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Impact of COVID-19 on the energy consumption of commercial buildings: A case study in Singapore

Senhong Cai, Zhonghua Gou

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ABSTRACT

Numerous studies have demonstrated that commercial activities have significantly reduced during COVID-19, while there are few studies disclosing the consequent impacts on the energy consumption of commercial buildings. This study explores the changes in energy consumption of different types of commercial buildings in Singapore under the impact of the pandemic, using commercial building energy performance data from 2017 to 2020 (n=540). The sampled buildings include 93 hotel buildings, 303 office buildings, 106 retail buildings, and 38 mixed developments. The analysis mainly used linear regression and paired sample t-test. The results showed that relative to 2019, the mean energy use intensity (EUI) of sampled commercial buildings decreased by 56.77 kWh/m² in the pandemic year (2020), a plunge of 19.9%. The extent to which the EUI of each type of commercial building is affected by the pandemic is found as: mixed development>retail>office>hotel. The study also identified the factors that significantly influenced the EUI of commercial buildings before and during the pandemic. The results of the study complement existing knowledge about the factors influencing energy consumption in commercial buildings by considering the impact of the pandemic and furthermore contribute to the improvement of energy management in commercial buildings by providing directions for building energy efficiency approaches.

1. Introduction

Since the outbreak of COVID-19 was first reported in December 2019, it affected more than 200 countries and regions by 2020, with significant changes in global human activity. In an unprecedented effort to contain the spread of the virus, many countries and regions adopted quarantine measures that include city closures, work stoppages, a ban on gatherings, and working and studying at home [1–3]. The economic impact of the pandemic is wide-ranging with COVID-19 potentially costing the world approximately 2 trillion US dollars in 2020 alone [4], decreasing global GDP by 4.6% [5], and having a huge impact on energy [6–11], environment [6,12,13], and tourism [14,15]. For example, considering energy, there is a clear downward trend in overall energy demand globally as most factories and businesses shut down and commercial and industrial demands decline. Global oil is experiencing an unprecedented shock with a sharp decline in oil demand for industrial, commercial, domestic, and transportation uses, which has led to significant pressure on supply and demand balances and storage to control oil prices [11]. COVID-19 witnessed the lowest growth rate of global energy demand since the 1930s, with global energy demand falling by 6% and electricity demand by about 2% in 2020 [5]. Considering the environment, different types of waste indirectly create many environmental problems, with restriction measures leading to increased online shopping activities by consumers and thus increased household waste. Medical waste has also increased. For instance, Wuhan hospitals produced an average of 240 metric tonnes of medical waste during the outbreak compared to their previous average of fewer than 50 tonnes [13]. Considering tourism, revenues from global destinations could be hit hard as COVID-19 has spread globally. In the coming years, the US tourism industry could lose billions of dollars due to COVID-19 [15].

The COVID-19 pandemic also had a significant impact on the operation of all types of commercial buildings and their energy consumption. Numerous studies have demonstrated a significant reduction in commercial activity during the pandemic, resulting in lower energy consumption in commercial buildings. Zhang et al. [14] noted that hotels, which underpin the tourism industry and are key to attracting large numbers of...
tourists, hit rock bottom to delay the spread of the pandemic, resulting in reduced revenue and energy consumption in tourist cities. Further, due to quarantine measures during the pandemic, some hotels became quarantine areas, offsetting the reduction in electricity consumption. Business travel also fell sharply, accelerating the significant drop in hotel occupancy rates and frequent hotel closures [16]. While studying office buildings, Deis et al. [17] noted that in early March 2020, 1.4 million employees were working in Manhattan, US. In May 2020, during the home-based period, the number quickly dropped to 41,000 employees as offices allowed only essential staff to continue working to slow the spread of the virus. As employees moved to work in their homes, total energy consumption, such as electricity and natural gas, declined. Retail was one of the hardest-hit sectors of the pandemic [18], while retail buildings were also hit hard with many locations unable to conduct in-store shopping due to lockdowns [16]. Local retailers turned to online sales, leading to a significant reduction in demand for retail space [19]. Buechler et al. [20] concluded that tighter government restrictions and greater mobility reductions are closely associated with reduced electricity consumption, particularly in retail and leisure.

Prior to the pandemic, the building sector accounted for 40% of global energy consumption and resources, 25% of global water use, one-third of greenhouse gas emissions [21], and 28% of global CO₂ emissions [22]. The energy efficiency of buildings has had and can still have a significant effect on overall energy efficiency efforts [23]. Of all buildings, commercial buildings are a crucial part of any country’s building stock [24] and consume a significant share of energy. For example, commercial buildings in Canada account for approximately 36% of the country’s energy consumption [25]. In 2020, the US used 18% of its end-use energy in the commercial sector [26]. The potential for emission reduction and energy efficiency in the building sector is huge [27,28]. To promote CO₂ reduction in the building sector, attention should first be paid to commercial buildings, which have a higher CO₂ reduction potential than residential buildings [29]. To make commercial buildings more energy-efficient, it is important to understand the energy consumption levels and influential factors of commercial buildings, which vary according to the type of function. Shopping malls have the highest energy consumption intensity at more than twice that of hotels and approximately five times that of office buildings [30]. Table 1 demonstrates the influential factors of energy consumption in each type of commercial building. It can be concluded from existing studies that heating, ventilation and air conditioning (HVAC) influences energy consumption in all types of commercial buildings, but the same factors have different results for different features, such as floor area for retail and office. The same building type presents different results for different studies, such as hotel’s star rating and the occupancy of hotel.

Generally, studies have focused on the factors that influence energy consumption in commercial buildings in normal years, but there has been limited understanding of energy consumption in commercial buildings under the impact of COVID-19. Therefore, there is a need to study the impact of the pandemic on the energy consumption of commercial buildings to better guide commercial building sector to manage energy efficiency. Gui and Gou [43] found that the energy consumption of green buildings is related to social and economic activities, which led to the inclusion of green certification as a factor influencing energy consumption in this study. Furthermore, the factors that are found to be influential in the energy consumption of commercial buildings during normal periods need to be investigated under the circumstance of COVID-19 to understand the uncertainty of energy consumption conditions in future scenarios. Before the pandemic, commercial buildings had great potential to reduce energy consumption, and after being significantly hit by the pandemic, even more so, their energy consumption reduction presents new opportunities for planning the commercial sector energy demand.

Singapore is a Southeast Asian country that relies heavily on commercial activities to develop its economy. In response to the public health crisis, Singapore adopted a series of restriction policies that immediately slowed the spread of the virus [44]. Social distancing measures were phased in from 10 March 2020, and stricter recommendations and regulations were gradually introduced [45]. On 7 April 2020, Singapore adopted the Circuit Breaker Measure in the form of legislation [46]. For the duration of the implementation period, Singapore required service premises that meet daily needs to be open; workplaces, entertainment venues, attractions, and places of worship to be closed; and hotels including all entertainment facilities to be closed, while schools to fully convert to home learning. The impact of the restriction policies on Singapore’s overall economic situation was significant, with the Singapore economy contracting by 5.4% in 2020 according to the Economic Survey of Singapore 2020 [47]. Within the service sectors, the retail trade sector contracted by 16%, with department stores declining by 40%. The office space market plunged by 11% for the year due to a weak economic environment. International arrivals in 2020 were 85.7% lower than the previous year, and hotel room revenue for the year was S$1.2 billion, down 71.2% [48]. Singapore is an excellent case study for studying the impact of COVID-19 on building energy consumption in commercial buildings, based on the significant impact on commercial buildings in Singapore during COVID-19.

In general, there is a lack of research using real data to examine the role of COVID-19 on energy consumption in commercial buildings. To narrow this gap, this study explores the impact of COVID-19 on commercial building energy consumption in Singapore, including the changes in commercial building energy use intensity (EUI) during the pandemic, and the factors influencing EUI for each commercial building type before and during the pandemic, by using data on the EUI of commercial buildings in Singapore before and during the pandemic.

The main questions of the study are as follows. How much did the pandemic influence the energy consumption of commercial buildings? Which building type in the commercial sector was most influenced by the pandemic in terms of energy consumption? What factors influenced the EUI of each commercial building type before and during the pandemic?

2. Methodology

2.1. Data collection

The data for this study on energy consumption in Singapore’s commercial buildings was obtained from the Singapore government’s public data website [49], which contains national data on Singapore’s economy, education, environment, infrastructure, technology, and other aspects. The data used in this study were published by the BCA (Building and Construction Authority), which contains the commercial building energy performance data collected through BCA’s Building Energy Submission System (BESS) under the legislation on Annual Mandatory Submission of Building Information and Energy Consumption Data for Section 22FJ “Powers to Obtain Information” of the Building Control Act. It ensures that the data used in the study are real measurements collected under local government legislation, providing reliability for the study. The data is available for public to download and use in the form of a tabular file.

The data contains basic information on green commercial buildings in Singapore, including building name, building address, main building type, year obtained TOP (Temporary Occupation Permit)/CSC (Certificate of Statutory Completion), GM (Green Mark) certification (a local green building rating system), gross floor area, percentage of air-conditioned floor area, average monthly building occupancy rate, age of chiller, centralized air-conditioning plant efficiency, and percentage usage of LED. The data also includes the EUI of each commercial building from 1 January 2017 to 31 December 2020 (SGT), which provides information on the energy consumption of each building for the 4 years.
Table 1: Literature review table of influential factors of energy consumption in commercial buildings.

| Reference | Place       | Factors                                      | Methods                                      | Findings                                                                 |
|-----------|-------------|----------------------------------------------|----------------------------------------------|--------------------------------------------------------------------------|
| [31]      | Jiangsu, China | HVAC, monitoring, lighting, domestic hot water, and building envelope system | Economic evaluation model                    | HVAC and lighting are major energy users in hotels. HVAC system, monitoring system, lighting system, domestic hot water system, and building envelope system are the five energy-saving retrofit technical measures with the highest application ratio. |
| [32]      | Jiangsu, China | HVAC, lighting, monitor and control system  | Mathematical statistics analysis            | Application of energy-efficient LED light can achieve energy-saving rate of 70.85%. |
| [33]      | Shanghai, China | Occupancy rate and hotel's class              | Statistical analysis                         | The EUI for 3-star, 4-star and 5-star hotels are 61.95 kgce/m², 73.18 kgce/m² and 86.64 kgce/m² respectively. The relationship between occupancy rate and EUI is difficult to identify. The energy use intensity for individual building is not strictly correlated with hotel's star rating. |
| [34]      | Lijiang, China | Hotel star rating, number of guest rooms, room revenue, and number of workers | Regression methods                           | The number of guest rooms, hotel star rating, room revenue, and number of workers are the major determinants of hotel energy performance. Hotel star rating and yearly occupancy rate represented a standardized distribution of EUI. |
| [35]      | UK          | Floor area, stock composition, and the envelope | Multiple regression models                   | Significant factors included the sales floor area of the store, the stock composition, and the thermo-physical characteristics of the envelope. Volume of sales had the statistical significance of operational usage factors on annual electricity demand. |
| [36]      | Australia   | Scale, temperature, and HVAC                  | Building simulation                          | Retail buildings contribute 35% to commercial sector’s energy use. The energy intensity of retail buildings in hotter climates is higher than the national average, as is the energy intensity of smaller buildings. HVAC represents 43% of electricity consumption for retail and office buildings. |
| [37]      | Seoul, South Korea | Year built, number of floors, number of elevators, and total floor area | Coefficients of determination of statistical analysis | In office buildings, new buildings did not always consume less energy than old buildings. The district, year built, number of floors, number of elevators, and total floor area did not adequately explain annual total energy consumption. |
| [38]      | China       | Mainly for the air-conditioning system        | Energy consumption simulation and orthogonal experiment | The order for the building’s influential factors is air-conditioning system: lighting density -> indoor design temperature -> exterior window type -> outside shading -> fresh air volume -> personnel density -> roof type. COP of refrigeration unit = window-wall ratio -> exterior wall type. |
| [39]      | Shenzhen, China | Physical, environmental, and social factors | Extra-Trees prediction models                | Building type is the most significant factor, followed by ambient temperature, month, structure, floor area, and rent price. The external wall material is the least significant factor. The specific energy consumption of office buildings showed an opposite trend to the floor area. |
| [40]      | USA         | Cooling, lighting, equipment, natural gas | Artificial intelligent algorithms and cluster analysis | Cooling energy primarily manipulates the total energy indicating more than 80% degree in terms of confidence level. The main subenergy determining total energy is different in disparate stages. |
| [41]      | Ranchi, India | Plan shapes and daylighting                   | Thermal models                               | Intensity of light is reduced by 35% in baseline building. For temperate buildings with rectangular footprints, buildings with L footprints, and buildings with H footprints are preferable when targeting net-zero energy status. |
| [42]      | Norway      | Refrigeration, HVAC and LED lighting         | Tao Vanilla benchmarking method and broken line models | New refrigeration, HVAC and LED lighting made the aggregated energy savings ranged from 25% to 56%. |

2.2. Data filtering

In order to improve data quality and ensure the reliability of analysis results, the data was initially processed and filtered out data suitable for the study. In the raw data, there were many buildings with data missing some information, which made them unusable and were screened out and removed. There were certain data values that were invalid, or were not applicable to this study and were therefore excluded from the analysis. For example, data for certain buildings had an EUI of 0 kWh/m² in a given year, indicating that these buildings were not in the range of normal operation. In addition, some buildings showed invalid data, such as a centralized air-conditioning plant efficiency of 117 kW/RT (unit used to describe the cooling capacity of the air-conditioning; RT stands for Refrigeration Ton), which was also excluded as anomalous data. Finally, we obtained 540 sample data from the original data and these commercial buildings cover five districts of Singapore.

2.3. Climate adjustment

Singapore’s weather is rather stable for its tropical climate and cooling is the main energy consumption source in buildings [50]. However, most studies show that weather factors have a significant effect on energy consumption for heating and cooling in buildings [51,52]. The outdoor air temperature changes under different years, which affects the energy consumption level of the buildings. Therefore, it is reasonable to conduct climate adjustment on the raw EUI data of the buildings from 2017 to 2020 for evaluation and analysis. Climate adjustment is usually performed using various energy efficiency assessment software, including inverse modeling toolkit research project (IMT RP-1050) [53,54], which can calculate correction factors by Variable-Based Degree Day Method (VBDDM) and Change-Point model (CP) based on independent variables such as heating degree day (HDD) and cooling degree day (CDD). In order to simplify the algorithm and increase the efficiency of the analysis, this study used Four Parameter model (4P), consisting of annual HDD and annual CDD, and the reliability of this method has been confirmed in similar studies [55,56]. The climate adjustment in this study was performed in two steps: 1) calculation of annual HDD and annual CDD based on climate data; 2) derivation of correction coefficients by multiple regression.

The climate data required for the first step were obtained from the Singapore Meteorological Service website [57]. The annual HDD and annual CDD are the sum of the differences between the daily average outdoor temperature and the reference temperature. The average temperatures below the reference temperature are counted as HDD and above the reference temperature are counted as CDD. Therefore, a reference temperature needs to be determined for the calculation. In this study, the reference temperature was set at 18.3°C as international standard recommended by the American Society of Heating, Refrigerating and
Air-Conditioning Engineers (ASHRAE) [58], which is also used as the reference temperature in most countries around the world. The calculation of annual HDD and annual CDD was carried out using the average daily air temperature compared to the reference temperature as follows:

\[
HDD = \sum_{i=1}^{n} (T_i - T_{\text{mean}}) \\
CDD = \sum_{i=1}^{n} (T_{\text{mean}} - T_i)
\]

where the daily average temperature of day \( i \) is taken as the average of the daily maximum and minimum temperatures of day \( i \), i.e., \( T_{\text{mean}} = (T_{\text{max}} + T_{\text{min}})/2 \); \( T_j \) is the reference temperature, i.e., 18.3°C. Eqs. (3)–(5) represent the process of deriving correction coefficients through multiple regression. Eq. (3) shows the multiple regression between the independent variables (i.e., annual HDD and annual CDD) and the dependent variable (annual energy consumption). Eq. (4) shows the process of determining the correction coefficient \( \text{CORR}_{jk} \), which uses the regression coefficients \( b_{ij} \) and \( b_{kj} \) obtained from the above multiple regression. Finally, the values of the climate-adjusted normalized building energy consumption are calculated using Eq. (5) by deducting the correction coefficients from the raw building energy consumption data determined above for each year in the different building types.

\[
Y_{jk} = b_{ij} \cdot HDD_{jk} + b_{kj} \cdot CDD_{jk} + b_{0j}
\]

\[
\text{CORR}_{jk} = \bar{b}_{ij} \cdot (HDD_{jk} - NHDD_{jk}) + \bar{b}_{kj} \cdot (CDD_{jk} - NCDD_{jk})
\]

\[
Y_{jk} = Y_j - \text{CORR}_{jk}
\]

where \( Y_j \) represents the energy consumption of building type \( j \) in year \( k \); \( HDD_j \) represents the HDD of building type \( j \) in year \( k \); \( CDD_j \) represents the CDD of building type \( j \) in year \( k \); \( b_{ij} \) represents the regression coefficient of HDD\(_j\); \( b_{kj} \) represents the regression coefficient of CDD\(_j\); \( b_{0j} \) represents the non-seasonal energy consumption; \( \text{CORR}_{jk} \) represents the correction coefficient of building type \( j \) in year \( k \); \( NHDD_j \) represents the 10-year average HDD\(_j\) in year \( k \); \( NCDD_j \) represents the 10-year average CDD\(_j\) in year \( k \); \( Y_{jk} \) represents the climate-adjusted building energy consumption. The final results show that Singapore does not need heating, so only the value of CDD is considered in the climate adjustment. The CDDs for each year are as follows: 3612.8 in 2017, 3714.6 in 2018, 3945.0 in 2019, and 3759.9 in 2020.

2.4. Data overview

Table 2 shows the descriptive statistics for the continuous numerical data normalized for each commercial building type. It can be observed that for all commercial buildings, the degree of variation in the range of data for each variable is large, which also provides the potential for subsequent exploration of the influence of EUI by these variables. For example, the year obtained TOP/CSC can illustrate the differences in energy performance of buildings built in different periods. In addition, it is noteworthy that the mean EUI for all building types shows a relatively smooth trend in the three years prior to the pandemic (2017–2019), with a largely steady increase. The mean EUI decreased significantly in 2020 compared to the pre-pandemic period, which leads to the initial assumption that the pandemic has a significant impact on the energy consumption of commercial buildings. In the 540 sampled data, frequency statistics were conducted on the disaggregated data and the following statistics can be derived from Table 3. Among the main building types of commercial buildings, hotel, office, retail and mixed development account for 17.2%, 56.1%, 19.7% and 7.0% respectively, with office accounting for the largest proportion and mixed development for the smallest. In addition, more than half of commercial buildings have GM certification, accounting for 52.8%.

2.5. Analysis techniques

The study used IBM SPSS Statistics 26, one of the world’s leading statistical analysis software, commonly used to analyze data in similar studies [59–61]. The specific analysis methods used linear regression analysis and paired sample t-test analysis. In statistics, linear regression is a type of regression analysis that models the relationship between one or more independent and dependent variables using a least-squares function called a linear regression equation. Regression models are used to describe relationships between variables by fitting a line to the observed data, which estimate how the dependent variable changes as the independent variable(s) change. The case of only one independent variable is called simple linear regression and the case of more than one independent variable is called multiple linear regression. In the results, when the p-value is less than 0.05, it indicates that the independent variable has a significant influence relationship on the dependent variable, and vice versa. The regression coefficient is a parameter in the regression equation that indicates the magnitude of the effect of the independent variable on the dependent variable. The multiple linear regression equation is as follows:

\[
y = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n + \epsilon
\]

where \( y \) is the predicted value of the dependent variable; \( \beta_0 \) is the y-intercept; \( \beta_1 \) is the regression coefficient of the first independent variable \( x_1 \); \( \beta_n \) is the regression coefficient of the last independent variable \( x_n \); and \( \epsilon \) is model error [62].

The paired sample t-test is used for the comparison of measures in a paired design or own control design. A paired design involves pairing subjects according to certain important characteristics and then randomly assigning two subjects from each pair to the two treatment groups. The main output parameters include calculated test statistic observed value, corresponding possibility\( P \) and mean difference. When the \( P \)-value is less than 0.05, it indicates a significant difference between means and vice versa [63].

The adequacy and reliability of the sample size for regression analysis is a prerequisite for conducting the analysis, so this study used the G*Power (version 3.1.9.7) software to validate this. In this software, it is necessary to select the type of statistical test and the power analysis (in this study, multiple regression analysis and prior inspection were selected, respectively). Next, this study entered 0.35 as the effect size (representing the true effect size of the test, with 0.35 being a strong effect), the probability of error (typically 0.05), and the sample size of per group for the multiple regression. After that, this software can output the actual power, representing whether the sample size is valid or not. The results showed that the minimum power value is 0.95 (generally greater than 0.8 is acceptable) among all output power results for all models required in this study, so the available sample size is sufficient and reliable for the analysis.

According to Fig. 1, the specific three steps of the study were as follows.

First, the general situation of the changes in EUI by year before and during the pandemic was explored. The mean value of EUI for each year from 2017 to 2019 was used as the dependent variable and the year was used as the independent variable to conduct a simple linear regression analysis to derive the general situation of the changes in the mean EUI by year for all commercial buildings. Considering that the overall energy consumption levels vary greatly between different building types, which have a more varied degree of impact on the final results, the overall data was also categorized by main building types. Separate linear regression analyses were conducted to explore how the mean value of EUI changed each year. The 2020 EUI values were predicted from the regression model and compared to the actual values to derive the changes during the pandemic.

Second, to explore whether the pandemic had an impact on the energy consumption of different types of commercial buildings, paired sample t-test analysis was conducted in this study. The EUI of the four
Table 2
Data description.

| Parameters                                      | Hotel            | Office           | Retail           | Mixed Development |
|------------------------------------------------|------------------|------------------|------------------|-------------------|
| Year Obtained TOP/CSC (year)                   | 1900 2017        | 1900 2017        | 1973 2017        | 1968 2016         |
| Gross Floor Area (m²)                          | 357.00 127860.00 | 23187.52 20246.18 | 2300.00 452045.00 | 6256.00 581511.00 |
| Percentage of Air-conditioned Floor Area (%)   | 0.07 1.00        | 0.18 0.74        | 0.01 1.00        | 0.37 1.00         |
| Average Monthly Building Occupancy Rate (%)    | 0.30 1.00        | 0.15 0.17        | 0.30 1.00        | 0.60 1.00         |
| Age of Chiller (year)                          | 0.00 22.00       | 4.98 6.53        | 0.00 33.00       | 0.00 30.00        |
| Centralized Air-conditioning Plant Efficiency (kW/RT) | 0.54 1.52       | 0.14 0.21        | 0.29 1.03        | 0.55 1.10         |
| Percentage Usage of LED (%)                    | 0.00 1.00        | 0.30 0.33        | 0.00 1.00        | 0.00 1.00         |
| EUI of 2017 (kWh/m².year)                      | 53.71 571.77     | 101.58 107.93    | 10.42 916.32     | 16.51 686.48      |
| EUI of 2018 (kWh/m².year)                      | 44.26 580.02     | 98.22 350.36     | 39.45 909.98     | 55.35 725.04      |
| EUI of 2019 (kWh/m².year)                      | 41.65 584.72     | 103.24 29.68     | 29.68 986.27     | 157.96 756.75     |
| EUI of 2020 (kWh/m².year)                      | 36.30 822.05     | 107.93 32.25     | 29.68 986.27     | 69.47 526.38      |

Note: Min means minimum, max means maximum, and SD means standard deviation.
building types was divided into three groups, the EUI of 2017–2019 respectively and the EUI of 2020, representing the energy consumption in normal years and during the pandemic, and t-tests were conducted for each group.

Finally, to further explore the relationship between the EUI and various factors for different building types in normal years and under the impact of the pandemic, the overall data was divided into hotel, office, retail, and mixed development for multiple linear regression analysis. In the regression analysis, EUI of the 3 years before the pandemic (2017–2019) were respectively used as the dependent variables of model 1–3, which could represent the situation in normal years. The models used year obtained TOP/CSC, gross floor area, percentage of air-conditioned floor area, average monthly building occupancy rate, age of chiller, centralized air-conditioning plant efficiency, percentage usage of LED, and GM certification as independent variables, where GM certification was a dummy variable and the other variables were continuous numerical variables. In addition, the difference value between the EUI in 2020 and the mean EUI from 2017 to 2019 was analyzed separately as the dependent variable, which reflects the changes in energy consumption during the pandemic, and this regression model was used as model 4, with the independent variables remained unchanged. Model 4 allows exploring the factors affecting the changes of EUI in different building types after the COVID-19 outbreak. A synthesis of the results based on the above three steps of analysis summarized the conclusions of this study.

3. Results

3.1. Results of simple linear regression

In Fig. 2, a scatter chart is obtained based on the mean value of EUI for commercial buildings from 2017 to 2019. The linear regression equation for the trend line is $y = 9.4624x - 18820$ (x is the year and y is the mean EUI), where $R^2 = 0.9315$ and its numerical magnitude indicates the degree of fit between the estimated value of the trend line and the corresponding actual data, with $R^2$ close to 1, indicating an excellent fit. This equation predicts a mean EUI of 294.05 kWh/m² in 2020, while the actual mean EUI in 2020 is 237.28 kWh/m², with a difference of 56.77 kWh/m², a plummet of 19.9% relative to the mean EUI in 2019, indicating that the general energy consumption of commercial buildings in 2020 changed significantly due to COVID-19.

In Fig. 3, the data was categorized by the main building type to obtain a scatter chart of their respective mean EUI from 2017 to 2019 and to derive the line regression equations. Both before and during the pandemic, the energy consumption level is highest for retail and lowest for office in commercial buildings. The equations are:

- Hotel: $y = 4.1854x - 8168.5$, $R^2 = 0.8562$; office: $y = 3.7040x - 7242.5$, $R^2 = 0.7367$;
- Retail: $y = 26.538x - 53167$, $R^2 = 0.9491$; mixed development: $y = 20.654x - 41401$, $R^2 = 0.9279$ (x is the year and y is the mean EUI). Among them, the mean values of EUI in hotel, office, retail, and mixed development are all positively correlated with year. The regression equations for all the four types of buildings have an $R^2$ greater than 0.7, showing an high degree of fit. Based on the regression equations for each building type, the mean values of EUI predicted in 2020 were 286.01 kWh/m² for hotel, 241.20 kWh/m² for office, 439.76 kWh/m² for retail, and 320.08 kWh/m² for mixed development, while the actual mean values of EUI in 2020 were 241.54 kWh/m² for hotel, 202.97 kWh/m² for office, 334.13 kWh/m² for retail, and 230.29 kWh/m² for mixed development, with a difference of 44.47 kWh/m², 38.22 kWh/m², 105.63 kWh/m², and 89.79 kWh/m² respectively, representing a decrease of 15.8%, 16.0%, 25.3%, and 29.6% respectively, relative to 2019. It can be observed that the extent of energy consumption impacted by the pandemic is mixed development>retail>office>hotel.

3.2. Results of paired sample t-test

Table 4 shows the results of t-test for EUI of different commercial building types before and during the pandemic, where mean difference indicates the mean EUI of 2017-2019 minus the mean EUI of 2020. It can be seen that there was a significant difference (p<0.05) in EUI for all building types in the three years prior to and during the pandemic. In addition, in terms of the difference between the mean EUI before and during the pandemic, hotel, retail, and mixed development all showed an increasing trend from year to year, except for offices, which first decreased and then increased (from 28.437 kWh/m² to 28.286 kWh/m² to 35.846 kWh/m²). Energy consumption during the outbreak was lower than in the three years prior to the outbreak. The results of the t-test confirmed that the EUI of commercial buildings was impacted by the pandemic, providing the premise for subsequent research on the factors influencing energy consumption during the pandemic.

| Item          | Numbers | Percentage | Cumulative Percentage |
|---------------|---------|------------|-----------------------|
| Main          | Hotel   | 93         | 17.2                  | 17.2                  |
| Building Type | Office  | 303        | 56.1                  | 73.3                  |
| Type          | Retail  | 106        | 19.7                  | 93.0                  |
|               | Mixed Development | 38       | 7.0                   | 100.0                 |
| GM            | No      | 255        | 47.2                  | 47.2                  |
| Certification | Yes     | 285        | 52.8                  | 100.0                 |

Fig. 1. Analytical framework.
Fig. 2. Mean EUI scatter chart of all sampled commercial buildings.

Fig. 3. Mean EUI scatter chart of main building types of commercial buildings in Singapore.

Table 4
Paired sample t-test results of EUI for different building types.

| Main Building Type | 2017 & 2020 | 2018 & 2020 | 2019 & 2020 |
|--------------------|-------------|-------------|-------------|
|                    | t           | P-value     | Mean Difference | t   | P-value     | Mean Difference | t     | P-value     | Mean Difference |
| Hotel              | 3.257       | 0.000       | 30.933       | 4.662 | 0.000       | 38.090       | 4.956 | 0.000       | 39.304       |
| Office             | 6.609       | 0.000       | 28.437       | 7.777 | 0.000       | 28.286       | 11.778 | 0.000       | 35.846       |
| Retail             | 3.203       | 0.030       | 31.869       | 5.175 | 0.000       | 46.237       | 11.486 | 0.000       | 83.421       |
| Mixed Development  | 2.254       | 0.030       | 31.869       | 3.072 | 0.004       | 42.548       | 8.706  | 0.000       | 73.177       |

3.3. Results of multiple linear regression

The results of the collinearity diagnostics showed that the VIF values of the variables in each model were between 1.037 and 1.743, all less than 3, indicating that there was no multicollinearity among the variables and the model results were stable, so the models had high stability and reliability in explaining the factors affecting energy consumption. The data from the different types were entered into SPSS for multiple linear regression analysis and the corresponding results from model 1–4 were obtained in Table 5, which represented the normal situation (model 1–3) and changes during COVID-19 (model 4).

For hotel, model 1–4 were not significant overall (p(F)>0.05). For office, model 1–4 were all significant overall (p(F)<0.05). Among the independent variables, EUI was influenced by a significant positive correlation of the percentage of air-conditioned floor area ($p<0.05, \beta>0$) and the percentage usage of LED ($p<0.05, \beta>0$) in model 1–3. There was a significant negative correlation between EUI and GM certification in model 3 ($p=0.026<0.05, \beta=-0.144<0$). The difference value of EUI was influenced by a significant negative correlation of the percentage
of air-conditioned floor area in model 4 ($p=0.006<0.05$, $\beta=0.166<0$). There was a significant positive correlation between the difference value of EUI and the average monthly building occupancy rate for office ($p=0.020<0.05$, $\beta=0.137>0$). For retail, model 1-4 showed significant results overall ($p(F)<0.05$). In model 1-3, EUI was significantly influenced by both the year obtained TOP/CSC and the average monthly building occupancy rate ($p<0.05$), and EUI was positively correlated with both variables ($\beta>0$). The gross floor area showed a significant negative correlation with EUI in model 3 ($p=0.038<0.05$, $\beta=0.181<0$), while the percentage of air-conditioned floor area showed a significant positive correlation with EUI in model 1 and model 2 ($p<0.05$, $\beta>0$). Although both the age of chiller and the centralized air-conditioning plant efficiency had a significant influence on the difference value of EUI in model 4 ($p<0.05$), the former had a negative correlation ($\beta=-0.258<0$), and the latter had a positive correlation ($\beta=0.367>0$). For mixed development, model 1-4 were all not significant overall ($p(F)>0.05$).

In the analyses of the general situation, the overall trend of EUI in the three years prior to the pandemic (2017-2019) showed a year-on-year increase, indicating that the development in commercial buildings with the continued growth of the country’s economy led to a continuous increase in overall energy consumption. The energy consumption of commercial buildings plummeted by 19.9% under the impact of the pandemic, consistent with the reduction in the operation of all types of commercial buildings during the pandemic. For the main types of commercial buildings, both before and during the pandemic, the energy consumption level is highest for retail and lowest for office, which is consistent with the results of [30]. Under the impact of COVID-19, the use of each commercial building type was significantly reduced due to the restriction policies in Singapore, resulting in a decrease in energy consumption. The t-test results confirmed the difference in energy performance before and during the pandemic. The impact of COVID-19 on commercial buildings was: mixed development>retail>office-hotel. Hotel occupancy declined substantially due to the pandemic, but hotels were used as quarantine areas during the lockdown period and for the studied hotels, it showed that more than one third of the hotels were used as quarantine areas (35/93) [64], which offset their substantial degree of vacancy. As a result, hotel energy consumption was the least affected of all building types. The energy wasted by office during non-occupied time is significant in normal years, with more energy used during non-working hours (56%) than during working hours (44%) [65], resulting in the energy consumption not showing a significant decrease due to reduced use during the pandemic. The results showed that mixed development was most affected by the pandemic and should be the priority type of energy management under the pandemic.

In normal years, the EUI of commercial buildings was significantly influenced by the following independent variables: the year obtained TOP/CSC, the percentage of air-conditioned floor area, the percentage usage of LED, the average monthly building occupancy rate, the GM certification, and the gross floor area. It can be found that HVAC and lighting systems, as main energy consumption systems of commercial buildings, significantly influence their energy consumption, specifically the percentage of air-conditioned floor area and the percentage usage of LED, the former influencing office and retail, and the latter influencing office. It is generally believed that new buildings consume less energy than older buildings, and it is concluded that the age of office buildings does not correlate with EUI [37]. This study found that the EUI of hotel, retail, and mixed development was significantly influenced by the year obtained TOP/CSC (reflecting the age of the building), with newer buildings showing higher energy consumption, which complements the existing studies on the influential building age on EUI in various commercial building types. In addition, this study found that only the EUI of retail was influenced by the average monthly building occupancy rate, which was not reflected in hotel, indicating that hotel EUI was not significantly influenced by occupancy rate. Some studies have suggested that the relationship between hotel occupancy rate and EUI was difficult to determine [33], while [34] demonstrated that yearly occupancy rate represented a standardized distribution of EUI in hotel. This study completes the existing findings on the relationship between EUI and occupancy rate in hotel. Office buildings with GM certification consume less energy than non-green office buildings, indicating that green certification has important positive implications for energy efficiency in office buildings, which provides guidance for energy consumption evaluation methods in the green certification evaluation system. In retail, the higher the gross floor area, the lower energy consumption, and the analysis is consistent with existing research findings that small retail buildings consume more energy than the national average [36].

The changes in energy consumption during the pandemic for each building type were influenced by the percentage of air-conditioned floor area, the average monthly building occupancy rate, the age of chiller, and the centralized air-conditioning plant efficiency. The changes of EUI during COVID-19 were mainly influenced by HVAC with the specific variables being the percentage of air-conditioned floor area, the age of chiller, and the centralized air-conditioning plant efficiency. This reminds us that we should take a more cautious attitude towards the utilization of HVAC in the management of energy consumption in commercial buildings during the pandemic, as this is the key to energy changes in the context of the pandemic. In the results, the higher the percentage of air-conditioned floor area, the higher the vari-

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### Table 5

| Main Building Type       | Model 1 (2017) | Model 2 (2018) | Model 3 (2019) | Model 4 (Difference Value) |
|--------------------------|---------------|---------------|---------------|---------------------------|
| Hotel                    | None ($R^2=0.056$) | Year Obtained TOP/CSC*: $\beta=0.262$ ($R^2=0.081$) | Year Obtained TOP/CSC**: $\beta=0.0312$ ($R^2=0.060$) | None ($R^2=0.054$) |
| Office                   | Percentage of Air-Conditioned Floor | Percentage of Air-Conditioned Floor | Percentage of Air-Conditioned Floor | Percentage of Air-Conditioned Floor |
| Area*: $\beta=0.230$; | Area*: $\beta=0.227$; | Area*: $\beta=0.236$; | Area*: $\beta=0.151$; GM Certification*: $\beta=0.391$ | Area*: $\beta=0.166$; Average Monthly Building Occupancy Rate*: $\beta=0.157$ ($R^2=0.026$) |
| Percentage Usage of LED*: $\beta=0.136$ ($R^2=0.062$*) | Percentage Usage of LED*: $\beta=0.141$ ($R^2=0.065$*) | Percentage Usage of LED*: $\beta=0.077$* | Percentage Usage of LED*: $\beta=0.077$* |
| Retail                   | Year Obtained TOP/CSC***: $\beta=0.510$; Percentage of Air-Conditioned Floor Area*: $\beta=0.186$; Average Monthly Building Occupancy Rate***: $\beta=0.441$ ($R^2=0.364$*** | Year Obtained TOP/CSC***: $\beta=0.530$; Percentage of Air-Conditioned Floor Area*: $\beta=0.187$; Average Monthly Building Occupation Rate***: $\beta=0.391$ ($R^2=0.329$) | Year Obtained TOP/CSC*: $\beta=0.372$ ($R^2=0.061$) | Air-Conditioned Floor Area*: $\beta=0.416$ ($R^2=0.009$) |
| Mixed Development        | None ($R^2=0.140$) | None ($R^2=0.127$) | None ($R^2=0.054$) |

Note: *$p<0.05$; **$p<0.01$; ***$p<0.001$. Discussion
ation of energy consumption in mixed development while the lower the variation of energy consumption in office. The reason may be that the mixing degree of each function in mixed development is different, and the usage rate may be smaller in areas with high air-conditioning coverage, which leads to the opposite result with the office.

4. Conclusion

This study investigated the energy consumption data of commercial buildings from 2017 to 2020, using Singapore as an example. By comparing the overall EUI of commercial buildings and EUI of each commercial building type before and during the pandemic, this paper investigated the extent to which commercial buildings were influenced by COVID-19 and complemented existing findings on the factors influencing energy consumption in commercial buildings in normal situations and innovatively examined the factors influencing energy consumption in commercial buildings under the impact of the pandemic. Linear regression analysis and paired sample t-test were used in the study and conclusions were drawn as follows.

(1) Both before and during the pandemic, the energy consumption level is highest for retail and lowest for office in commercial buildings. Relative to 2019, the mean EUI of commercial buildings in Singapore decreased by 56.77 kWh/m² in the pandemic year (2020), a plunge of 19.9%.

(2) The mean EUI reductions for each building type were 44.47 kWh/m² for hotel, 38.22 kWh/m² for office, 105.63 kWh/m² for retail, and 89.79 kWh/m² for mixed development, a decrease of 15.8%, 16.0%, 25.3%, and 29.6% respectively, relative to 2019. The degree of decrease in energy consumption in the pandemic year was mixed development>retail>office>hotel. The results of the t-test confirmed that the EUI for each building type was significantly influenced by the restriction policies under the pandemic.

(3) For EUI in normal years, hotel is positively influenced by the year obtained TOP/CSC (reflecting building age); office is positively influenced by the percentage of air-conditioned floor area and the percentage usage of LED and negatively influenced by the green certification; retail is positively influenced by the year obtained TOP/CSC, the percentage of air-conditioned floor area, and the average monthly building occupancy rate and negatively influenced by the gross floor area; and mixed development is positively influenced by the year obtained TOP/CSC.

(4) For changes in EUI during the pandemic, hotel is not significantly influenced by any variable; office is positively influenced by the average monthly building occupancy rate and negatively influenced by the percentage of air-conditioned floor area; retail is positively influenced by the centralized air-conditioning plant efficiency and negatively influenced by the age of chiller; and mixed development is positively influenced by the percentage of air-conditioned floor area. HVAC is a key influential factor in the energy changes of commercial buildings during the pandemic.

This study has several limitations which need to be considered for generalizing the results. First, the data obtained had a certain amount of missing information and the screening of data resulted in a relatively small sample size for the study although it meets the basic requirement for the statistic comparison. Second, the raw data provided only typical commercial buildings and did not cover other commercial building types such as restaurants and banks. Moreover, the number of commercial buildings for each main building type was not evenly distributed in the sample, with most of the data being office buildings related. Finally, the information contained in the database did not cover all aspects of building energy consumption. Subsequent studies should attempt to include more comprehensive information related to commercial building energy consumption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Senhong Cai: Methodology, Investigation, Data curation, Writing – original draft. Zhonghua Gou: Conceptualization, Supervision, Writing – review & editing.

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