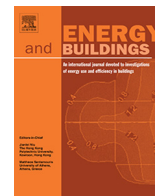




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The impact of COVID-19 on higher education building energy use and implications for future education building energy studies



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ABSTRACT

Although COVID-19 has significantly changed the higher educational sector, there are few studies revealing how this pandemic has changed the energy use of higher education buildings. This study was conducted not only to disclose the energy use change under COVID-19 but also to identify the corresponding facilities management strategies for future learning and teaching delivery modes under virtual campuses. This study collected the energy use data of 122 buildings across five campuses in Griffith University, located in Southeast Queensland, Australia, during the COVID-19 academic year (February 17, 2020, to February 21, 2021) and during a typical normal academic year (February 18, 2019, to February 16, 2020) by PI Vision Platform, and compared the data using the *t*-test and multiple linear regression. The results indicated that learning and administration activities became off campus during the pandemic, while research activities remained on campus. During the COVID-19 academic year, an amount of 9,646,933 kWh energy or around 24.88 kWh/m² of energy use intensity was saved, which accounted for 16% of the total energy use per academic year. Specifically, the shutting down of air conditioning in academic buildings, administration buildings, retail buildings and teaching buildings during COVID-19 saved 4,566 kWh (1.13 kWh/m²), 966 kWh (0.8 kWh/m²), 1,472 kWh (1.4 kWh/m²) and 860 kWh (1.3 kWh/m²) of electricity use per week, respectively, which accounted for 51.5%, 44.3%, 48.3% and 57.1% of total energy use per week during this period, respectively. Based on this analysis and the changing educational environment, this study also speculated on the energy implications of future teaching and learning practices, which provided guidance to the facilities management under virtual campuses.

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1. Introduction

The 2019 coronavirus disease (COVID-19) has impacted the world since December 2019 [1]. The COVID-19 pandemic has had a profound influence on many industries, including agriculture, manufacturing, finance, education, healthcare, sports, tourism, food and energy [2,3]. Among these, higher education is one of the most impacted sectors as nationwide closures have impacted over 91% of the global student population [4]. During the COVID-19 pandemic, most universities adopted online courses to prevent the concentration of student populations and the spread of the virus [5]. The online courses inevitably led to changes in occupancy conditions as well as variations of energy use on higher education campuses. This study aimed to understand the energy use and occupancy changes during COVID-19 to help inform learning and

teaching delivery modes and energy-saving strategies of higher educational institution in the future.

Energy use by higher educational institutions is complex as they usually include a range of spaces with different functions, such as offices, classrooms, laboratories and meeting rooms [6]. These spaces allow for various activities, such as research, teaching and administration [7]. In normal buildings, occupancy condition may refer to the occupancy rate, using schedule and so on. As for higher educational buildings, function, activity and discipline may determine the occupancy rate and using schedule. For example, lecture room may have higher occupancy rate. Laboratories for research may have long operation hours [8] while teaching spaces may only be used on working days [7]. Different occupancy conditions directly impact energy use in higher educational institutions. Khoshbakht et al. [9] investigated 80 university buildings in Australia and found that research buildings have the highest energy use intensity (EUI) while academic offices had the lowest EUI. These findings have been upheld by other studies in Australia

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[7], the UK [10,11] and China [8]. The high EUI of research spaces might result from the long working hours [8] even during holidays [7]. Some studies have indicated that, in addition to academic offices, teaching spaces such as lecture rooms also have low EUI [12]. Other studies have also focused on the disciplines of occupants, revealing that occupants majoring in science and medicine used more energy while those majoring in social science and humanities used less energy [13].

As occupancy conditions are directly related to energy use, changes in occupancy conditions will undoubtedly result in changes to energy use. Therefore, it is necessary to research the energy-saving potential under occupancy condition transformations caused by any intervention. Table 1 shows previous studies on energy saving under changes in occupancy conditions. In general, previous studies have all indicated that appropriate changes in occupancy conditions can save energy. However, most of these studies were based on simulations [12,14,15] or hypothetical scenarios [10]; there is a lack of real data to verify the energy-saving potential. In fact, most existing studies on energy saving in higher educational institutions have been based on two approaches. One has focused on the buildings themselves, such as high-efficiency measures [16] and smart equipment [17], changing of indoor environment quality requirements [18] and adopting renewable energy [19]. The other has focused on occupant behaviour, such as switching sockets, lighting and air conditioning usage [20]. These studies regarded the higher educational buildings as regular buildings and overlooked the special occupancy conditions—and the resulting impact of the COVID-19 public health crisis—relating to energy use in higher educational institutions.

In addition to policy transformations relating to academic terms [21] and course timetable changes [12,15], there are many other policies relating to future occupancy changes in higher educational institutions. Future campus predictions have become a hot topic. According to the [22], the features of future campus can be summarised as follows: 1) increasingly diverse student demographics; 2) a rising demand for lifelong learning; 3) the on-campus experience remaining key; 4) lifecycle-driven design and automation to improve sustainability; 5) a greater understanding of user needs enhancing productivity; and, 6) internal and external synergies driving innovation. Under such circumstances, future campuses may have faster networks to transport data and an augmented environment for portable devices [23]. Additionally, with students now able to attend classes and perform many other academic tasks online, university campuses have become less focused on traditional lecture-based teaching and more on learning the softer skills needed in an ever-changing world. Campuses thus need to adapt to meet the changing needs, demands and uses at a time when virtually all information is readily available online [24].

Accordingly, the ‘virtual campus’ concept has been proposed. A virtual campus usually refers to the online offerings of a college or

university where student learning is completed either partially or wholly online, often with the assistance of a course convenor and teaching assistant. This can offer students greater flexibility in terms of the schedule, lower tuition fees and broader subject choices [25]. Previous studies have already indicated that, despite not being face-to-face, virtual campuses offer an effective teaching method [26] and can differentiate the grades of different students [27]. Under such circumstances, these campuses may use less energy than traditional campuses. However, there have been no studies verifying the hypothesis. COVID-19 has provided the opportunity to study the energy-saving potential arising from a transition to online courses and virtual campuses as most universities adopted online courses during the pandemic.

Generally speaking, there is a lack of existing studies on energy saving in relation to occupancy conditions using real data, on energy use changes in relation to occupancy conditions attributable to policy intervention, and on the energy-saving potential of online courses and virtual campuses. To fill these gaps, this study investigated the energy use characteristics and energy-saving potential of a university in Australia, analysed the occupancy condition changes during the COVID-19 pandemic as well as proposed future changes to campus learning and teaching modes. The main objectives of this study are understanding the occupancy condition change under COVID-19, exploring the energy saving potential of virtual campus, and speculating the future campus energy management. This paper comprises five sections. Section 2 introduces the case study, including the data collection method and online course policy under COVID-19, and the analysis strategies. Section 3 presents the analysis results. Section 4 analyses the occupancy conditions and energy-saving potential during COVID-19, proposes three campus modes in the future and summarises the implications and limitations of this study. Section 5 summarises the conclusions and significance of this research.

2. Methodology

2.1. Data collection

2.1.1. Case study: Griffith university

Griffith University is a comprehensive university located in southeastern Queensland, Australia. It has five campuses across Brisbane and the Gold Coast, as shown in Fig. 1. The two cities are in a subtropical climate zone with hot, humid summers and moderately dry, warm winters [28]. Due to the influence of moisture, maritime airflow from the western side of the subtropical anticyclonic cells over low-latitude ocean waters results in the average summer temperature in Brisbane and the Gold Coast being below 30.3 and 28.7 °C, respectively, while the average winter temperature in Brisbane and the Gold Coast is above 10.2 °C and 12 °C, respectively [29]. Therefore, there is a high demand for cooling in summer but little demand for heating in winter.

Table 1
Studies on energy saving with the occupancy condition change.

Reference	Country	Intervention	Occupancy Condition Change	Energy Change
[21]	Australia	Terms setting transformation	The university's work focus shifted from teaching to research after transformation to trimester system	Trimester system saved more energy on teaching while used more energy on research
[15]	China	Timetable optimized	The occupancy of classrooms in the optimized timetable is relatively concentrated timewise	The proposed timetabling reduced the energy use of teaching by 3.6% in the autumn semester
[12]	Korea	Timetable optimized	lectures for graduate students and undergraduate should be scheduled before 8:00 pm and during 9:00 am to 6:00 pm.	The proposed timetabling shows 4% energy saving during heating and cooling season.
[14]	Brazil	Setting occupancy data	Different number of people, operation hours, area use per day, etc.	Potential annual savings in electric energy use for the campus could be around 9.6%
[10]	UK	Change some of the current norms and conventions	Change the teaching timetable to hold lab classes and research practices out of ‘peak’ demand times but during daylight hours	A potential energy saving measures

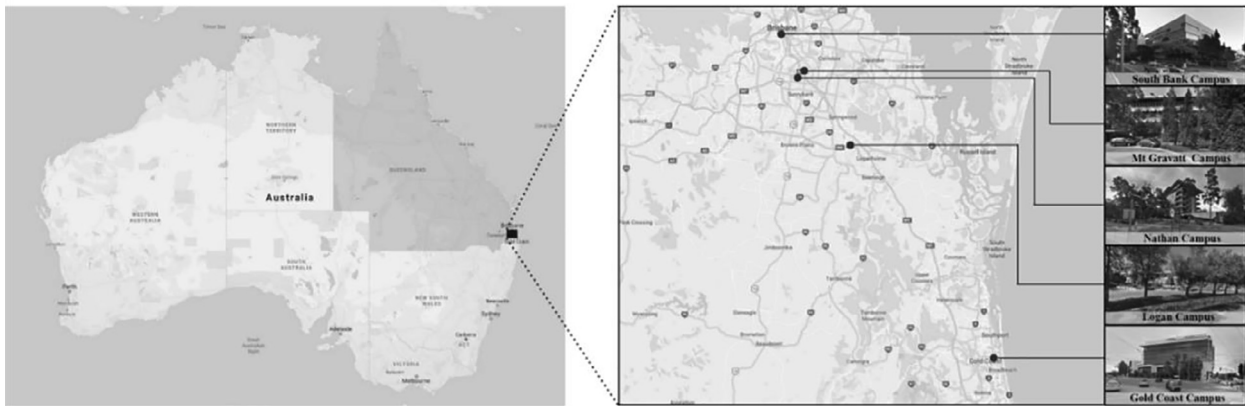


Fig. 1. Location of five campuses of Griffith University.

Since March 2020, COVID-19 has spread throughout Queensland. As one of the top higher educational institutions in Queensland [30], Griffith University has taken active countermeasures to deal with the adverse impacts of COVID-19 on the health of students and staff. After the first week of trimester 1, the university promoted online courses for all years. At the beginning of April (around April 5, 2020), the University suggested that all staff work from home and that the campuses during this period be regarded as virtual campuses. After April, as the infection rate had decreased, the university proposed the ‘Return to Campus’ policy to facilitate the orderly return of students and staff to campuses [31]. Stage 1 of ‘Return to Campus’ started on May 17, 2020, allowing the key staff who supported essential learning, teaching and research activities to return to campuses. Most research staff were not included in stage 1 [31]. Stage 2 of ‘Return to Campus’ began around June 28, 2020, during which research activities that required face-to-face collaboration or access to specific resources unavailable off-campus were allowed to return to campuses. However, where research activities could be effectively and efficiently undertaken remotely, researchers and research support staff were still advised to continue working remotely during stage 2 [31]. Stage 3 of ‘Return to Campus’ began around August 16, 2020, and commenced the transition for the remaining staff. All teaching and learning, research and enrichment activities were back to campus [31]. By the end of February 2021, the campuses were ready to open again with all services accessible to students and staff. Fig. 2 shows the three stages of the ‘Return to Campus’ policy.

The current study compared the whole academic year impacted by COVID-19 pandemic (from February 17, 2020, to February 21, 2021) with a typical normal academic year (from February 18,

2019, to February 16, 2020) to identify the changes in occupancy conditions and energy-savings during COVID-19. The two academic years had the same climate conditions: they both had 290 ± 10 18 °C heating degree days and 1520 ± 50 18 °C cooling degree days [32]. The two academic years also had the same course structures: 3 weeks of orientation, 12 weeks of trimester 1, 12 weeks of trimester 2, 12 weeks of trimester 3, 3 weeks of study days and 3 weeks of exams. However, the COVID-19 academic year had only 7 weeks of holidays while the typical normal academic year had 8 weeks of holidays. Trimester 1 was from the end of February to the beginning of June, trimester 2 was from the beginning of July to the beginning of October, and trimester 3 was from the end of October to the beginning of February. During each trimester, the students attended classes and teaching activities were frequent. Orientation always preceded each trimester. During this period, students registered for their courses and some orientation lectures were held. Study days were often after each trimester, during which students prepared for their exams. Exams often came after study days, during which period students sat for their exams.

2.1.2. Sample buildings

In this study, 122 buildings across the five campuses were selected for comparison between the two academic years. Basic information, such as the buildings’ main function, ground floor area, usable floor area and the number of floors is summarised in Table 2. The main function was defined according to the Higher Education Funding Council for England initiative [33]. However, this function definition of the whole building was too generic to reflect the complexity of space use in higher educational buildings. For instance, academic buildings have comprehensive functions

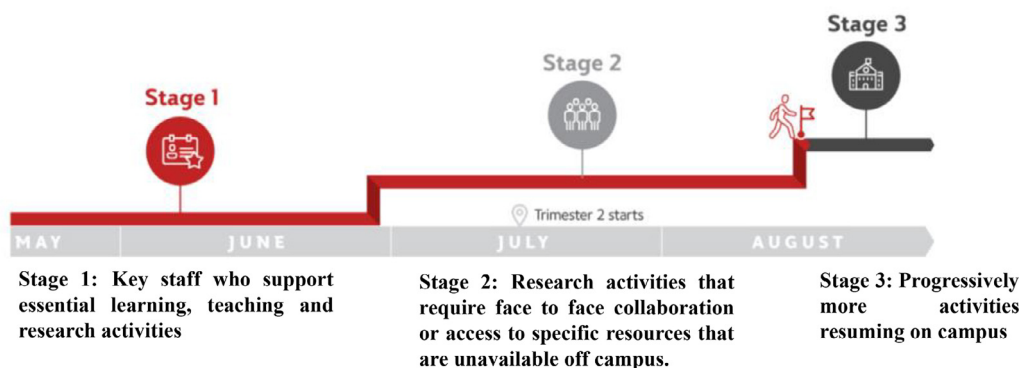


Fig. 2. Three stage of policy “Return to Campus”

Table 2
Basic information of studied buildings.

Main Function	Number of buildings	Gross Floor Area (m ²)				Usable Floor Area (m ²)				Number of Floor			
		Mean	Max.	Min.	Std.	Mean	Max.	Min.	Std.	Mean	Max.	Min.	Std.
Academic	57	5415.1	30476.5	292.1	4854.5	3326.2	15882.1	221.23	2786.2	5.263	12	2	2.0
Administration	17	1850.6	5697.7	130.0	1806.8	1199.4	3718.0	114.8	1133.8	2.824	5	1	1.0
Infrastructure	10	268.2	511.6	41.0	175.6	0	0	0	0	1.500	2	1	0.5
Research	7	2762.4	5439.0	202.7	1728.0	1798.2	3741.9	173.9	1174.3	4.000	6	2	1.2
Residential	9	2879.1	4888.2	204.3	1524.6	2092.3	3330.4	195.8	1101.7	4.667	8	2	1.7
Retail	6	747.2	1971.1	54.8	628.9	495.0	1101.0	50.7	337.9	2.667	4	2	0.7
Sport Recreation	6	856.3	2474.9	104.9	840.4	582.4	1804.6	28.9	657.3	2.000	2	2	0.0
Teaching	10	981.5	2387.9	206.9	660.4	548.1	877.6	175.1	262.9	3.300	7	2	1.4

such as teaching, research and administration. Hence, a more precise definition of the function of each room instead of the whole building was needed to study the energy use of different spaces across the two academic years. Accordingly, in this study, each room was described in terms of eight functions: research, academic, teaching, administration, information services, residential, commercial, and non-habitable. The information on each room was collected from Griffith SpaceAid, a digital platform that includes the space functions and related information of all campus buildings, floors, and rooms.

The energy use of all buildings in Griffith University has been collected by smart meters via the PI Vision platform since December 2014 [9]. Energy use data are collected hourly and can be easily accessed online. In this study, energy data from the two academic years were collected weekly as the university arranged courses and academic activities on a weekly basis.

2.2. Analysis techniques

The analysis flow chart is shown in Fig. 3. First, this study compared the energy use during all academic periods for all buildings using the *t*-test to understand the differences in occupancy conditions between the two academic years. Next, this study compared the energy use by different types of buildings during the COVID-19 academic year to understand the occupancy conditions for different types of work during different COVID periods. Finally, the study established relationships between the areas of spaces with different functions and their energy use in the two academic years and compared the two academic years to determine the occupancy conditions of different types of work during different COVID-19 periods.

2.2.1. *T*-test

The *t*-test was adopted in RStudio to determine if there were significant differences in energy use between the typical academic year and the COVID-19 academic year. RStudio is a cross-platform integrated development environment designed for R language and has always been adopted for data analysis in similar studies [7,21]. The *t*-test is an inferential statistical analysis to identify whether a significant difference exists between the means of two groups after an intervention [34]. Existing studies have adopted the *t*-test to analyse energy use variations under specific interventions [35,36]. The *t*-test calculation is provided as Eq. (1) [37]:

$$t = \frac{\bar{d}}{\sqrt{N^{-1}S_d^2}} \quad (1)$$

The input parameters of the *t*-test include *t*, *df*, the *p*-value and the mean difference. The parameter '*t*' shows a quantile corresponding to a standard *t* distribution, and '*df*' shows the degree of freedom, which means the number of independent or freely variable data in the sample. For *N* random samples, the degree of

freedom is *N*-1. The *p*-value indicates the significance: when the *p*-value is below 0.05, the null hypothesis that there is no difference between the means of the two groups is rejected, and the difference is significant. The mean difference shows the mean value of the differences of all paired samples. In this study, the differences were the energy use values in the typical academic year minus those in the COVID-19 year.

2.2.2. Multiple linear regression

Multiple linear regression (MLR) in RStudio was applied to define the impacts of different functions on energy use during the two academic years. MLR has proven to be a simple way to associate building energy use with influencing variables [38]. The main advantage of this method is its ease of use; indeed, no specific expertise is required, against engineering methods [39], and it has the advantage of minimising the amount of input data to avoid repetitive work [40]. Besides, the solutions obtained from the application of the MLR method can be considered generic and applicable to similar conditions. Previous studies have used MLR to associate energy use in buildings with different types of influential variables, such as climate variables [41], building variables [7] and social economic variables [42]. Assuming that *k* variables were selected for a study, the MLR model could be written according to Eq. (2) [43]:

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \dots + \beta_kx_k + \epsilon \quad (2)$$

In this study, *x* was the floor area of each function and *y* was the weekly energy use of each COVID-19 period. The output of the regression model includes the intercept, estimate, *p*-value and *R*². The 'estimate' is each ' $\beta_{1...k}$ ' term in Eq. (2), which represents the increase in energy use when the area of the function is increased by 1 m². The intercept is β_0 in Eq. (2), which represents the energy use when the total area of all function equals to 0, namely the energy use to maintain the operation of the building. The *p*-value represents the significance of the model, with the regression model being statistically significant if the *p*-value is below 0.05. *R*² shows the percentage of the dependent variable variation that is explained by a linear model; the closer *R*² is to 1, the better the model fits the data. Finally, ϵ is the difference between the actual value and the estimated value.

3. Results

3.1. Data overview

The average EUI variations for each building type during the typical academic year and the COVID-19 academic year are shown in the appendix. The green block means the trimesters while the red block means the holidays. As most of the infrastructure buildings were chiller houses, which have a much higher EUI compared with other types of buildings, the EUI variations of infrastructure buildings are shown in a separate diagram. Besides infrastructure

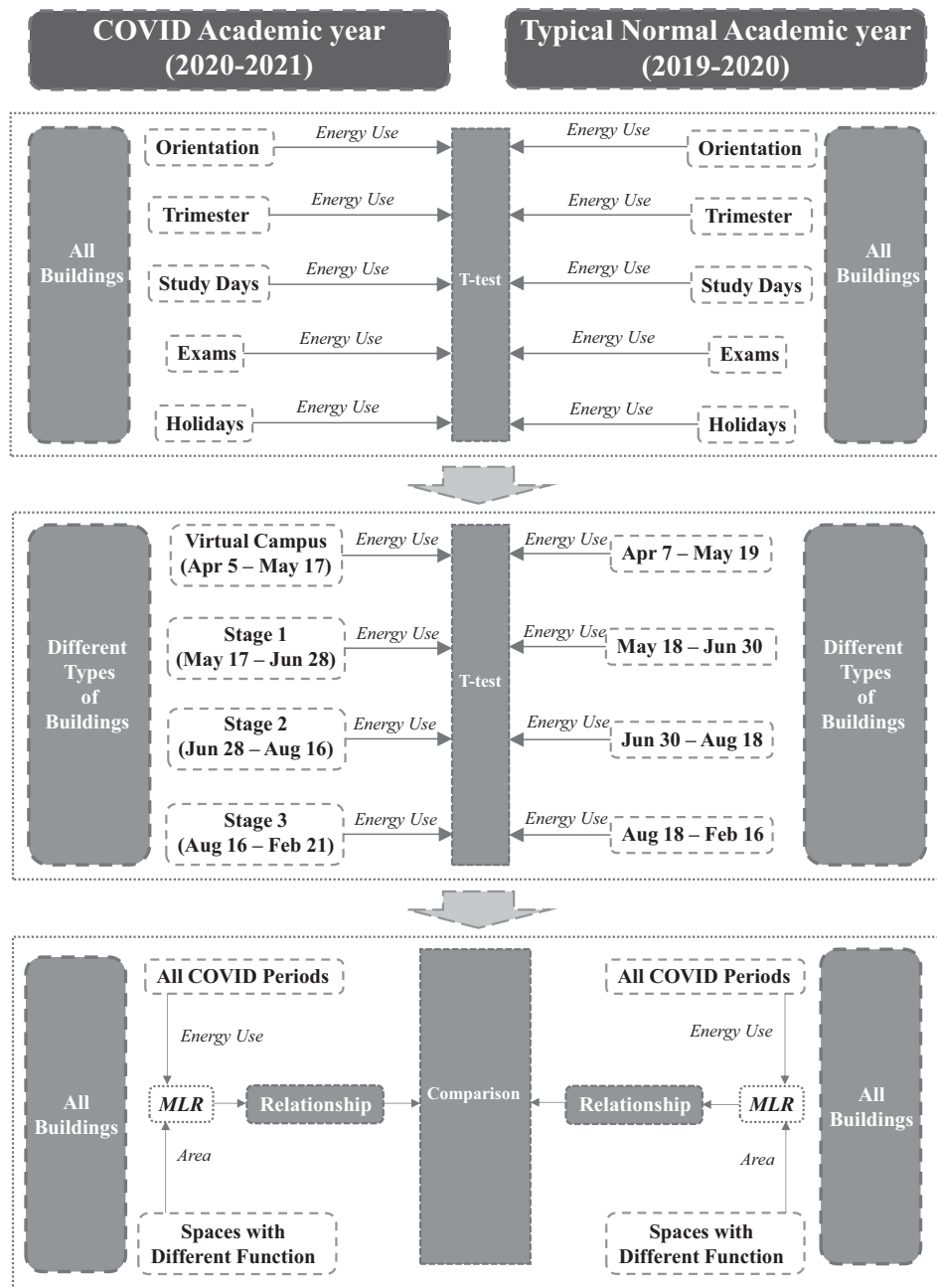


Fig. 3. Analysis flow chart.

buildings, research buildings had the highest EUI. In general, after the COVID-19 pandemic began to spread in Australia from March 2020, the EUI of all types of buildings decreased. However, due to the coming winter and the decreased demand for cooling, the EUI of some types of buildings—such as retail, administration and teaching buildings—in the typical academic year decreased as well; this variation was highly significant for infrastructure buildings.

Fig. 4 shows the total energy use of different types of buildings during different periods in the typical academic year and the COVID-19 academic year. Academic buildings used more energy, while retail, sport recreation, and teaching buildings used less energy. The energy use during trimesters and exam weeks was higher while the energy use during holidays was lower. Generally, in the COVID-19 academic year, most types of buildings—including academic building and administration buildings—used less energy during all periods, while there were few differences in energy use

for research buildings in the typical academic year and COVID-19 academic year.

3.2. Energy use differences between the two academic years

Table 3 shows the *t*-test results of all sampled buildings during different periods. The *p*-values indicated that there were significant differences in energy use per week between the two academic years. Regarding the mean differences, the most significant decreases in energy use in the COVID-19 academic year were in Trimester 1 and the exam period, while the energy use during orientation declined the least among all periods. These findings could be explained by the higher number of students enrolled in trimester 1 than in other trimesters and because the pandemic was most serious in trimester 1 (from March 2020 to June 2020); therefore, after adopting online courses, students left their classrooms to take

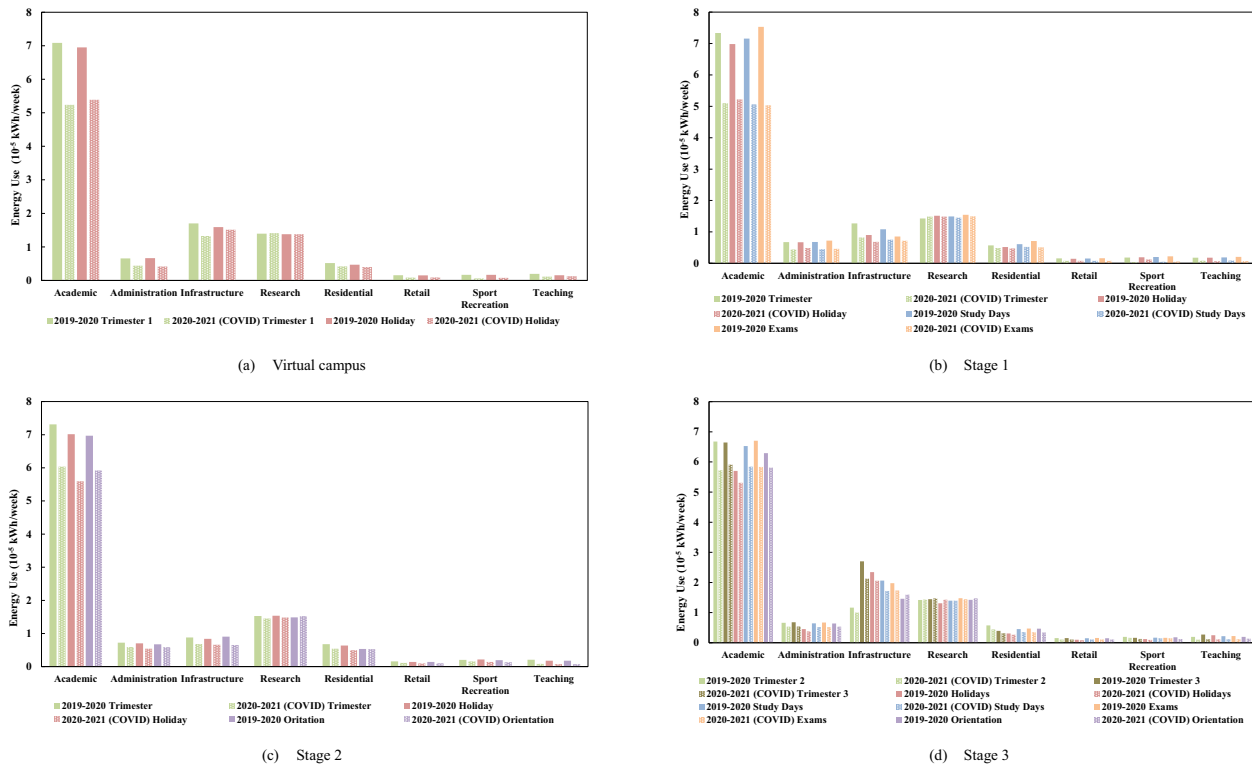


Fig. 4. Total energy use of different types of building during different time periods in typical normal academic year and COVID academic year.

Table 3

T-test results of all sample buildings during different academic periods.

Period	t	df	p-value	Mean of differences (kWh/week)
Orientation	3.259	121	0.001**	449.5
Trimester 1	6.56	121	<0.001***	1848.5
Trimester 2	9.319	121	<0.001***	1433.3
Trimester 3	5.16	121	<0.001***	1424.6
Study Days	8.281	121	<0.001***	1618.8
Exams	9.534	121	<0.001***	1829.3
Holidays	8.002	121	<0.001***	1582.6

(***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$).

these courses from home, which saved considerable energy during this period. As for the increased energy use during exam weeks in typical academic years, this could be due to students—even those who were usually absent from campus—needing to attend to take exams and obtain course credits. However, during the COVID-19 pandemic, all exams were taken online, resulting in energy saving on campus. Orientation weeks usually provide life and study guidelines for newly enrolled students, and because the energy use during this period is lower than during other periods, the reduction in energy use was also lower.

Table 4 shows the *t*-test results of all sampled buildings during different COVID-19 periods. The analysis only includes the energy

use during trimesters because the energy use during these periods could adequately reflect the occupancy transformations during the COVID-19 pandemic. The *p*-values indicated that the differences in energy use between the typical academic year and the COVID-19 academic year were significant. From the perspective of the mean differences, the differences in energy use during the virtual campus stage and stage 1 were the most significant, while the differences in energy use during stages 2 and 3 were less significant. During stages 2 and 3, key staff supporting essential learning, teaching and research activities as well as those involved in research activities requiring face-to-face collaboration or access to specific

Table 4

T-test results of all sample buildings during different COVID periods.

Period	t	df	p-value	Mean of differences (kWh/week)
Virtual Campus	7.5687	121	<0.001***	2277.0
Stage 1	7.7509	121	<0.001***	2666.9
Stage 2	10.224	121	<0.001***	1665.3
Stage 3 (trimester 2)	7.7698	121	<0.001***	1251.0
Stage 3 (trimester 3)	5.1599	121	<0.001***	1424.6

(***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$).

resources could return to campus, accounting for the greater energy use.

Table 5 shows the *t*-test results for different types of buildings during different COVID-19 periods. For academic buildings, there were significant differences in energy use between the typical academic year and the COVID-19 academic year during all COVID-19 periods. Academic buildings combine teaching, administration and research, and most of the spaces in academic buildings were used for teaching. Therefore, undoubtedly there were significant reductions in energy use during the COVID-19 pandemic because of the switch to online teaching. From the perspective of the mean difference, the differences became less pronounced during stages 2 and 3 than stage 1. In terms of administration buildings, the *p*-values indicated that only the differences during stage 3 were significant, which may be because administration staff were allowed to return to campus first. From the perspective of the mean differences, the energy use gaps between the two academic years decreased from stage 1 to 3. In terms of infrastructure buildings, the energy use differences between the two academic years in stage 3 were the most significant considering both the *p*-values and mean differences. Most of the infrastructure buildings are chiller houses, which use more energy in summer. Therefore, the energy used in stage 3 by infrastructure buildings was considerably higher, resulting in the energy use differences for this stage being more statistically significant. In terms of research buildings, there were few difference in energy use between the two academic

years. Research buildings usually provide specialised spaces with specific experimental equipment, and the research work in such spaces usually cannot be performed at home. Therefore, many researchers may have chosen to continue their research in the research buildings instead of working from home, despite university restrictions of some on-campus activities, which resulted in minimal differences in energy use between the two academic years. In terms of residential buildings, except for during trimester 3 in stage 3, the energy use differences between the two academic years were significant. From the perspective of the mean differences, the differences were most significant during stage 2 and trimester 2 in stage 3, implying that more students living on campus chose to leave in trimester 2. The pattern of energy use by retail buildings was similar to that of academic buildings: the differences were more significant during the virtual campus period and stage 1 and less significant during stages 2 and 3 regarding the mean differences. In terms of sports recreation buildings, the differences in energy use between the two academic years were insignificant during all COVID-19 periods, indicating that these buildings were still in operation during the COVID-19 pandemic. As for teaching buildings, the differences in energy use between the two academic years were significant during all COVID-19 periods. However, the differences were more significant during trimester 3 in stage 3, which may result from more energy used for cooling in summer in the typical academic year compared with the COVID-19 academic year.

Table 5

T-test results of different types of building during different COVID periods.

Type	Period	t	df	p-value	Mean of differences (kWh/week)
Academic	Virtual campus	6.3348	56	<0.001***	3242.9
	Stage 1	6.9106	56	<0.001***	3923.7
	Stage 2	8.8958	56	<0.001***	2234.9
	Stage 3 (trimester 2)	7.5239	56	<0.001***	1667.7
	Stage 3 (trimester 3)	5.4216	56	<0.001***	1291.9
Administration	Virtual campus	1.9367	16	0.071	1285.2
	Stage 1	2.0775	16	0.054	1373.6
	Stage 2	1.8238	16	0.087	789.9
	Stage 3 (trimester 2)	2.1385	16	0.048*	749.8
	Stage 3 (trimester 3)	2.4138	16	0.028*	818.7
Infrastructure	Virtual campus	3.1755	9	0.011*	3757.1
	Stage 1	3.1325	9	0.012*	4497.0
	Stage 2	2.8977	9	0.018*	1976.2
	Stage 3 (trimester 2)	1.6643	9	0.13	1610.3
	Stage 3 (trimester 3)	2.6528	9	0.0264*	5761.1
Research	Virtual campus	-0.30888	6	0.7679	-252.7
	Stage 1	-1.2619	6	0.2538	-866.5
	Stage 2	1.6746	6	0.145	1081.2
	Stage 3 (trimester 2)	-0.18634	6	0.8583	-201.1
	Stage 3 (trimester 3)	-0.2648	6	0.8	-379.4
Residential	Virtual campus	3.5892	8	0.007**	1075.7
	Stage 1	2.917	8	0.019*	930.7
	Stage 2	4.166	8	0.003**	1492.9
	Stage 3 (trimester 2)	4.8043	8	0.001**	1444.1
	Stage 3 (trimester 3)	0.66425	8	0.525	833.0
Retail	Virtual campus	2.6393	5	0.046*	1156.6
	Stage 1	2.4504	5	0.058	1286.0
	Stage 2	2.3913	5	0.062	782.4
	Stage 3 (trimester 2)	2.3694	5	0.064	742.9
	Stage 3 (trimester 3)	3.1994	5	0.024*	766.8
Sport Recreation	Virtual campus	1.7802	5	0.135	1731.5
	Stage 1	1.5853	5	0.173	2328.4
	Stage 2	2.3844	5	0.063	631.0
	Stage 3 (trimester 2)	1.8113	5	0.1299	565.3
	Stage 3 (trimester 3)	1.4111	5	0.2173	658.1
Teaching	Virtual campus	3.4496	9	0.007**	828.4
	Stage 1	3.7771	9	0.004**	938.6
	Stage 2	2.9371	9	0.017*	1234.5
	Stage 3 (trimester 2)	2.6537	9	0.026*	928.0
	Stage 3 (trimester 3)	1.9841	9	0.079	1524.7

(***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$).

3.3. Impacts of different functions on energy use in the two years

Table 6 shows the results of multiple linear regression between energy use and the area of spaces with different activities. The table only shows the activities that were highly related to energy use. The p-values indicated that all the regression models were significant. However, research, academic and non-habitable buildings had the greatest impact on energy use. Research spaces provide academic researchers with laboratories and offices; academic spaces comprise research, teaching and administration spaces related to academic staff; and non-habitable spaces are not occupied by people, such as building service areas. From the perspective of estimates, an increase in academic space did not directly lead to more energy use, implying that the use of academic spaces impacted energy use only slightly. From the perspective of intercept, the energy use to maintain the operation of the whole building during COVID academic year were less than that during typical normal academic year, indicating the energy saving during COVID academic year.

Fig. 5 shows the relationship between spaces with different activities and energy use. The impact indicates the increase in energy use when the space area increases by 1 m². In general, during the COVID-19 pandemic, research spaces impacted energy use more, which indicated that during this period researchers accounted for a larger proportion of all people on campus compared with during the typical academic year. Especially during stages 1 and 2 and trimester 2 in stage 3, the research spaces impacted energy use more compared with during the virtual campus stage, indicating that during the virtual campus stage there were many students or staff who still chose to work on campus. During the typical academic year, more energy was used on building services to operate the whole building, while during the COVID-19 academic year, because there were less staff on campus, less energy was used on building services. However, the results indicated that during trimester 3 in stage 3, the area increase of non-habitable spaces impacted energy use significantly, which may have been caused by the inaccurate intercept calculated by the model.

4. Discussion

4.1. Occupancy condition under COVID-19

Although Griffith University proposed a top-down policy in response to COVID-19, the real occupancy conditions under COVID-19 were complex, and the usage patterns of different people—such as administration staff, students and researchers—were different. At Griffith University, online courses began from mid-March 2020, and while the university suggested that all staff work

from home at the beginning of April, the suggestion was voluntary. Therefore, from the beginning of April, all the campuses could be regarded as virtual campuses. However, the results of the t-test demonstrated that some staff continued working on campus, as the mean difference in energy use still increased after the virtual campus stage.

With the easing of COVID-19, at the end of May 2020 the university proposed the 'Return to Campus' policy. During stage 1, this policy allowed key staff who support essential learning, teaching and research activities [31] to return to campus. In fact, during this stage, the number of administration staff on campus reached a minimum as the mean difference in energy use by academic buildings and administration buildings peaked.

At the end of June, stage 2 of the 'Return to Campus' policy began, and this stage was also the beginning of trimester 2. During this stage, research activities that required face-to-face collaboration or access to specific resources were permitted to recommence on campus [31]. However, in reality, most research buildings were still in operation during all COVID-19 periods as indicated by the t-test results for research buildings: there was no significant difference in energy use between the two academic years. This may have been because the universities allowed key research staff to remain on campus during the pandemic, and even though some laboratories were free of staff the air conditioning remained running to maintain clean and safe conditions for potentially dangerous laboratory equipment and reagents. Research buildings are different from the research spaces in other buildings in terms of providing specific experimental instrument, which would result in more energy use in these buildings [7], and it is difficult for researchers to continue their work away from laboratories. Therefore, once they were permitted to return to campus, researchers came back to their laboratories to continue their work, which is consistent with some previous studies [44]. Additionally, the t-test results for teaching buildings and residential buildings indicated that stage 2 had the most coursework students off-campus, resulting in the greatest mean differences in energy use. Stage 2 was at the beginning of trimester 2, so some students may not have returned to campus after the holidays as they knew that the courses would be held online; before trimester 1, students would not have known that online courses would be offered so they stayed on campus after enrolment as the university allowed a few students to remain under the condition of ensuring safe distancing.

Stage 3 of 'Return to Campus' was from mid-August 2020 to the end of February 2021. This period contained the last week of trimester 2 and the whole of trimester 3. Because there were fewer students taking courses in trimester 3 as these courses were all elective [21], fewer students returned to campus, as indicated by the mean difference in energy use of teaching buildings. However, more staff and ordinary researchers in academic buildings

Table 6
MLR results of different types of building during different COVID periods.

COVID periods	Academic years	p-value	R ²	Intercept		Research		Academic		Not Habitable	
				p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate
Virtual campus	Normal	<0.001***	0.68	0.007**	2724.0	0.018*	3.297	0.007**	-5.879	<0.001***	8.552
	COVID	<0.001***	0.66	0.026*	1955.6	<0.001***	4.557	0.006**	-5.163	<0.001***	6.773
Stage 1	Normal	<0.001***	0.76	0.010*	2145.0	<0.001***	5.041	0.007**	-4.823	<0.001***	6.917
	COVID	<0.001***	0.74	0.146	718.2	<0.001***	6.337	0.012*	-3.904	<0.001***	4.904
Stage 2	Normal	<0.001***	0.78	0.014*	1823.0	<0.001***	6.609	0.035*	-3.332	<0.001***	4.750
	COVID	<0.001***	0.79	0.183	902.5	<0.001***	6.399	0.019*	-3.426	<0.001***	4.746
Stage 3 (trimester 2)	Normal	<0.001***	0.74	0.014*	1999.3	<0.001***	5.265	0.009**	-4.546	<0.001***	6.115
	COVID	<0.001***	0.74	0.059	1437.2	<0.001***	5.616	0.006**	-4.447	<0.001***	5.848
Stage 3 (trimester 3)	Normal	<0.001***	0.51	0.002**	4566.5	0.446	1.534	0.003**	-9.284	<0.001***	2.168
	COVID	<0.001***	0.57	0.013*	1237.6	0.102	2.810	0.003**	-8.073	<0.001***	10.294

(***: p < 0.001; **: p < 0.01; *: p < 0.05).

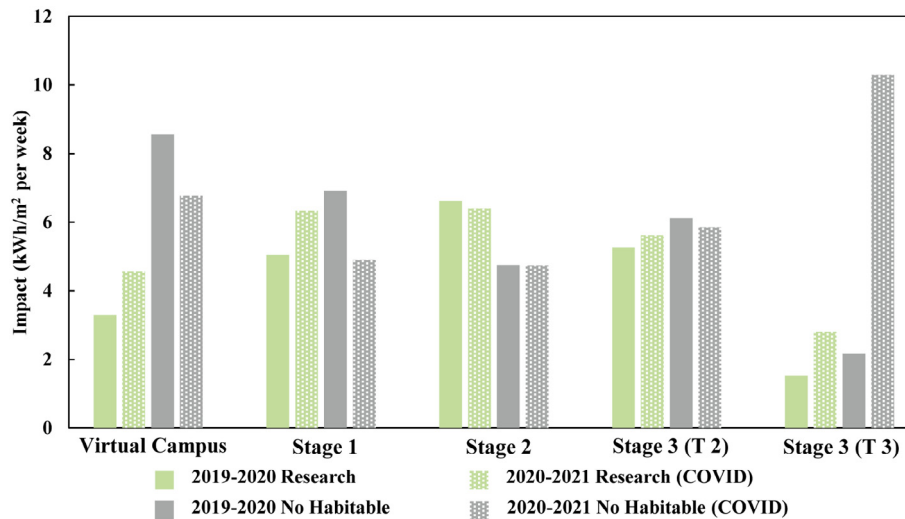


Fig. 5. Relationship between space with different activities and energy use.

returned to campus during stage 3, as indicated by the continued decrease in the mean difference in energy use for academic buildings and administration buildings.

In general, three occupancy conditions were identified. Administration staff began to work from home during the virtual campus stage, with this number reaching a peak during stage 1 and then declining gradually during stage 2 as they began to return to campus. The occupancy pattern for ordinary researchers working in academic buildings may have been the same as for administration staff. However, researchers working in research buildings returned quickly to campus after stage 1. Most student undertaking coursework chose to leave campuses after the end of trimester 1—that is, at the end of stage 1—and did not return until the end of stage 3.

4.2. Potential energy savings under COVID-19

Although COVID-19 had brought many challenges, the switch to online courses and virtual campuses has resulted in energy savings. Based on calculations for the two academic years across the same combination of weeks, the energy use during the typical academic year was 62,206,199 kWh while the energy use during the COVID-19 academic year was 52,559,266 kWh. During the COVID-19 academic year, 9,646,933 kWh, around 24.88 kWh/m², was saved, which accounted for 16% of the total energy use in the academic year. Some scholars even found more energy saved in other university during COVID-19 [44,45]. This huge energy saving may have been caused by the reduced hours of building equipment operation. Previous studies have pointed out that building services such as air conditioning account for a large proportion of energy use in higher education buildings [15]. At Griffith University, the HVAC (Heating Ventilation and Air-conditioning) systems in some types of buildings, such as academic buildings, administration buildings, teaching buildings and retail buildings, was shut down for a couple of weeks (usually from 2 to 13 weeks) during the COVID-19 pandemic. There were 31 academic buildings, four administration buildings, three retail buildings and three teaching buildings that shut down their HVAC systems during the virtual campus stage and stages 1 and 2 of the 'Return to Campus' policy. Academic buildings usually account for the largest proportion of buildings in higher education institutions and used the most energy [7,21]. Therefore, these buildings were responsible for the greatest energy savings during the COVID-19 pandemic: among the 31 academic buildings, each building shut down its HVAC system for 9 weeks on average and saved an average of 4,566 kWh (1.13 kWh/m²) per week during this period, which accounted for

51.5% of their total energy use per week during the period. Among the four administration buildings, each building shut down its HVAC system for 10 weeks on average and saved an average of 966 kWh (0.8 kWh/m²) per week during this period, which accounted for 44.3% of their total energy use per week during such period. Among the three retail buildings, each building shut down its HVAC system for 9 weeks on average and saved an average of 1,472 kWh (1.4 kWh/m²) per week during this period, which accounted for 48.3% of their total energy use per week. As for three teaching buildings, each building shut down its HVAC system for 9 weeks on average and saved an average of 860 kWh (1.3 kWh/m²) per week, which accounted for 57.1% of their total energy use per week.

4.3. Future campus scenarios

Previous studies have already pointed out that with the development of Internet, online courses will become a popular trend and an effective teaching method in the future [24,26,27]. To confirm the energy-saving potential of virtual campuses, this study investigated the energy use characteristics in Griffith University during COVID-19 and analysed the occupancy conditions during this period. The results indicated that online courses indeed saved considerable energy, especially for teaching and administration. Additionally, the virtual campuses during COVID-19 decreased the traffic demand among campuses, which directly reduced carbon emissions and energy use [46]. In fact, the daily round trip between campuses by car or shuttle bus not only increases emission but also wastes time. Online courses can better facilitate teaching across campuses and provide students with more flexibility to fit their schedule [25]. Therefore, it is feasible for higher educational institutions to propose online courses, especially lectures, considering the energy savings and flexibility in time management that would arise. On the other hand, some academic activities cannot be undertaken at home, such as research that needs special experimental instruments as well as tutorials and workshops that require practice and/or face-to-face communication.

In general, considering the possibility of future public health crises or pandemics, online courses may still be promoted. Future teaching and learning could operate according to three modes. The first mode could be entirely virtual campuses: all courses, including lectures, tutorials and workshops would be held online. In the entirely virtual campus, the focus of energy management should shift to research. For teaching areas, lighting and air conditioning should be controlled centrally and the equipment in teach-

ing areas would be used only when needed under special conditions. Under such circumstances, 100% of the energy for teaching and learning would be saved. The second mode could be half-virtual campus: lectures would be held online while other classes requiring practice and/or face-to-face collaboration, such as tutorials and workshops, would still be held on campus. On a half-virtual campus, the electrical appliances of lecture areas should be controlled centrally, while those for workshops and tutorials should be smart-controlled. Under such circumstances, the energy for lectures would be effectively saved while tutorials and workshops continue to use the resources on campus. The third mode could be non-virtual campus: all classes would be held on campus. In non-virtual campuses, functions should be arranged appropriately and the campus should adopt a combination of smart control and centralised control for energy management, the latter for different functions and the former according to different occupancy conditions. Under such circumstances, although the campuses could be regarded as regular campuses, energy would still be saved to the greatest extent.

4.4. Implication and limitation

Building energy policy has primarily focused on building design (e.g., the thermal performance of building envelopes) and building services (e.g., air conditioning and lighting). In recent years, studies have addressed the fact that energy is not used by buildings but by occupants, as occupancy conditions significantly influence the building's operations and consequent energy uses [8,12,21]. The COVID-19 pandemic significantly reduced the occupancy load of non-residential buildings and therefore reduced their energy use. This study used a higher education campus to determine the extent of energy use reduction in university buildings due to occupancy load reduction during the pandemic. This has some important implications for the use of flexible occupancy schedules to reduce the energy load of buildings. The occupancy condition changes during the pandemic may remain for some time since people are still encouraged to maintain social distancing and to avoid large gatherings. The uncertainty regarding future public health crises also requires these practices. Therefore, it is to be expected that the occupancy load and therefore energy load for non-residential buildings will be reduced to different extents during and after the pandemic and even in the future. Accordingly, energy benchmark and building service standards will be required to adjust to suit these changes and to be more flexible and resilient according to changes in occupancy conditions.

Furthermore, the COVID-19 pandemic has raised the fundamental question of whether some non-residential buildings are needed at all since many types of work can be conducted online. This study used a higher education campus to prove that teaching and learning indeed occur online, resulting in a significant amount of energy saving. The changes to teaching and learning modes due to the pandemic will be long-lasting since many universities have acclimatised to this delivery mode and have found it to be a more efficient utilisation of teaching and learning resources. Considering that lectures are increasingly moving online, there may be fewer students and teaching support staff on campus simultaneously, thereby reducing the energy load of the whole campus. On the other hand, as research is still conducted on campus, the energy consumption of laboratory buildings has not significantly reduced. As shown in this study, many research buildings were still running during the pandemic and their energy use was not lower than in previous years. However, the energy profile of the whole campus has shifted and needs to be restructured in terms of energy management for campus life and facilities management.

This study confirmed the energy-saving potential by online courses during the COVID-19 pandemic and provided guidance

on policy settings for online courses in higher educational institutions in the future. However, this research also had some limitations. For example, this study only investigated one university; the results need to be verified by more universities in the future. Additionally, although the climate in the two academic years was quite similar overall, the weather may have been different in different weeks, which was not taken into consideration.

5. Conclusion

Taking Griffith University as an example, this study compared energy use characteristics during the COVID-19 academic year (February 2020–February 2021) with energy use in a typical academic year (February 2019–February 2020). The differences in energy use during different COVID-19 periods between the two academic years were determined by the *t*-test and the impacts of spaces dedicated to different activities on energy use were determined by multiple linear regression. Based on the results, the occupancy conditions during each COVID-19 period were analysed, as well as the energy-saving potential of virtual campuses. Finally, suggestions for policy settings in higher educational institutions were provided. The conclusions of this study are summarised as follows:

- 1) The top-down policy during COVID-19 made occupancy conditions complex. Administration staff began to work from home during the virtual campus stage, with the number of administration staff choosing to work from home reaching a peak in stage 1 before they began to gradually return to campus during stage 2. For researchers working in academic buildings, their occupancy pattern may have been similar to that of administrative staff, while researchers working in research buildings continued their laboratory research during all COVID-19 periods. Most students undertaking coursework chose to leave campus after the end of trimester 1 (stage 1) and did not return to campus until the end of trimester 3 (stage 3).
- 2) Calculations for the two academic years across the same combination of weeks revealed that during the COVID-19 academic year, 9,646,933 kWh of energy was saved, which accounted for 16% of the total energy use during the typical academic year. Due to the shutting down of the HVAC system during COVID-19, academic buildings, administration buildings, retail buildings and teaching buildings saved 4,566, 966, 1472 and 860 kWh per week on average, respectively, during this period.
- 3) The future of teaching and learning could be summarised in three scenarios: entirely virtual campuses, half-virtual campuses and non-virtual campuses. For energy management, entirely virtual campuses should adopt centralised control, half-virtual campuses should adopt centralised control for lecture areas and smart control for tutorials and workshops, and non-virtual campuses should adopt a combination of centralised and smart control. Such conditions would help campuses effectively save on energy use.

In summary, this study identified the exact energy saving potential of online courses via a real case study. This study also analyzed the occupancy condition change under COVID-19, which implied how and why the energy use was saved. In addition, this study proposed three possible campus modes in the future and their corresponding energy management methods. This study provides significant implications for the future higher educational campus in terms of energy management, which would be significantly helpful for university campus to achieve campus energy sav-

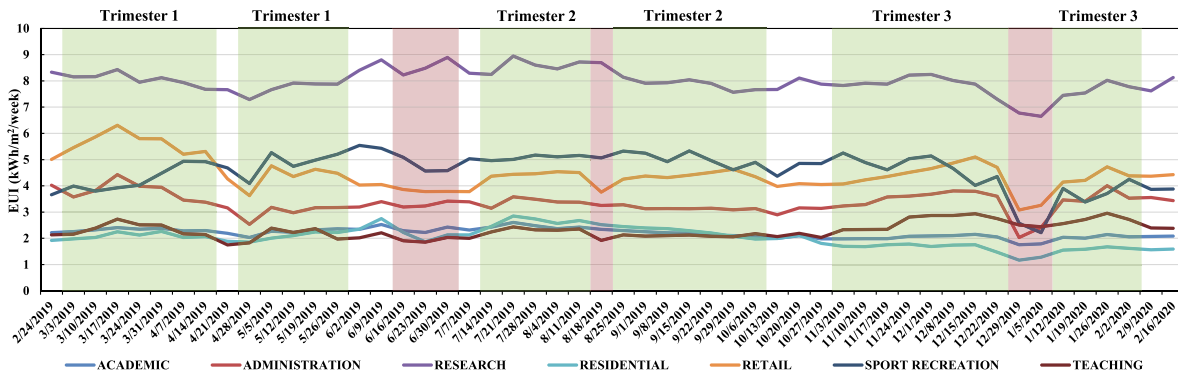
ing and carbon emission reduction goals. For the future, more university campus in different climates will be studied to verify the results.

Declaration of Competing Interest

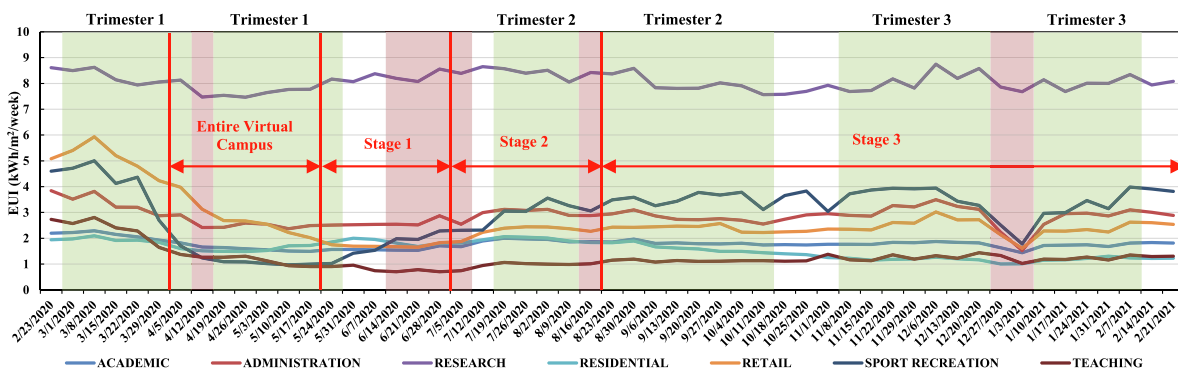
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

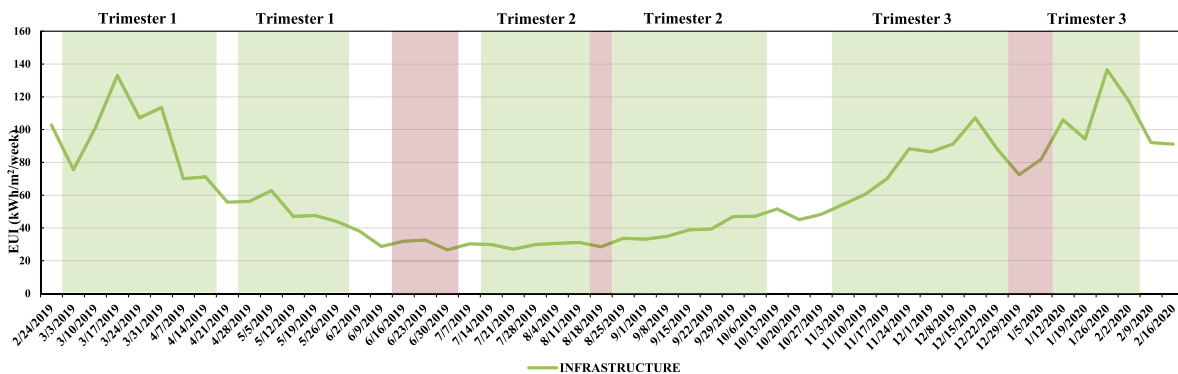
EUI variation during typical normal academic year and the COVID academic year.



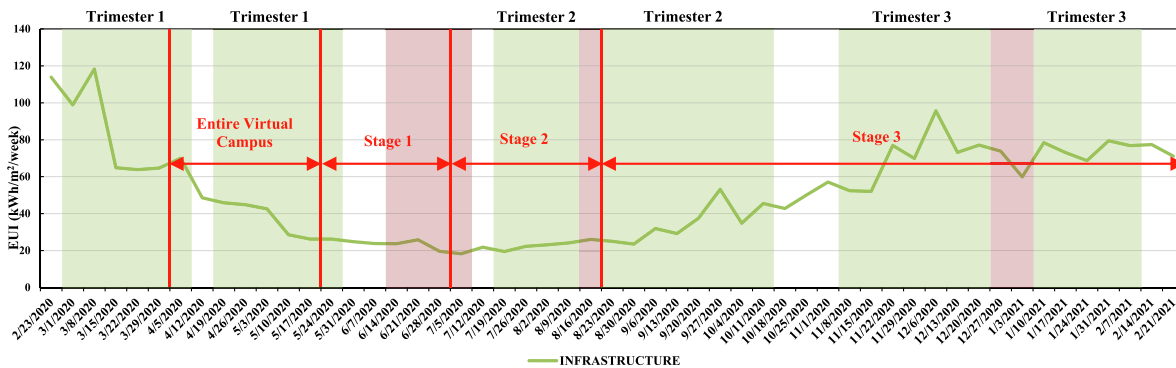
(a) EUI in typical normal academic year (non-infrastructure building)



(a) EUI in COVID academic year (non-infrastructure building)



(b) EUI in typical normal academic year (infrastructure building)



(c) EUI in COVID academic year (infrastructure building)

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