Performance Evaluation and Resilience Testing of a Passivhaus School

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Abstract

Passivhaus has emerged as a reliable solution for reducing the environmental impact of buildings. Buildings designed to Passivhaus standards have a proven track record of very low energy use. In the UK context, these buildings can provide comfortable buildings with little heating requirement and almost no cooling. However, buildings generally have a service life of more than 50 years and evolve in their function and operations. In that case, increased global warming due to changing climate might mean that Passivhaus buildings, designed without comfort cooling, may not be resilient to future extreme weather events. Using a case study example of a Passivhaus school, this paper evaluates operational performance (energy and thermal comfort) of Passivhaus buildings and test it under possible future scenarios.

Key Highlights

- Operational performance assessment of a school designed to Passivhaus standards.
- Scenario testing with evolving occupant patterns and future climate resilience.
- Performance comparison of Passivhaus buildings with traditional buildings.

Practical Implications

Findings from this study will add to a body of evidence for improving resilience in already high-performance Passivhaus buildings. The resilience testing assessment done for this case study will also be applicable for a wider range of building performance and adaptation analyses, in the building industry.

Introduction

The world's current emissions trends will raise global temperatures by at least 2.7°C this century, exceeding the Paris Agreement goal of 1.5°C (WMO, 2022). To manage the consequences of high carbon emissions, the IPCC (2021) proposed to achieve carbon neutrality by 2050. As per the amended Climate Change Act (2015), the UK has set a target of zero emissions by 2050.

Building-related CO_2 emissions account for about 39% of global carbon emissions (IEA, 2020). This suggests that the building sector can play a vital role in meeting UK's climate targets. It will require a system-wide transformation in the construction sector, which can be achieved by promoting low or zero-energy buildings. The Passivhaus approach, as an international leading design standard of low energy consumption and high environmental performance, has become the focus of global sustainable development (Sofia & Kesidou, 2018). However, it remains unclear whether buildings designed to current Passivhaus standards can adapt to future changes, such as shifting climate and evolving occupants' behaviour patterns (Druckman et al., 2011).

This study assesses the current performance and future resilience of a Passivhaus school in the UK. Besides empirical data analysis of the case study building, a calibrated simulation model is used to explore various future building operation and climate change scenarios.

Background

Operational Performance in School Buildings

Operational performance assessment is a generic approach for gaining feedback on building performance in use (Khalfan, 2017). A systematic performance assessment can identify improvement areas in buildings and provide lessons for other similar buildings across the built environment (Hay et al., 2018).

Educational building is one of the fastest growing sectors in the UK (Hopfe & McLeod, 2015). Schools in the UK account for 8% of total energy use in the construction sector (IEA, 2020). Thermal comfort in classrooms is strongly associated with symptoms of sick building syndrome (SBS), i.e. reduced concentration, cognitive ability and academic performance (PHE, 2013). A study in UK showed that for every 2°C rise in temperature in the 25-32°C range, student productivity dropped by 2% (CIBSE, 2020). The parameters that affect the risk of building overheating include external climatic conditions, building shape and form, building fabric properties, internal gains, etc (Teli er al., 2011). Research has shown that many school buildings in the UK are unsuitable for hot summers, due to features as low thermal mass and high glass facades (Teli er al., 2011). The trend of summer warming will further promote the occurrence of building overheating. Table 1 lists the thermal comfort thresholds applicable to schools in the UK.

Table 1: Thermal comfort thresholds for schools

Categories	Thresholds	Standards
Temperature in summer (Prevent of overheating)	≤ 25°C	BS EN 16798 (BSI, 2019)
Temperature in heating season (Prevent of cold draught)	20°C-25°C	BB101 Guideline (2018)

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Operational energy performance of buildings is tracked via various benchmarking guides. Table 2 introduces the energy performance benchmarks for school buildings from commonly used guidance documents in the UK.

Table 2: UK school energy use (kWh/m^2) benchmarks

Benchmark	**Elec/Gas**	
CIBSE TM46 (2015)	Typical	150/40
CIBSE Guideline F (2019)	Good practice	113/22
	Typical	164/32
CIBSE Benchmarking tool	Good practice	97/35

Passivhaus Design Approach

Passivhaus was created to achieve long-term climate goals and net zero carbon in the construction sector. Passivhaus Designer's Guide (Feist & Kaufmann, 2021) is a widely used approach and is considered to be the leading international standard for low-energy design, mandating very high performance requirements (see Table 3). Key features of a Passivhaus are super insulation; thermal bridge-free structure; air-tight envelope; mechanical ventilation with heat recovery (MVHR); and high-performance doors and windows.

Table 3 Outline of the Main Passivhaus Criteria

Passivhaus criteria	**Value**
Specific heating load	≤ 15 kWh/(m^{2}a)
OR Specific heating demand	≤ 10 W/m^2
Specific cooling load	≤ 15 kWh/(m^{2}a)
OR Specific cooling demand	≤ 10 W/m^2
Specific total primary energy demand	≤120 kWh/(m^{2}a)
Air tightness	≤ 0.6 ach@50Pa
Overheating frequency	≤ 10%

Nevertheless, Passivhaus's high performance comes at a cost and can cost 5%-10% more than typical regulatory compliant buildings (Wang et al., 2019). In addition, there is a concern that super insulation and high air tightness can exacerbate the risk of overheating in the current and future warmer climates (Ladipo, 2016).

Methods

This study follows a case study approach. The framework of the methods, shown in Figure 1, combines operational performance assessment with building performance modelling. A calibrated simulation model is used to test future climate and operation change scenarios. Energy and unintended thermal comfort underperformance are the main aspects being assessed.

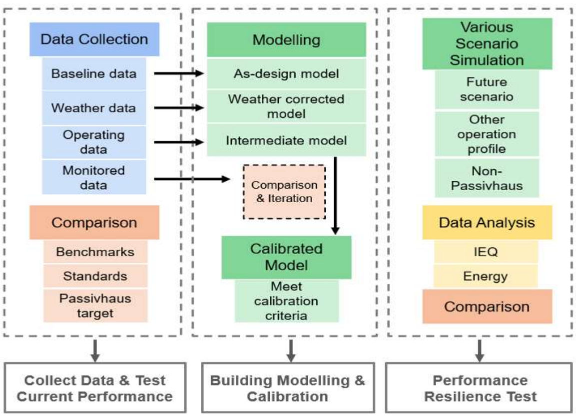

Figure 1: Overview of Methodological Framework

Stage 1: Data collection and Performance Assessment

Data collection protocol, as per IPMVP (EVO, 2018) and ASHRAE Guide 14 (2015) was followed. Following data was collected:

- Building design, including geometry and system equipment details were obtained from the building's design stage documents.
- Weather data used was from a nearby weather station (University of Exeter, 2022).
- Operational information such as occupancy levels, HVAC, lighting and other system operations was derived from design documents and stakeholder feedback.
- Regular metering and utility bills provided the energy use data. Space temperatures were also recorded at designated locations in the case building.

The measured energy and environmental performance were compared to the environmental standards, UK energy benchmarks, and Passivhaus targets.

Stage 2: Performance Modelling and Calibration

Evidence-based calibration process was undertaken as per CIBSE TM63 (2020) (Jain et al., 2020). The process is divided into the following two stages:

- An intermediate model is developed using the collected building data in DesignBuilder V7.0 (DesignBuilder Software Ltd., 2022), which uses EnergyPlus V9.4 (U.S. Department of Energy., 2021).
- Deviations between the simulation inputs of the intermediate model were fine-tuned as per further evidence collected from the site. Validation criteria used for model calibration is as per ASHRAE Guideline 14/ IPMVP (Table 4).

Table 4 Validation Criteria for the Model Calibration

Statistical indicators	**Hourly data**	**Monthly data**
Cv (RMSE)	< 30%	< 15%
NMBE	< 10%	<±5%

Stage 3: Resilience Testing

The calibrated simulation model is used to explore a variety of future climate and operational scenarios. The results are compared with relevant regulatory standards and benchmarks. The scenarios explored include future climate change, the addition of night school operation pattern, and the assumption that the building was not constructed following Passivhaus standards.

Case Study Building

The 2-storey, 1767m^2 primary school building is located in South Wales and designed to the Passivhaus standard. The annotated aerial photographs in Figure 2 illustrate the school grounds and surroundings.

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Figure 2 Aerial Photo of the School Site

Building Fabric

The building fabric has high insulation levels (low U-value) and excellent airtightness designed to form a continuous thermal envelope. To minimise solar gains in summers and to avoid overheating, vertical shadings and overhangs are installed along the south-facade. The fabric details and along with Passivhaus targets are shown in Table 5.

Table 5 Building Fabric Details

	Element	Value	Target	Component
U-value (W /m²K)	Wall	0.14	≤ 0.15	Timber; Plasterboard; Fibreboard
	Roof	0.11	≤ 0.15	Acoustic tile; Plasterboard; Fibreboard; Sheeting
	Floor	0.13	≤ 0.12	Timber; Mineral fibre; Concrete; Plasterboard; Fibreboard
	Window	0.80	≤ 0.85	Argon filled; triple glazed with coating; Aluminium / Timber frame
G-value		0.63	≤ 0.50	-
Air permeability (ach@50Pa)		0.60	≤ 0.60	-

Occupancy and Operations

The building is designed for 242 (220 pupils and 22 staff) occupants. Typical spaces in the building consist of classrooms, meeting rooms, some offices and circulation areas. Table 6 shows the timetable of a typical classroom in this school.

Table 6 Classrooms Timetable of the Case Study School

Time	Description	Duration
5:30	School Unlock Time	-
8:45 – 9:00	Pupil Registration; Arrival	15’
9:00 – 10:30	First Morning Section	90’
10:30 – 10:50	Morning Break	20’
10:50 – 12:30	Second Morning Session	40’
12:30 – 13:20	Lunch Break	50’
13:20 – 15:15	Afternoon Session	115’
15:15 – 17:00	Staff Work and Cleaning	105’
Total Teaching Time	-	245’ (4.08h)
Total Break Time	-	70’ (1.16h)

Mechanical systems

The building has a mixed ventilation strategy supported by MVHR (Mechanical Ventilation with Heat Recovery). MVHR for the main occupied areas (efficiency: 82.3%) is driven by a main Air Handling Unit (AHU), while the kitchen is serviced by a separate AHU. The windows on facades are designed to be operable for providing natural ventilation. These windows are manually operated, supplemented by a some of automatic control.

The building's heating is provided by a low temperature hot water system using a gas boiler (SEER: 97.64%). There is also another small gas boiler (SEER: 89%) to satisfy hot water demand. Radiators installed in the occupied spaces to control heat supply (set point 20°C). In summer, natural ventilation is the main form of space cooling as no active cooling system is installed.

Lighting and Equipment

The school has an energy-efficient lighting system with fluorescent lights installed in teaching and office spaces. It is also equipped with daylight-compensated PIR sensors to provide automatic lighting control. The lighting load in classrooms is 4 W/m², and 5 W/m² for meeting rooms and office spaces.

The equipment in teaching areas have varying loads, such as computer at 0.8 W/m^2, while projector or smartboard was 4.2 W/m^2. Total equipment load is estimated as 16 W/m^2 (CIBSE Guide A, 2021).

Results

Based on energy consumption and hourly air temperature monitoring records over a one-year period (September 2018 to August 2019), an operational performance evaluation of the case building is done.

Building Energy Performance

The total annual energy use of the building is monitored as 39.6 kWh/m^2. Figure 3 indicates the breakdown of energy use, provided by building management systems (BMS). Two-thirds of the building energy is used for lighting, power, and equipment. Also, the HVAC-related energy accounts for less than a quarter, which is significantly less than similar buildings, highlighting the impact of high-performance envelope. This can be seen when comparing the performance against energy benchmarks (Figure 4). The school’s fossil fuel EUI (i.e., energy used for heating and hot water purposes) is 90% less than any good practice benchmark. This means the building is far more fossil fuel efficient than the top 25% of school buildings in UK. EUI for electricity (i.e., energy used for occupant related lighting and small power use) is similar to the good practice benchmarks.

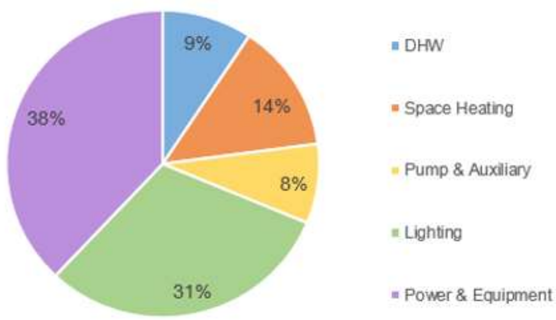

Figure 3 Breakdown of energy use per end-use

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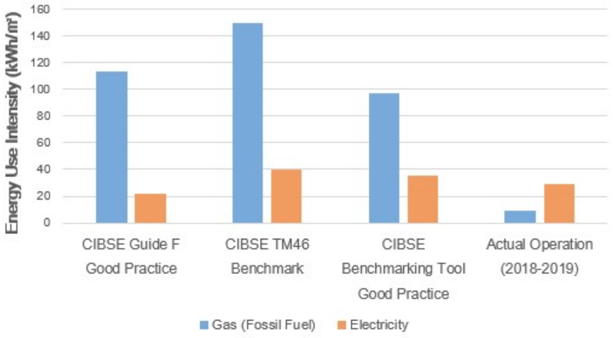

Figure 4 Comparison of actual annual gas and electricity usage against industry benchmarks

Thermal Comfort

Temperature data was collected from three classrooms in the building, one on the ground floor (D1) and two on the first floor (D2 and D3). Figure 5 summarizes the temperatures in readings recorded in these rooms during the occupied times. The air temperatures are between 20°C and 25°C for more than 80% of the occupied hours. The times when the temperatures exceed 25°C, indicating the beginning of overheating, is less than 5% of the occupancy time. This indicates that the building exhibits good resistance to summer overheating. It is worth noting that temperatures below 20°C are relatively more common than overheating temperatures, especially in D2 and D3, observed during the heating season.

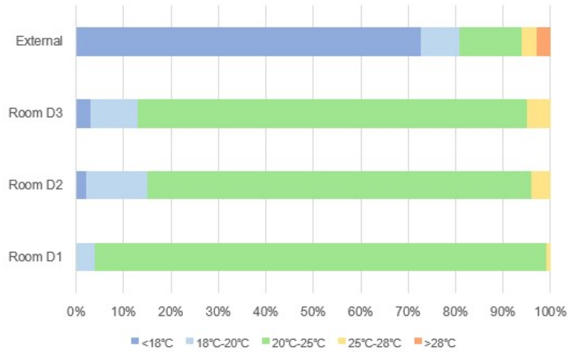

Figure 5 Annual air temperature distribution during occupied times

Figures 6 and 7 show more granular snapshots of monitored air temperature during a typical summer week and a typical winter week. During summer, the resilience of the building in maintaining comfort during times with high outdoor temperature is evident. Similarly, during winters, building system is able to maintain comfortable temperatures inside.

Figure 8 shows the full year of temperatures recorded in one of the classrooms. This map can be used to interpret, along with overheating instances, heating system operation of trends, such as, in the heating season, regular temperature changes are seen at 8:45 am and 17:00 pm on school days. This confirms when the room heating is turned on and off.

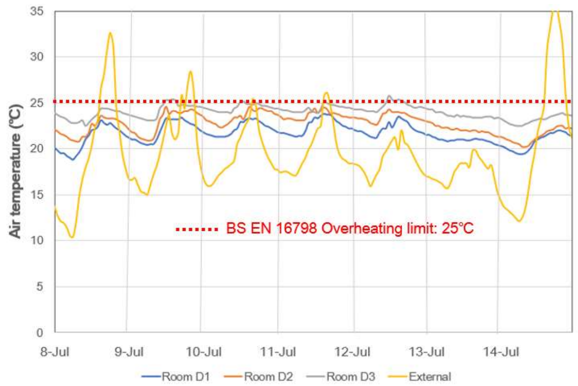

Figure 6 Temperatures during a typical summer week

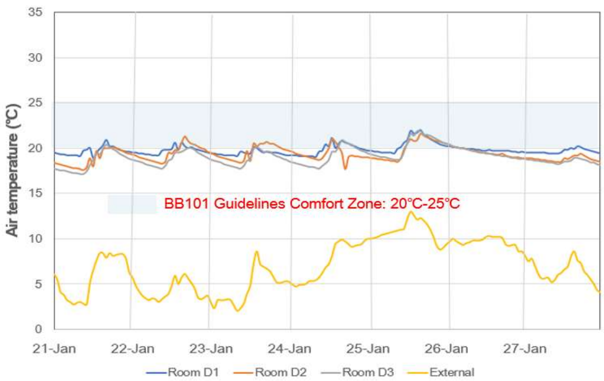

Figure 7: Temperatures during a typical winter week

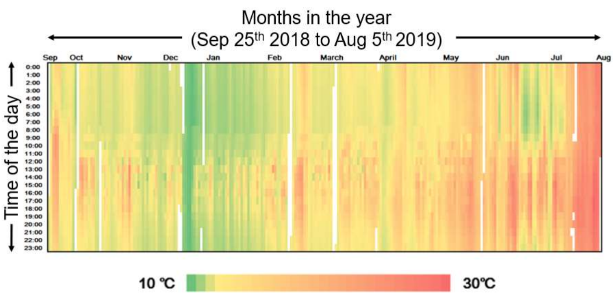

Figure 8 Heat map showing temperature changes in a classroom

Scenario Assessment

To test the case study boiling under various scenarios, a building performance simulation model (Figure 9) is developed. This model is then calibrated as per CIBSE TM63 and described in methods section.

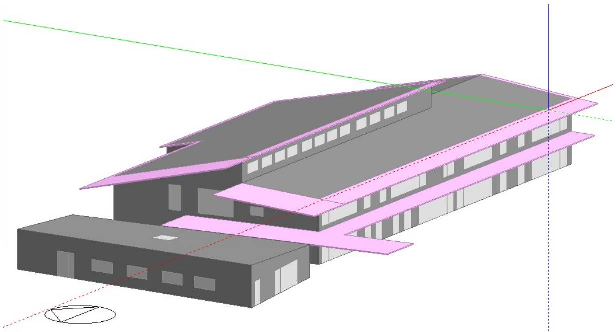

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Figure 9 Visualization of the school building model in DesignBuilder

During the evidence-based calibration process, data collected from the building design documentation was used to create the baseline building. Then along with actual weather data, post occupancy assessments were used to finetune the model inputs based on observed and inferred trends. By using the actual loads, operating trends and system control settings, calibrated model was achieved. Figure 10 shows the comparison of monthly gas and electricity use of the calibrated simulation results against measured values. The C_V(RMSE) and NMBE values are within the validation criteria described in Table 4. Figure 11 further shows the annual simulated and actual energy use categorised as per various end uses. The results show that there is good agreement between the simulated and measured values and no end-use cross compensation is happening in the simulation projection. Therefore, the simulation model can be considered calibrated and a reasonable representation of the actual building. It is now possible to assess the multiple scenarios to test building performance.

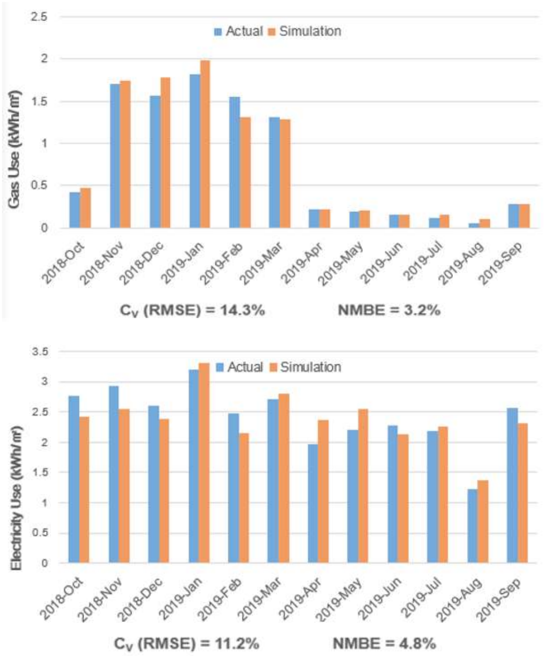

Figure 10 Simulated vs actual monthly gas use and electricity use

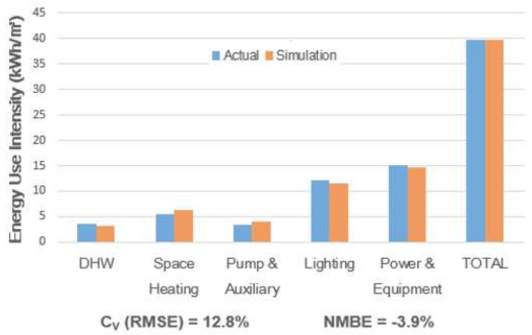

Figure 11 Simulated vs actual annual energy end-use

<u>*Scenario 1: How will the building perform in future climate context?*</u>

In this scenario, 50th percentile 2050 climate data, for the building location was selected. The Heating Degree Days (HDD) and Cooling Degree Days (CDD) in Table 7 indicate that by 2050, the severity and duration of hot and cold time will increase significantly, and the energy required for heating and cooling will be higher than now.

Table 7 HDD and CDD in current and 2050 climates

	HDD	**CDD**
Current	181.2	30.1
2050	244.2	69.5

Figures 12 and 13 show the comparison of indoor and outdoor temperatures in current climate and future climate for a classroom during a typical summer and winter week respectively. It can be observed that during summers, due to lack of active cooling and higher outdoor temperatures for longer periods, the indoor air temperature exceeds the overheating threshold levels more frequently. While in the winter months, the indoor temperature almost coincides with the current values, staying in the range of 20°C-25°C, meaning that the heating system can cope with the colder situations well.

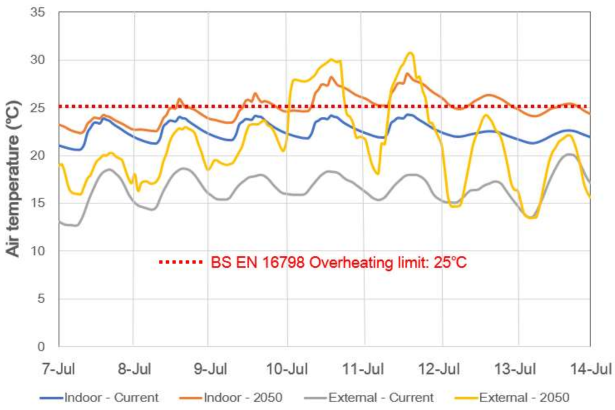

Figure 12 Summertime temperatures in current and future climate scenarios

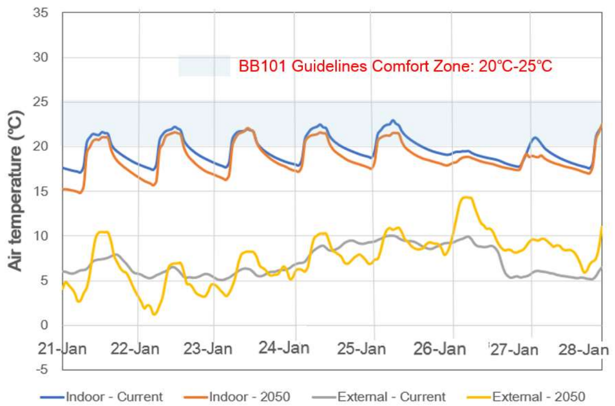

Figure 13 Wintertime temperatures in current and future climate scenarios

Figures 14 shows that the projected gas and electricity consumption in 2050 will be about 10% higher than the

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current situation. This is mainly attributed to the intense use of HVAC and its auxiliary systems because of rising temperatures.

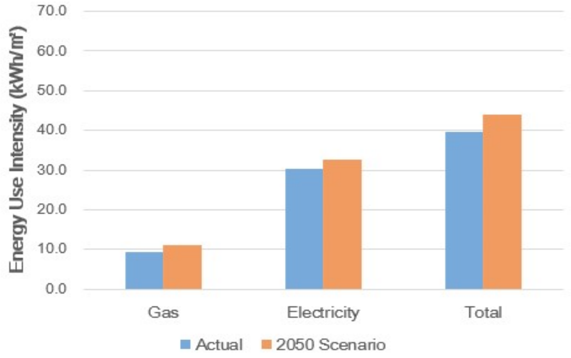

Figure 14 Current vs 2050 annual energy use

Scenario 2: How will the building perform if the building changes its current use and operating trends?

To assess building's resilience to changing operating and occupancy patterns, this study considers adding evening classes to normal school hours. More specifically, it is assumed that the school opening hours during the term are extended to 22:00. Two evening classes of 18:00-19:30 and 20:00-21:30 are added, followed by 30 minutes of cleaning. The major impact of this scenario change is expected to be seen in overall use of the building and its total energy use. Figure 15 compares the energy consumption of the building during current trends with the new scenario with added night school. Total building energy use with added 4 hours of night-time sees increase in both gas (heating) and electricity (lighting and small power). However, the main increase, >60%, is in electricity use increase due to the extended operating time of various devices.

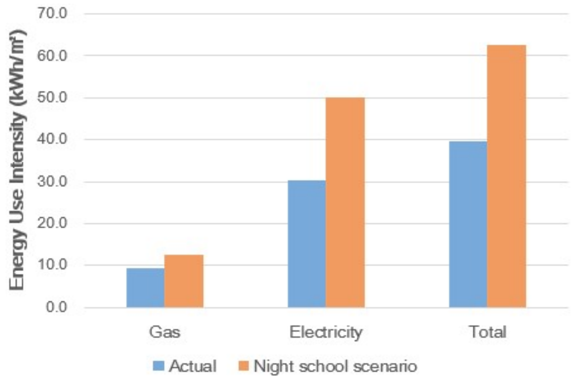

Figure 15 Current vs night school annual energy use

Scenario 3: How will the building perform if instead of a Passivhaus, the building was built to then UK regulatory standards?

In the third scenario, the building fabric parameters are assumed to meet the UK regulatory standards in place during the time of building construction. Table 8 lists the U-values and air tightness requirements as per UK regulatory, Approved Document L Volume 2 (2016), also known as Part L. These values for the fabric were used in the scenario 3 model instead of the Passivhaus values.

Table 8 Input data for fabric properties in scenario 3

	Element	Value as per Part L requirements	Passivhaus Criteria
U-value (W /m²K)	Wall	0.25	≤ 0.15
	Roof	0.18	≤ 0.15
	Floor	0.18	≤ 0.12
	Window	1.60	≤ 0.85
Air permeability (ach@50Pa)		0.98	≤ 0.60

The comparison of thermal performance during typical summer and winter weeks is shown in Figures 16 and 17. It can be seen that a building designed to Passivhaus standards is a few degrees warmer in both summer and winters, in comparison to the building designed to Part L requirements only. However, comparing the energy use change between the Passivhaus and Part L buildings (Figure 18), it can be seen that due to the poor envelope specifications, the gas use for heating in the school is almost 85% higher.

As expected, electricity use, which is related to MVHR, slightly dropped. The, almost doubling of gas use demonstrates the superiority of Passivhaus in energy performance.

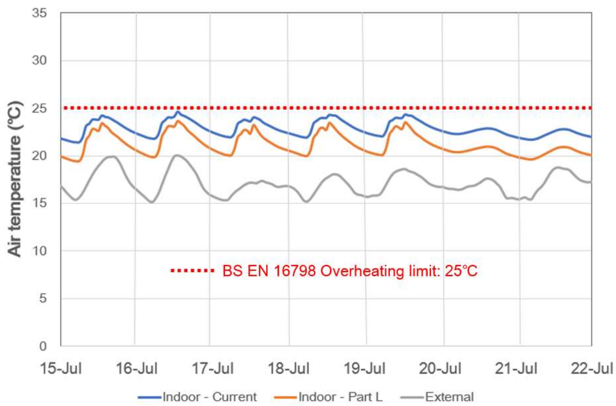

Figure 16 Summertime temperatures comparison for Passivhaus building vs Part L

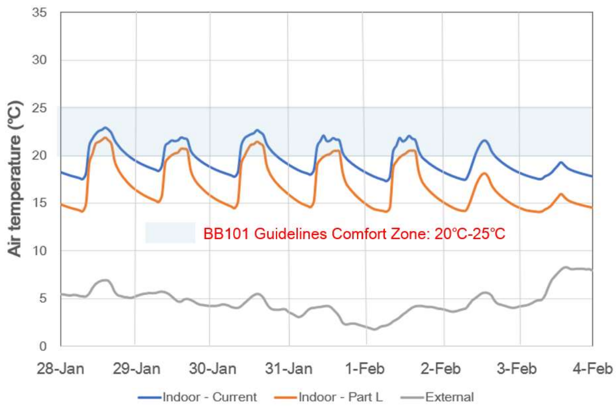

Figure 17 Wintertime temperatures comparison for Passivhaus building vs Part L

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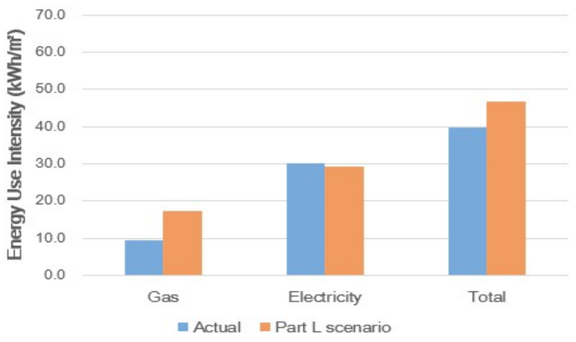

Figure 18 Current vs non-Passivhaus annual energy use

Discussion

The case study building achieves an extremely low level of energy consumption, mainly due to the savings in heating energy due to high envelope standards. Compared to traditional construction, Passivhaus solutions have a more robust performance during heating seasons. Thus, despite the higher cost of Passivhaus buildings, its airtightness and high thermal insulation provide great benefits in the long run, reducing the need for space heating in winter.

During the winter months the buildings also maintains good thermal comfort but there is a trend of consistently colder mornings in some classrooms. In those spaces there is a need to optimise the heating system start times, to turn on earlier in the morning by about an hour.

For summertime, the building designed without comfort cooling, appears to be struggling during heatwave periods as indoor temperatures are high, almost touching overheating levels. This gets increasingly challenging as future trends show that there is an risk of overheating in the school and there is a need for incorporation of comfort cooling to mitigate the adverse risks of extreme events in future climate scenarios.

Figure 19 and 20 compare the energy usage for various scenarios tested against industry benchmarks for gas and electricity use in school buildings.

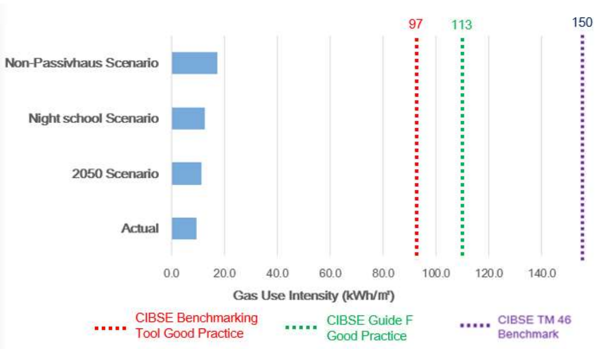

Figure 19 Comparison of gas use with benchmarks

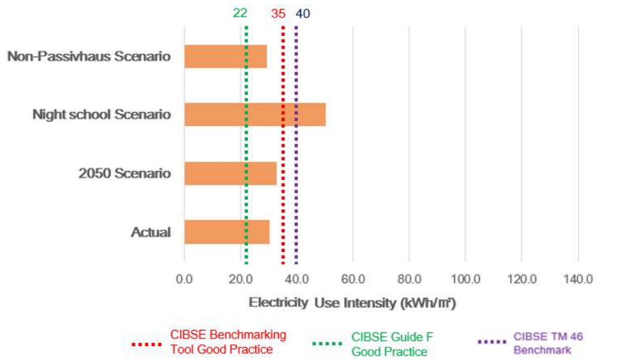

Figure 20 Comparison of electricity use with benchmarks

The key observation is that even if the building were to operate in the scenarios explored, its overall performance will be still better than most schools in the UK. Scenario with night school is worst performing amongst all, however this is in the case of better space time utilisation of the building, which in real terms is a positive change. It should however be noted that electricity uses in this building and other scenario are not far exceeding the good practice benchmarks. This is reflective of changing trends of more small power uses (such as IT equipment) getting integrated into school teaching processes.

Conclusion

Performance and resilience testing of the case study Passivhaus school showed that the following the high specification results in low energy use and comfortable indoor environmental quality. In the UK, Passivhaus buildings are generally designed to be cooled using natural ventilation. However as future climate trends show that temperatures in excess of 30 degrees will become more prevailing, there is a need to plan for building designs with option of adding active cooling to prevent overheating in future.

Another trend that is getting prevalent is more diversified usage of built infrastructure. Schools are often remaining open for longer for activities such as night schools or extracurricular activities. This can sometimes lead to a perceived underperformance compared to other schools and benchmarks. It is important that in these scenarios where better space-time utilisation of the space is happening, the buildings do not get unfairly penalised.

Acknowledgements

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