Benchmarking Buildings in the Context of Net-zero Targets:
Tracking Energy Performance of a Case Study from Design to Operation

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ABSTRACT: *To keep on track with the net-zero targets for the building sector, building energy benchmarking is essential. Benchmarking compares the building energy performance to established standards based on historical energy usage, and these benchmarks become aspirational goals. However, existing building energy data reveal a different consumption trend in recent times. Thus, actions are required to assess current benchmarks' relevance, development, and applicability so that buildings comply with the net-zero target. This paper compares the design and operational performance of a newly constructed building with existing benchmarks. Further, the feasibility of net-zero targets in an operating building is investigated using a calibrated energy model. Findings show that the building used 2.1 times more energy than design estimation. A key factor for this deviation was the change in operating hours, increasing from 10 hours per day during design to 24 hours in operations. This space-time utilisation increase made the building unable to achieve the performance needed for current net-zero benchmarks. This is one of the challenges that benchmarking systems need to address. The current benchmarks (to enable net-zero pathways) lack a broader range of maximum hours and should include a time normalisation factor to avoid penalisation for better space-time utilisation.*
KEYWORDS: *Energy Performance, Energy Benchmarks, Building Operational Stage, Net Zero Carbon*

1. INTRODUCTION

By 2050, the UK must achieve its zero-emission objective under the Climate Change Act 2008, as amended in 2019 (The Climate Change Act, 2019). As part of the UK's climate change target, the London Energy Transformation Initiative (LETI) proposes that by 2025, all new buildings should have low Energy Usage Intensity (EUI) and low space heating demand so that net-zero carbon emission from new buildings can be achieved by 2030 (LETI, 2020). To keep on track with the energy target, energy benchmarking of the buildings is required.

Energy performance benchmarking is a strategy for assessing a building's energy performance by comparing its energy consumption to a specified target or criteria based on historical energy consumption or established energy standards (Hong et al., 2013). Benchmarks can be derived in two ways: top-down and bottom-up. The top-down analysis examines macro or building-level energy before focusing on more specific variables such as the end-uses of the building. On the other hand, bottom-up evaluation accumulates the performance of a particular building at the system level, which is then aggregated into a single EUI representing a hypothetical building's overall performance (Hong, 2015).

In the UK, CIBSE Guide F (CIBSE, 2012), CIBSE TM46 (CIBSE, 2008), and the Energy Consumption Guides (ECG) Series (EEBPP, 1997) can be used to evaluate building energy consumption as the top-down benchmarks. Additionally, CIBSE Guide F also includes end-use benchmarks for bottom-up evaluation. These documents are industry-standard guidance protocols that inform local government regulatory needs while also providing benchmark values for building energy consumption. However, discrepancies in benchmark values from various sources make building performance evaluation more challenging. Furthermore, current building energy statistics show a different consumption pattern than these relatively dated energy benchmarks (Hong et al., 2013). Analysing data over time indicates that the building's energy consumption trend will certainly change, making the current benchmarks outdated (CIBSE, 2019). Additional research is needed to determine the relevance and development of these benchmarks and their suitability for buildings' design and operations as they move towards net-zero targets.

2. METHODOLOGY

In this paper, we used a newly built case study building to assess its performance against all the relevant benchmarks from the design stage to operation. We compared the targeted and achieved performance of the building, factoring in its various changes over time with various benchmarks. This helped us evaluate the benefits and limitations of benchmarks being used in the industry. Also, using a calibrated energy model, we were able to

undertake scenario testing and assess the practicality of meeting the net-zero targets in this already operational building. An overview of the proposed method is shown in Figure 1.

Figure 1:
Methodological Overview
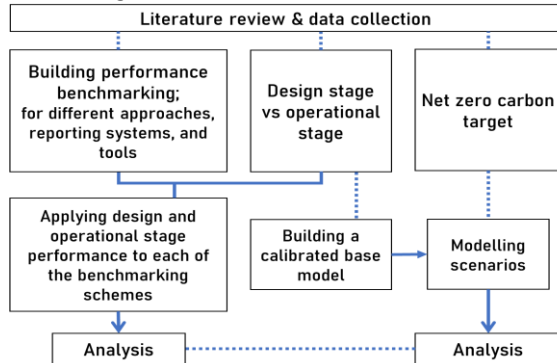
2.1 Literature Review and Data Collection

Initially, three key interrelated topics need to be studied as a part of the research.

- *Performance Benchmarking*

Thorough study and desk research of the energy performance benchmarking was conducted. It includes the understanding of benchmarking approaches (top-down and bottom-up), benchmarking systems and reporting in the UK, such as the CIBSE Guide F, CIBSE TM46, and ECG54, and the CIBSE Benchmarking Tool (Table 1).

- *Design Stage vs Operational Stage*

Benchmarking is explored using a case study building. Fundamental causes of the difference between the estimated and actual performance of the case study are identified. The data is collected from design documentation and modelling reports for CIBSE TM54, a modelling guide and reporting protocol for design stage energy projections (CIBSE, 2013). TM54 divides the parameters used in energy consumption prediction into low-end, mid-range, and high scenarios to provide a wider range of estimates. The mid-range scenario represents the typical energy use of a building. Meanwhile, the operational stage data is typically collected from post-processed and cleaned actual metered and monitored data of the building's electrical metering.

- *Net Zero Carbon Target*

As a response to the UK's environmental objectives in the future, the Climate Emergency Design Guide (CEDG) from LETI gives guidance on how to attain the carbon-neutral target by 2030. Additionally, the UK Green Building Councils (UKGBC) has created a feasibility study report to implement new net-zero carbon buildings (UKGBC, 2020).

The literature review aims to present a comprehensive overview and chronological evolution of the UK's benchmarking systems and their relevance towards future development.

Table 1:
Benchmarking Systems and Reporting in the UK

Benchmarking System & Reporting in the UK	Description
ECG54 – Energy Use in Further & Higher Education Buildings (Energy Consumption Guide Series) - 1997	It offers an energy usage and cost assessment approach and examines the primary influences on energy use in academic and auxiliary buildings and space functional categories.
GPG321 – Energy Efficiency for Further and Higher Education (Good Practice Guides) - 2002	The objective of this Guide is to educate universities and colleges on the potential for implementing energy efficiency, as well as to offer methods for doing so.
CIBSE Guide F – Building Energy Efficiency - 1996 (1st edition), 2004 (2nd edition), 2012 (3rd edition)	CIBSE Guide F provides energy efficiency principles and benchmarks. It comprises 'typical' and 'good practice' energy benchmarks for a wide range of available data on buildings, components, and end-uses.
CIBSE TM46 – Energy Benchmarks - 2008	The CIBSE TM46 is a publication of the Display Energy Certificate (DEC) benchmarks that are based on the original CIBSE Guide F and ECG 19 data with a significant simplification of values drawn from many sources as well as engagement with the industry. It allows the use of options to account for separate energy uses and longer occupancy.
CIBSE Benchmarking Tool - 2013	CIBSE Benchmarking Tool is an online platform that offers a more dynamic approach for more up-to-date and accurate benchmarks to understand current energy usage patterns in buildings. It aims is to progressively revise and update the energy benchmarks in CIBSE Guide F.
Climate Emergency Design Guide (CEDG) by LETI - 2020	The Climate Emergency Design Guide (CEDG) from LETI gives guidance on how to achieve the zero-emissions target by 2050 (The Climate Change Act, 2019).

2.2 Case Study Performance Against the Various Benchmarking Schemes

A comparison of the case study's energy consumption between the design and operational stages up to the subsystem level is carried out to identify which parameters are significantly causing the difference between the targeted and actual performance. The energy consumption for each stage is then compared against current relevant benchmarks to see which benchmarking system is the most appropriate or suitable for the design and operational stages.

2.3 Building a Calibrated Base Model

Using the DesignBuilder software (DesignBuilder, n.d.), a base model is created according to the mid-range scenario of the CIBSE TM54 (design stage reference) and detailed engineering drawings (operational stage reference) of the case study. After the simulation results of the base model from the design stage input have been obtained, it is then compared and fine-tuned with the actual measurement of energy usage so the model can be calibrated, which in this case are lighting, power, and HVAC system with its auxiliary.

2.4 Modelling Scenarios

Two scenarios are applied to the calibrated model;

- *Scenario 1: Actual Operational Hours and Utilisation at Design Stage*

One of the causes of discrepancies between the estimated and actual energy consumption is the change in building utilisation after the building is operational. By replicating actual operational occupancy numbers and hours on the base model for the design stage, attempts to reduce the energy used can be focused on design parameters that are unlikely to alter after the building operates. The significance of the operational hours for the overall energy consumption can also be evaluated. This scenario modifies the calibrated model with real operating hours and 100% building utilisation.

- *Scenario 2: Achieving Net Zero Operational Target*

The goal of Scenario 2 is to assess the feasibility of achieving net-zero operational carbon without significantly altering the building's current utilisation. Scenario 2 is a follow-up to Scenario 1, where further simulations are performed to achieve better building performance closer to the net-zero operational target. It modifies the final model input of scenario 1 by applying better values of several parameters than the CIBSE TM54 low-end scenario on the model; higher heating COP, higher cooling setpoint, and using low-end scenario for power and equipment density by reducing on-site server and IT loads as suggested by UKGBC on their feasibility study (UKGBC, 2020). The proposed LETI energy consumption target was used as the building's net-zero carbon target. According to LETI, Schools and offices should have an EUI equal to or less than 65 kWh/m^2/year and 55 kWh/m^2/year, respectively.

2.3 Result Analysis

After comparisons and simulations of the case study were completed, related analysis was carried out regarding; the difference and relevance of each benchmarking scheme for design and operational stage, effects of operational hours and building utilisation on building energy consumption, and building capability in achieving the net-zero operational target.

3. CASE STUDY

The case study building is an educational building that aims to achieve the highest possible grade for environmental, social, and economic sustainability.

Compared to its design stage assumptions, several significant changes occurred during the operational stage, including the building's operational schedule, changing from ten to twenty-four hours per day. Also, the Demand Control Ventilation (DCV) system failed to operate properly, resulting in the building's mix mode operation being run inefficiently during actual usage. With this change, and after the raw data has been cleaned, the total energy used in the operational stage (212.08 kWh/m^2) is 2.75 times higher than the design stage projections (77.00 kWh/m^2) (Fig.2).

Figure 2:
Comparison of Energy Consumption Design Stage (TM54) vs Operational Stage
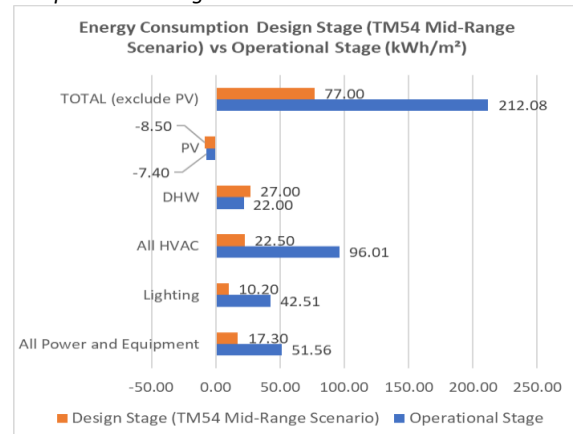
With all the differences between the two stages, Figure 2 illustrates that PV provides 87% of the estimated design stage at the operational stage. For power, the increase in the energy utilised is about three times. Meanwhile, the increase in lighting and all HVAC system end-uses for the operational stage are about 4.2 and 4.3 times higher than the design stage, respectively.
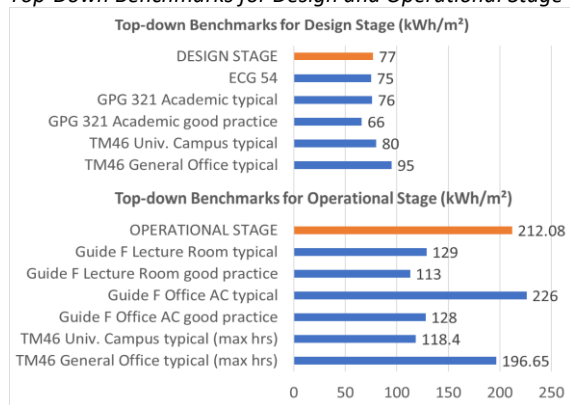
4. BENCHMARKING

Different benchmarks evaluation approaches serve distinct purposes in the building procurement process yet complement one another. A top-down assessment that compares the overall building's energy consumption with a similar building can encourage more energy efficiency at the design stage, while a bottom-up assessment help identifies inefficient subsystems when the building has operated. In the UK, Although CIBSE Guide F and CIBSE TM46 are considered out of date and need modification, their availability in terms of allowed maximum operating hours and separate energy end-uses makes them remain the primary guide for building energy consumption benchmarks.

In evaluating the top-down approaches in benchmarking, benchmarks that are comparable for this case study building are selected, considering the building's functionality and value of the benchmarks. Given the significant difference between the energy used in each stage, the benchmark comparison is also separated as seen in

Figure 3. The considered comparable benchmarks for the design stage are the benchmark values that are more or less 30% than the energy used prediction of the case study building. At the design stage, it can be seen that the comparable benchmarks have a similar building typology with the case study, which is an academic or higher educational building. However, none of the benchmarks is from the CIBSE Guide F, not even its 'Education' building category. Meanwhile, at the operational stage, the figure expresses that the closest comparable benchmarks are the energy consumption of typical offices from Guide F and TM46. It was also found that none of the Guide F for educational buildings or TM46 for university campuses with the maximum hours is comparable for either the design or operational stage.

Figure 3:

*Top-Down Benchmarks for Design and Operational Stage*
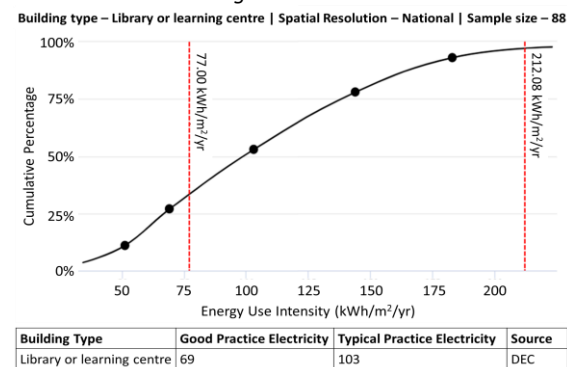
In another perspective of how the case study building performs, CIBSE Benchmarking Tool is used to locate where the building stands within the more updated typical building stock. Figure 4 shows that energy used in the operational stage (212.08 kWh/m^2) is at the higher end of the 88 building samples in the tool, while for the design stage (77.00 kWh/m^2), its energy consumption still does not comply with the good practice benchmark (69

kWh/m^2). The current building sample shows that the case study building's performance is still inferior to its peers, most likely because the comparison is not with identical operational conditions. However, this tool is currently in development; thus, data comparisons to other building typologies, such as offices, are not available yet.

Figure 5:

Bottom-Up Benchmarks for Design (TM54) and Operational Stage (kWh/m^2)
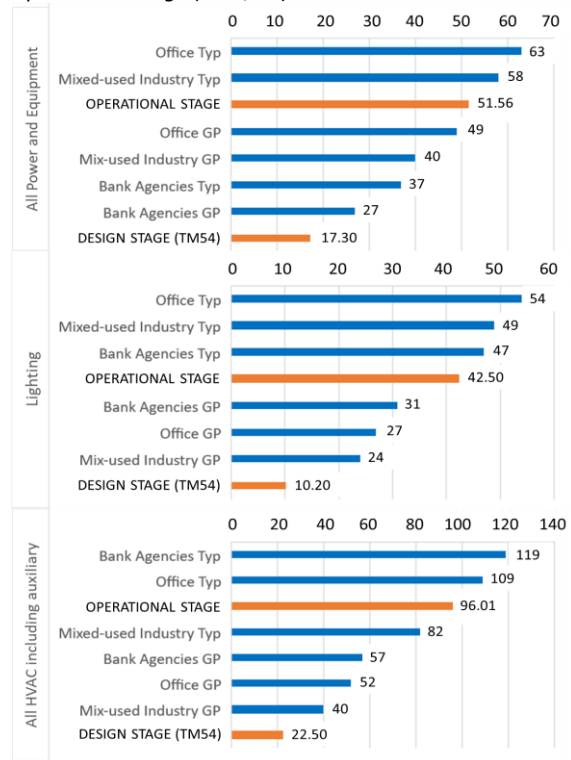
For bottom-up benchmarks, no building category from existing benchmarking schemes fits the functionality of the case study building. Thus, a few combinations of building categories are presented for comparison as an approach in identifying the closest category that might fit the case study building, then the energy end-uses in the design and operational stage are compared to the selected benchmarks. After considering the building's functionality from the building typologies available in Guide F, three categories with good practice (GP) and typical (Typ) benchmarks were selected, namely, office (standard and air-conditioned type), banks and agencies (agency with all-electric with cooling type), and mixed-use and industrial building (standard and air-conditioned office type).

Since the data collection of the case study building has a low granularity, the benchmarks are simplified into three categories for comparison; all power and equipment, lighting, and all HVAC system, including the auxiliary. Figure 5 compares

Figure 4:

Energy Consumption of Design and Operational Stage in the CIBSE Benchmarking Tool

Building Type	Good Practice Electricity	Typical Practice Electricity	Source
Library or learning centre	69	103	DEC

three end-use benchmarks for design and operational stages. It shows that the design stage's end-uses are too low compared to all selected benchmarks (roughly half of the closest benchmark value). Whereas for the operational stage, when viewed more extensively and comprehensively, the figures show that all of the case study building's end-uses fall within the office's benchmark range for good practice and typical. However, a broader range of building classification is required to get a more accurate building performance objective. Furthermore, to optimally perform bottom-up benchmarking, new data collection/protocols with a certain level of submetering are required to facilitate more accurate evaluation.

5. RESULTS AND ANALYSIS OF MODELLING SCENARIOS

5.1 Scenario 1: Actual Operational Hours on Design Stage

**Table 2:**
Changes in Parameter for Each Scenario

Parameter Used or Changes in Parameter	Base Model	Scenario 1		Scenario 2	
		1.1	1.2	2.1	2.2
TM54 mid-range value for all input data (incl. operating hours and utilisation)	v				
TM54 mid-range input data but with real operating hours as conditions (no DCV)		v	v		
TM54 mid-range input data but with 100% building utilisation			v		
TM54 mid-range input data except for HVAC (low-end) with real operating hours as conditions (no DCV) and 100% utilisation				v	
Better value for HVAC parameter and power density than scenario 2.1					v

As seen in Table 2, Scenario 1, two simulations were performed; Scenario 1.1 modifies the calibrated model (with TM54 mid-range input data) with real operating hours as conditions, whereas Scenario 1.2 applies both actual operational hours and 100% building utilisation. As seen in Figure 6, the overall building's energy used increases 2.15 times compared to the design stage after applying the twenty-four-hour operation and without the mixed-mode ventilation in use (Scenario 1.1). This rises to 2.73 times over the design stage estimate after 100% of equipment utilisation is applied (Scenario 1.2). Scenario 1.2 result comes out comparable to the operational stage performance except for the lighting that only consumes 66.13% of the actual measurement energy. It is most likely caused by the actual lighting density when the building operated is higher than the input data for the 100% utilisation scenario.

Scenario 1 asserts that high energy consumption does not always indicate inefficient operation; increased operational hours also play a significant role. Moreover, through operational modelling, inefficient building components can be identified and improved.

Figure 6:
Scenario 1 Energy Consumption Comparison with Design (TM54) and Operational Stage
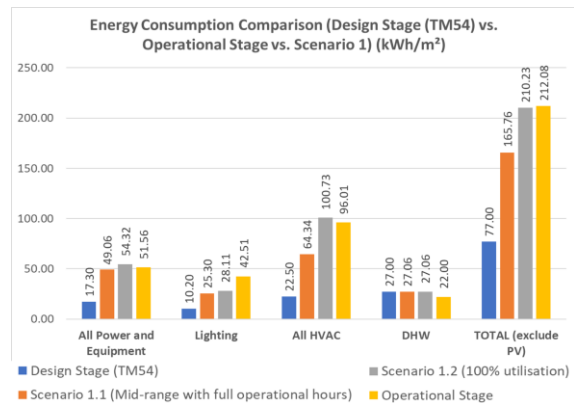

5.2 Scenario 2: Achieving Net Zero Operational Target

The energy consumption target used is the LETI target for commercial offices (55 kWh/m^2/year). LETI targets are limited to various archetypes not directly linked to the case study use. However, according to the benchmarking evaluation on the case study and its twenty-four operational hours, the case study building is more equivalent to an office than a university facility. Compared to the LETI target, the actual energy use of the case study building is 3.85 times higher. However, the LETI target, which considers NABERS modelling guidance (LETI, 2020), still only represents standard office hours. To make the target more contextual with actual conditions of the case study building, an increase of electricity consumption by 107% for office maximum hours (8760 hours/year) based on CIBSE TM46 is applied to the LETI target, which takes the target to 113.85 kWh/m^2/year.

Figure 7:
Energy Consumption Comparison of Scenario 1.2, 2.1, and 2.2
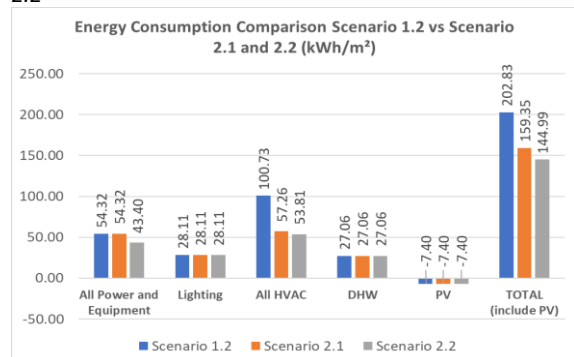
Two simulations were undertaken for Scenario 2 (Table 2). The first one (Scenario 2.1) is modifying Scenario 1.2 (which uses TM54 mid-range input data) to use the TM54 low-end input data for the

HVAC input parameter. The second simulation (Scenario 2.2) is adjusting the Scenario 2.1 model, with better value for HVAC parameters; higher heating COP, higher cooling setpoint, and using low-end scenario for power and equipment density by reducing on-site server and IT loads.

Figure 7 shows a gradual energy consumption towards the final simulation. Applying low-end building specifications for HVAC (Scenario 2.1) decrease 21.4% of energy consumption due to the energy used by the HVAC being reduced by roughly half. Meanwhile, compared to Scenario 2.1, Scenario 2.2 achieves a 9% decrease in energy consumption through a 6% reduction in HVAC and a 20% reduction in power and equipment energy consumption.

Table 3:
Energy Used of Scenario 2 Results Compared to Net Zero Operational Carbon Target

Target Benchmark / Scenario	Energy Used (kWh/m²)	Remaining Energy to Reach Target (kWh/m²)
LETI Commercial Offices	55.00	-
Increase of 107% LETI target	113.85	-
Scenario 1.2	202.83	88.98
Scenario 2.1	159.35	45.50
Scenario 2.2	144.99	31.14

Based on the results of the Scenario 2.1 simulation, it was determined that optimising the HVAC system is the first approach to decrease building energy consumption without changing the physical or functional configuration of the building. While this is a decent start, it can only cover 48.86% of the remaining energy to be reduced to achieve the LETI customised target (Table 3). After the calibrated model applies the actual building conditions and a scenario of improving the quality of the HVAC system and decreasing the IT loads is simulated, there is still 35% (31.14 kWh/m^2) of remaining energy that needs to be covered to achieve the target. Applying DCV System and improving renewable energy sources can increase more energy saving. Finally, the remaining energy should be offset using a recognised offsetting framework.

6. CONCLUSION

The significance of operating hours in defining the design target is indicated by the spike in building energy consumption, which climbed to 2.15 times the design intention when operating hours were raised from ten to twenty-four hours per day. It also affects the benchmarks' evaluation, as evidenced by the top-down assessment, which indicates that while the case study's performance at the design stage is comparable to that of a similar building typology, i.e., educational buildings, the closest comparable benchmarks at the operational stage are the energy consumption of typical offices

from CIBSE Guide F and CIBSE TM46, which took twenty-four operational scenarios into account (Fig. 3).

In conclusion, it is important to analyse the building's performance during the design and operational stages to determine the net-zero carbon target. It's difficult to maintain a compromise between net zero objectives and a building's optimal space-time use. According to the evaluation of existing benchmarks, the current benchmarks lack a broader range of allowed maximum hours for each building typology. LETI's target should include a time normalisation factor as a buffer against substantial changes that may occur during the operational stage.

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