Proceedings of 12th Masters Conference: People and Buildings
University of Westminster, 15th September 2023
Network for Comfort & Energy Use in Buildings: https://www.nceub.org.uk

Whole-Building Calibrated Energy Performance Simulation towards Energy Sufficiency and Net Zero Carbon. Case Study of a Medium-Sized Hotel

Shinku Benedict Tertsea[1,*], Antoine Regnier[2], Carola Koenig[1] and Zahir Dehouche[1]

[1] College of Engineering, Design and Physical Sciences, Brunel University London, UK.
[2] Intelligent Communities Lifecyle (ICL), IES Limited, Glasgow UK.
[*] benedict.shinku@brunel.ac.uk;

Abstract: The Performance Gap between design/rating and operational energy consumption of buildings results from prescriptive approaches for estimation of energy consumption using regulated loads, simplified steady-state models and assumption of Notional/Reference Buildings. The increasingly stringent requirements on energy efficiency/sufficiency and emissions in schemes such as the Future Homes Standard and NABERS-UK for offices, aimed at achieving Net Zero UK building stock, necessitates performance-based approaches that include unregulated loads and post-occupancy energy epidemiology in benchmarking the energy performance of different building typologies. This paper contributes to benchmarking the energy performance of hotels using an existing medium-sized hotel in London UK, as Case Study (CS). A whole-building dynamic thermal model of the CS was done in IESVE software and calibrated with actual occupancy, energy consumption and envelope construction/thermal data. Simulation of the model with contemporary Meteonorm weather file gave total electricity and natural gas consumption of 144.58MWh and 158.59MWh respectively, while $\mathbf{CO_2}$ emission was 53.17t $\mathbf{CO_2e}$. IPMVP verification of the hourly-simulated and measured electricity consumption showed NMBE (-5.04%) and CvRMSE (8.9%). The $\mathbf{CO_2}$ Factors were 0.19kg.$\mathbf{CO_2}$/kWh for (electricity) and 0.20kg.$\mathbf{CO_2}$/kWh (heat), both values corresponding to the reported UK $\mathbf{CO_2}$ Factors of 0.19kg.$\mathbf{CO_2}$ /kWh (electricity) and 0.20kg $\mathbf{CO_2}$/kWh @NCV (natural gas) for 2022.

Keywords: building energy model, net zero hotel, building simulation calibration, building decarbonization, Performance gap .

1. Introduction

Buildings account for approximately 30% (135 EJ) of global energy consumption and about 27% (10 $GtCO_2$) of operational-related CO_2 emissions (UNEP-GlobalABC, 2022). In the UK, a recent study showed that 23% of direct and indirect emissions and 59% of electricity consumption (emitting 31 Mt CO_2), was due to buildings (UK CCC, 2020). The global urgency to mitigate global warming, the negative impact of climate change and reach Net Zero in 2050 necessitated a reduction in emission of anthropogenic greenhouse gas, mainly CO_2, from buildings. The mitigation framework given in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR6), recommended efficiency, consistency, renewables and energy sufficiency; a state in which basic needs for energy services are met equitably and with respect for ecological limits (Bierwirth & Thomas, 2019). Given the diversity of building typologies, location characteristics, regulatory contexts, uses, occupancy and operational profiles, Building Energy Performance Modelling (BEPM) uses physics-based computer software tools to analyse loads, system sizes, energy consumption and emissions of buildings at design and/or use stage for verification of compliance with codes and regulations, optimize building performance or achieve sustainability rating (IESVE-BPM, 2023). BEPM, done for compliance with regulations and sustainability rating requirements compares the energy performance of the building, to that of the notional design or reference model of the actual building. This prescriptive approach has the advantage of simplicity and flexibility but fails to achieve energy-efficiency synergies and trade-offs among building energy end-uses. In contrast, BEPM using a performance approach requires buildings to meet defined performance benchmarks. The application of BEPM for optimisation is underscored by the review of (Pan et al., 2023) which reported that 23% of studies from 2011 till date optimised operational performance of several variables to achieve desired objective functions such as reducing energy costs and emissions. The same source stated that performance gap is reduced by calibration; an iterative process of fitting the design or operational parameters of the virtual model to those of the notional or actual building. In this paper, some of the recent work on calibrated building energy models and the performance gap are reviewed. A Case Study Building (CSB) and actual hourly power consumption measurements are used to demonstrate the modelling, simulation and calibration processes after the calibrated BEPM is verified with IPMVP protocol based on ASHRAE-14: 2014 criteria.

1.1 Previous Work and Research Problem

All buildings constructed to meet a prescribed energy standard or code are at risk of a performance gap; the difference between the predicted thermal and energy performance derived from computer simulations at design stage, and the actual measured building fabric and energy use during the use phase, sometimes up to 250% (Mitchell & Natarajan, 2020) and the causes of the Performance Gap at the operational phase of buildings are detailed in (Kerrigan et al., 2020) to include differences between design and actual occupancy patterns and occupant energy behaviour, unregulated loads. Among the 3 types of Energy Performance Gaps identified by (De Wilde, 2014), Type-1 (mismatch between thermal models and actual measurements) and Type-2 (mismatch between energy ratings provided by compliance test methods and energy display certificates as enshrined in regulation) are dominant sources of the energy performance gap. The same source reported that the magnitude of the performance gap is dependent on time, contextual factors like climate and building use, as well as the temporal resolution at which the performance gap is studied, building typology and recommended rigorous calibration of building thermal models as one solution to closing the gap. Calibration is the process of modifying or fine-tuning the inputs to a BEP model to correct the output so that it closely matches the actual performance and requires two data sets; the simulation data which is often based on the design values and assumptions made for building operation, and the metered data from the monitoring of the real building (CIBSE TM63, 2020). Recent work on reducing the performance gap in the UK building stock used calibrated models of offices, schools, hospitals and apartment blocks (Jain, 2021). In spite of the forecast increase of hotel rooms from 18 - 25 million between 2023 - 2046 (Sustainable Hospitality Alliance, 2017) and that they are reported to account for about 2% (363 MT of CO_2e) of global emissions (Compton, 2022), there is paucity of publications on calibrated energy models of hotel buildings. This paper attempts to address this research problem using whole-building calibrated simulation of a medium-sized hotel.

1.2 Contribution, Limitations and Impact of Research

The paper contributes an approach to benchmarking the energy use and emissions of buildings which can be applied to the UK Future Homes Standard, expected in 2025. The methodology also finds application in the effort to extend the NABERS-UK rating system to other building typologies, apart from offices. To improve the validity of building thermal models and the quality of benchmark values and reduce the energy performance gap and calibration effort, actual in-situ measurements of U-values of envelope elements in the building thermal models should be done. The measurements could be used to characterise construction, typology, use pattern and environmental conditions of buildings to enrich the database of benchmark compliance values for energy performance and emissions.

1.3 Aim and Objectives

This paper aims to standardise the development, simulation, calibration and validation of building thermal models suitable for decarbonization and Net Zero Carbon planning. The aim is achieved through the following objectives: collation of input parameters, creation of geometrical model, creation and assignment of construction and thermal properties, customisation of location, meteorological and simulation data, and simulation, verification and validation of the model.

2. Methodology

A case study semi-empirical quantitative approach was adopted for the study. Primary construction and operational data were obtained from the architectural design, equipment and material datasheets, and the Building Management System (BMS). The secondary data was obtained from applicable CIBSE and ASHRAE standards, energy audit and interviews with the utility and operations managers. Notional values were used in instances where data could not be obtained from aforementioned sources. The detailed methods are explained in section 2.1 – 2.5.

2.1 Description of Case Study Building

The CSB is a medium-sized hotel, constructed between 2005 – 2008 with 70 ensuite bedrooms has a Net Internal Area (NIA) of about 2636 m^2 and is located on a university campus in London. The North-end and South-end have Four (4) and Five (5) floors, respectively, ground floor inclusive. The CSB is connected to the public electricity, gas, water and sewer network and has a mechanically-ventilated spa pool, steam room and sauna on the ground floor which also has a kitchen, bar, restaurant and laundry. There is no central cooling system. Heating to conditioned spaces is provided through a hydronic system comprising natural gas boilers ($4 \times 100\%$), hot water supply and return piping, and radiators. The CSB has a Domestic Hot Water (DHW) system with 1500-litre storage capacity.

2.2 Site Location and Hourly Annual Weather Data

The IESVE®-ApLocate™ module is used for input and/or editing of site and weather data for simulation in the IESVE®-ApacheSim™ module and the Guidelines are given in (ApLocate, 2014). Table 2.1 contains a summary of site location and weather data settings used.

Table 2.1: Summary of ApLocate Site Location and Weather Data Settings

Variable(s)	Parameter(s)
Location Site and Data	London Heathrow; Lat. 51.53N, Long.0.47W; 33m above mean sea level; orientation is 21^o East of North; 0 hours ahead of GMT; 1-hour DST adjustment from April to October; Summer and Winter Ground Reflectance=0.2, Suburbs Terrain Type (CIBSE Guide A, 2021), External CO_2 concentration =420ppm, Normal Wind Exposure, Reference Air Density = 1200 kg/m^3.
Design Weather Data	Default system values for the location were used in the simulation.
Simulation Weather Data	IESVE® reads 2 file formats ***.fwt**, IES™ proprietary file type and ***.epw**, the US-DOE file format.

Simulation Calendar	The simulation calendar is set to 2022 without holidays because the CS is a hotel. The 2022 hourly measurements of actual energy consumption for the CS was also used for model calibration.

2.3 Thermal Model and Input Data for Construction and Thermal Templates

The thermal model was developed from geometrical parameters, materials, equipment and operational data of the CSB using ModelIT™, ApLocate™ and Apache™ modules in IESVE®. The model had 260 spaces grouped according to storeys and activity functions, 72 construction, and 19 thermal templates. A pictorial view of the IESVE® model is shown in Figure 2.1. The structure right side of the model is an adjoining building, considered a topographical shade in the model. The end of the building to the left of the page is the North-end.

Figure 2.1: Geometrical Model in IESVE®-Model Viewer™

An outline of the procedure for, applying assumptions on parameters, prioritising calibration data and the use of IESVE_iSCAN® module to create profiles for use in the model is given in (IES, 2020; CIBSE TM63, 2020).

Table 2.2: Summary of Input Parameters for Creation of Construction and Thermal Templates

Description	Input Data Sources
Construction Templates: Roof (2), Internal Ceiling/Floor (2), External Walls (60), Internal Partition (2), Ground/ Exposed Floor (2), External Window (1) and Doors (3)	**Fixed Parameters:** Site Plan drawings (incl. adjacent buildings and nearby objects), Building Geometry Drawings (DXF Format): Site Plan Drawings, Floor Plan Drawings, Floor and Occupancy Layouts, Elevation Drawings, Section Drawings, Construction details (U-values, Thermal Inertia), Equipment Layout Schematics, Equipment Schedule and Specifications, Airtightness and Infiltration, Lighting Layout, Plug Loads, Electricity and Natural Gas Emission Factors for UK. **Dynamic Parameters:** Room setpoints, Internal Gains, HVAC Control Strategies, Lighting Operations Schedules, System Operation Schedules, Occupancy Profiles, AMY Weather Data for Site Location.
Thermal Templates: System, Space Conditions, Internal Gains, Air Exchanges and Comfort Parameters for respective space functions.	

2.4 Profiles of Active Systems and Services

In IESVE®, Profiles are used to describe the time variation of thermal input parameters that are relevant to the operation of the building such as operating schedule of plant equipment, modulation of casual gains and ventilation rates, specifying the timing and degree of window opening and defining time-varying set-points and supply temperatures. A detailed description of profiles is available in the “Help Menu” of the IESVE® software. Daily, Weekly, Absolute and Free Form Profiles were assigned in the model according to the schedule information obtained from the energy audit, specified operating schedules, interview with the managers, and relevant standards.

2.5 Verification and Validation of Thermal Model

Model verification ensures that under the given relationship between input and output, the simulation gives the expected outcomes while validation is the use of calibration criteria to test that the model is as representative of the real building as possible. To verify the model, the total electrical energy, thermal energy and the respective CO_2 emissions were used to compute the CO_2 Emission Factors for electricity and heat (see Table 3.1). Furthermore, the actual measurements and simulated values of electric power consumption were plotted as shown of power consumption and to verify the model. Validation of the model was done using the ASHRAE-14: 2014 criteria stated in.

2.5.1 Calibration Test Criteria

The calculation of calibration test criteria was done using the formulae outlined in Equation 2.1 - 2.3. The acceptance or rejection criteria for hourly calibration of electricity consumption was checked against the values in Table 2.3.

$$Normalized\ Mean\ Bias\ Error, NMBE = \frac{1}{\bar{m}} \times \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} \times 100(\%) \qquad 2.1$$

$$Root\ Mean\ Square\ Error, RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \qquad 2.2$$

$$Coefficient\ of\ Variation\ of\ the\ Root\ Mean\ Square\ Error, C_vRMSE$$

$$= \frac{1}{m} \times \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \times 100\ (\%) \qquad 2.3$$

where

n the number of data points equal to the number of hours in a year (8760 hours)

$\bar{m}$ the Arithmetic Mean of measured power consumption

m_i the measured value of power consumption at each datapoint (hourly)

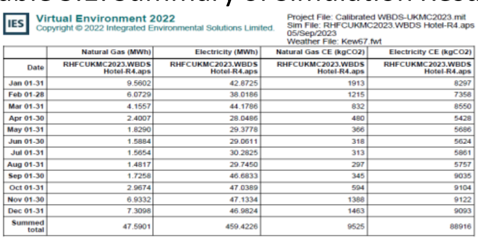
s_i the simulated values for each datapoint as output in IESVE®-Apache™ simulation

Table 2.3: Calibration criteria for energy defined in ASHRAE Guideline 14: 2014

Index	Error Range
NMBE	± 10%
C_vRMSE	30%

3. Results

The summary of electricity and natural gas consumption, and the corresponding emissions is presented in Figure 3.1. The comparison of actual and simulated results of electricity consumption is given in Figure 3.2. The calibration criteria are calculated and presented in Table 3.1: Summary of Simulation Results and Calibration of Electricity ConsumptionTable 3.1.


IES Virtual Environment 2022
Copyright © 2022 Integrated Environmental Solutions Limited.
Project File: Calibrated WBDS-UKMC2023.mit
Sim File: RHFCUKMC2023.WBDS Hotel-R4.aps
05/Sep/2023
Weather File: Kew67.fwt

	Natural Gas (MWh)	Electricity (MWh)	Natural Gas CE (kgCO2)	Electricity CE (kgCO2)
Date	RHFCUKMC2023.WBDS Hotel-R4.aps	RHFCUKMC2023.WBDS Hotel-R4.aps	RHFCUKMC2023.WBDS Hotel-R4.aps	RHFCUKMC2023.WBDS Hotel-R4.aps
Jan 01-31	9.5602	42.8725	1913	8297
Feb 01-28	6.0729	38.0186	1215	7358
Mar 01-31	4.1557	44.1786	832	8550
Apr 01-30	2.4007	28.0486	480	5428
May 01-31	1.8290	29.3778	366	5686
Jun 01-30	1.5884	29.0611	318	5624
Jul 01-31	1.5654	30.2825	313	5861
Aug 01-31	1.4817	29.7450	297	5757
Sep 01-30	1.7258	46.6833	345	9035
Oct 01-31	2.9674	47.0389	594	9104
Nov 01-30	6.9332	47.1334	1388	9122
Dec 01-31	7.3098	46.9824	1463	9093
Summed total	47.5901	459.4226	9525	88916

Figure 3.1: Monthly Summary of Simulation

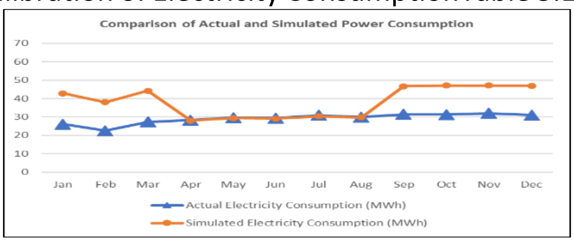


Figure 3.2: Actual vs. simulated Power consumption

Table 3.1: Summary of Simulation Results and Calibration of Electricity Consumption

Quantity	Annual Consumption (MWh)	Annual CO_2 Emissions $(kg.CO_2)$	NMBE	C_vRMSE	CO_2 Emission Factors $(kg.CO_2/kWh)$

Electricity	465.94	90177	-5.04%	8.9%	0.193
Natural Gas	46.76	9358	-	-	0.2

4. Discussion and Conclusion

The NMBE and $C_v RMSE$ of the model calibrated with actual hourly values of electricity consumption is within the respective acceptance ranges. The calculated CO_2 Emission Factors for electricity and natural gas consumption of the model also correspond to the values reported for the UK for 2022 (BEIS & DEFRA, 2022). The simulated electricity consumption shows agreement with actual measurements between the months of April and August. Additional data on the occupancy profile and operational schedule of the building is required to improve the model calibration between September and March. The approach used in this work will produce accurate results for buildings of other use classes.

5. References

ApLocate. (2014). *APlocate: Location and Weather User Guide*.

BEIS, & DEFRA. (2022). *Electricity GHG Emission Factors: Condensed Set*.

Bierwirth, A., & Thomas, S. (2019). *Energy Sufficiency in Buildings*.

CIBSE Guide A. (2021). *CIBSE Guide A. Environmental Design* (K. Butcher & B. Craig, Eds.; 8th ed.). Chartered Institution of Building Services Engineers. https://doi.org/10.4324/9780203118283-89

CIBSE TM63. (2020). *Operational Performance: Building Performance Modelling and Calibration for Evaluation of Energy in-use* (D. Mumovic, E. Burman, D. Naldzhiev, & K. Butcher, Eds.). The Chartered Institution of Building Services Engineers.

Compton, N. B. (2022, June 29). *What does it mean for a hotel to be Carbon Neutral?. A Guide to a New Wave of 'Green' Hotels*. The Washington Post. https://www.washingtonpost.com/travel/2022/06/29/carbon-neutral-hotels-green/

De Wilde, P. (2014). The Gap between Predicted and Measured Energy Performance of Buildings: A Framework for Investigation. *Automation in Construction*, *41*, 40–49. https://doi.org/10.1016/j.autcon.2014.02.009

IESVE. (2020). *IES Best Practice Calibration Workflow*.

IESVE-BPM. (2023). *Building Performance Modeling. Student Handbook. Supporting Architects, Engineers and Designers of the Future*. Integrated Environmental Solutions Limited. https://www.iesve.com/corporate/guides/bpm-student-handbook-2023v01.pdf

Jain, N. (2021). *Reducing the Performance Gap using Calibrated Simulation Models* [PhD, University College London]. https://discovery.ucl.ac.uk/id/eprint/10119634/

Kerrigan, R., Pyburn, I., Guerra Cabrera, A., Saini, N., Shiel, P., & West, R. (2020). Minimizing the performance gap of A-Rated Buildings while supporting high levels of user comfort. *ESim 2020: 11th Conference of IBPSA*.

Mitchell, R., & Natarajan, S. (2020). UK Passivhaus and the energy performance gap. *Energy and Buildings*, *224*. https://doi.org/10.1016/j.enbuild.2020.110240

Pan, Y., Zhu, M., Lv, Y., Yang, Y., Liang, Y., Yin, R., Yang, Y., Jia, X., Wang, X., Zeng, F., Huang, S., Hou, D., Xu, L., Yin, R., & Yuan, X. (2023). Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies. In *Advances in Applied Energy* (Vol. 10). Elsevier Ltd. https://doi.org/10.1016/j.adapen.2023.100135

Sustainable Hospitality Alliance. (2017). *Global Hotel Decarbonisation Report*.

UK CCC. (2020). *The Sixth Carbon Budget: Buildings*. www.theccc.org.uk

UNEP-GlobalABC. (2022). *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. United Nations Environment Programme. https://globalabc.org