatively stable over time. Considering the EUI of the car park ventilation system and that of the car park lighting and power system, the total EUI of the car park (EUI_c) is 9.7 kWh/ m^2/year, i.e., 34.9 MJ/m^2/year. The EUI of office premises (EUI_o) is 408 MJ/ m^2/year, which is the average EUI of three categories of office buildings, i.e., Grade A (398 MJ/m^2/year), Grade B (424 MJ/m^2/year) and Grade C (402 MJ/m^2/year) – according to the statistics of EMSD (2022a). Thus, the scaling factor ($SF_{e,c}$) for car park, calculated by Eq. (2), is 0.09.

$$SF_{e,c} = \frac{EUI_c}{EUI_o} \tag{6}$$

Where

EUI_c = EUI of car park (kWh/m^2/year)

EUI_o = EUI of office premises (kWh/m^2/year)

$SF_{e,c}$ = Scaling factor for energy use of car park

As mentioned earlier, carbon emission of commercial buildings is dominated by the part due to electricity use. Thus, the scaling factors for EUI of the different premises types were taken as the scaling factors for the respective carbon emission intensities. Following the normalization approach of Lai *et al.* (2008), the equivalent office internal floor area (EOIFA) of each type of premises was determined by applying the scaling factor to the respective internal floor area (Eq. (7)). Using such calculated results and the carbon emissions quantified by Eq. (1), the normalized annual carbon emission of the individual building was determined (Eq. (8)).

$$EOIFA_{e,i} = SF_{e,i} \times IFA_i \tag{7}$$

$$E_{norm} = \frac{\bar{E}}{\sum_{e,i} EOIFA_{e,i}} \tag{8}$$

Where

IFA_i = internal floor area of premises i (office, retail, or car park) (m^2)

$SF_{e,i}$ = scaling factor of energy use intensity for premises i

$EOIFA_{e,i}$= equivalent office internal floor area of premises i (m^2)

$\sum_{e,i} EOIFA_{e,i}$= total equivalent office internal floor area of individual building (m^2)

E_{norm} = normalized annual carbon emission of individual building (kg $CO_{2\text{-}e}/m^2$)

3.4 Scaling factor for normalization of maintenance cost

Similar to carbon emissions, building maintenance costs vary with the types of premises. To account for such variations and thus enable fair comparisons of the maintenance costs between the sampled buildings (with different mixes of premises types), the typical maintenance cost ratios between the different premises types, which were drawn from the interview responses, were taken as the scaling factors for normalization of the buildings' maintenance costs. With the base reference value for the cost scaling factor for office premises being 1.00, the scaling factor for maintenance cost of retail premises was 1.80 and that for car park was 0.25. Using these scaling factors, the equivalent office internal floor area of each type of premises was calculated by Eq. (9).

After calculating the equivalent office internal floor areas for different premises types, the maintenance costs for different scopes of maintenance work were normalized using Eq. (10). Summing these calculated results (Eq. (11)), the normalized annual total maintenance costs of individual buildings were obtained.

$$EOIFA_{c,i} = SF_{c,i} \times IFA_i \tag{9}$$

$$C_{norm,f} = \frac{\overline{C_f}}{\sum_{c,i} EOIFA_{c,i}} \tag{10}$$

$$C_{norm,T} = \sum\nolimits_f C_{norm,f} \tag{11}$$

Where

IFA_i = internal floor area of premises i (office, retail, car park) (m^2)

$SF_{c,i}$ = scaling factor (*SF*) of maintenance cost for premises i

$EOIFA_{c,i}$= equivalent office internal floor area of premises i (m^2)

$\overline{C_f}$= annual maintenance cost for scope f (R&M, capital project) ($)

$\sum_{c,i} EOIFA_{c,i}$= total equivalent office internal floor area of individual building (m^2)

$C_{norm,f}$= normalized annual maintenance cost of scope f ($\$/m^2$)

$C_{norm,T}$= normalized annual total maintenance cost of individual building ($\$/m^2$)

3.5 Correlation analysis and benchmarking

To identify if there exists any correlation between key parameters of the buildings' characteristics, carbon emissions and maintenance costs, the Pearson correlation coefficient (r) was calculated using the SPSS software. With r ranging between -1 and +1, a value of 0 indicates that there is no association between the two parameters. The stronger the correlation between the two parameters, the closer the value of r will be to either -1 or +1, depending on whether the correlation is negative or positive, respectively.

Benchmarking is a useful performance evaluation tool that enables the identification of best practices from organizations or buildings. To develop such tools, the carbon emissions and maintenance costs determined by the forgoing calculation processes were taken to construct benchmarking charts. With reference to some earlier studies (Lai, 2016; Lai & Lu, 2019), the charts constructed include not only those for total carbon emissions and total maintenance costs but also their constituent components. To visualize distinctions between the buildings in terms of carbon emission and maintenance cost, in particular, benchmarking charts with grouped performance curves - for buildings with capital projects implemented and for those without - were also constructed.

4. Results and discussion

4.1 Building characteristics

The 27 buildings studied comprise a heterogeneous mixture of retail, office and car park premises. Ranging from 6 to 36 years, the buildings were on average 21 years of age and their standard deviation (*S.D.*) was 8 years (Table 1). In terms of total IFA, the buildings vary from 4,569 m^2 to 135,284 m^2, with a mean value being 36,951 m^2. The tallest building has 46 storeys while the shortest one has only 2 storeys; on average, the sampled buildings are 16-storey high.

Table 1. Building characteristics

	mean	max	min	S.D.
Building age (years)	21	36	6	8
Number of storeys	16	46	2	13
Total IFA (m^2)	36,951	135,284	4,569	30,793

4.2 Quantified carbon emissions and maintenance costs

Averaged over the 6-year data period, the annual electricity consumption of the buildings ranges from 396,132 kWh to 18,011,138 kWh, and the mean consumption level was 4,270,057 kWh (Table 2). Correspondingly, the lowest annual carbon emission level found from the sample was 238 tonnes of $CO_{2\text{-e}}$ while the highest level was 10,548 tonnes of $CO_{2\text{-e}}$, which is around 4 times the average level. Based on the scaling factors, the EOIFA for carbon emission intensity shows a maximum value of 134,004 m^2, which is more than 70 times the minimum value and almost 4 times the mean value. The counterparts of EOIFA for maintenance costs, with mean value being 41,983 m^2, range from 2,149 m^2 to 153,439 m^2.

Table 2. Maintenance costs and carbon emission sampled buildings

	mean	max	min	S.D.
Annual electricity consumption (kWh)	4,270,057	18,011,138	396,132	4,839,224
Annual carbon emission (tonnes of $CO_{2\text{-}e}$)	2,632	10,548	238	2,866
$EOIFA_e$ (m^2)	35,788	134,004	1,869	34,753
$EOIFA_c$ (m^2)	41,983	153,439	2,149	40,447
Annual R&M cost ($)	2,653,855	13,982,845	212,038	2,988,269
*Annual capital project cost ($)	551,583	5,353,333	4,321	1,210,092
Annual BS cost ($)	2,357,681	9,946,668	173,198	2,337,416
Annual BW cost ($)	847,756	7,257,004	13,890	1,531,881
Annual total maintenance cost ($)	3,205,438	13,982,845	212,038	3,408,464

*Note: Cost values calculated based on those buildings with capital projects carried out.

As for maintenance costs, the currency of the dataset is Hong Kong Dollar ($), where $1 is about 0.128 US Dollars. The mean annual R&M cost of the 27 buildings was $2,653,855, which is approximately 5 times the mean annual capital project cost ($551,583). Since capital projects are implemented occasionally, only 13 of the buildings were found to have such projects carried out over the 6-year data period. Thus, the capital project costs in Table 2 were calculated based on the data of these 13 buildings. Compared with the R&M costs, the capital project costs were significantly lower.

On average, the annual total maintenance costs of the 27 buildings were between $212,038 and $13,982,845, with their mean cost level being $3,205,438. The annual cost for maintaining building services ($2,357,681) was almost 3 times the cost for maintaining builder's work.

For fair comparisons, the annual carbon emissions and annual maintenance costs were both normalized by the EOIFA of the respective building. Varied from 6 kg $CO_{2\text{-}e}/m^2$ to 165 kg $CO_{2\text{-}e}/m^2$, the mean level of the annual carbon emission is 77 kg $CO_{2\text{-}e}/m^2$, which is about half of the maximum level (Table 3). On average, the annual R&M costs account for around 80% of the total maintenance costs. The average cost spent on capital projects per year amounts to $\$16/m^2$, which corresponds to about a quarter of the average R&M cost and one fifth of the average total maintenance cost. With mean, maximum and minimum levels being $\$62/m^2$, $\$226/m^2$ and $\$16/m^2$ respectively, the building services (BS) maintenance costs are much higher than the counterparts of the building works (BW). Overall, the normalized annual total maintenance costs range from $\$17/m^2$ to $\$249/m^2$, and the average level is $\$79/m^2$, which is about one-third of its maximum level.

Table 3. Normalized annual carbon emission and maintenance costs of buildings

	mean	max	min	S.D.
Normalized annual carbon emission (kg $CO_{2\text{-}e}/m^2$)	77	165	6	41
Normalized annual R&M cost ($\$/m^2$)	63	157	17	34
Normalized annual Capital project cost ($\$/m^2$)	16	136	0	32
Normalized annual BS cost ($\$/m^2$)	62	226	16	44
Normalized annual BW cost ($\$/m^2$)	17	110	0.8	21
Normalized annual total maintenance cost ($\$/m^2$)	79	249	17	51

4.3 Correlations between key parameters

The Pearson correlation analysis was conducted using the data collected from the 27 buildings. For the correlation analyses involving capital project cost data, such data of 13 of the sampled buildings with capital projects implemented over the data period were considered. Results of the correlation analyses between the buildings' characteristics and their electricity consumptions and carbon emissions are summarized in Table 4. $EOIFA_e$ was found to exhibit a significant positive correlation with annual electricity consumption ($r = 0.810$) and annual carbon emission due to electricity consumption ($r = 0.815$). This is reasonable because buildings with a larger floor area would require more energy-consuming facilities, resulting in higher electricity consumption and thus higher carbon emission. Intriguingly, building age does not show a strong correlation with electricity consumption or carbon emission. This finding does not support the anticipation that buildings that are older would have their facilities deteriorated and thus consume more energy, generating more carbon emissions.

To examine whether maintenance cost is a significant factor making the older buildings less energy inefficient and hence emitting less carbon than anticipated, further analyses were conducted. As the correlation matrix in Table 5 shows, $EOIFA_c$ is a pivotal parameter exhibiting a significant correlation with all types of maintenance costs except the capital project cost. Notably, capital project cost shows a significant positive correlation with BW cost ($r = 0.663$) and a moderate correlation relationship with total maintenance cost, but it is not significantly correlated with R&M cost. Neither does it exhibit a significant correlation with building age. The highest positive correlation ($r = 0.937$) was found between R&M cost and total maintenance cost, implying that the former is a major cost element of the total cost required for maintaining the buildings. The correlation between BS cost and R&M cost is also high ($r = 0.933$). This indicates the significance of BS cost among the various costs required for providing repair and maintenance work for the buildings.

Table 4. Correlation matrix (building characteristics, electricity consumption and carbon emission)

	Age	EOIFA$_e$	Electricity consumption	Carbon emission
Age	1			
EOIFA$_e$	0.293	1		
Electricity consumption	0.045	0.810**	1	
Carbon emission	0.065	0.815**	0.993**	1

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

Table 5. Correlations matrix (building characteristics and maintenance costs)

	Age	EOIFA$_c$	R&M cost	Capital project	BS cost	BW cost	Total maintenance
Age	1						
EOIFA$_c$	0.274	1					
R&M cost	0.127	0.799**	1				
Capital project cost	0.337	0.114	0.169	1			
BS cost	0.100	0.748**	0.933**	0.300	1		
BW cost	0.361	0.508**	0.660**	0.663**	0.532**	1	
Total maintenance cost	0.231	0.741**	0.937**	0.503**	0.925**	0.814**	1

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

4.4 Relationship between carbon emission and maintenance cost

A plot depicting the relationship between annual carbon emission and annual total maintenance cost is displayed in Fig 1. There is a clear trend that the carbon emission of the building increases with the costs for maintaining the buildings. This, however, could not be taken a straightforward conclusion because the buildings are different in scale, which could be a factor affecting the resources needed for maintaining the buildings. To better investigate the trend between the buildings' carbon emissions and their maintenance costs, these parameters were normalized by the respective building's EOIFA. Plots of such normalized annual carbon emissions against normalized annual total maintenance costs, R&M costs and capital project costs are presented in Fig. 2(a) to (c).

Compared with the trend observed from Fig. 1, the upward trend of normalized annual carbon emissions against normalized annual total maintenance tends to plateau at around \$100/m^2 and even reverse afterwards (Fig. 2(a)). This suggests that with more maintenance resources devoted, it is likely that the carbon emission would drop. Given that the number of data points showing this likelihood in the present study is limited, research in future should endeavor to collect data from more buildings to test if this suggestion holds.

With a trend similar to that in Fig. 2(a), the normalized annual carbon emissions plotted in Fig. 2(b) initially increases with the normalized annual R&M cost, followed by plateauing and then declining as the R&M cost further increases. Plausible reasons for this observation include: i) R&M cost mainly accounts for ordinary repair work for facilities breakdowns. With more unplanned breakdowns, more corrective maintenance works are needed, which mainly fix ad-hoc maintenance problems rather than improve the energy efficiency or reduce the carbon emission of deteriorated facilities; and ii) further input of R&M cost allows more preventive maintenance works to be carried out, which helps the upkeep of the facilities and hence their energy performance. To proof the validity of these plausible reasons, future research is needed to, for example, collect sub-categories of corrective and preventive maintenance cost data for detailed analysis.

The relationship between carbon emission and capital project cost is plotted in Fig 2(c). Although there is no apparent pattern of the data points, it is noted that such buildings (with capital projects implemented) have a moderate carbon emission intensity level - ranging between 40 and 120 kg CO_{2-e}/m^2. The normalized capital project cost range is below $\$140/m^2$, which in practice is often constrained by budgets (Lai, 2010). Different from R&M cost, capital project cost usually covers major retrofits, e.g. replacement of air-conditioning systems. Replacing the degraded facilities with new ones, the energy efficiency of the facilities can be improved significantly. As a result, an increase in capital project cost generally effects more building energy retrofits and hence a decrease in carbon emission intensity. However, since no obvious upward or downward trend can be observed from the plot, it is not clear whether the implemented capital projects were ineffective in reducing carbon emissions or whether those projects were not intended for improving building energy performance. These uncertainties, therefore, warrant further investigations.

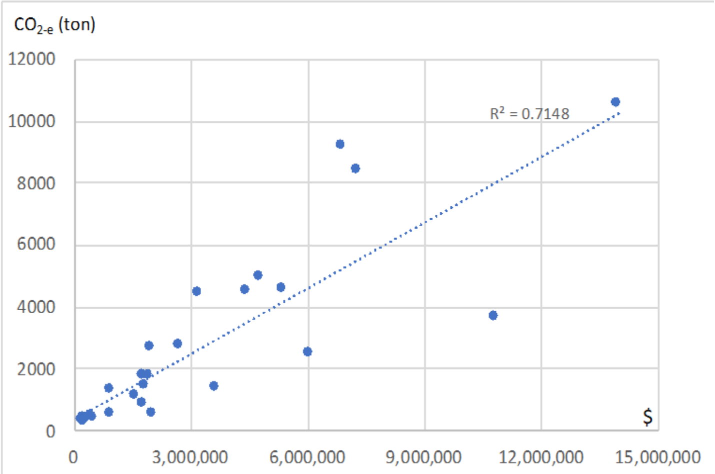


Fig 1. Annual carbon emissions vs annual total maintenance costs

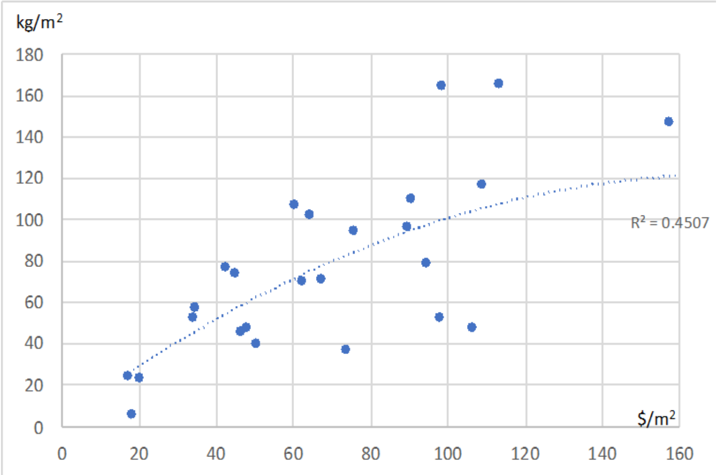


Fig. 2(a) Normalized annual carbon emissions vs normalized annual total maintenance costs

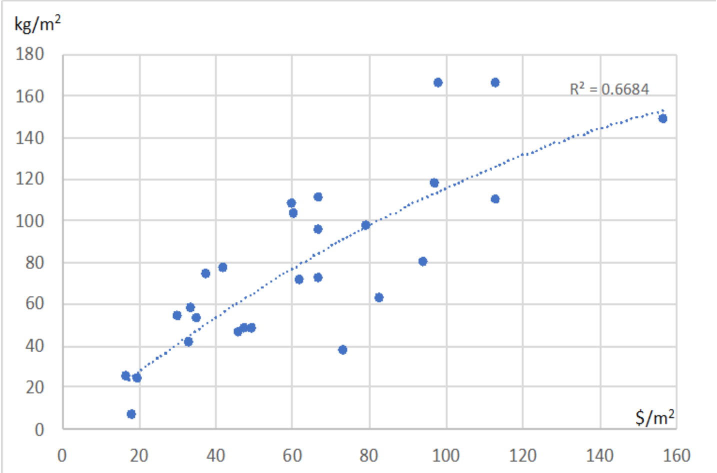


Fig. 2(b) Normalized annual carbon emissions vs normalized annual R&M costs

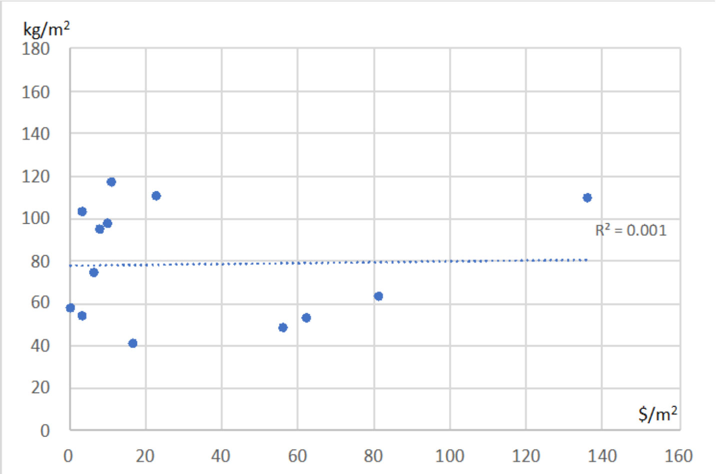


Fig. 2(c) Normalized annual carbon emissions vs normalized annual capital project costs

4.5 Benchmarking maintenance cost and carbon emission

Percentile curves of the annual total maintenance cost, R&M cost and capital project cost, which can serve as benchmarking charts, are plotted in Fig. 3(a) to 3(c). Common to all these charts, there is a gradual upward curve before reaching the 90% percentile, followed by a sharp cost increment in the last 10% percentile, resulting in a plateau-like pattern on the charts. The 90% percentile values for the total maintenance cost and R&M cost are $7,040,375 and $5,611,328, respectively. The median level of total maintenance cost is $1,926,993, which is about 1/7 of the maximum level (Fig 3(a)). The median of the R&M cost is $ 1,789,222, which is nearly 9 times of its minimum value ($212,038) (Fig 3(b)). When analyzed based on all the 27 sampled buildings, the capital project cost at the 90% percentile level is $1,421,543 (Fig 3(c)), which is about 1/3 of the 90% percentile value of R&M cost (Fig 3(b)). Excluding those buildings without capital project costs, the inflection point of the curve appears at the 70% percentile level, i.e. $ 802,695 (Fig 3(c)).

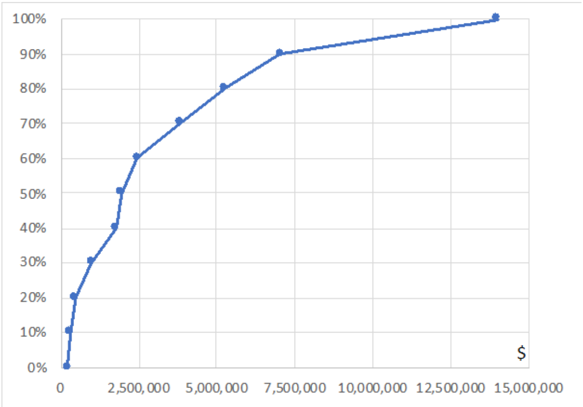


Fig. 3(a) Benchmarking chart for annual total maintenance costs

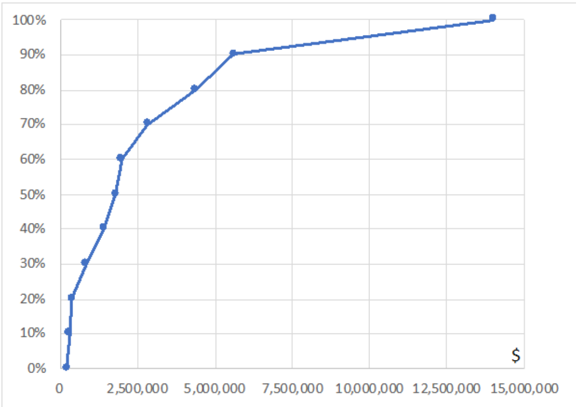


Fig. 3(b) Benchmarking chart for annual R&M costs

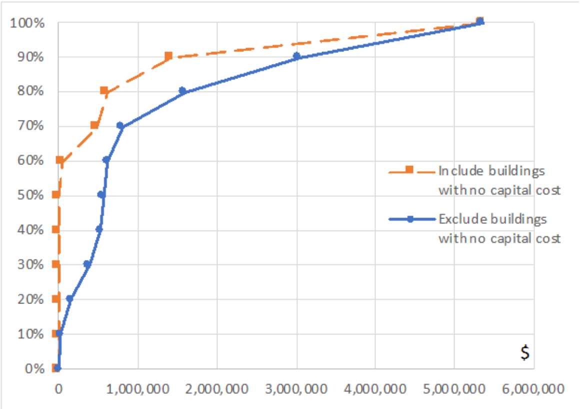


Fig. 3(c) Benchmarking chart for annual capital project costs

Compared with the benchmarking charts plotted based on the raw data, the benchmarking charts of normalized annual total maintenance costs and normalized annual R&M costs demonstrate an almost linear pattern up to the 90% percentile (Fig 4(a) & 4(b)). The 90% percentile levels of the normalized annual total maintenance cost and normalized annual R&M cost are $\$131/m^2$ and $\$104/m^2$, respectively. The median levels of normalized annual total maintenance cost and normalized annual R&M cost are $\$67/m^2$ and $\$61/m^2$, respectively. The normalized annual capital project cost increases significantly after the 60% percentile, no matter considering only those buildings with capital projects executed or all the sampled buildings (Fig 4(c)). With the buildings without capital project cost included in constructing the benchmarking chart, the 60% percentile level of the normalized annual capital project costs is \$3.6/m^2 and the 80% percentile level is \$15.9/m^2. Excluding those buildings without any capital project cost, the 60% percentile level is \$18.3/m^2 and the 90% percentile level is \$77.7/m^2.

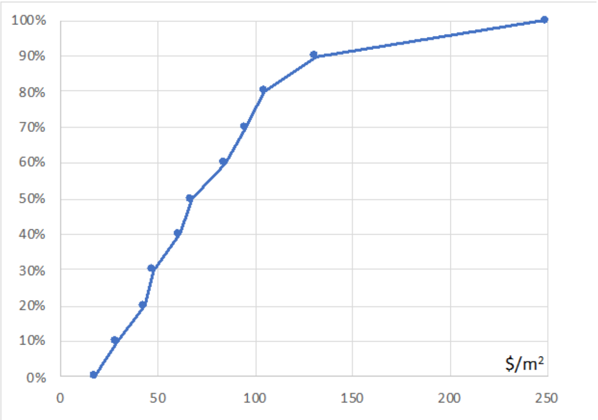


Fig. 4(a) Benchmarking chart for normalized total annual maintenance costs

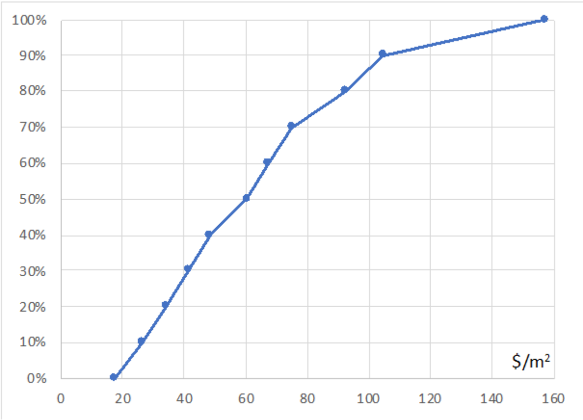


Fig. 4(b) Benchmarking chart for normalized annual R&M costs

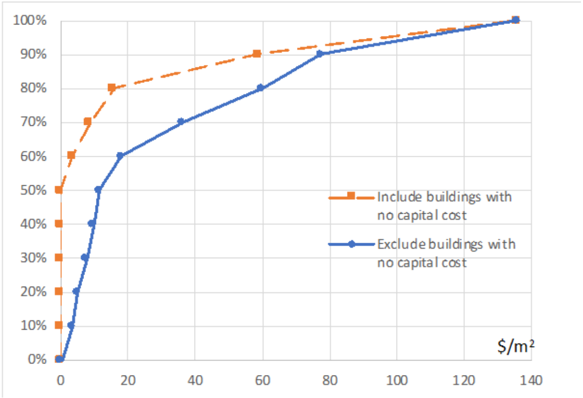
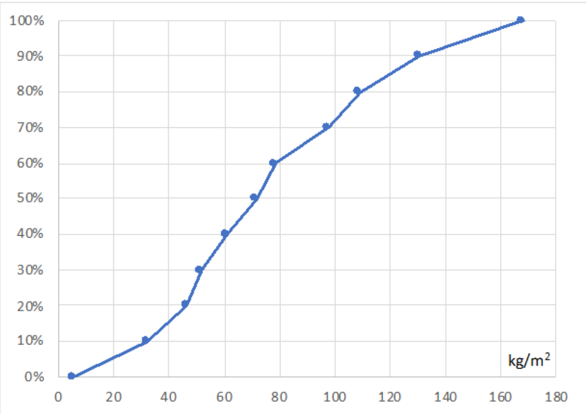


Fig. 4(c) Benchmarking chart for normalized annual capital project costs

Resembling a rather linear upward trend, the benchmarking chart for normalized annual carbon emissions, which was plotted based on all the sampled buildings, exhibits gentle increments within the initial 20% percentile range (Fig. 5). In Fig. 6, the plot for normalized annual carbon emissions of buildings without capital projects also show a rather linear rise up to the 50% percentile, followed by a slower increasing rate towards the 70% percentile and then sharp increments until the 90% percentile. On the other hand, the normalized annual carbon emissions of buildings with capital projects demonstrate a slower linear ascent, especially before the 40% percentile and beyond the 60% percentile. This benchmarking curve spans a narrower range of carbon emission intensities - from 40 kg/m^2 to 117 kg/m^2, the latter being around 2/3 of the highest emission intensity of the buildings with capital projects. These observations lead to the following propositions. First, buildings with a higher carbon emission intensity, which are under larger pressure to curb their carbon emission, are more resourceful in reducing their emission intensity. Such buildings are upmarket buildings with more financial and manpower resources for implementing capital projects. Second, buildings with a relatively lower carbon emission intensity are of a lower quality. With a lower building income drawn from, for example, rentals paid by tenants, these buildings are less motivated to implement capital projects to reducing carbon emission. To prove whether these propositions are true, further studies are needed.



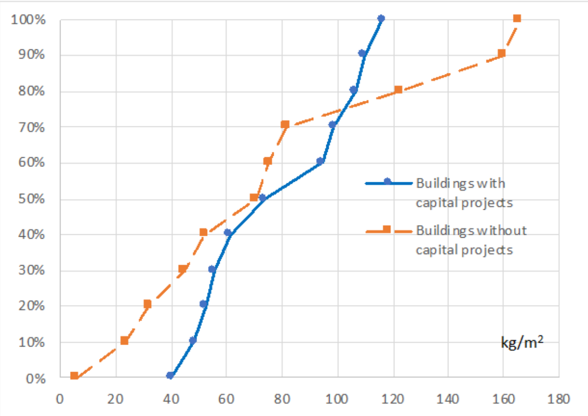


Fig. 5 Benchmarking chart for normalized annual carbon emissions

Fig. 6 Benchmarking chart for normalized annual carbon emissions of buildings: (i) with capital projects, (ii) without capital projects

5. Conclusions

In parallel to the widespread environmental concerns, research on building energy use has continued to expand. Yet, in-depth empirical inquiries into the carbon emissions arising from building energy use remain limited. The scarcity of sensitive data, particularly building maintenance cost data, has exacerbated the longstanding challenge to research on the relationship between carbon emission and maintenance cost of buildings. In order to bridge this research gap, as reported above, detailed longitudinal data of carbon emission and maintenance cost were amassed from 27 commercial buildings for investigation. In addressing the problem of inherent differences in carbon emission and maintenance cost between different types of premises in commercial buildings, a normalization method involving determination and assignment of appropriate scaling factors for the premises was developed, enabling fair comparisons of the carbon emissions and also the maintenance costs between the buildings.

Through a series of correlation analyses, it was revealed that building age is significantly correlated with BW cost, while the building area, quantified in terms of equivalent office internal floor area (i.e. the normalization factor developed in this study), shows a significant correlation with carbon emission and all types of maintenance costs except capital project cost. However, capital project cost is moderately correlated with total maintenance cost. The strong positive correlation between BS cost and R&M cost indicates the significance of BS cost among the various costs for maintaining the buildings.

The finding that carbon emission intensities of the buildings decrease with increasing capital project costs is important. It implies that capital projects, especially those energy retrofits, can significantly reduce carbon reduction. In addition to having the benchmarking charts constructed for carbon emission and various types of maintenance costs of the buildings, it is also found that the range of carbon emission intensities of those buildings with no capital projects implemented is much wider than the counterpart of those buildings with capital projects implemented. These revelations imply: i) buildings with a higher carbon emission intensity are upmarket buildings with more financial and manpower resources for implementing capital projects; and ii) buildings with a relatively lower carbon emission intensity are relatively low-end buildings that are less motivated to implement capital projects to reducing carbon emission. Besides serving as propositions to be examined in similar studies on other regions in future, these findings provide guidance for decision-makers. For example, owners or facilities managers of commercial buildings can prioritize energy retrofits as a key strategy to mitigating carbon emissions of their buildings. In devising financial incentive schemes, policy-makers can consider allocating funding specifically for low-end or small commercial buildings, enabling them to undertake capital projects.

Admittedly, the scope of this study is not unlimited. Factors that may influence the maintenance cost and carbon emission, including user demand, building quality, maintenance practice and so on, were not investigated. Engineering parameters affecting building energy use and hence carbon emission, e.g. thermal properties of building envelope and efficiencies of building services installations, were not covered by the study. While these limitations need to be addressed in future research, the methodology of the above study could be taken to investigate more buildings. When more findings of this kind become available, a range of stakeholders including researchers, facilities managers and environmental policy-makers will benefit from gaining a deeper understanding of how carbon reduction can be achieved through effective deployment of maintenance resources. Not only can researchers and facilities manager benefit from adopting a credible approach to quantify and benchmark buildings' carbon emissions and maintenance costs, but the policy-makers can also take the findings as reference when formulating policies that aim to attain low-carbon buildings.

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