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# Electricity consumption variation of public buildings in response to COVID-19 restriction and easing policies: A case study in Scotland, U.K.

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## ABSTRACT

A growing number of studies have showed energy demand changes during COVID-19; this study aims to further disclose the impact of the restriction and easing policies on the energy consumption of public buildings where occupants' usage and activities are regulated in response to the pandemic. This study analyzes half-hourly electricity consumption data of 35 public buildings covering 6 building types in the Perth and Kinross Council area in Scotland, U.K., over the span of 2020 and 2021. The results show that the restriction has a greater impact on the electricity reduction in the first year of the pandemic than that in the second year. In response to the restriction, the electricity use intensity of all public buildings reduces significantly ($p < 0.001$) except office buildings with no significant reduction ($p > 0.05$); secondary schools have the highest electricity consumption reduction (275.04 kwh/day), while museums have the lowest reduction (58.62 kwh/day). In addition, the electricity consumption and electricity use intensity of museum, library and school buildings are inversely proportional to the restriction intensity, while this is opposite for office buildings. Combing restriction intensity and mobility data, this research reveals the different impacts of the restriction policies on the electricity consumption of public buildings during the pandemic, which reflects people's changing attitudes and behaviors towards COVID-19. The results provide a reference basis for energy management to develop more realistic energy demand policies based on public building types and to optimize the electricity supply load and energy profile during the COVID-19 pandemic.

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## 1. Introduction

WHO (World Health Organization) announced that it had witnessed a global pandemic in Feb. 2020 and officially named the virus COVID-19 [1,2]. To suppress the outbreaks of the fast spreading COVID-19, many countries and regions have issued unprecedented lockdown and restriction policies as per their own national and local conditions [3,4]. These policies and measures also have a far-reaching influence on many industries and social aspects, including the environment [5,6], medical care [7], education [8], travel [9,10], industrial production [11–13], economy [14,15] and energy [16–18]. Among them, the energy sector is one of the most vulnerable sectors due to the lockdown and restriction policies. According to the data provided by the IEA (International Energy Agency)'s *World Energy Outlook* report, global energy demand decreased by 6% during the COVID-19 pandemic in 2020, of which coal usage amount went down about 7%, while electricity demand decreased by about 2% [19]. In addition, carbon

emissions from the global fossil fuel industry could be cut by a record 2.5 billion tons, with a year-on-year decrease of over 5%. This was the first drop since the 2008 financial crisis and achieved the largest falling since World War II.

Many scholars have investigated the impact of the COVID-19 pandemic on energy consumption in different aspects. Some of them focus on the impact on fossil energy resources like coal, natural gas, and oil. For instance, Smith et al. [20] applied the global vector auto regressive model (GVAR) to assess the effect of the COVID-19 pandemic on global fossil fuels consumption and the $CO_2$ emission during the period of 2020 Q1-2021 Q4. The results indicated that while fossil fuel consumption and $CO_2$ emissions decreased significantly in the first quarter following the outbreak, they would return to or even exceed pre-crisis levels within two years, with the growth being expected to be stronger in developing economies than in developed economies. Norouzi [21] analyzed the impact of COVID-19 on the oil and gas industry and showed that the short-term impact would be a reduction in petroleum consumption of nearly 25%, followed by a slow recovery to the former amount and even growth more. The long-term impact would result in a 30% to 40% reduction in capital expenditures and Research &

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Development investments in the U.S. regional oil and gas markets. Norouzi and de Rubens et al. [4] developed a comparative regression and neural network model to analyze the impact of COVID-19 on petroleum demand in China, which displayed that the severity of the COVID-19 could significantly affect petroleum demand both directly and indirectly, and the elasticity of petroleum demand towards the population of the infected people reached −0.1%.

There are a growing number of studies focusing on the impact on electricity consumption in particular. For instance, Lou et al [22] analyzed individual smart meter data from Arizona and Illinois to examine the extent to which COVID-19 restriction measures (especially the mandates of school closure and limiting business operations) affected the electricity consumption behavior of low-income and ethnic minority groups in the United States. The results showed that the mandates of school closures and limiting business operations increased residential electricity consumption by 4–5%, but reduced commercial electricity consumption by 5–8%; the increase in electricity consumption was greater for low-income and ethnic minority groups. Buechler et al. [23] investigated the changes in electricity consumption in 58 different countries and regions from January to October 2020, so as to reveal the relationship between these changes and government restrictions, mobility metrics and electricity sector characteristics in different countries. As indicated by the results, stricter government restrictions and larger decreases in mobility (particularly retail and recreation) were strongly linked to reductions in electricity consumption, while these relationships were strongest in the initial phase of the COVID-19 pandemic. Prol et al. [24] conducted a study of the impact of COVID-19 restrictions on short-term electricity consumption in European countries and the United States, indicating that within 5 months of announcing "stay-home" order, most countries and states saw cumulative declines in electricity consumption between 3% and 12%. Later on, Italy, France, Spain, California, Austria and New York returned to baseline consumption in late July, whereas Britain and Germany maintained below baseline levels. The results proved that the correlation between the severity of restrictions and the reduction in daily electricity consumption was non-linear.

Nevertheless, the current research on the impact of COVID-19 on energy consumption is geared towards the whole industry, or only towards a few specific industries like transportation [25], while few of them investigated energy consumption in the building industry which accounts for 38% of world's total energy consumption. There are some studies on residential buildings where energy may increase due to working from home policies [26–29], while public buildings are largely missed out in the relevant studies. Public buildings, accessible to the public and funded from public sources, are sensitive to the restriction policies which regulate the public gathering activities. These buildings are also energy intensive due to central, high-load air-conditioning and pose great challenges to carbon emission reductions. On the other hand, as the virtual technologies advance and are widely used, the functions of some public buildings (such as libraries and museums) can be replaced online in a digital form, while providing greater time flexibility and public involvement; in other words, public buildings offer great opportunities to reduce carbon emissions. The implementation of restriction policies and measures resulting from this COVID-19 pandemic provides an opportunity to conduct relevant studies to verify this hypothesis.

Overall, there is a lack of relevant studies using real data on the changes in electricity consumption of public buildings during the COVID-19 pandemic to investigate the public building energy-saving potential. To fill this gap, this study utilizes a database containing half-hourly electricity consumption of public buildings in Perth and Kinross, Scotland, U.K., in order to explore the impact of the restriction policies on the electricity consumption of different types of public buildings during the COVID-19 pandemic, thereby indicating the differences in electricity consumption caused by changes in the occupancy condition and use frequency regulated by the policies.

## 2. Methodology

### 2.1. Case selection

Perth and Kinross, situated in the central area, is one of the 32 authority regions in Scotland, U.K. (Fig. 1). Higher as the area is in its latitude, it is influenced by the warm Atlantic Current and is a temperate maritime climate, cold and wet in winter, cool and humid in summer. In winter, it achieves the monthly average minimum temperature in December (0.53 °C), and in summer, it achieved the monthly average maximum temperature in July (20.08 °C). Therefore, this place has considerable heating demand in winter, and moderate cooling demand in summer.

Since the first positive case of COVID-19 was confirmed in Scotland on March 1, 2020, the virus has spread and developed rapidly in the region. As of January 16, 2022, Scotland has cumulatively 1,085,696 confirmed cases, including 10,038 deaths [30]. To curb the spread of the virus, control the COVID-19 spread, and reduce the adverse impact of the virus on people's health, the Scotland government has taken measures to address this challenge from the very beginning. Among them, the most effective measure is the introduction of restriction policies [31].

On 20 March 2020, the Scotland government announced that schools and nurseries would be closed. From March 24, 2020, Scotland entered a phase of stringent restrictions, namely lockdowns, during which all public buildings would be closed. Later on, as the number of infection cases began to decline with the COVID-19 pandemic being partially contained, on May 21, 2020, the Scotland government released a route map to show the sequence in which the current restrictions would be gradually eased, announced on May 29, 2020. As the spread of the virus was sup-



**Fig. 1.** Location map of Perth and Kinross.

pressed and the number of infection cases kept declining, on Jun 19, 2020, the Scotland government announced a second phase of easing restrictions. On July 10, 2020, as the virus was suppressed and the number of infected cases kept declining, the Scotland government announced that it had entered the third phase of easing restrictions. Due to the fluctuation and rebound of the COVID-19 pandemic, the restriction policies had been tightened, but it was still in the third phase. On January 5, 2021, due to the rapid spread of the Delta variant, the Scotland government announced another lockdown. As the tests expanded and the vaccination rate increased, the government announced that primary school students in certain grades can return to school full-time from February 22, 2021. As the COVID-19 pandemic was further suppressed and the vaccination rate increased, the home quarantine policy was lifted on April 2, 2021, and all students were allowed to return to school on a full-time basis on April 6, 2021. Some public buildings such as libraries and museums could reopen on April 26, 2021. From May 17, 2021, further restrictions had been eased. On August 9, 2021, the Scotland government has completely lifted the restrictions on body distance and assembly, and all public buildings were allowed to operate.

To sum up, according to the main restriction policies and measures against pandemic adopted by the Scotland government, in this research, it divides the year 2020 and 2021 into three periods respectively, namely non-restriction period (normal period), stringent restriction period and easing restriction period. The time frame for each period is indicated in Table 1.

Based on this time frame, this study compares the electricity consumption of different public buildings. It is also noticed that public holidays may affect the use of these buildings. Therefore, it is essential to consider the public holidays and the corresponding time in the analysis. Fig. 2 includes both the public holidays in Scotland in 2020 and 2021 and the restriction period. It can be seen that Scotland has the same number of public holidays in 2020 and 2021, and both are 9 days, but the specific time slots of the public holidays are varied.

### 2.2. Data collection

The dataset of electricity use (EU) for local authority self-owned public buildings in Perth and Kinross were acquired through the Open Data Perth and Kinross website [32]. This dataset contains the 11 types of public buildings such as car park, depot, library, museum, nursery school, offices, primary school, pumping station, revenue, secondary school and the environment service, which includes the daily electricity energy consumption data and each building's internal area of 61 buildings from 2020 to 2021. The EU data are automatically recorded by the smart meter every half an hour, which can guarantee the accuracy of the data. The information of internal area is used to calculate electricity use intensity (EUI).

Since some buildings in the dataset fail to indicate specific building types and the EU data during certain time of some buildings have been missed, they are not suitable for the analysis and are excluded in the analysis. Through a series of data screening,

**Table 1**
Time frame for each period.

| Year | Period | Time |
|------|--------|------|
| 2020 | Non-Restriction Period | 2020/01/01–2020/03/23 |
| | Stringent Restriction Period | 2020/03/24/-2020/05/28 |
| | Easing Restriction Period | 2020/05/29–2021/01/04 |
| 2021 | Stringent Restriction Period | 2021/01/05–2021/04/01 |
| | Easing Restriction Period | 2021/04/02–2021/08/08 |
| | Non-Restriction Period | 2021/08/09–2021/12/25 |

it finally determined 6 types public buildings for this study: depot, library, museum, offices, primary school and secondary school, with a total of 35 buildings for the follow-up analysis. Table 2 lists out the selected building types and the number of buildings of each type, and also summarizes the basic statistics of the internal area.

### 2.3. Climate adjustment

The heating and cooling loads of a building vary with the climatic conditions of different years, thereby affecting the electricity consumption. In particular, the climatic factors such as outdoor air temperature can have a significant impact on the energy load of building heating and cooling [33,34]. It indicates that in different years the outdoor air temperatures can affect different levels of energy consumption in the building. So, it would be biased to directly evaluate and compare EU and EUI in different restriction periods using the raw data. To solve this problem, climate adjustment is recommended to normalize building electricity consumption data for different climatic conditions over a cyclical time frame (weekly, monthly, quarterly or annually); after that, it is possible to compare the energy consumption of different periods on the same basis [35].

According to the previous research, climate adjustment was conducted using various energy-saving assessment software, such as the inverse modeling toolkit research project (IMT RP-1050) [36,37]. The IMT RP-1050 can calculate correction factors by variable-based degree day method (VBDDM) and change-point model (CP) based on independent variables such as the values of heating degree day (HDD) and cooling degree day (CDD). Nevertheless, to improve timeliness and help calculate, in this research, it adopts a four-parameter model (4P) consisting of monthly HDD and monthly CDD to calculate the correction factor. In this method, it mainly performs multiple regression on building energy consumption and the local climate representative indicators of HDD and CDD, and its validity and reliability have also been verified in previous researches [38]. The climate adjustment of this method is implemented in two steps: (1) calculate HDD and CDD based on climate data; (2) deduce the correction factor by multiple regression.

The climate data for the first step are obtained through the time and data website [39]. The monthly HDD and monthly CDD mean the sum of the difference between the average outdoor daily temperature and the reference temperature within a month, respectively. Provided that the average temperature is lower than the reference temperature, it shall be included in the HDD, and if the temperature higher than the reference temperature, it shall be included in the CDD. Notably, there are great differences in the selection of reference temperature among countries and regions in the world. Based on the international standard recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), this research sets the reference temperature at 18.3 °C. Currently, there are many approaches to calculate HDD and CDD. The easiest way is to compare the daily average temperature with the reference temperature, and for the relatively complicated approach, one can compare the daily pattern based on the temperature with the reference temperature. In this research, it simply calculates HDD and CDD by comparing the daily average temperature with the reference temperature. The specific calculation formula:

$$HDD = \sum_{i=1}^{n}(T_b - T_{meani}) \tag{1}$$

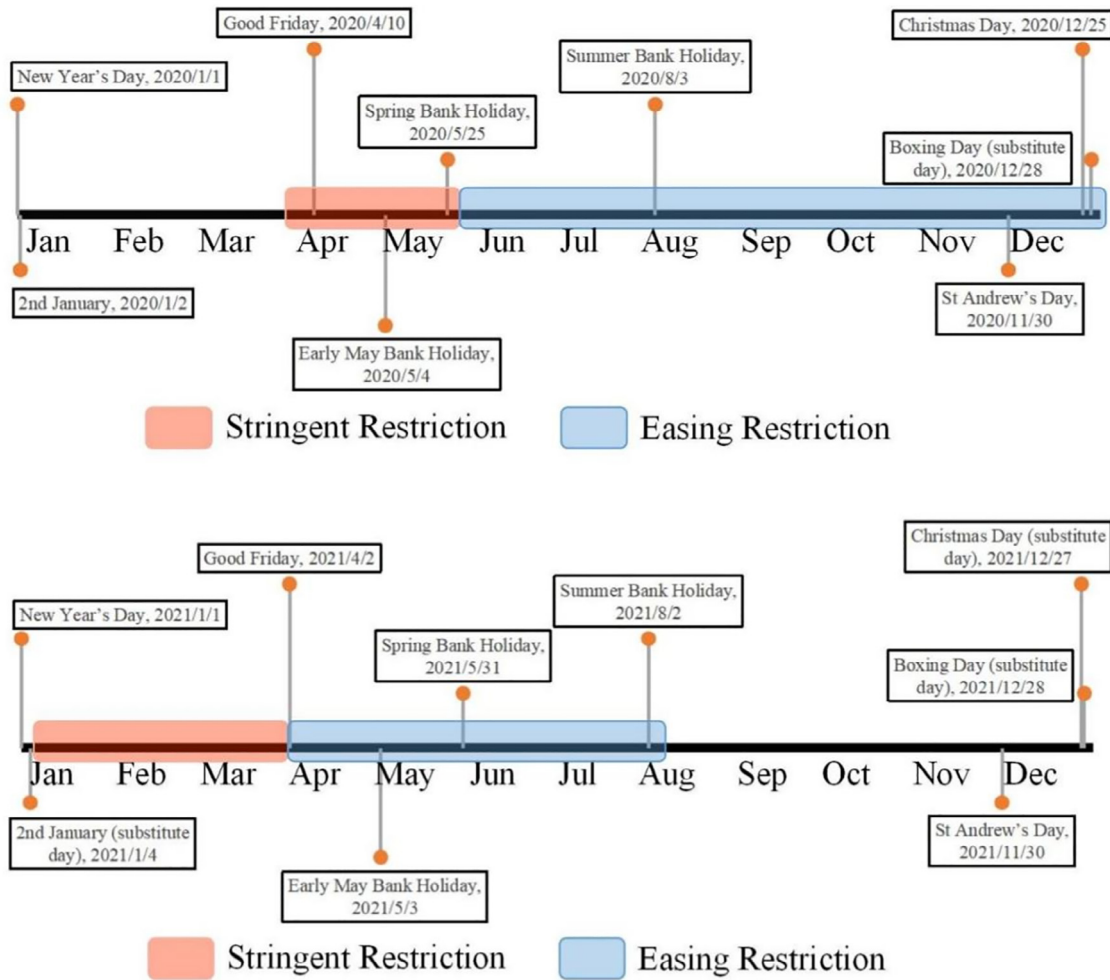$$CDD = \left(\sum_{i=1}^{n}(T_{meani} - T_b)\right) \tag{2}$$

**Fig. 2.** The public holidays in Scotland in 2020 and 2021 and the restriction period.

**Table 2**
The selected buildings' information.

| Building Type | Number of Cases | Internal Area (m$^2$) | | |
|---|---|---|---|---|
| | | Average Value | Maximum Value | Minimum Value |
| Depot | 1 | 877 | 877 | 877 |
| Library | 1 | 458 | 458 | 458 |
| Museum | 1 | 332 | 332 | 332 |
| Offices | 3 | 568 | 879 | 84 |
| Primary School | 14 | 314 | 554 | 54 |
| Secondary School | 15 | 1285 | 1720 | 471 |

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.$T_{meani} = (T_{maxi} + T_{mini})/2$; $T_b$ is the reference temperature, i.e. 18.3 °C.

In the second step, it utilizes the following (3)–(5) equations to deduce the correction factor through multiple regression, where equation (3) is the multiple regression between independent variable (i.e. monthly HDD and CDD) and the dependent variable (i.e. monthly electricity energy consumption). In Eq. (4), it indicates the process of determining the correction factor ($CORR_{jk}$) by using the regression coefficients ($b_{1j}$ and $b_{2j}$) obtained from the above multiple regression. It ends up with adopting Eq. (5) to deduct the correction factor from the above-identified raw data of monthly electricity energy consumption for different buildings,

thereby calculating the climate-adjusted normalized building electricity energy consumption.

$$Y_{jk} = b_{1j} \cdot HDD_{ij} + b_{2j} \cdot CDD_{ij} + b_{0j} \tag{3}$$

$$CORR_{jk} = \hat{b}_{1j} \cdot (HDD_{jk} - NHDD_j) + \hat{b}_{2j} \cdot (CDD_{jk} - NCDD_j) \tag{4}$$

$$Y_{jk_{ta}} = Y_{jk} - CORR_{jk} \tag{5}$$

where $Y_{jk}$ represents the electricity energy consumption of building category j in month k;$HDD_{jk}$ represents the HDD of building category j in month k; $CDD_{jk}$ represents the CDD of building category j in month k; $b_{1j}$ represents the regression coefficient of$HDD_{jk}$; $b_{2j}$ represents the regression coefficient of$CDD_{jk}$; $b_{0j}$ represents the non-seasonal energy consumption;$CORR_{jk}$ represents the correction

coefficient of building category j in month k; $NHDD_j$ represents the 10-year average $HDD_j$ in month k; $NCDD_j$ represents the 10-year average $CDD_j$ in month k; $Y_{jk_{ta}}$ represents the climate-adjusted normalized building electricity energy consumption.

### 2.4. Analysis techniques

The analysis process is indicated in Fig. 3. There are three main steps. First, this research used independent sample T-test to compare and analyze the EU and EUI differences of various public buildings in restriction periods (stringent restriction and easing restriction period) and non-restriction period in recent two years, so as to understand the effects of restriction policies for COVID-19 on EU and EUI. Second, this study compared the average EU and EUI of various public buildings during the stringent restriction period and easing restriction period in the same year of 2020 and 2021, respectively, to understand the impact of different restriction intensity on EU and EUI. Last, this research further used independent sample T-test to compare and analyze the differences of EU and EUI of various public buildings during stringent restriction period in 2020 (the first year of the COVID-19) and in 2021 (the second year of the COVID-19) respectively, and easing restriction period in 2020 and in 2021 respectively, to understand the effects of similar restriction period on EU and EUI of various public buildings at different stages of the COVID-19 pandemic.

IBM SPSS Statistics 24 is used in the independent sample T-test of this research, which is a one of the world-famous statistical analysis software, commonly used for data analysis in similar research [40,41]. Wherein, independent sample T-test is a method of inferential statistics, making use of the samples from population to judge that whether the average of the two populations is significantly different. Therefore, it can be used to analyze change of

building energy consumption under specific intervening measures. The mainly output parameters include calculated test statistic observed value, corresponding possibility P and mean difference. Wherein, test statistics is t statistics, its mathematical definition is [42]:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{X}_1 - \bar{X}_2}} \tag{6}$$

where $\bar{X}_1$ is the mean of the first group of samples, $\bar{X}_2$ is the mean of the second group of samples, and $S_{\bar{X}_1 - \bar{X}_2}$ is the standard error of the difference between the mean of the first group of samples and the second group of samples.

In addition, when P value is smaller than 0.05, the null hypothesis that there are no significant differences between the two populations shall be rejected, and it shall be thought that there are significant differences between the two populations; vice versa. While for the independent sample T-test in Section 3.2 of this research, the mean difference means that differences that the EU or EUI of various public buildings in the non-restriction period deducts that during restriction period (stringent restriction and easing restriction period) in these two years. For the independent sample T-test in Section 3.4, the mean difference means the differences that the EU or EUI of various public buildings during stringent restriction period or easing restriction period in 2020 deducts that during stringent restriction period or easing restriction period in 2021.

In addition, since some groups only contain EU and EUI data for one single building, it is important to validate whether the existing sample size (Table 3) is sufficient and reliable to be used for the independent sample T-test. To do so, this paper used G*Power
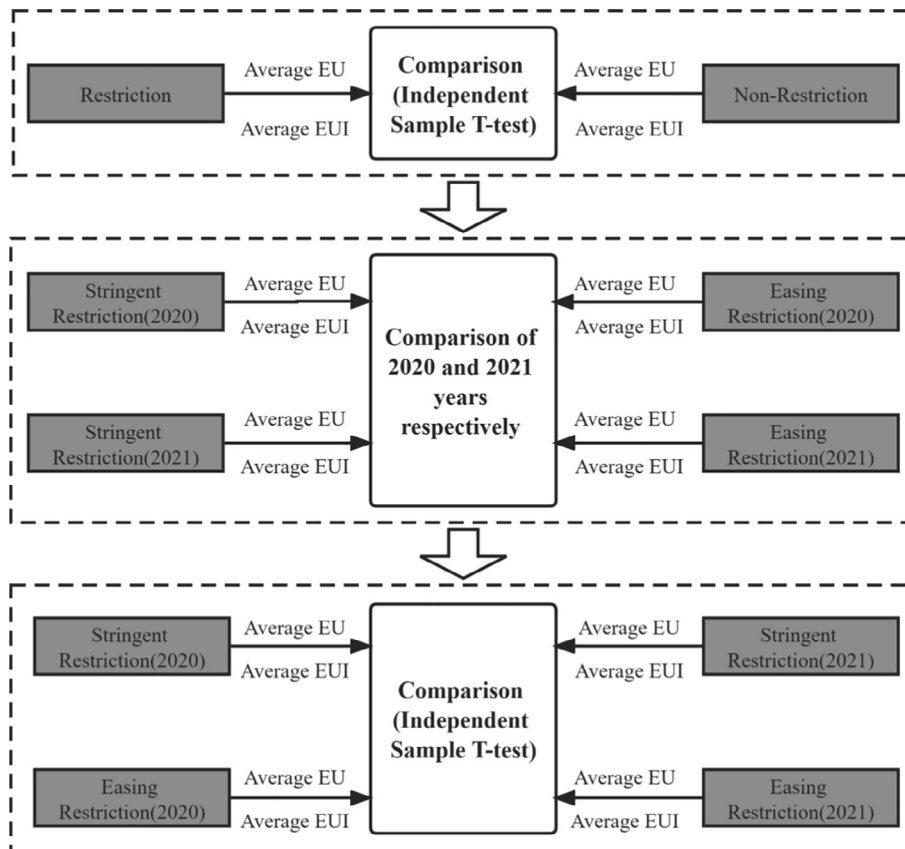


**Fig. 3.** Analysis flowchart.

**Table 3**
The sample size (EU and EUI datasets) of different building types.

| Building Type | Non-Restriction Period Sample Size | Restriction Period Sample Size | Stringent Restriction Period Sample Size (2020) | Easing Restriction Period Sample Size (2020) | Stringent Restriction Period Sample Size (2021) | Easing Restriction Period Sample Size (2021) |
|---|---|---|---|---|---|---|
| Depot | 216 | 503 | 66 | 221 | 87 | 129 |
| Library | 216 | 503 | 66 | 221 | 87 | 129 |
| Museum | 216 | 503 | 66 | 221 | 87 | 129 |
| Offices | 648 | 1509 | 198 | 663 | 261 | 387 |
| Primary School | 3024 | 7042 | 924 | 3094 | 1218 | 1806 |
| Secondary School | 3240 | 7545 | 990 | 3315 | 1305 | 1935 |

3.1.9.7 software for the validation. In this software, it is necessary to select the type of statistical test and power analysis to be performed (two independent samples T-test and post-hoc analyses were selected respectively in this study). Next, this study input effect size d (0.5 is acceptable in this case), α err prob (0.05 in general), and each group sample size for T-test. After that, this software can output the power (1-β err prob) parameters. Among all the output power results in this study, the minimum power value is 0.86 (generally more than 0.8 is acceptable), so the existing sample size is sufficient and reliable for the analysis in this study.

## 3. Analysis

### 3.1. Data overview

Table 4 is the average daily EU of 6 types of public buildings in different restriction periods. Museum buildings have the lowest EU all the time, with an average consumption of 150.68 kwh. Office buildings have the highest EU all the time, with an average consumption of 1266.44 kwh. The next are secondary school buildings, with an average consumption of 1040.39 kwh. Museums usually make the ambient light dark to protect the exhibits, leading to relatively low lighting power density and low EU (150.68 kwh). Office buildings are where people stay for a long time every day, and are operated longer than other public buildings, resulting in a relatively high energy consumption. Further observation can find that, the average EU of secondary school buildings is much higher than that of primary school buildings, as the average internal area of secondary school buildings (1,284.83 m$^2$) is much higher than that of primary school buildings (314.32 m$^2$), therefore, there are more energy-consuming equipment and services. At the same time, the students of secondary schools conduct more intensive learning activities than the students of primary schools. Comparing the average EU of secondary and primary schools in different periods, it can be found that, the average EU of primary schools during the stringent restriction period is much higher than other two periods, while the average EU of secondary schools is much higher during the easing restriction period. This is mainly because the Scotland government believes that the virus is less likely to infect young

people and therefore allows primary school students to return to school for full-time study in the later part of the stringent restriction period, while only allowing all secondary school students to return to school for full-time study during the easing restriction period.

Fig. 4 shows the variation trend of average weekly EUI of various public buildings. The red block indicates the stringent restriction period (lockdown), while the blue block indicates the easing restriction period. The EUI of office buildings is obviously higher than that of other types, indicating that the energy efficiency of the office building is much lower than the buildings of other types. Meanwhile, although the average EU of primary schools is much lower than that of secondary schools, the EUI of primary schools is higher than that of secondary schools. In accordance with the variation trend of EUI, during the stringent restriction period in 2020, the EUI of various public buildings lowered obviously, wherein, the EUI of library lowered maximally, as the library buildings were closed during the stringent restriction period, therefore, the EU lowered and further led to the lowering of EUI. For offices, the EUI lowered during the stringent restriction period in 2020, however, the decreasing amplitude was limited. This is largely because while the government encouraged people to work from home, some people, especially people working with some government bodies need to go to offices for handling public affairs in the pandemic. Under such circumstance, electric appliances and air conditioning in the office buildings still ran continuously. After that, in the easing restriction period of 2020, with the implementation in different phases of easing restriction, more and more public buildings could be reopened, therefore, the EUI of various buildings increased. While at the beginning of the stringent restriction period in 2021, Scotland government announced to close most of public buildings again, and asked people to stay at home; therefore, the EUI of the public buildings correspondingly lowered again, excepting for offices for similar reasons in 2020. After that, in the middle and later stage of the stringent restriction period in 2021, due to the reduction of the COVID-19 cases, Scotland government allowed primary school and secondary school students to go back to school even in the stringent restriction period, therefore, the EUI of primary schools, secondary schools and libraries increased obviously. In the easing restriction period of 2021, with the cancellation of the

**Table 4**
The average daily EUs.

| Building Type | Total Average EU (kwh) | Non-Restriction Period Average EU (kwh) | Stringent Restriction Period Average EU (kwh) | Easing Restriction Period Average EU (kwh) |
|---|---|---|---|---|
| Depot | 612.54 | 548.11 | 658.26 | 499.95 |
| Library | 759.97 | 685.17 | 578.99 | 731.58 |
| Museum | 150.68 | 132.73 | 96.05 | 148.76 |
| Offices | 1266.44 | 1220.42 | 1290.64 | 1189.72 |
| Primary School | 385.83 | 353.40 | 360.34 | 350.36 |
| Secondary School | 1040.39 | 956.23 | 882.12 | 988.62 |

**Fig. 4.** Variation trend of average weekly EUI.

restriction, the EUI of library further increased, while that of office lowered. In addition, due to school vacation, the EUI of primary and secondary schools lowered again at the beginning of July.

### 3.2. Comparison between restriction and non-restriction periods

This study used independent sample T-test to compare and analyze the EU and EUI of various public buildings in restriction periods (stringent restriction and easing restriction period) and non-restriction periods in recent two years to understand the effects of restriction policies for COVID-19 on EU and EUI. The results are shown in Table 5. The mean differences were calculated by the EU or EUI of various public buildings in the non-restriction period deducting that during the restriction period in these two years.

The differences in EU and EUI of various public buildings between restriction periods and non-restriction periods are statistically significant, expect for the mean difference in EUI between restriction periods and non-restriction periods for offices, which is not statistically significant. Wherein, the building type with the maximum EU mean difference is secondary school (275.04 kwh/day), followed by library (244.28 kwh/day) and depot (210.42 kwh/day), while the building type with the minimum EU mean difference is museum (58.62 kwh/day). It indicates that the restriction policies greatly affect the two public building types of schools and libraries, which are dedicated for educational and cultural activities with larger internal area and higher base energy consumption. As for why the mean difference of EU for secondary schools is significantly larger than that of primary schools, one of the possible reasons is that secondary schools have larger internal

area, which leads to more energy-consuming equipment accordingly, and therefore has a higher energy reduction potential due to the restriction policy. However, the mean difference of EU for museums is significantly smaller than that for libraries; one of the main reasons is that museums have a much lower base energy consumption and therefore have a limited energy reduction potential. In addition, depot also has a relatively high EU mean difference, which is mainly due to the large reduction in commercial activities and occupancy condition during the restriction period, thus significantly reducing the demand for commercial buildings and thus making depot have a large reduction in EU during the restriction period compared to the non-restriction period.

The building type with the maximum EUI mean difference is library (0.05 kwh/m$^2$/day), followed by primary school (0.032 kwh/m$^2$/day), while the building type with the minimum EUI mean difference is museum (0.016 kwh/m$^2$/day). This indicates that compared to museums, libraries have larger internal areas and higher base energy, and therefore have not only higher EU reduction potential but also higher EUI reduction potential. The case is different for educational buildings; compared to primary schools, secondary schools with larger internal areas and relatively higher base energy consumption, have higher EU reduction potential but lower EUI reduction potential.

### 3.3. Comparison between stringent restriction and easing restriction in the same year

To understand the effects of the restriction intensity on EU and EUI, this study compared the average EU and EUI of various public

**Table 5**
T-test results for two independent samples of EU and EUI.

| Building Type | EU | | | EUI | | |
|---|---|---|---|---|---|---|
| | t | P-value | Mean of differences (kwh/day) | t | P-value | Mean of differences (kwh/m$^2$/day) |
| Depot | 11.390 | <0.001* | 210.42 | 11.390 | <0.001* | 0.022 |
| Library | 8.227 | <0.001* | 244.28 | 8.227 | <0.001* | 0.05 |
| Museum | 13.050 | <0.001* | 58.62 | 13.050 | <0.001* | 0.016 |
| Office | 8.260 | <0.001* | 150.48 | 0.753 | 0.452 | 0.024 |
| Primary School | 15.194 | <0.001* | 105.93 | 18.118 | <0.001* | 0.032 |
| Secondary School | 11.881 | <0.001* | 275.04 | 13.810 | <0.001* | 0.02 |

(* indicates p < 0.001).

buildings during stringent restriction periods and easing restriction periods in 2020 and 2021, respectively, as shown in Fig. 5. In both years, the average EU and EUI of offices are the highest, while those of museum are the lowest. Further observation can find that, the average EU and EUI of library and museum in the stringent restriction period are much lower than those in the easing restriction period, while the case for offices is on the contrary: the average EU and EUI in the stringent restriction period is much higher than that in the easing restriction period. It indicates that the EU and EUI of the cultural buildings are inversely proportional to the restriction intensity, while those of office buildings are proportional to the restriction intensity. This is mainly attributed to the fact that library and museum, as the cultural buildings, are not used as much as office buildings. Therefore, they can be closed quickly, and their electricity consumption can immediately decrease. However, offices show a different situation entirely: people's routine work cannot be ceased immediately, so there is a lag in the reduction of electricity for office buildings. This lag effect has also been found in the study [43] which showed that while all industries were affected by the pandemic outbreak, the time of reduction of electricity consumption and recovery varied by industry, and in some industries such as government organizations, the lag effect can even cover several weeks. The EU and EUI variation of depot, primary school and secondary school are different in 2020 and 2021. The EU and EUI of these three building types in the stringent restriction period are lower than those in the easing restriction period in 2020, while the EU and EUI of these three buildings in the stringent restriction period are higher than those

in the easing restriction period in 2021. It indicates that, the EU and EUI of the educational buildings and the commercial buildings are inversely proportional to the restriction intensity in 2020, but are proportional to the restriction intensity in 2021. This is because in the stringent restriction period of 2021, with fewer COVID-19 cases and more people vaccinated, the Scotland government allowed schools to reopen; primary and secondary school students were able to return to school on a full-time and part-time basis. Hence, the EU and EUI of primary school and secondary school increased.

### 3.4. Comparison of stringent restriction and easing restriction in different years

To understand the impact of similar restriction periods on EU and EUI, this study further used the independent sample T-test to analyze and compare the differences of EU and EUI of various public buildings during the stringent restriction period in 2020 and in 2021, as well as the easing restriction period in 2020 and in 2021. The results are shown in Table 6. Among them, the mean difference was calculated by the EU or EUI of various public buildings during the stringent restriction period or the easing restriction period in 2020 deducting that during the stringent restriction period or the easing restriction period in 2021.

According to Table 6, during the stringent restriction period, the differences in EU and EUI of various public buildings between 2020 and 2021 are statistically significant, expect for offices. In addition, the EU and EUI for all types of public buildings are lower in 2020
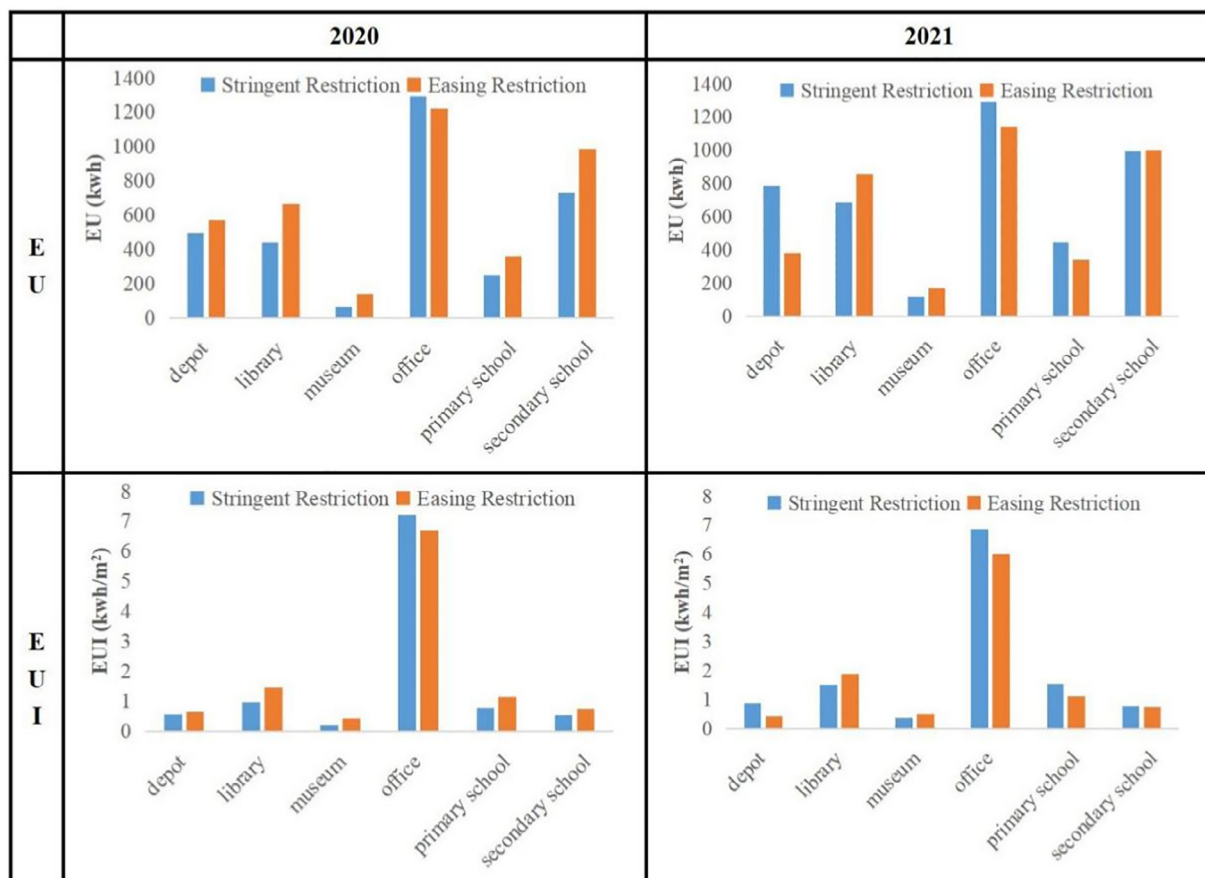


**Fig. 5.** Comparison of average EU and EUI in different restriction periods in 2020 and 2021.

**Table 6**
T-test results for two independent samples of EU and EUI in the stringent restriction and easing restriction periods.

| Building Type | Stringent Restriction Period EU | | | Stringent Restriction Period EUI | | | Easing Restriction Period EU | | | Easing Restriction Period EUI | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | t | P-value | Mean of differences (kwh/day) | t | P-value | Mean of differences (kwh/m²/day) | t | P-value | Mean of difference (kwh/day) | t | P-value | Mean of differences (kwh/m²/day) |
| Depot | −10.529 | <0.001* | −290.92 | −10.529 | <0.001* | −0.33 | 10.427 | <0.001* | 192.14 | 10.427 | <0.001* | 0.22 |
| Library | −7.287 | <0.001* | −248.81 | −7.287 | <0.001* | −0.54 | −5.780 | <0.001* | −192.59 | −5.780 | <0.001* | −0.42 |
| Museum | −10.711 | <0.001* | −55.24 | −10.711 | <0.001* | −0.17 | −5.248 | <0.001* | −28.69 | −5.248 | <0.001* | −0.09 |
| Office | −0.044 | 0.965 | −0.81 | 5.196 | <0.001* | 0.35 | 5.523 | <0.001* | 79.40 | 14.736 | <0.001* | 0.68 |
| Primary School | −13.535 | <0.001* | −192.15 | −14.436 | <0.001* | −0.77 | 1.226 | 0.221 | 20.84 | 0.712 | 0.477 | 0.04 |
| Secondary School | −10.409 | <0.001* | −264.56 | −10.395 | <0.001* | −0.21 | −0.500 | 0.617 | −18.22 | −0.338 | 0.736 | −0.01 |

(* indicates p < 0.001).

than in 2021 during the stringent restriction period. This indicates that even though they are all under a stringent restriction, people may take different views towards the pandemic. Specifically, 2020 is the beginning of the COVID-19 pandemic, and due to the surge in daily COVID-19 cases and deaths, and a lack of awareness about the new virus, people's attitudes and mindset towards the COVID-19 pandemic were more of a panic and concern than they were during the stringent restriction period of 2021, the second year of the pandemic. In this regard, people were more likely to comply with restriction policies and drastically reduce the use of various public buildings in 2020. The building type with the maximum EU mean difference is depot (−290.92 kwh/day), followed by secondary school (−264.56 kwh/day) and library (−248.81 kwh/day), while with the minimum EU mean difference is office (−0.81 kwh/day). The building type with the maximum EUI mean difference is primary school (−0.77 kwh/m²/day) and library (−0.54 kwh/m²/day), while with the minimum EUI mean difference is museum (−0.17 kwh/m²/day). This demonstrates that people under the stringent restriction would even reduce the use of the educational buildings like secondary school and primary school and the cultural buildings like library in the initial stage of the COVID-19 pandemic. These types of buildings are not designed to sustain people's basic livelihood, so a sharp reduction in the use of these buildings would not significantly affect people's normal life.

During the easing restriction period, the differences in EU and EUI of various public buildings between 2020 and 2021 are statistically significant, expect for primary school and secondary school. Among them, the EU and EUI of library and museum are lower in 2020 than in 2021 during the easing restriction period, while the EU and EUI of depot and office are higher in 2020 than in 2021 during the easing restriction period. The building type with the maximum EU mean difference is library (−192.59 kwh/day), followed by depot (192.14 kwh/day), while with the minimum EU mean difference is museum (−28.69 kwh/day). The building type with the maximum EUI mean difference is office (0.68 kwh/m²/day), while with the minimum EUI mean difference is museum (−0.09 kwh/m²/day). This indicates that during the easing restriction period in 2020, due to the concerns still growing in this stage of the COVID-19 pandemic, people would not immediately increase their use of library and museum, but would more likely increase their use of depot, a building with strong commercial ties, and office, a building closely related to work, in order to sustain personal income to cope with the uncertainty of the future. By the easing restriction period in 2021, people would have become more accustomed to and accepted the existence of the COVID-19 pandemic, so the use of non-essential cultural buildings would begin to increase in the easing restriction period after the stringent restriction period.

## 4. Discussion

### 4.1. The impact of restriction on the electricity consumption of public buildings

To more accurately discuss the results, this paper uses the stringency index proposed and calculated by the Oxford Coronavirus Government Response Tracker (OxCGRT) project to represent the restriction intensities at different times during the epidemic. This index reflects the rigor of government restriction policies, mainly calculated according to school closures, workplace closures, cancellation of public events, restrictions on public gatherings, closures of public transport, stay-at-home requirements, public information campaigns, restrictions on internal movements, and international travel controls. The value is between 0 and 100, with a higher score indicating more stringent restriction policies (i.e. 100 = the most stringent restriction) [44].

Fig. 6 shows the line graph of the stringency index plotted by the project for the UK during the COVID-19 pandemic. By comparing it with the variation trend of average weekly EU for different types of public buildings in Fig. 7, it can be seen that in the middle to late March 2020, as the government enacted various restriction policies and announced entering the stringent restriction period, the stringency index increased sharply, and the average EU of all public buildings had decreased in different degrees during this period. Among them, the educational buildings like secondary school and the cultural building like library have larger average EU reduction amplitude than others. This is mainly because these two types of public buildings are not essential for maintaining people's lives, so reducing the use of them during the COVID-19 pandemic would not have a large impact on people's lives. At the same time, secondary school and library have a larger internal area and base energy consumption, so they have a greater potential for energy reduction than primary school and museum. In the middle to late May 2020, the stringency index began to decline as government restrictions were easing, and the average EU of all categories of public buildings increased to varying degrees. In early January 2021, due to the spread of the Delta coronavirus, the stringency index rise to a higher level than in 2020, and the average EU of all types of public buildings started to decrease again, but at a lower rate than during the stringent restriction period in 2020, which means that in 2021, people were more accustomed to and accepted the existence of the COVID-19 pandemic, and therefore, the occupancy behavior and usage frequency of public buildings increased in the stringent restriction period in 2021 compared to the stringent restriction period in 2020. In general, as the restriction intensity increases, electricity consumption in public buildings decreases, and vice versa. The electricity reduction is different at different stages of the pandemic given the similar restriction inten-
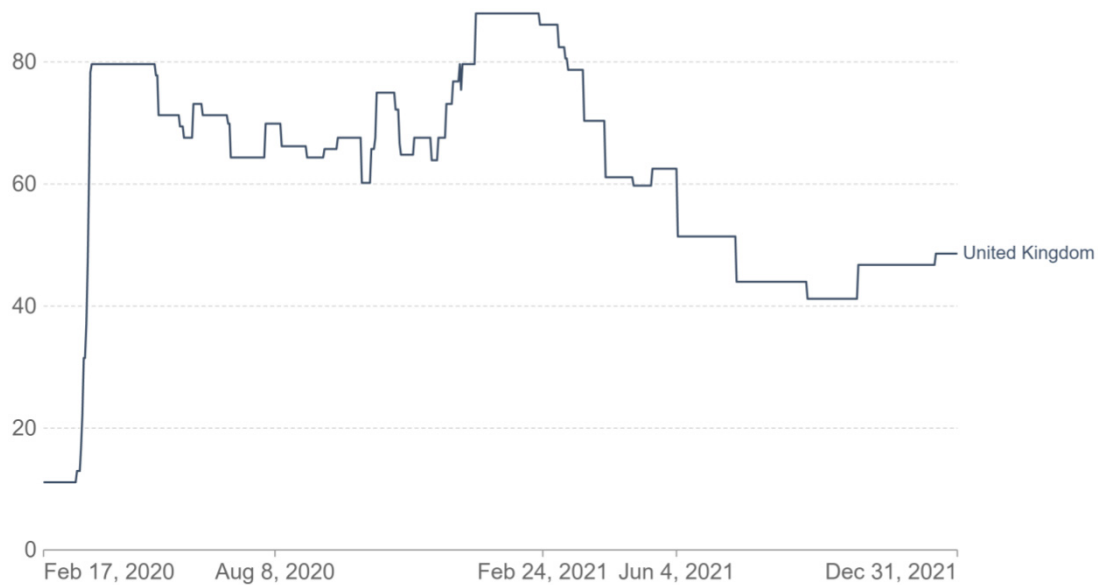
**Fig. 6.** Line graph of the stringency index during the COVID-19 pandemic in UK (image source: Our World in Data).
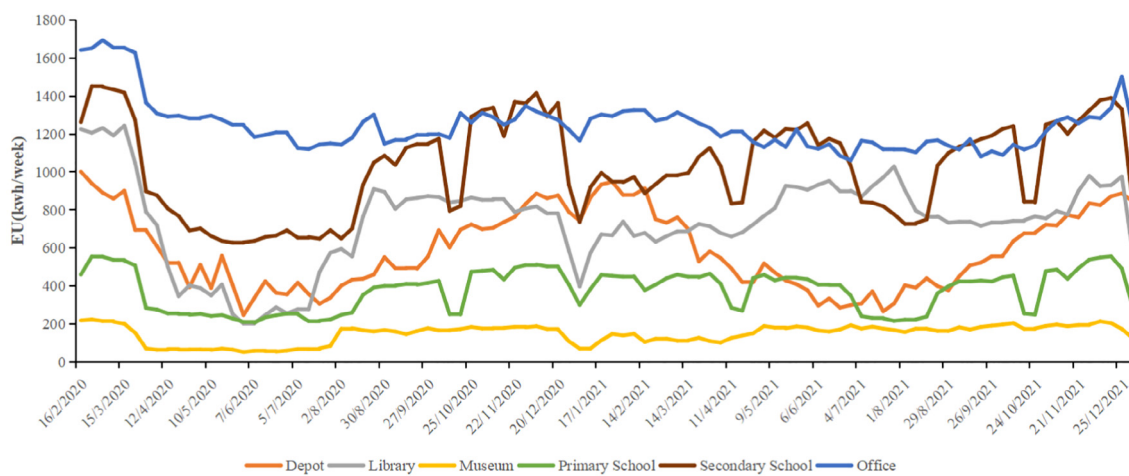


**Fig. 7.** Variation trend of average weekly EU for different types of public buildings.

sity; especially in the later stages of the COVID-19 pandemic, as people have accepted the existence of the pandemic, even stronger restrictions lead to less electricity reduction.

### 4.2. The impact of use frequency on the electricity use of public building

The electricity consumption of public buildings is directly related to use frequency. Although there is no direct data about the occupancy condition and use frequency, this paper uses data provided by Google in the COVID-19 Community Mobility Report, which indicates the people's activities in cities and as indirect evidence of the use of public buildings [45]. Fig. 8 shows the amount of change in people's mobility and number of visitors at specific locations (e.g., residential, parks, grocery & pharmacy stores, retail & recreation, transit stations, workplaces, etc.) during the COVID-19 pandemic relative to the baseline time (January-February 2020). By comparing Fig. 8 with 7, the variation of the average weekly EU of various public buildings, we can observe that, from middle to late March 2020, as the government issued various restriction policies and announced the entry of a stringent restric-

tion period, the mobility in retail & recreation, transit stations, workplaces dropped sharply, and the electricity reduction of public buildings was almost synchronous. This is the reason why the average EU of office, library and museum in this study decreased during this period. Nonetheless, the three types of public buildings have different EU reduction degrees during this period. Museum has the lowest EU reduction, followed by office, while library has the highest EU reduction. This is mainly because museum has lower base energy consumption and smaller internal area, so it has lower EU reduction potential, while office tends to run high energy-consuming equipment such as central air conditioning for the whole common area even if few people work inside, thus leading to a lower EU reduction compared to library. In addition, compared to the stringent restriction period in middle to late March 2020, the mobility reduction in these three types of locations during the stringent restriction period in January 2021 was less, indicating more mobility. This further confirms the previous assumption that the occupancy behavior and usage frequency of public buildings would increase during the stringent restriction period in 2021 (the second year of COVID-19) compared to the stringent restriction period in 2020 (the first year of COVID-19)
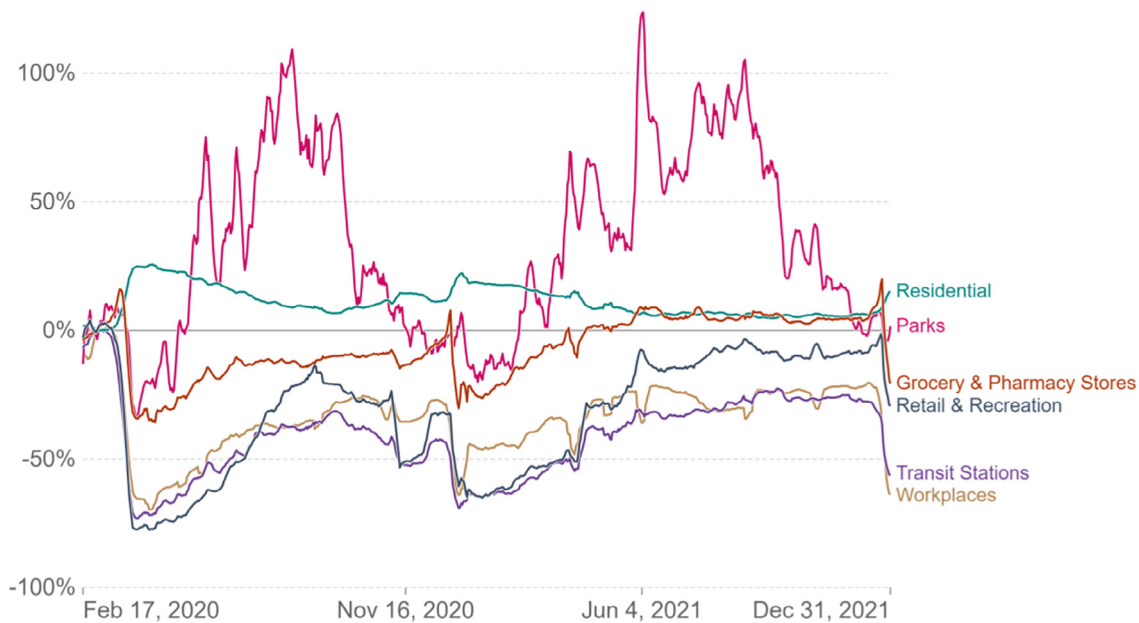
**Fig. 8.** Line graph of the amount of change in people's mobility at specific locations during the COVID-19 pandemic relative to the baseline time in UK (image source: Our World in Data).

as people become accustomed to and accepted the presence of the COVID-19 pandemic.

### 4.3. Implication and limitation

It has been confirmed that the occupancy behavior and use frequency of building can have a significant impact on the building energy consumption [46,47]. During the COVID-19 pandemic, the implementation of government restriction policies and measures led to changes of usage frequency and mobility in various public locations, whereas further affected the energy consumption of public buildings. This study compares and analyzes the EU and EUI of different types of public buildings during different stages of COVID-19 pandemic, which has important implications for exploring the potential for building energy savings due to different restriction policies and measures. Meanwhile, since the COVID-19 pandemic has not yet over, and other public health crises are also likely to occur in the future, energy baselines and building service standards for different types of public buildings should be appropriately adjusted to accommodate these changes and make the building energy saving potential more flexible and resilient according to changes in usage frequency and occupancy behavior.

In addition, with the outbreak of the COVID-19 pandemic, as well as the proposal of concepts such as "virtual campus" and SOHO (small office and home office), a fundamental question is raised, that is, whether some traditional school and office buildings are necessary, because many functions related to study and work can be completed and accessed remotely in digital form at home or online, providing users with more flexibility. In this case, these public buildings may consume less energy. Most of the current research is based on simulation [48,49] or hypothetical scenarios [50]. This study takes advantage of the opportunity provided by the implementation of COVID-19 restriction policies to study the real energy consumption data, which provides support for confirming this hypothesis and has important practical implications. The energy implication of the COVID-19 pandemic is critically disclosed in this study by comparing two years' restriction and easing policies implemented at different stages considering people's

mindset and behavioral changes towards the virus. This has not been considered in previous energy studies of the pandemic. Furthermore, the research also helps energy managers to formulate more realistic electricity demand management policies based on building types during the COVID-19 pandemic and optimize electricity supply loads and energy profile.

However, there are some limitations of this study. First, due to the limitation of data acquisition, the samples come from the same city and the sample size from each building type is not equal; the generalization of the conclusion requires further studies in a larger scale. As the use frequency of various public buildings may vary among people in different regions and environments, more areas should be investigated and analyzed in the future to improve the study. Second, due to the lack of data on each building's own characteristics and detailed occupancy condition, this paper only provides a narrative analysis of the impact of restriction policies on energy consumption, while more sophisticated statistical modeling is needed to further predict the energy impact in the future when remote working, learning, and playing are becoming more and more popular.

## 5. Conclusion

Using the Perth and Kinross region of Scotland, UK as the case, this study investigated the electricity consumption data of local authority owned public buildings in 2020 and 2021. By comparing the EU and EUI of various types of public buildings during different restriction periods, this study found different energy saving potentials of public buildings. Furthermore, the impact of restriction intensity and mobility on building energy consumption was also discussed in this paper. The main conclusions of this study are summarized as follows:

(1) The library buildings with a larger internal area and higher base energy consumption during non-restriction periods offer higher EU reduction potential (244.28 kwh/day) and higher EUI reduction potential (0.05 kwh/m$^2$/day) compared to other buildings.

(2) The EU and EUI of the cultural buildings such as library and museum are inversely proportional to the intensity of the restriction in both 2020 and 2021. While the EU and EUI of offices are proportional to the intensity of the restriction in both years.

(3) The EU and EUI for depot, primary school and secondary school buildings are inversely proportional to the intensity of restriction in 2020 and proportional to the intensity of restriction in 2021.

(4) Except for depot and office buildings, the EU and EUI of all public buildings in the first year's stringent and easing restriction period are lower than those in the second year's stringent and easing restriction period.

(5) The difference of the electricity variation of different types of public buildings reflects their different functions and roles in people's daily life, while the difference of electricity variation of public buildings as a group reflects people's attitudes and behavioral changes towards the virus at different pandemic stages.

At present, due to the possibility of the continued development and longevity of the COVID-19 pandemic and the uncertainty of the future public health crises, the government still encourages people to maintain a certain social distance, which will change public building occupant's behavior and usage frequency for a considerable period, and thus reduce the electricity consumption of public buildings. Even in the future, after the pandemic is over, the usage frequency and electricity load of various public buildings may be reduced to some extent compared to the pre-pandemic because people have accustomed to this lifestyle and use habits. However, it will take a longer period of time to confirm or disprove this hypothesis. For now, policymakers need to develop electricity demand management policies that are more in line with current realities based on building types and functions, to appropriately adjust energy benchmarks and building service standards to accommodate these changes, and to optimize the energy profile and electricity supply loads of different types of public buildings at the city level, and to restructure and adjust electricity supply facilities.

## 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.

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