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A longitudinal assessment of the energy and carbon performance of a Passivhaus university building in the UK

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ABSTRACT

There is a limited number of university buildings designed to the Passivhaus standard, therefore, only a few studies have assessed the standard's adoption in this context. This paper aims to address this significant gap by investigating the energy and carbon performance of The Enterprise Centre (TEC), a UK university building, designed and certified to the Passivhaus standard. The building's energy performance was monitored for four years and was predicted by the Passivhaus Planning Package (PHPP) simulations. Results show that TEC met the primary energy requirement of 120 kWh/m^2 and space cooling requirement of 15 kWh/m^2 during the first four years of operation, as well as the space heating requirement of 15 kWh/m^2 during the first two years. TEC had significantly reduced heat losses and heating demand, due to the very high airtightness, 0.21 m^3/(m^2·h) @50 Pa, and low envelope U-values. The building had significantly lower annual carbon emissions and energy consumption compared to CIBSE TM46 benchmarks and other conventional university buildings. TEC is an excellent building in terms of primary energy, heating consumption, cooling demand, airtightness and carbon emissions. This study bridges the gap on the adoption of the Passivhaus Standard for university buildings to reduce energy consumption and carbon emissions.

Author statement

Sepideh S. Korsavi: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Visualization.
Rory V. Jones: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Review & Editing, Supervision.
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1. Introduction

Global temperatures are rising due to an increase in greenhouse gas emissions (GHGE) [1]. Through the amendment to the UK Climate Change Act, the government is committed to reducing the UK's net carbon emissions by 100% relative to 1990 levels by 2050 [2].

The UK Government has acknowledged that public and higher education sectors have an important role to play in tackling climate change [3]. UK universities are in a unique position to lead the way forward in tackling climate change for the following reasons: 1) universities have become significant energy consumers and carbon emitters due to their large size, population, diverse buildings, and activities (including teaching, research, accommodation and catering) [4]; 2) universities present themselves as leading on sustainability challenges and climate science through their research, which provides rich opportunities for them to innovate [5].

Higher Education Institutions (HEIs) in the UK are required by the Higher Education Funding Council for England (HEFCE) to set reduction targets and develop carbon management plans to reduce their carbon footprints. The UK government also provides grants to universities to encourage sustainable improvements to their buildings through SALIX funding [6]. Therefore, universities have made efforts to improve the energy performance of their existing buildings, as well as construct new and more energy-efficient buildings by implementing environmental design strategies. A survey among UK HEIs showed that a high percentage of institutions (83%) have embarked on a range of technical,

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Acronyms

AHU	Air Handling Unit
BMS	Building Management System
BSRIA	Building Services Research and Information Association
CD	Cooling Demand
CHP	Combined Heat and Power
EC	Electricity Consumption
HDD	Heating Degree Days
HEI	Higher Education Institutions
RIBA	Royal Institute of British Architects
OSB	Oriented Strand Board
PE	Primary Energy
PHPP	Passivhaus Planning Package
PV	Photovoltaic
SWHC	Space and Water Heating Consumption
SHC	Space Heating Consumption
TEC	The Enterprise Centre
TC	Total Consumption
UEA	University of East Anglia
VAV	Variable Air volume

non-technical and management interventions to improve their energy performance [7]. Brite Green [5] analysed 126 English universities and showed that 60% of universities used an Environmental Management System (EMS) to manage their emissions.

Numerous energy-efficiency standards and rating systems have been developed to reduce heating demands and to evaluate the performance of buildings [8]. The International Passivhaus standard is among the most stringent [9]. Passivhaus is a performance standard initially devised in Europe in the 1980s by Wolfgang Feist a German Physicist and Bo Adamson a Swedish Engineer [10]. Passivhaus can be defined as a building with very low heating/cooling loads, primary energy consumption and CO_2 emissions [11]. The concept of Passivhaus is based on a 'Fabric First' principle by reducing heat losses [12], which can be achieved by highly insulated and airtight envelopes, passive solar gains, removal of thermal bridges and an efficient mechanical ventilation system with heat-recovery (MVHR) [13,14]. It is also designed to maximise the application of passive design strategies, such as natural ventilation, daylighting [15,16] and night cooling [12,17] to reach the criteria. Furthermore, the Passivhaus standard provides excellent cost-effectiveness particularly in the case of new buildings. Stephan and Myttenaere [11] demonstrated that over a building's lifespan, a Passivhaus building is the most cost-effective with the initial higher investment costs, offset by reduced operational costs in the longer term.

Many studies have investigated the viability of the Passivhaus standard for residential buildings [1,17–21], however, there is a limited number of studies on its adoption specifically for university buildings and even fewer where the actual operational performance has been evaluated longitudinally over several years. Some studies suggest that designing university buildings to the Passivhaus standard can be more challenging due to their more complex technical building services [22], heterogeneous use patterns, greater diversity of spatial and equipment requirements, as well as daily and seasonal changes in occupancy, thereby requiring greater automation and sometimes more elaborate concepts [23].

There are a few non-residential Passivhaus designed university buildings globally, including the extension to the Holztechnikum at Salzburg University of Applied Sciences in Austria in 2009 [23]; Hadlow College London that achieved UK Passivhaus Awards 2012 [24]; the multi-use lab space in University of Bradford, UK, certified in 2015 [25]; Herefordshire Archive and Records Centre UK which has received Passivhaus certification in 2016 [26]; the University of Leicester's 13,000 m^2 Centre for Medicine, the largest non-residential project that achieved 2017 UK Passivhaus project [27]; the Tüwi building at the University of Natural Resources and Life Sciences in Vienna, Austria, certified in 2018 [22] and the Woodside Building for Technology and Design at Monash University, Melbourne that achieved 2020 Australia Passivhaus certification [28]. Due to the limited number of university buildings currently designed to the Passivhaus standard, only a few research studies have previously assessed the standard's adoption in this context. This paper aims to address this significant gap.

1.1. Aim and objectives

This study aims to investigate the operational energy and carbon performance of The Enterprise Centre (TEC), an exemplary non-residential Passivhaus certified university building in the UK. The paper reports on the modelled performance at the design stage and actual performance of the building over the first 4 years of occupation, to achieve the following objectives:

- Investigating the building's actual energy performance and comparing it with the Passivhaus standard
- Comparing the building's actual energy performance with modelled energy performance using the Passivhaus Planning Package (PHPP)
- Investigating the contribution of the solar PV systems on electricity consumption
- Investigating the building's actual operational carbon emissions

2. Methodology

2.1. The Passivhaus Standard

For a building to be certified to Passivhaus standard, it must meet the following requirements [8,23,29,30]:

- Space Heating Demand should not exceed 15 kWh/m^2 annually.
- Space Cooling Demand should not exceed 15 kWh/m^2 annually.
- Primary Energy Demand should not exceed 120 kWh/m^2 annually for all applications (space heating, space cooling, water heating and electricity).
- Airtightness should be maximum of 0.6 air changes of a building's volume per hour at 50 Pa pressure.

2.2. Building description

The Enterprise Centre (TEC) at the University of East Anglia (UEA) part of the Norwich Research Park was designed and built to the Passivhaus standard, later to be known as the Passivhaus Classic standard, as defined by the Passivhaus Institute. It opened to staff and visitors in June 2015. The building achieved the rating BREEAM Outstanding with a score of 93%, which is the Building Research Establishment Environmental Assessment Method to assess a buildings' sustainability.

The building won the Royal Institute of British Architects (RIBA) East Award 2017 and RIBA East Sustainability Award and to date has achieved 32 awards mainly for design, innovation and sustainability. It is an exemplar of sustainable design characterised by its low embodied carbon achieved through its construction. The team of designers performed a carbon analysis of the building which included disposal, site works, transport, design and manufacturing, maintenance, repair and replacement to calculate the Total Embodied Lifecycle Emissions which is less than 500 $kgCO_2/m^2$. This number is significantly lower than other conventional university buildings, even the ones built to 'best practice' standards. TEC is an exemplar of a low embodied carbon building using bio-renewable and natural materials from local resources. The building used a unique low carbon concrete mix for the foundations, reed thatched clerestory roofs, external wall cladding panels of Norfolk Long straw and recycled newspapers for insulation. The internal wall finishes include hemp, nettle, clay, and silica natural paints sourced within 50 km of the site. Several other local natural materials used in TEC include Norfolk flint, re-processed glass and reclaimed oak.

TEC provides a hub for businesses to rent space either within an open plan office space supporting start-up companies, spaces for networking, research and development activities and space for businesses to grow into dedicated two to six-person offices. The ‘E’ shaped building over two storeys has a gross floor area of 3426 m^2. The long sides of the two main wings face south to maximise the amount of daylight and to collect solar gains in winter (Figs. 1 and 2). The North Wing of the building provides flexible floor space for offices, meeting rooms and hot desks and the South wing provides teaching and learning facilities. A predominantly transparent exhibition space links the two wings, and at its centre a 300-seat lecture theatre forming the middle of the E (Fig. 1). Figs. 3 and 4 show the external façade and internal spaces. TEC has 160 photovoltaic panels installed with a system power of 48.70 kW.

The building is aided by an intelligent control system that is linked to the university’s centralised Building Management System (BMS). Passive Infrared and microwave sensors control LED lights. TEC has Variable Air Volume (VAV) units that sit on V_{min} until the internal air temperature of a space increases above the set point temperature of 23 °C or the CO_2 within a room exceeds its set point. The VAV uses heat recovery from the internal gains to equalise the temperature throughout the building. There is also a minimal wet heating system that operates for 2–2.5 h on cold mornings to boost the temperature before the first occupation. When the temperature exceeds 23 °C + 3 °C in the summer, the VAV provides greater volumes of outside air to cool the building and utilises a night cooling strategy with the aid of thermal mass from the exposed ground floor concrete slab. A heat recovery unit provides fresh and filtered incoming air which is heated from internal stale air being expelled outside. A demand-led mechanical ventilation system controlled by occupancy and CO_2 sensors delivers fresh air to keep occupants comfortable in all rooms. The 300-seat lecture theatre is the only area cooled by a conventional mechanical cooling system due to the significant fluctuations in occupation and cooling load needs. Furthermore, occupants can open the building’s triple-glazed windows manually. A display panel in each room contains two LED lamps that indicate to occupants the need to close windows or indicates that windows can be opened.

Front of House operations staff ensure the south teaching and learning wings windows are closed each evening, and when high temperatures are expected the following day, large ground floor doors within the exhibition wing are opened manually before leaving for the night. When the building’s night temperature settings are triggered, the ventilation fan speeds increase, and automatic clerestory windows open to allow night purging and cooling of the ground floor concrete slab. Early morning cleaning staff close the doors to retain the captured cool air.

The U-values (W/m^2K) of the TEC building’s envelope and glazing can be found in Table 1. U-values are calculated based on design requirements and Passivhaus Planning Package (PHPP) simulations suggested by Architype architects.

2.2.1. Airtightness

Passivhaus certification is a contractual deliverable and airtightness is a measurable entity. Airtightness testing in this building was carried out by Building Services Research and Information Association (BSRIA) which is a UK-based testing organisation to provide specialist services in construction and building engineering.

The team of TEC designers with architects, structural engineers and services engineers were all Passivhaus trained and experienced to produce designs that could be sealed with Passivhaus certified airtightness tapes. The main contractor team appointed a dedicated Air Tightness Champion.

The design included an internal skin of Oriented Strand Board (OSB) which would be protected from damage by fixing battens to the inside face of the OSB, such that the final inner skin of recycled gypsum plasterboard would form a cavity for services and fixings clear of the OSB skin and leaving it undamaged. OSB was installed in large panels and butted together and before the battens were attached, every joint line

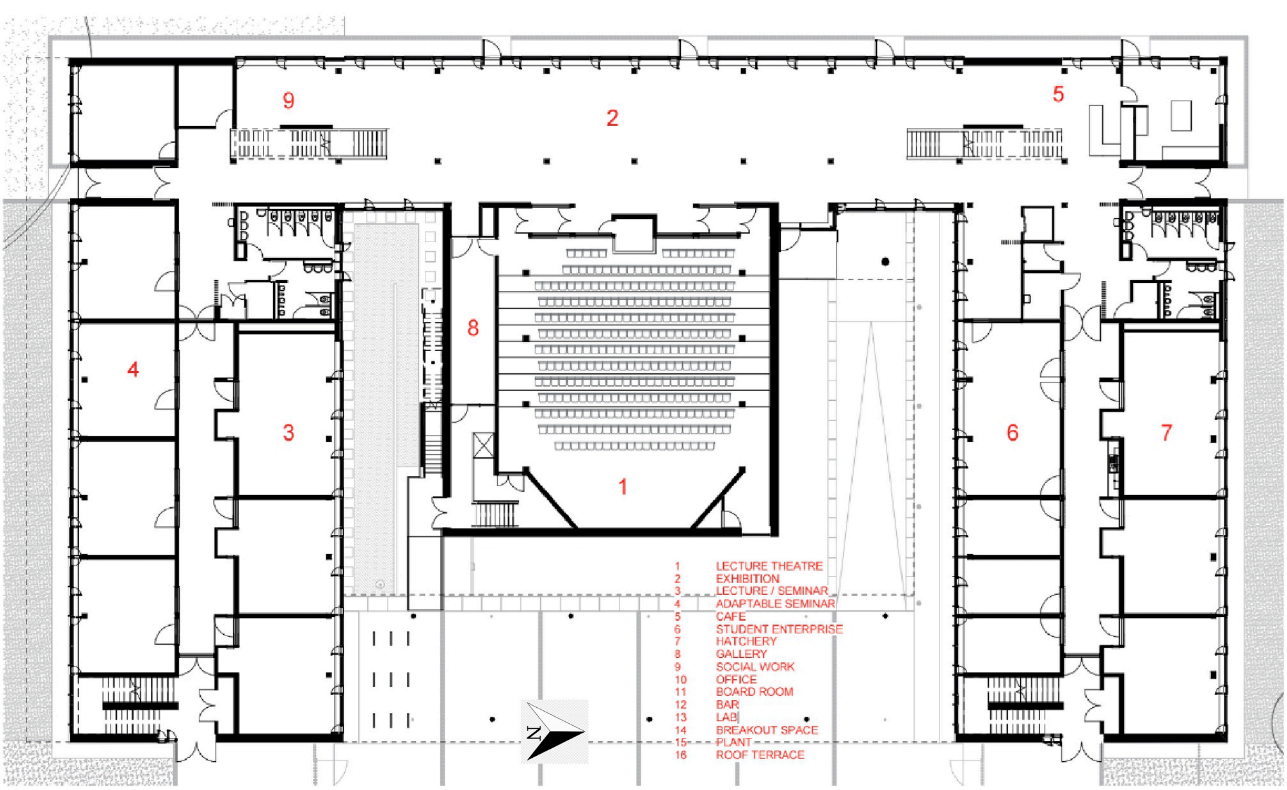

Fig. 1. The ground floor of The Enterprise Centre by Architype [31].

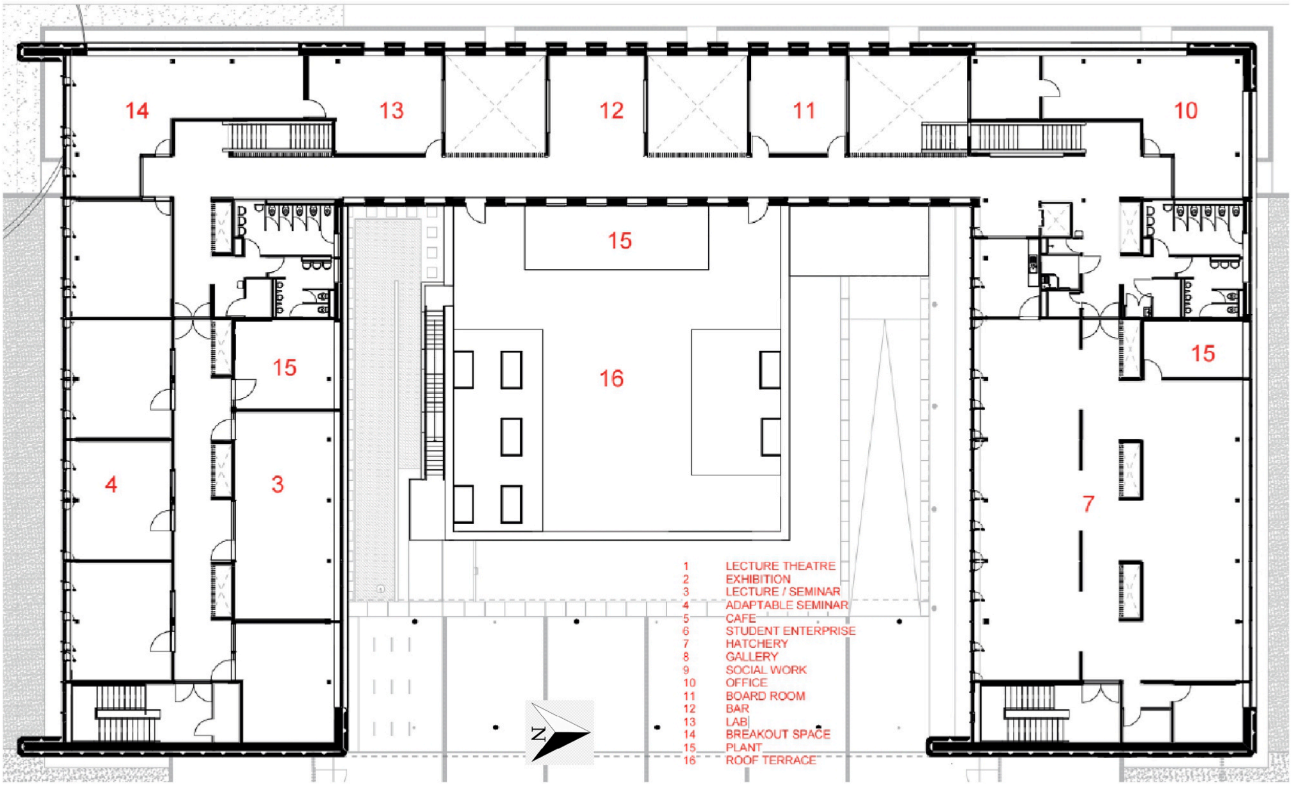

Fig. 2. First-floor plan of The Enterprise Centre by Architype [31].

Fig. 3. The façade of The Enterprise Centre by Architype [31].

Fig. 4. Internal spaces within The Enterprise Centre by Architype [31].

Table 1
U-values W/(m^{2}K) of envelope and glazing.

U-value	Sections	(W/m^{2}K)
Glazing	Windows north elevation average	0.64
	Windows east elevation average	0.66
	Windows south elevation average	0.62
	Windows west elevation average	0.65
	Roof lights	0.76
Envelope	Theatre walls	0.11
	Thin oak walls	0.14
	Main walls	0.12
	Main walls below ground	0.12
	Entrance lobby wall	0.19
	External display wall	0.28
	Clerestory walls	0.21
	Basement walls	0.15
	Basement walls above ground	0.19
	Main roof	0.13
	Link roof	0.13
	Theatre roof	0.09
	Theatre roof lights	0.19
	Clerestory roof	0.13
	Entrance ceiling	0.09
	Slab	0.14

with the floor, ceiling, corner and butt joints received airtightness tapes and then the battens were applied. Finally, every panel of OSB was individually inspected by the airtightness champion and any gaps in joints or damage to the OSB integrity was corrected with airtightness tape patches, and then signed-off as approved by the airtightness champion before being over clad with the recycled gypsum boards.

The contractor while being confident that the design, materials and work flows would provide a good level of airtightness, they instigated three phases of testing for airtightness using independent assessors, shown in Table 2.

To carry out the first test, the contractor worked to complete the early installation of the windows to one wing, and after closing up the two uninstalled door openings and placing an internal seal to separate the remainder of the building, the first test was undertaken which yielded an airtightness figure of 0.31. Work proceeded with the remainder of the building and a second and full building test took place which yielded an airtightness figure of 0.245. During the second test, some areas of weakness such as around some of the external doors were identified, and rectification works were undertaken shortly after. Finally, the third test was undertaken and certified by the Passivhaus Trust at a figure of 0.21. Repeating measurements has resulted in reducing measurement uncertainty. The building achieved an airtightness of 0.21 m^3/(m^2·h) @50 Pa, which is almost three times better than what is required to achieve Passivhaus certification. Airtightness is emphasised in the Passivhaus standard because of its importance in reducing energy losses [32,33].

Considering that the airtightness of buildings with excellent airtightness remain durable [34] and the building was not redeveloped or extended [35], the study assumes that airtightness did not change significantly over four years. The study on 17 Passivhaus projects as part of a research project of the International Energy Agency, "IEA Task 28, Annex 38", re-measured airtightness of buildings ageing from 1.4 to 10.5 years [34]. According to the results in this study, the airtightness of buildings with excellent airtightness (<0.6 m^3/m^2·h) remained durable [34]. Furthermore, there is a large risk that airtightness would decrease if the building was redeveloped or extended [35], which was not the case for TEC during the studied period.

Table 2
Airtightness testing by BSRIA.

Date of Tests	Design Air Leakage Criteria	m^3/(m^2·h) @50 Pa
March 14, 2015	Measured m^3/(m^2·h) @+50 Pa	0.31
	Measured m^3/(m^2·h) @-50 Pa	0.31
April 25, 2015	Measured m^3/(m^2·h) @+50 Pa	0.26
	Measured m^3/(m^2·h) @-50 Pa	0.23
May 30, 2015	Measured m^3/(m^2·h) @+50 Pa	0.22
	Measured m^3/(m^2·h) @-50 Pa	0.20
Average of airtightness for the last test		0.21

2.2.2. *Power generation and PV systems*

University of East Anglia Campus has its own power generation capability derived from three smaller engines and one large engine, all of them turning electrical generators and all running on natural gas. The generated power feeds into the university campus internal power grid. This grid is also fed by various solar panel installations across the campus.

TEC has a roof area totalling 480 m^2 fitted with 160 PV Modules, with system power of 48.70 kWp (kilowatt peak) and maximum efficiency of 98%. The type of PVs is SOLON Black monocrystalline modules with a weight of <10 kg/m^2. The installed PVs are highly rated bituminous waterproofing systems with membranes resistant to high levels of structural and thermal movement. The panels make optimum use of the roof and avoid shading by elevation. TEC solar PV generation is prioritised to the building first and any over generation then feeds the university campus internal grid.

2.3. *Climatic conditions*

To investigate the relationship between heating loads and outdoor conditions, Fig. 5 shows the variance of outdoor temperature in box plots for the four years studied and Fig. 6 shows mean outdoor temperature for each month in these four years. During 2015–2016, outdoor temperatures were taken from local weather stations that were a maximum 3 miles away from the building's site [36]. During the period 2016–2019, 5 minutely outdoor weather data were collected on-site using a weather station located 50 m from the building. Results in Fig. 5 show that mean and median outdoor temperatures were highest in 2015–16 and lowest in 2016–17.

2.4. *Measurements*

This study recorded the energy use data of TEC from August 2015 until July 2019. The energy use was measured using a series of main and sub-meters. Automated meter reading records of the energy consumption of TEC were taken at daily intervals. Table 3 shows the space usage and electrical power end-uses related to the electrical sub-meters monitored in TEC building.

2.5. *PHPP simulation*

Passivhaus Planning Package (PHPP) is a building energy calculation

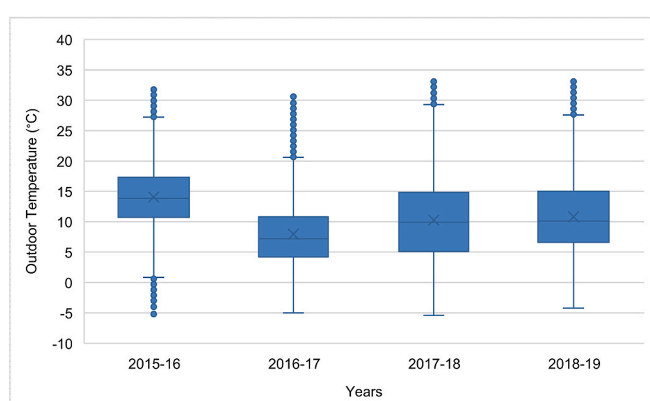

Fig. 5. Variance in outdoor temperature for the 4 years of study.

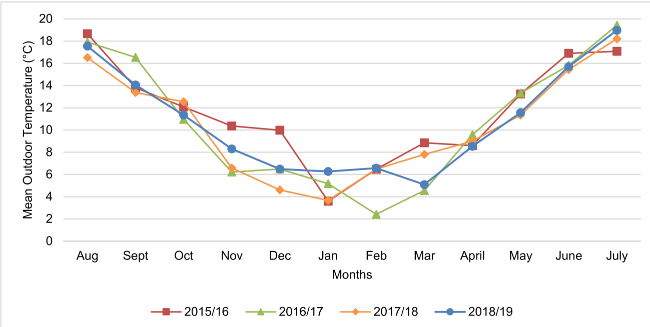

Fig. 6. Mean outdoor temperature for different months of each year.

Table 3
Space usage and electrical power end-uses related to the electrical sub-meters.

Name	Space usage	Power for
North Wing Lower	Segregated offices of different sizes (2–8 people per office)	Lighting and sockets to the offices and exhibition wing, 1 kitchenette, 2 automatic doors and 8 powered door locks and data switch racks
North Wing Upper	Open plan office space for SME businesses	Lighting and sockets to the open-plan office space, 1 kitchenette, 2 automatic doors, 8 powered door locks
South Wing Lower	Teaching rooms and 1 office space for 4 people	Lighting and sockets in the teaching rooms and office space
South Wing Upper	Teaching rooms	Lighting and sockets in the teaching rooms and data switch racks
Lecture Theatre	Lecture theatre	Artificial lighting, Audio Visual and Platform Lift
MCC1 (North Wing)	Running pumps for the wet heating system; Swegon Gold heat recovery plant; Variable speed fans to Air Handling Unit (AHU); Clerestory rooftop powered windows	
MCC2 (South Wing)	Running Swegon Gold heat recovery plant; Variable speed fans to AHU; Clerestory rooftop powered windows	
MCC3 (300-seat lecture theatre)	Running Swegon Gold heat recovery plant; Variable speed fans to AHU and Cooling plant	
Café	Lighting and sockets in the café and food preparation room	
Water Heating	Electric water heating in the south wing lower and upper toilet facilities	
Lift	Building's main lift	

tool produced by the Passivhaus Institute to assist architects and mechanical engineers to design Passivhaus or low energy buildings [16] and to model their performance [33,37]. According to the Passivhaus Institute, the verification of a Passivhaus design should be carried out using the PHPP software [38]. The accuracy of the PHPP has been validated many times by comparing modelled energy use to monitored energy use in projects in Europe [39]. The PHPP simulations have considered different parameters such as the U-value, g-value and thermal bridges for different architectural components such as walls, windows, doors and facades. A comparison of the outdoor temperatures used in the PHPP modelling and the actual mean outdoor temperatures measured over the four years are shown in Table 4, which confirms the validity of the inputs for the simulations. The comparison shows a slight difference which is because the data on the second column in Table 4 is based on historical weather file implanted into simulations and the third column is based on real measured data. An appropriate weather file called GB0013a-Hemsby (Source: Meteonorm V6.) from a close station to the building was chosen for simulations.

2.6. Heating degree days (HDDs)

Measuring the energy efficiency of a building should be done by considering all the factors that impact energy consumption, including the weather [40]. Fluctuations in annual space heating demands can

Table 4
The comparison between outdoor temperatures used in PHPP simulations and measured mean outdoor temperature.

Month	Outdoor temperature (°C) used in PHPP Simulations	Mean Outdoor temperature (°C) measured over four years
Aug	17.3	17.7
Sep	14.8	14.4
Oct	11.2	11.7
Nov	7.5	7.9
Dec	5.1	6.9
Jan	4.8	4.7
Feb	5.3	5.5
Mar	6.8	6.6
Apr	8.9	8.9
May	12	12.4
Jun	15.1	16.0
Jul	16.6	18.4

often be explained by variations in outdoor temperature. Several studies have employed heating degree days (HDDs) to understand energy use patterns for buildings and communicate these patterns to building users [40–43]. HDD is a climatic indicator and a measure of the severity and duration of cold weather, which are used to adjust heating energy demands based on outdoor conditions [41,44,45]. To calculate HDD, the difference between the base temperature (T_b) and daily mean outdoor air temperature (T_{out}) is summed only when $T_{out} < T_b$ [44,46], *Equation (1)*.

$$HDD_m = \sum_{i=1}^{30} T_b - T_{out} \quad T_{out} < T_b \qquad \text{Eq (1)}$$

The study by Harvey [46] has proposed three base temperatures for HDD: the indoor thermostat setting; the outdoor temperature at which heat loss balances the internal heat gain; and, the outdoor temperature at which internal and solar heat gains are balanced by heat loss. This study has considered 'base temperature' as the outdoor temperature at which heat loss balances the internal heat gain. In the UK, the Carbon Trust [47], which provides effective advice to help businesses reduce carbon emissions, and CIBSE TM46 [48], which offers a comprehensive outline of building energy benchmarks, both recommend a base temperature of 15.5 °C [47] as considered in several other studies [41,49].

3. Results

In this section, the results of the four-year performance evaluation are presented and compared to the modelled predictions using PHPP. In Section 3.1, the energy performance of TEC is investigated, including primary energy, total energy consumption, electricity consumption, space cooling demand, and space and water heating consumption, as well as a heating degree days analysis to examine the changes in annual heating consumption due to variations in climatic conditions. In Section 3.2, PHPP predictions of energy consumption are compared to actual consumption. In Section 3.3, the generation from the PV systems installed on the roof of the building is evaluated. In Section 3.4, the operational carbon performance of the building is investigated.

3.1. Energy performance

3.1.1. Primary energy

Primary energy (PE) is an appropriate metric to compare and evaluate building systems [50]. It is defined as the energy used to produce the energy delivered to the building, including losses that occur during generation, transformation and distribution [17,33]. The energy used within TEC is provided by a Combined Heat and Power (CHP) plant onsite at the UEA, as well as solar PV panels on the building's roof. The CHP engines generate electricity and capture the produced wasted heat during the process for space and water heating. This effective way of capturing wasted heat to provide useful thermal energy has resulted in achieving a low primary energy conversion factor for space and water heating consumption.

The primary energy conversion factors in this study are 2.6 for electricity consumption (EC) and 0.7 for space and water heating consumption (SWHC), i.e. 2.6 and 0.7 kWh of primary energy are required for 1 kWh of electricity and heating energy at the site, respectively. These factors are based on those provided in the PHPP software and tailored to the specific context of the building, energy source and location by the building designers. *Equation (2)* shows the calculation of total primary energy using the conversion factors for electricity and heating consumptions. Generally, primary energy factors are greater than 1 due to distribution losses from production to point of use.

$$PE = 2.6 * EC + 0.7 * SWHC \quad \text{Eq (2)}$$

Actual and predicted primary energy and total energy consumption of TEC for the four years are presented in Fig. 7. TEC met the 120 kWh/m^2 primary energy requirement for Passivhaus standard during the first four years of operation. However, primary energy use has been increasing year-on-year, narrowly achieving this target with 115.4 kWh/m^2 in 2018–19. The predicted annual primary energy use of TEC using PHPP was 111 kWh/m^2, which is higher than actual primary energy use in Year 1 (85.4 kWh/m^2) and Year 2 (102.8 kWh/m^2), almost equal to that in Year 3 (110.7 kWh/m^2) and less than that in Year 4 (115.4 kWh/m^2).

3.1.2. Total energy consumption

The total annual energy use of TEC has increased over time from 43.5 kWh/m^2 in 2015–16 to 57.6 kWh/m^2 in 2018–19 (32.4% increase over three years). PHPP predicted the annual energy use of TEC as 59 kWh/m^2, resulting in an overestimation for the first two years (43.5 kWh/m^2 and 52.9 kWh/m^2), but a more accurate estimation of the consumption in the third and fourth year (59.4 kWh/m^2 and 57.6 kWh/m^2). Electricity consumption, which also includes space cooling demand and the use of electric water heaters in some toilets, accounts on average for around 65% of the total energy consumption of the building (ranging from 61.2 to 68.5%), which was close to the value estimated using the PHPP (62%). As the building's energy consumption changes according to the building's activities, it is important to highlight that actual energy consumption suppresses the simulated energy values.

3.1.3. Electricity consumption

Annual electricity consumption of TEC has increased year-on-year from 28.9 kWh/m^2 in 2015–16 to 39.5 kWh/m^2 in 2018–19 (Fig. 7). The estimated electricity by PHPP (36.7 kWh/m^2) is higher than the actual value in the first year (28.9 kWh/m^2), almost equal to actual values in the second (34.6 kWh/m^2) and third years (36.4 kWh/m^2) and lower than that in the fourth year (39.5 kWh/m^2).

Fig. 8 shows the electricity consumption in distinct building spaces equipped with monitored sub-meters (Table 2). It also shows the electricity demand of the lift and the instant electric water heaters used to provide hot water to some toilets. Electricity consumption in all spaces except MCC2 and the Lift has increased during the studied years. In each year, the café accounts for the highest electricity consumption reaching a total of 33936 kWh in 2018–19, an increase of 72.2% since 2015–16 (19712 kWh). The lecture theatre has had the biggest increase in electricity consumption (86.1%) from Year 1 (4744 kWh) to Year 4 (8827 kWh).

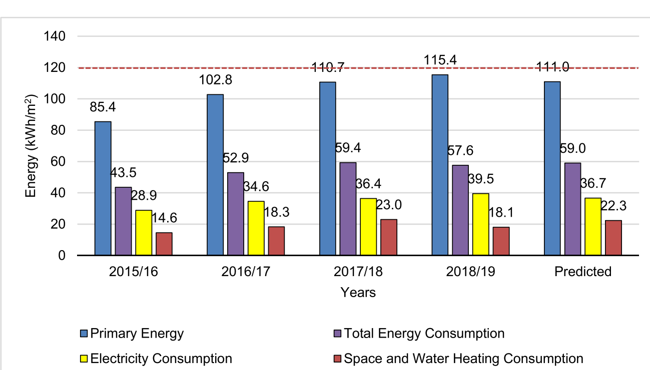

Fig. 7. Actual and estimated energy consumption of TEC.

3.1.4. Cooling demand

The 300-seat lecture theatre (MCC3) is the only space in the building mechanically cooled due to the significant fluctuations in occupation and cooling load needs. The sub-metered electricity consumption for MCC3 (Fig. 8) indicates the cooling demand of the building: 8233 kWh in 2015/16 (equivalent to 2.4 kWh/m^2), 8657 kWh in 2016/17 (equivalent to 2.5 kWh/m^2), 11273 kWh in 2017/18 (equivalent to 3.3 kWh/m^2) and 8875 kWh in 2018/19 (equivalent to 2.6 kWh/m^2). The building achieved the Passivhaus requirement of 15 kWh/m^2 for space cooling demand for the first four years of occupation. PHPP predicted a cooling demand of 2.9 kWh/m^2, slightly higher than the actual values achieved in Years 1, 2 and 4.

3.1.5. Space and water heating consumption

Plate Heat Exchangers are used to transfer the heat delivered to the building by Combined Heat and Power (CHP) plant and make it available to the wet space heating system (radiators) and hot water system (additional to the electric water heaters). Space and water heating consumption was lowest in the first year (14.6 kWh/m^2) and highest in the third year (23 kWh/m^2) (Fig. 9). Energy for space heating increased from 12.3 kWh/m^2 in Year 1 to a peak of 20 kWh/m^2 in Year 3 and decreased to 15.4 kWh/m^2 in Year 4.

The building achieved the Passivhaus requirement of 15 kWh/m^2 for space heating demand during the first two years of occupation, however, it failed to meet the target in 2017–18 (20 kWh/m^2) and 2018–19 (15.4 kWh/m^2). PHPP estimated the annual space heating consumption as 14.2 kWh/m^2, which is close to the actual space heating demand in Year 1.

Fig. 10 shows the monthly space heating consumptions (SHC) plotted against HDDs with a base temperature of 15.5 °C and Fig. 11 against mean outdoor temperature. It should be noted that non-weather-related heating use, such as hot water, is not included in this analysis. According to the definition of R^2 value which is the measure of how much of the variability in the outcome is accounted for by the predictor [51,52], the R^2 values in Figs. 10 and 11 suggest that 81% of changes in space heating energy consumption can be explained by HDDs and outdoor temperature.

3.2. PHPP estimations and accuracy

The PHPP predictions of energy consumption compared to actual consumptions are presented in Table 5. The PHPP estimations are generally within the 30% performance gap observed by several studies [53–55] between modelled and actual energy consumption of buildings. Typically, the performance gap refers to buildings using more energy than expected. It is important to note that in this study, TEC often performs better than the estimations provided by the PHPP and therefore uses less energy than was predicted, especially during the first two years. The measured consumptions over the four years indicated that PHPP tended to overestimate primary energy (PE), total energy consumption (TC), electricity consumption (EC), space and water heating consumption (SWHC) and cooling demand (CD). The results of this study confirm the accuracy of the PHPP tool in estimating energy demand, as indicated in previous studies [20,33,37].

The gap between modelled and actual energy consumption could possibly be related to the slight difference between outdoor

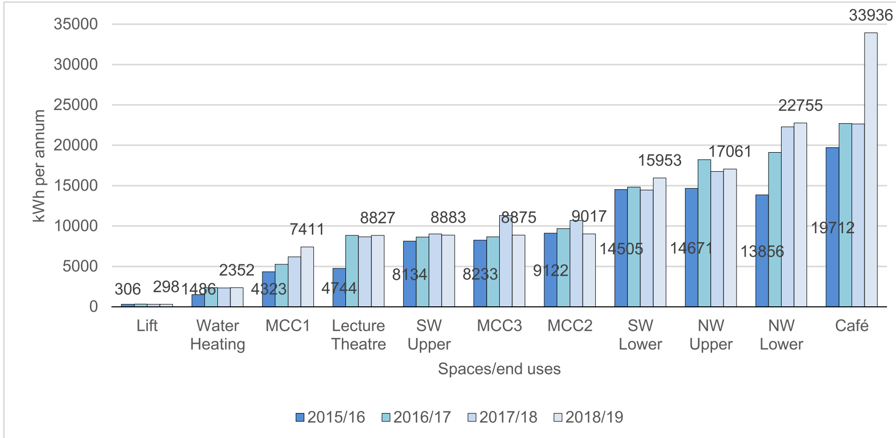

Fig. 8. Electricity consumption in distinct spaces/end uses measured by sub-meters.

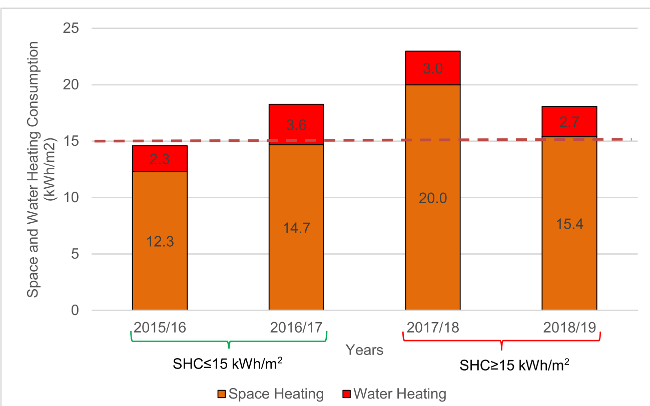

Fig. 9. Breakdown of space and water heating consumption in different years.

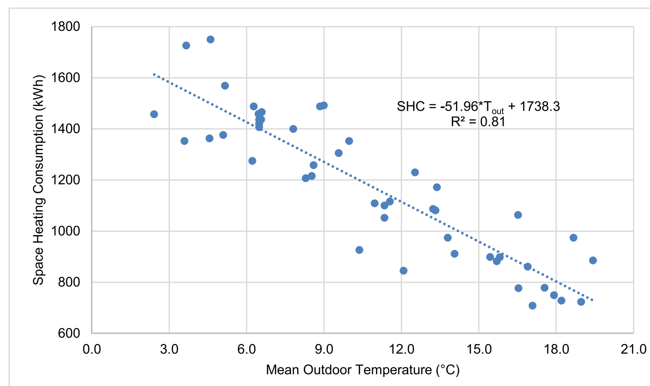

Fig. 11. Monthly space heating consumption against mean outdoor temperature.

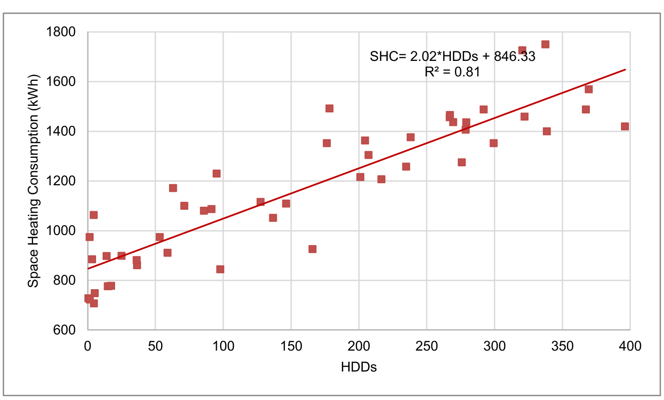

Fig. 10. Monthly space heating consumption against the HDDs.

temperatures used in PHPP simulations and measured mean outdoor temperature, and different buildings' operational activities than considered in simulations, which are explained in detail in section 4.2.

3.3. PV system generation

Total electricity consumption of the building is provided by the CHP located on the university campus and PV systems installed on the roof of the building. Total electricity consumption, electricity provided by CHP and PV systems generations during the first four years are presented in Table 6. Electricity generation from the PV systems has been relatively consistent throughout the studied years, from 45040 to 45662 kWh. However, due to the increasing year-on-year overall electricity use in the building, the percentage of the building's electricity consumption covered by the PV systems has decreased from 45% in Year 1–34% in Year 4. Consequently, the amount of electricity supplied by the CHP on campus has grown over time from 54052 to 89706 kWh. The PV generation estimated by PHPP (43580 kWh) is slightly lower than the actual PV generation during the first four years (45040–46370 kWh). Based on the PHPP estimation of PV generation, the building would generate 35% of its electricity requirements, however, PV generation has provided 38.7% of total electricity consumption during these four years. This proportion has been greater in 3 out of the 4 years of operation.

Fig. 12 shows PV generation and electricity consumption for each month. Average monthly electricity consumption over four years shows a stable trend between 8888 and 10925 kWh, however, PV generation is varied for different months. During the summer months, PV generation is higher and accordingly provides a higher proportion of TEC's electricity consumption. The results of this study show that the PV systems averagely over the four years produced maximum electricity during July (6699 kWh/month) and minimum energy during December (791 kWh/month). This can be attributed to the climatic conditions and solar radiation, as supported in the study by Mihaia et al. (2017) [1]. On average over the four years, the PV systems have generated more than 60% of the building's electricity demand in August (67.8%), July (65%), May (63.5%) and June (62.2%) and less than 10% of its electricity demand in December (8.2%) and January (9.25%).

Table 5
PHPP underestimations and overestimations of energy consumption.

Period	Actual Consumption (kWh/m^2)					Predicted (kWh/m^2)					Deviation (%) of PHPP from actual consumption				
	PE	TC*	EC	SWHC	CD	PE	TC	EC	SWHC	CD	PE	TC	EC	SWHC	CD
2015/16	85.4	43.5	28.9	14.6	2.4	111	59	36.7	22.3	2.9	23.1	26.3	21.3	34.5	17.2
2016/17	102.8	52.9	34.6	18.3	2.5						7.4	10.3	5.7	17.9	13.8
2017/18	110.7	59.4	36.4	23.0	3.3						0.3	-0.7	0.8	-3.1	-13.8
2018/19	115.4	57.6	39.5	18.1	2.6						-4.0	2.4	-7.6	18.8	10.3

* TC = EC + SWHC; CD is included in the EC.

Table 6
Annual electricity generation by PV systems and electricity provided by CHP on the campus.

Annual Generation	Solar PV Generation		Electricity provided by CHP on the campus		Total Electricity Consumption (kWh)
	kWh	%	kWh	%	kWh
2015–16	45040	45	54052	55	99092
2016–17	46370	39	72200	61	118570
2017–18	45921	37	78700	63	124620
2018–19	45662	34	89706	66	135368
PHPP	43580	35	80209	65	123789

3.4. Carbon emissions

The source for heating in this study is gas which compared to electricity stands for a lower proportion of CO_2 emission, as suggested in the study by Lawrence et al. [56]. According to the UK Government Greenhouse Gas Conversion Factors by Department for Business, Energy and Industrial Strategy [57], the CO_2 emission factor for heat is 0.2 $kgCO_2/kWh$ and for electricity is 0.35 $kgCO_2/kWh$. For this building, the team of designers considered slightly modified CO_2 emission factors, 0.22 $kgCO_2/kWh$ for heat and 0.46 $kgCO_2/kWh$ for electricity, to adjust to the specific context of the building, energy source and location.

Table 7 shows that energy-related CO_2 emissions have increased during the four years from 10.5 $kgCO_2/m^2$ in Year 1–16 $kgCO_2/m^2$ in Year 4. According to the simulation results by PHPP, CO_2 emissions for electricity (including space cooling and electric water heating), space and water heating, and total energy consumption are 10.8, 4.8 and 15.6 $kgCO_2/m^2$, respectively. Whilst carbon performance in Year 1 (10.5 $kgCO_2/m^2$) and Year 2 (13.8 $kgCO_2/m^2$) were better than what was projected by PHPP (15.6 kg/m^2), CO_2 emissions are more consistent with PHPP estimations in Year 3 (15.7 $kgCO_2/m^2$) and Year 4 (16.0 $kgCO_2/m^2$).

To have a deeper analysis of reductions in greenhouse gas emissions, it is important to investigate the contributions that PV systems make [18]. PV systems in this building have reduced 24.5 $kgCO_2/m^2$ (38%) of electricity fuel carbon emissions during these four years. It should be highlighted that the PV systems decrease 30% of fuel carbon emission for total energy consumption.

4. Discussion

4.1. Criteria of Passivhaus Standard

TEC was designed and built to Passivhaus Classic standard as defined by the Passivhaus Institute, and its compliance was certified based on as built PHPP modelling results. To see if this modelled compliance has been achieved in operation, the results derived for the four years of monitoring are compared against the Passivhaus standard requirements (Table 8).

Table 7
Annual carbon emissions for energy used in the building ($KgCO_2$).

Period	Reduced ($kgCO_2/m^2$)	Emissions ($kgCO_2/m^2$)		
	PV	Electricity	Space and water heating	Total Emissions
2015/16	6.0	7.3	3.2	10.5
2016/17	6.2	9.7	4.1	13.8
2017/18	6.2	10.6	5.1	15.7
2018/19	6.1	12.0	4.0	16.0
PHPP	5.8	10.8	4.8	15.6

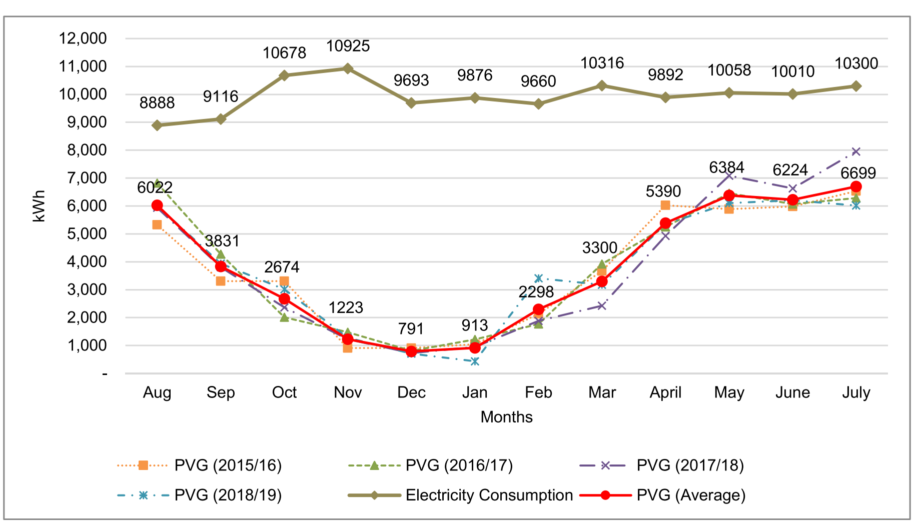

Fig. 12. PV generation and electricity consumption for each month (Note: Numerical values relate to average monthly electricity consumption and PV generations over the four years).

This study shows that:

- TEC met the primary energy target of 120 kWh/m^2 per year in all four years.
- TEC met the space heating demand target of 15 kWh/m^2 per year in the first two years.
- TEC met the space cooling demand target of 15 kWh/m^2 per year in all four years.
- TEC met the airtightness requirement of 0.6 m^3/(m^2·h) @50 Pa.

The results suggest the necessity to check the annual performance to make sure that the Passivhaus standard criteria are met each year. The next section of the paper discusses the potential factors that caused the variations in energy consumption in different years.

4.2. Potential factors affecting variations in annual energy consumption

TEC's energy consumption has varied over time, slightly increasing year by year in the first three years. To identify possible root causes of these variations, a chronological account of the buildings' operational activities is documented. These activities were either out of the buildings' usual operations or were developed with time.

The lower total energy consumption in the August 2015–July 2016 period could be explained by the building's lower occupation levels in the first year of operation. TEC was handed over in June 2015 and it was initially occupied by the building operating team, however, it did not reach full occupation until spring 2016. Occupation took place gradually and differently in different parts of the building. Occupation of the North wing started when the building operators (The Adapt Low Carbon Group) moved in during July 2015 (13 persons), followed by the eight-person ground floor business unit soon after. From then, a gradual flow of tenants moved into the small business incubator units, ranging from one-person desks in the open-plan office to six-person offices. In May 2016, the final empty six-person office on the ground floor of the North wing was taken over by a business bringing with them a number of high-performance computing equipment. Although the majority of spaces were actually let by the time of Practical Completion, some businesses did not move into TEC straight away due to terminating leases elsewhere. The South wing teaching facilities began occupation from the start of the new academic year in September 2015, but the 300-seat lecture theatre was used from August 2015 to accommodate a small number of events such as the TEC Grand Opening. The tenant business taking over at the TEC café commenced activities in October 2015.

The increased energy use in August 2016–July 2017 could be explained by more appliances, in September 2016, two microwave ovens were provided for the kitchenettes of the North wing, following a request from the business tenants, the high performance computers being run 24 h each day seven days a week, and a higher number of events, such as graduation ceremonies and conferences. During this period the marketing team generated a steady conferencing and seminar business stream for the lecture theatre, board room, seminar rooms and the exhibition wing, in addition to the scheduled teaching activities. The increase in catering for these events outside of core hours also contributed to higher than expected energy consumption, particularly noticeable from June of 2017. Besides, in July 2017, TEC was used for the first time to screen the four-day Summer Graduation ceremonies streamed live all day in the 300-seat lecture theatre and a number of ground floor seminar rooms. Although the main event took place in a separate building, TEC facilities were used for those guests that could not be accommodated in the graduation hall. The catering facilities had been deliberately designed not as a production kitchen but as a satellite retail outlet with fridges for pre-prepared food items and minimal reheat capability, reducing the building's energy demand excluding cooking, air extraction, etc. The original catering tenant's three-year lease ended in August 2018 and was not renewed. A new catering tenant took a new lease and brought in additional facilities including freezers, a dishwasher, food heating appliances, and food counters (chilled and hot) and would have a noticeable effect upon energy consumption. The increase in heating consumption in 2016/17 compared to 2015/16 can also be related to lower mean outdoor temperatures in 2016/17 (6 °C) compared to that in 2015/16 (8.6 °C).

During the August 2017–July 2018 period, TEC accommodated a similar number of conferences and events as in the previous period, apart from the live streaming of the graduation ceremonies in the lecture theatre, which was not required as the Summer Graduations took place outside the UEA campus. The rest of the building's teaching spaces and business units had similar occupation and energy requirements to the previous period. However, the energy consumption for this period is higher than that in 2016/17. This could be explained by two time-related setting anomalies manually overridden in the BMS, which had been noted as commencing around June 2017 (as an increase in energy consumption) but were finally identified and corrected in spring 2018. Both anomalies caused a significant increase in electrical power and primary heat consumption for the 300-seat lecture theatre. The overridden and incorrect settings resulted in the lecture theatre air conditioning systems constantly operate in the evenings and over the weekends, even though the room was not occupied. It was concluded that the two settings had been adjusted during two separate events by manually extending the clock settings. Unfortunately, once the two events had been completed, the system settings had not been returned to the core weekday hours. The increase in heating consumption in 2017/18 compared to 2015/16 can also be related to lower mean outdoor temperatures in 2017/18 (6.9 °C) compared to that in 2015/16 (8.6 °C).

The building operated normally during the August 2018–July 2019 period and no irregular events were noted. The decrease in heating consumption in 2018/19 compared to 2017/18 can also be related to higher mean outdoor temperatures in 2018/19 (7.3 °C) compared to that in 2017/18 (6.9 °C). For TEC to meet the criteria of Passivhaus standard annually, it is necessary to be aware of and control the building's operational activities and settings.

4.3. Energy consumption comparison

TEC has proved to be a highly energy efficient building with significantly reduced energy consumptions compared with conventional university buildings. CIBSE TM46 [48] establishes energy benchmarks for university buildings of 80 kWh/m^2 for electricity and 240 kWh/m^2 for fossil-thermal. According to Hawkins et al. [58], it is expected that university buildings would typically have higher electricity use but lower heating use than TM46 rates. TEC's electricity and heating consumptions are significantly lower than the benchmarks with electricity use up to 63% lower (28.9–39.5 kWh/m^2) and heating use up to 16 times lower (14.6–23 kWh/m^2).

Similar percentages of energy savings are observed when

Table 8
Comparing the results of this study against the criteria of Passivhaus standard.

Criteria	Passivhaus standard criteria	Unit	2015–16		2016–17		2017–18		2018–19	
Primary Energy	120	kWh/m^2.annum	85.4	✓	102.8	✓	110.7	✓	115.4	✓
Space Heating Demand	15	kWh/m^2.annum	12.3	✓	14.7	✓	20.0	×	15.4	×
Space Cooling Demand	15	kWh/m^2.annum	2.4	✓	2.5	✓	3.3	✓	2.6	✓
Airtightness	0.6	m^3/(m^2·h)@50 Pa	0.21 (airtightness test undertaken in 2015)							

benchmarking TEC against existing university buildings in the UK. For example, a UK study based on De Montfort University's buildings indicated that annual electricity consumption per m^2 ranged from 74 to 100 kWh/m^2 and annual heating use per m^2 ranged from 98 to 109 kWh/m^2 [41], suggesting that TEC's electricity consumption is lower by up to 60% and its heating consumption is lower by up to 80% than those energy consumption figures. A sector review of UK higher education [59] showed that energy consumption among university buildings ranged between 259 and 330 kWh/m^2, which is up to six times higher than TEC's total energy consumption per m^2 (43.5–57.6 kWh/m^2).

TEC has also demonstrated comparable energy performance values to other Passivhaus university buildings. For example, PHPP estimations for the University of Leicester's Centre for Medicine, the UK's largest Passivhaus building, suggests annual space heating demand of 15 kWh/m^2 and a total annual primary energy use of 116 kWh/m^2 [27]. TEC's PHPP estimation provides similar values of 14.2 kWh/m^2 for heating consumption and 111 kWh/m^2 for primary energy. However, as outlined in Table 5, both PHPP estimations are higher than the actual average annual consumptions as the building performs better compared to estimated values.

4.4. Carbon emissions

The CIBSE TM46 [48] CO_2 benchmark for university buildings is 89.6 $kgCO_2/m^2$ for total electricity and fossil-thermal CO_2 emissions. Similarly, the study by Amber et al. [60] suggests that average CO_2 emissions for a typical university building in England is around 90 $kgCO_2/m^2$. Annual emissions from electricity and heat demand associated with the TEC building are 10.5–16 $kgCO_2/m^2$, which is up to 8.5 times lower. This clearly demonstrates the benefit of designing University buildings to Passivhaus standard to reduce carbon emissions compared to conventional buildings.

5. Conclusion

This paper presents the results of a modelled and actual performance of a UK university building certified to the Passivhaus standard over four years. To investigate the operational energy and carbon performance of the building, its performance is compared against Passivhaus standard and PHPP predictions.

- The results show that TEC met the primary energy target of 120 kWh/m^2 for Passivhaus standard and the cooling demand target of 15 kWh/m^2 in all four years. This building also met the space heating demand target of 15 kWh/m^2 in the first two years. TEC has the potential to meet the Passivhaus requirements, especially when activities are controlled within design expectations. The building had significantly reduced heat losses and heating demand, due to the very high airtightness, 0.21 $m^3/(m^2 \cdot h)$ @50 Pa, and low envelope U-values.
- TEC's electricity and heating consumptions were significantly lower than the CIBSE TM46 energy benchmarks with electricity use up to 63% lower (28.9–39.5 kWh/m^2) and heating use up to 16 times lower (14.6–23 kWh/m^2). TEC proved to be a highly energy-efficient building with significantly reduced energy consumptions compared to other conventional university buildings.
- The study compared PHPP predictions of energy consumption against actual consumption and they were within a 30% performance gap. In this study, TEC performed better than PHPP estimations and therefore used less energy than predicted, especially during the first two years. The performance gap could possibly be related to the slight difference between outdoor temperatures used in PHPP simulations and measured mean outdoor temperature, and different buildings' operational activities than considered in simulations.
- Solar panel installations feeding into the campus power grid provided around 38.7% of the electricity requirements of the building. PV systems generated more than 60% of the building's electricity demand in August (67.8%), July (65%), May (63.5%) and June (62.2%). Solar panels reduced 24.5 $kgCO_2/m^2$ of electricity fuel carbon emissions during these four years.
- Annual emissions from electricity and heat demand associated with the TEC building (10.5–16 $kgCO_2/m^2$) was up to 8.5 times lower than CIBSE TM46 CO_2 benchmark and average emissions for a typical university building in the UK. This highlights the importance of designing University buildings to Passivhaus standard to reduce carbon emissions.

This building is an exemplary energy-efficient building for future university buildings. This research contributes to the field of energy-efficient buildings and bridges the gap on the adoption of Passivhaus Standard for university buildings to reduce energy consumption and carbon emissions. Lessons learnt from TEC can be practised by building designers and examined by researchers for future university buildings certified to Passivhaus standard.

Author statement

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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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