

**Microgrid techno-economic
optimisation for benchmarking
operational net-zero metrics in a
hotel typology**

**A Thesis Submitted for the
Degree of Doctor of Philosophy**

By

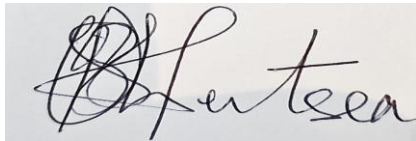
Shinku Benedict Tertsea

**Department of Mechanical and
Aerospace Engineering, Brunel
University London**

2026

DECLARATION

I, Shinku Benedict Tertsea, hereby affirm that the material contained within this thesis has not been previously submitted for any other academic award and is in compliance with the University's guidelines and regulations for research. Additionally, I certify that all the work presented in this thesis is my own original work and that any assistance received in conducting the research and composing the thesis has been appropriately acknowledged and cited.



9th June 2026

SHINKU Benedict Tertsea (PGR 1534318)

Date

ABSTRACT

Hotels account for about 1.5% of global energy-related emissions and an estimated 0.6% of UK energy demand in the operational phase. Hence, they have significant potential to contribute to sustainability and Net Zero through reduction in energy and carbon intensity. In the UK, the ongoing reform of the Energy Certificate System to include headline metrics suitable for monitoring energy efficiency, and the introduction of the UK Net Zero Carbon Buildings Standard (UKNZCBS) are beneficial initiatives for the achievement of net zero in hotels. This work applied a quantitative case study research design framed on a three-pronged methodology to evaluate feasibility of operational net zero for a mid-range (3-star) non-resort hotel located in London, UK over a 28-year lifetime. A baseline dynamic simulation model of the hotel (with 2022 as base year) was developed in IESVE™ and calibrated against the measured power consumption, using ASHRAE-14 Guidelines. The calibration confirmed the model within the verification acceptance range (NMBE= 4.75%, CvRMSE = 12.6%). Additional models were developed from the calibrated model by application of 30 energy efficiency measures and future weather files under SSP2-4.5 scenarios. Evaluation of the energy and carbon performance of the models between the baseline year and 2050 showed that climate change resulted in a 15% and 230% reduction in EUI and emissions, respectively. The highest reduction in EUI (40%) over the corresponding period occurred from reduction of envelope U-values to conform with the “2025 UK Future Buildings Standard” (UKFBS), lighting retrofit from fluorescent to LED, and application of Adaptive Ventilation (AV) strategy, translated to 236% emissions reduction. The second part of the methodology entailed creation of a solar-PV generation model in HelioScope™ and in the third part, electrical and thermal loads from IESVE™ and the solar-PV generation HelioScope™ were coupled to a microgrid model in HOMER Pro™, with random day-to-day and timestep variability of 10% and 20%, respectively. The variabilities accounted for the sensitivities of the energy profile to uncertainties in weather, occupancy and operational schedule, service levels, and occupant energy behaviour. The microgrid model was simulated under existing and projected macroeconomic (medium GDP growth) conditions, reference energy and emissions forecasts, and sensitivity variables (expected inflation rate, grid carbon intensity and minimum renewable fraction).

The least cost microgrid yielded an IRR (6.2%), ROI (4.1%), discounted payback (12 years) and energy cost savings of £109,698. The benchmark values of operational net zero metrics calculated from the least-cost microgrid model were: EUI of 256 kWh/m² (EUI_{el} = 105 kWh/m², EUI_{th} = 406 kWh/ m²), CEI (87 CO₂/m²), ECI (29.48 £/m²). The solar-PV generation model for the case study gave: (40.1 kW capacity, 43.8 MWh annual production, 75.5% Performance Ratio, and 906 kWh/kWp specific yield). Comparison of the results to the limits and targets of operational net zero metrics in the UK Green Building Council (UKGBC) Paris Proof Methodology (PPM), UKNZCBS and Cornell Hotel Sustainability Benchmark Index (CHSBI) for fifty 3-star non-resort hotels located in London, UK. The computed EUI, CEI and ECI values were significantly-above the CHSBI benchmarks due to disproportionate thermal and electrical energy demand. The retrofit pathway with the highest EUI reduction did not lead to operational net zero in 2050 under the UKGBC-PPM, nor the UKNZCBS frameworks. In addition, the target 40 kWh/m² of Gross Internal Area (GIA) for onsite renewable energy generation specified in the UKNZCBS was not met. Unlike the hotel-specific room-night normalised energy, carbon, and cost metrics such as kWh/room-night, kgCO₂e/room-night and RevPAR (Revenue per Available Room, the metrics in this study were floor-area normalised to align with the UK Building Regulations thereby easing regulatory oversight of hotel energy efficiency and decarbonisation. The methodology of this work is a novel contribution to the planning of energy efficiency and net zero projects, applicable to any building typology and the benchmark values of EUI, CEI and ECI are a useful addition to the body of evidence for operationalisation of the UKNZCBS. Regardless, the generalisability of the results is limited by the purposive sampling technique adopted to select the case study, and the application of deterministic safety margins to electrical and thermal loads in the microgrid model to account for uncertainties in weather, occupancy, and operational schedules. Hence, statistical sampling and detailed sensitivity and uncertainty analysis should be incorporated in future research to enhance the application of the results to energy efficiency and decarbonisation policy and project planning.

PUBLICATIONS ASSOCIATED WITH THIS RESEARCH

1. Shinku, B.T., Regnier, A., Koenig, C. and Dehouche, Z. (2023) 'Whole-building Calibrated Energy Performance Simulation towards Energy Sufficiency and Net Zero Carbon. Case Study of a Medium-sized Hotel', 12th Masters Conference: People and Buildings, University of Westminster, London, United Kingdom, 15 September 2023, <http://dx.doi.org/10.5258/SOTON/P1144>.
2. Shinku, B.T., Regnier, A., Koenig, C. and Dehouche, Z (2024) 'Whole-Building Calibrated Energy Performance Simulation towards Energy Sufficiency, Climate Resilience and Net Zero Carbon: Case Study of a Medium-Sized Hotel', Winter Conference and AHR Expo, Chicago, USA, 20 – 24 January 2024. ASHRAE Transactions, 130, pp.484-492.
3. Shinku, B.T. (2025) Net Zero Carbon Methodology and Benchmark Metrics for a Commercial Typology', CIBSE IBPSA-England Technical Symposium: Fit for 2050-Achieving Net Zero through Intelligent, Resilient, and Sustainable Design in the Built Environment, University College London, United Kingdom, 24 -25 April 2025. Available at: [2025 Technical Symposium Papers](#)

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LIST OF ABBREVIATIONS AND ACRONYMS

ach	Air changes per hour
AHCC	Alamdari and Hammond Convection Coefficients
APS	Announced Pledges Scenario
AM	Air Mass
AR	IPCC Assessment Report
BAPV	Building Applied Photovoltaics
BAU	Business - As -Usual
BER	Building Emissions Rate
BEST	Building Energy Simulation Tool
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaics
BREEAM	Building Research Establishment Environmental Assessment Method
BRUKL2	UK Building Regulations, Part L2
CEI	Carbon Emissions Intensity
CFC	Chlorofluorocarbon
CHSBI	Cornell Hotel Sustainability Benchmark Index
CI	Carbon Intensity
CIBSE	Chartered Institution of Building Services Engineers
COP-1	The first Conference of the Parties
CS	Case Study
CSP	Concentrated Solar Power
C _v RMSE	Coefficient of Variation of the Root Mean Square Error
DEC	Display Energy Certificate
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
DXF	Drawing Exchange Format or Drawing Interchangeable Format is a type of Computer Aided Design (CAD) file that enables interchange of data and designs across CAD applications.
DG	Distributed Generation
ECI	Energy Cost Intensity
EEM	Energy Efficiency Measure

EER	Energy Efficiency Rating
EPC	Energy Performance Certificate
ESI	Extraterrestrial Solar Irradiance
ETS	Emissions Trading System
EU	European Union
EUI	Energy Use Intensity
EUI _{el}	Electrical Energy use Intensity
EUI _{th}	Thermal Energy Use Intensity
FFP	Free Form Profile
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GIA	Gross Internal Area
GLA	Greater London Authority
HEI	Higher Education Institution
HEM	Home Energy Model
HFC	Hydrofluorocarbon
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Energy
LCEA	Lifecycle Environmental Assessment
LEED	Leadership in Energy and Environmental Design
LHA	Local Hour Angle
LMS	Least-cost Mitigation Scenario
MRT	Mean radiant Temperature
M&V	Measurement and Verification
NDC	Nationally Determined Contribution
ND-NEED	Non-domestic National Energy Efficiency Database
NIA	Net Internal Area

NMBE	Normalised Mean Bias Error
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NZB	Net Zero Building
NZCB	Net Zero Carbon Building
NZE	Net Zero Energy
NZEB	Net Zero Energy Building
NZH	Net Zero Hotel
NZrB	Net Zero-ready Building
PEF	Primary Energy Factor
PEF _e	Primary Energy Factor for electricity
PEF _{gas}	Primary Energy Factor for natural gas
PFC	Perfluorocarbon
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
ppb	parts per billion
ppm	parts per million
POA	Plane of Array
PPM	Paris Proof Methodology
PPT	Paris Proof Target
PR	Performance Ratio
RE	Renewable Energy
RF	Radiative Forcing
RMSE	Root Mean Square Error
RPOA	Rear Plane of Array
SAP	Standard Assessment Procedure
SDG	Sustainable Development Goal
SDM	Solar Decomposition Model
SR	IPCC Special Report
STC	Standard Test Conditions
STM	Solar Transposition Model

SSP2-4.5	Shared Socioeconomic Pathway corresponding to a future world with moderate population growth, uneven economic development, and slow progress on sustainability goals with an associative radiative forcing of 4.5 W/m ² by 2011 relative to pre-industrial levels. It represents a future where emissions continue near current levels until 2050 then gradually decline without reaching net zero by 2100.
TER	Target Emissions Rate
TRL	Technology Readiness Level
TMY	Typical Meteorological Year
RdSAP	Reduced Standard Assessment Procedure
SHA	Sustainable Hospitality Alliance
STEPS	The IEA Stated Policies Scenario
TRL	Technology Readiness Level
UKFBS	United Kingdom Future Buildings Standard
UKGBC	United Kingdom Green Building Council
UK-MCS	United Kingdom Microgeneration Certification Scheme
UKNZCBS	United Kingdom Net Zero Carbon Buildings Standard
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US-DOE	United States Department of Energy
WCED	World Commission on Environment and Development
WEF	World Economic Forum
WGBC	World Green Building Council
WMO	World Meteorological Organisation
ZCr	Zero Carbon-ready

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SYMBOLS, VARIABLES AND TECHNICAL PARAMETERS

Symbol	Unit	Description
A_g	m^2	Total Gross Internal Area of the building
A_n	m^2	Total occupiable floor area of the building
A_u	m^2	Total floor area of building not designed to be occupied
α	$^\circ$	Solar altitude
β	$^\circ$	Tilt angle of the PV module
γ	rad	Day angle
$C_{cap, fixed}$	£	System Fixed Capital Cost
CDE	%	Cooling Delivery Efficiency
C_{cs}	£/kWh	Capacity Shortage Penalty
		Penalty for Emissions:
$C_{emissions}$	£	$\frac{C_{emissions}}{1000} = \frac{c_{CO_2} M_{CO_2} + c_{CO} M_{CO} + c_{UHC} M_{UHC} + c_{PM} M_{PM} + c_{SO_2} M_{SO_2} + c_{NO_x} M_{NO_x}}{1000}$
$C_{fuel, eff}$	£	Effective price of fuel
$C_{om, fixed}$	£/year	The system fixed O&M cost
$C_{om, other}$	£/yr	Other O&M cost; $C_{om, other} = C_{om, fixed} + C_{cs} + C_{emissions}$
c_p	J/kg.K	Specific heat capacity of air at constant pressure
ϵ_1, ϵ_2	-	Internal and External surface emissivity.
D_{hg}	h	Time difference (advance of 4 minutes per degree)
DT_l	h	Difference between local and standard time
E_0	-	Eccentricity correction factor
E_{cs}	kWh/yr	Total Capacity Shortage
E_{demand}	kWh/yr	Primary and deferrable load.
E_{unmet}	kWh/yr	Unmet electrical load
ϵ_1, ϵ_2	-	External and internal surface emissivity
F_{1-2}	-	Shape Factor; the fraction of radiation emitted from surface of area A_1 and A_2 and vice versa (F_{2-1})
F_o	-	Fourier Number

Symbol	Unit	Description
f_f	-	Furniture Factor
g	kg/kg	Humidity ratio of room air
g_i	kg/kg	Humidity ratio of supply air
H_e	hr	Hours of Exceedance
HDE	%	Heating Delivery Efficiency
HEFF	-	Heating Efficiency Factor
HRP	%	Heat Rejection Pump and Fan Power Fraction
h	$^\circ$	Sun elevation angle
h_c		Convective Heat Transfer Co-efficient
h_r		Radiative Heat Transfer Coefficient
θ_z	$^\circ$	Zenith angle
θ_i	$^\circ$	angle of incidence between the solar direction and the collector normal
σ	$W/m^2.K^4$	Stefan-Boltzmann constant ($5.6697 \times 10^{-8} W/m^2.K^4$)
I_b		Direct beam component of global solar radiation
I_{bN}		Normal solar beam radiation on horizontal surfaces
I_d		Diffuse component of global solar radiation
I_H		Hourly global solar radiation on a horizontal surface
I_0		Hourly Extraterrestrial Solar Irradiance
I_{sc}	W/m^2	Solar constant = $1367 W/m^2$
j	-	Day number of the year ranging from 1 on January 1 to 365 on 31 December
k	-	Clearness Index/Cloudiness Coefficient
$POAI_d$		Point of Array Irradiance due to direct radiation
$POAI_{u,sky}$		Point of Array Irradiance due to downwelling diffuse radiation
$POAI_{u,ground}$		Point of Array Irradiance due to solar radiation reflected from land surface
Q	W	Net heat flow into an air mass

Symbol	Unit	Description
Q_{conv}	W/m ²	Convective heat flux
Q_r	W	Net radiative heat loss from a surface
r_v		Vapour Resistivity
SCoP	%	Seasonal Coefficient of Performance
SSEER	%	System Seasonal Energy Efficiency Rating
λ	W/m ² .K	
λ	°	Longitude
$\dot{m}$	kg/s	Air mass flowrate
ρ_a	kg/m ³	Air density
ρ_{ref}	kg/m ³	Reference air density
R		Combined radiative/convective resistance of an air gap
$R_{\text{se}}, R_{\text{si}}$		External and internal surface resistance
SA_e, SA_i		External and internal Solar Absorptance/ Absorptivity
$S_1, S_2, S_3, \dots S_n$	m ²	Floor areas of separately-occupied spaces
S_e	hr	Sunshine duration
S_j	hr	Day length
S_t	m ²	Total floor area of occupied spaces
T_a	°C	Air Temperature
T_{comf}	°C	Comfort Temperature
T_i	°C	Supply temperature of the air
T_l	h	Local time
T_{max}	°C	Maximum acceptable temperature
T_n	°C	Temperature at the node
T_{MRT}	°C	Mean Radiant Temperature of a space
T_{op}	°C	Operative Temperature
T_{rm}	°C	Exponentially-weighted running mean of the daily mean outdoor air temperature.

Symbol	Unit	Description
T_s	$^{\circ}\text{C}$	Mean surface temperature
T_{sv}	-	True solar time
T_{upp}	$^{\circ}\text{C}$	Upper Limit Temperature
v	m/s	Wind speed
V	m^3	Volume of air
V_r	m^3	Room volume
w	kg/s	Water vapour gain
W	W/m^2	Total radiation emitted by a plane surface
W_e	-	Daily Weighted Exceedance
φ	$^{\circ}$	Latitude
ψ	$^{\circ}$	Solar Azimuth angle
ω°	$^{\circ}$	Hour angle

1.0 INTRODUCTION

The concerns over the increasing contribution of building-related anthropogenic emissions to global warming and climate change necessitated sustainable solutions to increase the resilience of buildings and the associated energy systems. In combination with microgrid technology, several case studies demonstrated that reduction in energy performance, increase in energy efficiency, integration of renewable energy resources and reduction in carbon emissions are achievable in a Net Zero Building. The Paris Agreement of 2015 stimulated interest in research on NZBs for new construction despite the substantial energy consumption and emissions from other existing commercial buildings such as hotels. Further to this, guidelines, standards, policies and regulations with prescriptive- and performance-based measures for deep renovation and retrofit of existing buildings to NZBs were defined by governments, multilateral institutions and professional bodies for global, regional and/or national application. In the UK, the traditional EPC system contains two headline metrics: EER and EIR. The former (rated as A – G), is a measure of cost of annual heating and fixed lighting energy costs per square metre per year, while the latter measures GHG emissions per square metre per year. EER and EIR are calculated for new and existing dwellings using energy demand assumptions in SAP and RdSAP, respectively, rather than actual measured values. In non-domestic buildings, EER and EIR are derived from BER using the SBEM by a full modelling using approved NCM tools. As a prescriptive compliance measure, SBEM uses the regulatory benchmark TER to verify compliance with Part L of the BRUKL which requires that $BER \leq TER$ for (non-domestic buildings). As part of the effort to operationalise NZBs as NZEB and NZCB, the traditional EPC is being reformed to 4 headline metrics: fabric performance (insulation, airtightness and U-values), heating system efficiency (heating efficiency and carbon intensity), smart readiness (smart controls, flexibility, battery/storage integration) and energy cost (£/year). The calculation of the new metrics will be based on the HEM, a half-hourly dynamic simulation of annual energy use, emissions and energy costs.

The following sections of this chapter provide context for the use of an existing 3-star UK hotel as case study for techno-economic optimisation of a microgrid to determine representative values of EUI, CEI and ECI metrics for commercial buildings. The principles underlying the development of these metrics- fabric quality, low-carbon

energy systems, renewable energy integration, digital readiness, and cost efficiency- and calculation of the indicative benchmarks, align closely with the new EPC metrics, widely-adopted NZH frameworks, the UKNZCBS, international certification systems (LEED, BREEAM, Passivhaus etc), and the Sustainable Hospitality Alliance and Partners' "Net Zero Methodology for Hotels".

1.1 BACKGROUND OF THE STUDY

Globally, operational and embodied energy in buildings have direct and indirect impacts on the environment and constitute about 30% (41 EJ) of final energy consumption (137 EJ), accounting for 27% (10 GtCO₂) of energy -related CO₂ emissions. Furthermore, the use of fossil fuels in building energy services contributes approximately 8% to worldwide CO₂ emissions while generation of electricity and heat for buildings accounts for 19% of worldwide emissions (UNEP-GlobalABC, 2022). Embodied emissions from the manufacture and transportation of materials for building construction contribute 6% to global carbon emissions (IEA, 2022). In spite of improvements in energy efficiency and adoption of renewable energy technologies, the IEA reported that overall energy demand and emissions from the building sector continued to grow at an annual average of 1% between 2015 – 2023 (IEA, IRENA and UNCCHC, 2023). The energy demand of the building sector and related emissions, are projected to increase up to 2050 due to rising human population, forecast to reach 9 billion (UNFPA, 2022), increasing urbanisation, with 68% of human population projected to inhabit urban areas in 2050 (UNCTAD, 2021), and growth in building floor area, expected to reach 493 billion m², from 218 billion m² in 2015 (UNEP-GlobalABC, 2022), of which at least 60% are already built and in use (Twinn, et al., 2019).

The IEA's "World Energy Outlook" for building energy consumption (IEA-WEO, 2024) and the Emissions Gap Report (Roe et al., 2024), present varied scenarios for building sector energy consumption and emissions energy and emissions from 2023 – 2050. The IEA-STEPS reflects sectoral and country assessments of energy, and industrial policies for planned manufacture of clean energy technologies to provide a benchmark for potential achievements (and limitations) of developments in energy and climate policy (IEA-GEC, 2024).

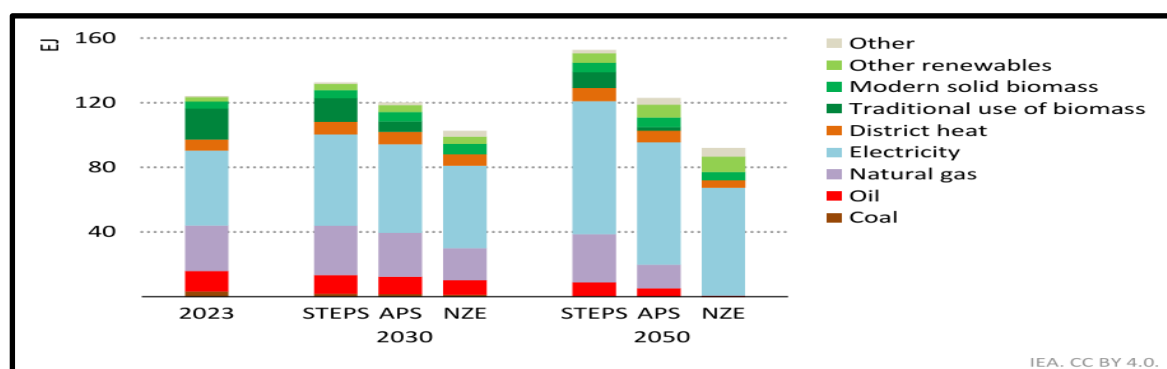


Figure 1.1: Energy Demand in Buildings by Fuel and Scenario: 2023-2050 (IEA-WEO, 2024)

In Figure 1.1, IEA-STEPS projects that building sector energy demand will decelerate to 0.7% between 2024 – 2050, from the annual average increase of 1% between 2015 – 2023, reaching 153 EJ in 2050, and forecasts a 2.4 °C temperature rise by 2100. However, the APS which assumes that all climate commitments made by governments and industries globally, including NDCs, will be met in full and on time, forecasts an average annual decrease of 0.5% from 2024, reaching 120 EJ in 2030 and is associated with a 1.7 °C temperature rise in 2100. The NZE scenario, which defines the pathway to NZ CO₂ for the global energy system by 2050, and projects a further decline of global energy consumption to 100 EJ by 2030 is based on a 1.5 °C target temperature rise by 2050 and seeks to meet the energy-related UN SDGs.

The difference between IEA-STEPS and IEA-APS is the “implementation gap” that needs to be closed for decarbonisation targets to be achieved while that between IEA-APS and IEA-NZE is the “ambition gap” that must be bridged for the goals of the Paris Agreement to be reached. The IEA-APS and IEA-NZE scenario are predicated on modern access to energy, technological advancements and quicker progress of new technologies to higher Technology Readiness Levels, underpinned by consistent levels of implementation of energy, climate and net zero policies. The varied outcomes between IEA-APS and IEA-NZE are because the former anticipates faster access to modern energy such as clean cooking technologies over traditional biomass. An aggregation of IEA-STEPS, IEA-APS, IEA-NZE and LMS to evaluate the NZ potential of end use energy sectors showed that building sector emissions have a mitigation potential of 3.2 Gt.CO₂ and 4.2 Gt.CO₂ in 2030 and 2035 respectively (Roe *et al.*, 2024) under NZE scenario (1.5°C temperature limit).

The ongoing global discourse on energy consumption, climate change and net zero policies is occasioned by available scientific evidence linking global warming and climate change to the accumulation of anthropogenic emissions in the troposphere, in excess of the natural GHG emissions (NSW.Gov.au., 2017), resulting in long-term shifts in meteorological parameters like temperature, horizontal irradiation, relative humidity and wind speed (Robert & Kummert, 2012). This concept of “Climate Change” poses interconnected adverse consequences and significant risks to health, economy and building energy performance (Bazazzadeh, et al., 2021; D’Agostino et al., 2022). These risks are manifested in the increased frequency and intensity of extreme weather events such as heatwaves, wildfires, floods, storms, warmer winters,

torrential precipitation and droughts (Carbon Brief, 2023), with the ten (10) warmest years since 1850; 2023 (1st), 2016 (2nd), 2020 (3rd) occurring within the last decade, and average global temperatures exceeding the pre-industrial (1850–1900) average by 1.35°C in 2023 (NOAA, 2024). Hence, net zero is construed as a mitigation measure, with its implementation building the resilience of buildings to climate change impacts.

“Net Zero” refers to the target of reducing to zero, the GHG emissions that cause global warming by balancing the amount released into the atmosphere with the amount removed and stored by carbon sinks and certified offsets (Kyriacou & Burke, 2023). The GHG emissions include CO₂, CH₄, N₂O, SF₆, CFCs, Halocarbons (chlorine- and bromine- containing substances), HFCs and PFCs.

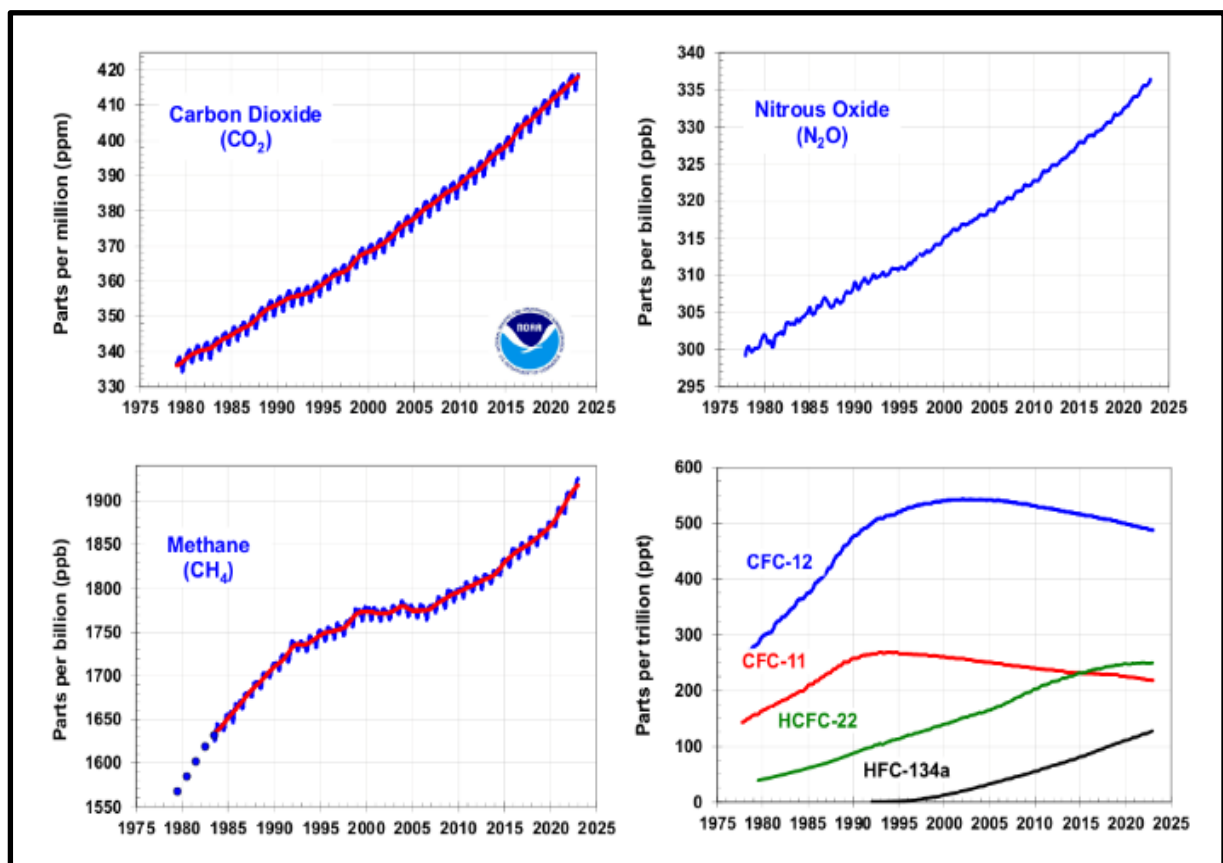


Figure 1.2: Trends in Global Atmospheric GHG Concentrations, 1980 – 2023. The chart in top-right (an extract of the Keeling Curve) shows that atmospheric CO₂ concentration increased from less than 340 ppm to about 420ppm in 2022 (Dlugokencky et al., 2023).

Measurements of atmospheric GHG concentrations from several remote sites around the world (Figure 1.2) show that CO₂, CH₄ and N₂O increased to 425 ppm, 1940 ppb and 338 ppb, respectively, between 1980 – 2024. The increase is attributable to the

longevity of CO₂ in the atmosphere (at least 100 years), coupled with being the GHG having the highest RF, and its natural abundance in the atmosphere, relative to the other GHGs, and the significant amounts released annually from anthropogenic, mainly energy-related, activities. In the built environment sector, “Net Zero” is intrinsic to Net Zero Energy and Net Zero Carbon buildings, and encompasses energy efficiency, emissions reduction and integration of renewable energy sources in the building energy system.

In this study, the framework for evaluating the NZB pathways is formed from the IEA-STEPS, IEA-APS, IEA-NZE and LMS future scenarios. In the context of the studied case of an existing UK hotel, a STEPS-aligned energy and carbon intensity trajectory implies compliance with the minimum energy efficiency standards in Part L2 of the 2002 Building Regulations, which was applicable during the design of the hotel between 2004 - 2005. As the hotel underwent minimal energy efficiency improvements after commissioning in 2007, the subsequent changes in the regulations had little effect on energy intensity, resulting in slow decline. The imperative for a more rapid decline, consistent with the national climate neutrality targets, triggered the UK government, professional bodies such as WGBC, UKGC and CIBSE, and multilateral organisations such as UNEP to enact, adapt and adopt policies, regulations, roadmaps, building energy codes and standards to accelerate reduction of energy intensity (UNEP, 2024), evidenced in prevailing approaches for evaluating energy and emissions intensity in the UK.

In furtherance of the Net Zero objective, several countries enacted sustainable building and construction policies, guidelines and codes to improve energy efficiency, reduce emissions and improve uptake of renewables. Implementation of these policies is by a prescriptive or performance-based approach. The Prescriptive Approach specifies items and/or methods to reach an energy efficiency or emissions target while the Performance Approach specifies the target to be reached and may require building energy simulation modelling to demonstrate compliance.

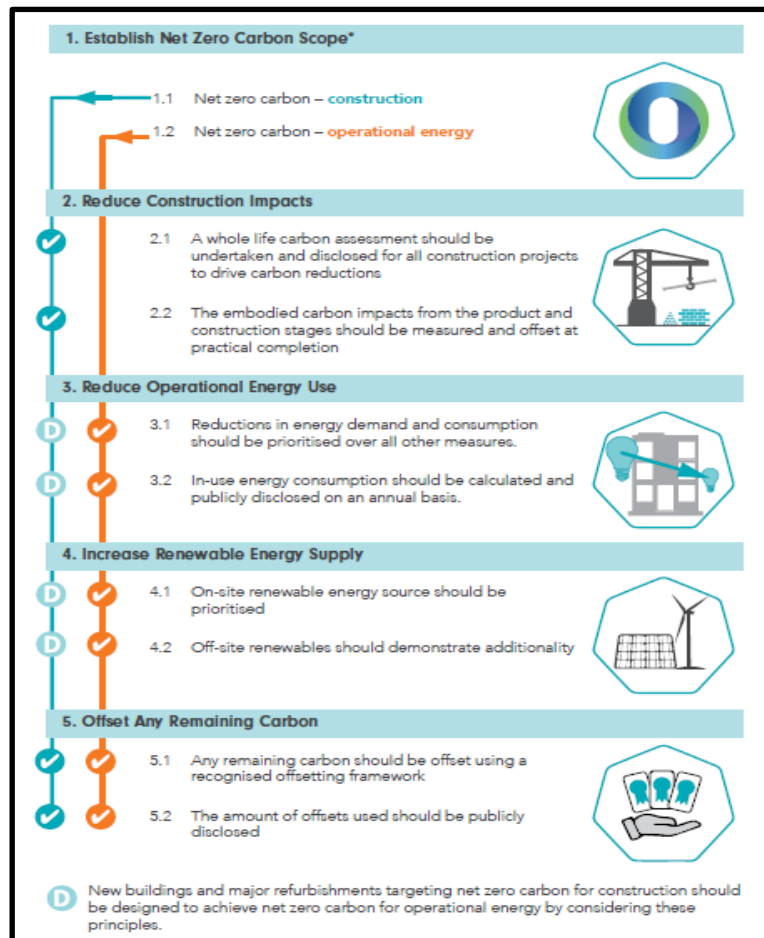


Figure 1.3: Steps to Achieving Net Zero Carbon in the UK (Twinn, et al., 2019).

The UKGBC and CIBSE adopted the framework in Figure 1.3 for definition and calculation of Net Zero Carbon in new buildings and major renovations (Net-zero carbon-construction) and “Net-zero Carbon-operational Energy” in buildings that are in the Use Phase (Twinn, et al., 2019).

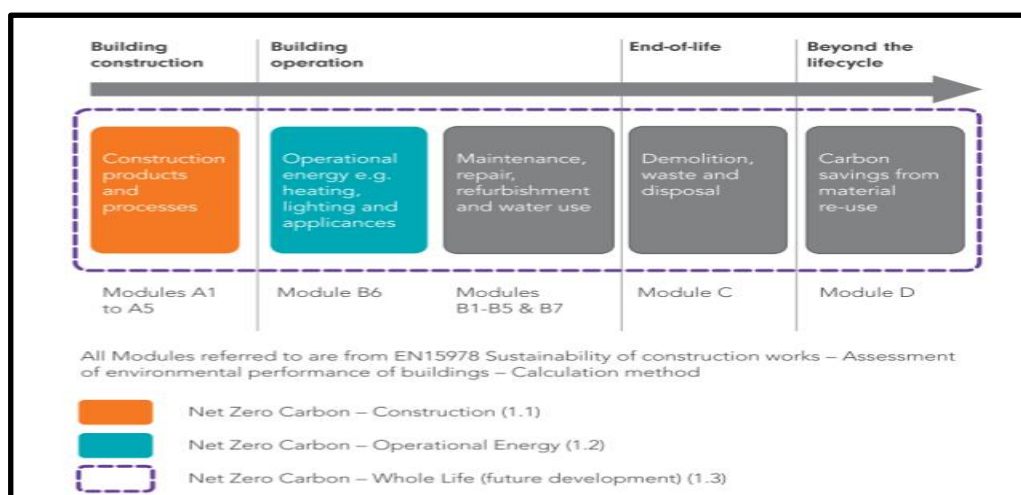


Figure 1.4: BS EN 15978:2011 Modules for Building LCEA

The guidelines for identifying building phases for scoping, monitoring, accounting and NZC assessment given in BS EN 15978:2011 (Figure 1.4) is adopted by the UKGBC and CIBSE. Modules (A1-A5) cover the calculation of Net Zero Carbon-Construction and module B6 is for Net Zero Carbon-Operational Energy. Net Zero Carbon-Construction is the state “when the amount of carbon emissions associated with a building’s production and construction stages up to practical completion is zero or negative, through the use of offsets or the net export of on-site renewable energy”, while Net Zero Carbon Operational Energy is the state “when the amount of carbon emissions associated with the building’s operational energy on an annual basis is zero or negative”. Whereas embodied carbon emissions are projected to dominate future building emissions as grid decarbonisation increases, this thesis focused on Module B6 (Operational Energy) because operational carbon emissions currently represent the largest share of total building emissions and create a cumulative climate burden due to their annual recurrence (Environmental Audit Committee, 2022). Hence, it is envisaged that the most-significant determinant for achieving the 78% emissions reduction, by 2035, set in the UK’s Sixth Carbon Budget is operational efficiency.

The foregoing context on operational emissions informs the current trend of policy actions, regulatory changes, introduction of energy codes and standards, reflective of the IEA-APS, to accelerate the decline of energy and carbon intensity. This creates an “Implementation Gap” between stated policies, national commitments in the form of NDCs, and guarantees from sectors such as the Hospitality Industry. Hence, IEA-APS entails aggressive implementation of EEMs in new buildings, deep renovations, retrofit of existing buildings, and uplift of renewables in the energy mix.

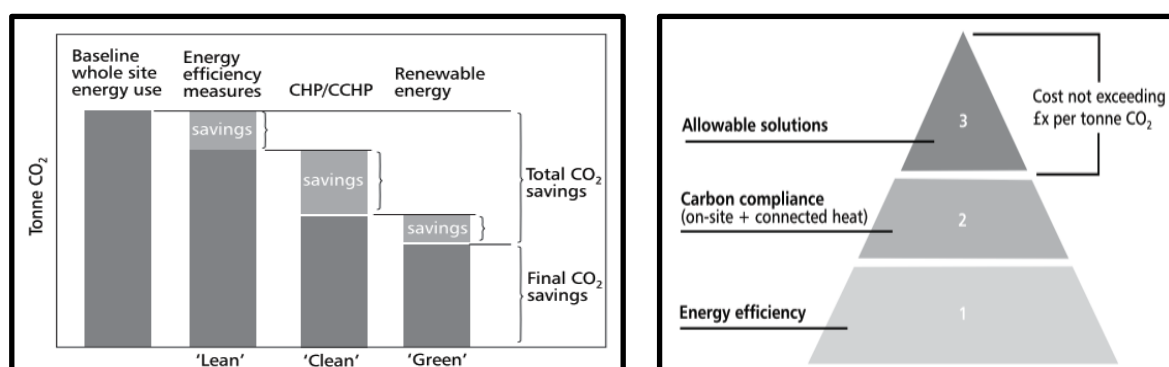


Figure 1.5: GLA Energy (left) and Carbon (right) Hierarchy (Cheshire, 2012)

In the UK, the “Energy or Carbon Hierarchy” shown in Figure 1.5, is adopted by the UKGBC, the GLA and CIBSE and aligns with the 2021 Building Regulations, IEA-APS,

and provides an objective basis for implementing the IEA-NZE trajectory. In the framework, the process to reach Net Zero buildings starts with the definition of a “Baseline Whole Site Energy Use” based on compliance with the Building Regulations. EEMs are then applied to secure initial CO₂ savings, to make the building “Lean”. Electrification of final energy services (such as heat) and/or replacement of delivered fossil fuel energy sources with cleaner options lead to additional CO₂ savings and the building becomes “Clean”. The integration of renewable energy to provide some or all of the final/end-use energy requirement of the building results in additional CO₂ savings and makes the building “Green”. The carbon savings required to make the building “Lean”, shown in Figure 1.5, are from application of EEMs, implementation of digitalisation and smart technologies for energy management and grid flexibility, leveraging existing cost-effective technologies (efficient lighting, insulation, electrification, and HVAC improvements), transitioning to clean fuels, behavioural changes and material efficiency.

Building EEMs reduce the rate at which energy is lost through the physical structure (envelope) of the building (passive measures), and the rate at which energy is used in the building (active measures) without compromising the physical, thermal, acoustic and visual comfort of occupants. A recent report revealed that the building sector is off-track to achieving Net Zero by 2050 (IEA, 2022), substantiating an earlier position (Architecture-2030, 2015) that an increase in the rate of energy efficiency renovation and retrofit of existing buildings is required for the Buildings Sector to reach NZC in 2050. EEMs are categorised into three broad types: No-cost/low-cost (requiring no investment appraisal), medium cost (requiring only a simple payback calculation) and high capital cost (measures requiring detailed design and a full investment appraisal). It is recommended (Cheshire, 2012) that they should generally be considered in their order of economic payback, complexity and ease of application. The foregoing shows that the “Implementation Gap” between IEA-STEPS and IEA-APS predisposes the hotel to higher operating expenses from future emissions penalties, expensive energy efficiency retrofits and risk of becoming a stranded asset or outright liability. As a commercial entity, this unfavourable situation necessitates a more aggressive approach to reducing energy and carbon intensity as stipulated in the IEA-NZE scenario.

The IEA-NZE is a normative scenario that describes what must happen to reach net zero by 2050. It is aligned with the 1.5 °C pathway and requires renovation of at least 20% of the existing building stock to Zero Carbon-ready or Net Zero-ready Buildings by 2030 (UNEP, 2024), deep electrification, and large-scale deployment of clean energy. In this sense, “Net Zero Carbon Building” is defined as an energy efficient building, powered by on-site and off-site renewable energy sources, with any remaining emissions offsetting”. A detailed categorisation of Net Zero Buildings into four (4) is given in (Marszal et al., 2011; Ahmed et al., 2022), namely; Net-Zero Site Energy buildings, Net-Zero Emissions buildings, Net-Zero Source Energy buildings, and Net-Zero Cost Energy buildings, and justified the use of multi-criteria decision methods for optimisation of technical, financial and environmental factors in NZEB development. Furthermore, the “IEA Efficient World Scenario” suggests that implementing currently available cost-effective technologies and leveraging existing digital solutions could, respectively, double global energy efficiency by 2040, and achieve energy efficiency improvement of 3070 TWh, representing about 12% of 2018 global Energy Performance, (IEA, 2021a). In the buildings sector, the net zero outlook to 2030, (Calvin et al., 2023; IEA, 2024) projects a 30% – 50% improvement in EUI and 45% -50% reduction in annual CO₂ emissions compared to 2010 levels. These data reflect an “Ambition Gap” that must be closed to transition buildings to net zero by going beyond the IEA-APS requirements. The WGBC, “Net Zero Carbon Buildings Commitment”, a part of the “Advancing Net Zero Programme” (WorldGBC-ANZ, 2023) aligns with IEA-NZE, targeting to get all buildings to net zero by 2050.

The monitoring and tracking of the decline of energy and carbon intensity enables objective measurement of the progress towards net zero. The PPM, pioneered by the Dutch Green Building Council is a tracking methodology which is based on a projected 60% reduction in EUI by 2050 (the PPT year), with the balance of 40% to be powered from zero carbon energy. The PPM adopts a top-down calculation based on the estimated capacity of low carbon energy supply available in 2050 and allocates this capacity to different economic and built environment sectors, and individual building levels to determine an EUI target; a building’s maximum annual Energy Performance relative to its floor area. The underlying theoretical basis of the PPM as adopted by the UKGBC is that if each building were to reduce its current EUI by 60%, the projected

low-carbon electricity that would be available in 2050, estimated at 40% of current electricity demand, would be sufficient for all buildings (UKGBC, 2020a).

Table 1.1: UKGBC Paris Proof EUI Targets (UKGBC, 2020a)

Scope	Metric	Interim Targets			Paris Proof Target
		2020-2025	2025-2030	2030-2035	2035-2050
Whole building energy	kWh _e /m ² (NLA) / year	160	115	90	70
	kWh _e /m ² (GIA) / year	130	90	70	55
	DEC rating	D90	C65	B50	B40
Base building energy	kWh _e /m ² (NLA) / year	90	70	55	35
	kWh _e /m ² (GIA) / year	70	55	45	30
	NABERS UK star rating	4.5	5	5.5	6
Tenant energy	kWh _e /m ² (NLA) / year	70	45	35	35

NLA = net lettable area GIA = gross internal area

The UKGBC set out interim and PPT benchmarks of EUI for whole-building, base building and tenant areas. The Paris Proof Targets shown in Table 1.1 were developed to provide guidance on expected levels of energy performance for commercial offices aspiring to achieve operational net zero, based on 2020 assumptions for the predicted UK economy-wide renewable energy share, making them variable. Hence, the values are only indicative even for offices, necessitating specific studies to define indicative PPTs for other building typologies.

The foregoing STEPS, APS and NZE scenarios are largely political imperatives that discountenance the cost impact of net zero despite the importance of clarity on the economic implications of implementing EEMs and increasing renewable energy, on the affordability of energy. This drawback is addressed in the LMS which is based on economic optimisation of energy and carbon intensity. Another drawback of the mentioned scenarios is that they do not take Indoor Environmental Quality (IEQ) requirements into consideration and are strictly based on zero external energy balance that results from the use of renewable energy sources and purchased offsets to cover many building loads. Hence, in a holistic measure of net zero progress, there should be a balance of the optimal cost, reduction of energy and carbon intensity, and IEQ.

In summary, the IEA-STEPS, IEA-APS and IEA-NZE scenarios contribute to the attainment of net zero targets in new build and existing hotels, in diverse but complementary ways. As in other building typologies, passive design optimisation, placement of a limit on upfront embodied carbon, reduction of operational energy

demand, elimination of fossil fuels from the Power Generation Mix and provision of onsite renewables and storage are required to get hotels to net zero. The IEA-STEPS scenario provides a baseline for the extent of energy and carbon intensity reductions required for net zero and illustrates the “Ambition Gap” between current practice and the required performance. The IEA-APS is more ambitious than the IEA-STEPS and assumes that the UK Climate Change Policy and NDCs are delivered and shows the policy trajectory for reduction of energy and carbon intensity in buildings. As net zero by 2050 requires rapid decarbonisation of buildings, major energy efficiency improvements and increased renewable energy uptake to align with the 1.5 °C pathway, the UKNZCBS sets mandatory limits and targets for operational energy, embodied upfront carbon, requirements for low-carbon heating, and onsite renewable generation as envisaged in the IEA-NZE scenario. This is more so, when viewed against the background of a changing climate and the imperative to ensure resilience measures in buildings.

In this study, the net zero metrics for commercial buildings is investigated by translating the IEA-NZE pathway into building-level performance metrics in a mid-rise, concrete-framed 3-star UK hotel. The IEA-NZE pathway to deep efficiency, electrification, reduction in carbon intensity and renewable energy uplift in hotels are operationalised in the UKNZCBS limits and targets on EUI, emissions and minimum onsite renewable generation. This is consistent with the UK legal requirement which set binding national carbon budgets and 2050 net zero target. In this sense, hotels must meet the limits and targets set in the UKNZCBS and provide measured data for verification of net zero alignment. Hence, the net zero metrics (EUI, CEI and ECI) and their indicative benchmarks derived from this study have direct link to the UKNZCBS, the UK Climate Change Policy, and the global climate scenarios.

1.2 STATEMENT OF THE PROBLEM

Hotels are an energy-intensive sector with energy consumption accounting for between 3% - 6%, and about 60%, of their operating costs and carbon emissions, respectively (Upadhyay & Vadam, 2015). Hotel carbon emissions are also responsible for 2% (363 MTCO₂e) of global emissions (Compton, 2022). A recent report showed that on average, hotels account for about 1% of annual global emissions and under a BAU scenario, global hotel emissions are projected to increase to a cumulative value of 82 GT.CO₂ by 2050, from 2010 levels report (SHA, 2017). Other available reports

on energy performance of commercial buildings revealed that, energy profiles, the climatic zone of location, occupancy patterns, EEMs and integration of renewables are important for energy performance improvements, reduction of emissions and attainment of NZH (Hotel Energy Solutions, 2011a; Arup et al., 2021; Greenview, 2021; Iturralde-Carrera *et al.*, 2023). As the number of hotel rooms is forecast to increase worldwide from 18 to 25 million between 2023 and 2046 (SHA, 2017b), a methodology for NZHs was established and applied to study the transformation of an existing UK hotel to net zero (Arup et al., 2021). In recognition of the projected global increase in the number of hotel rooms, there is global consensus, and action has commenced, to decarbonise the hospitality sector.

Hence, the 2021 CHSBI report on water and energy use of 25,576 hotels from 31 international hotel groups, stated that carbon intensity of hotels decreased by 10% between 2015 – 2018, with the greatest reduction of 23.4% recorded from UK hotels (Ricaurte & Jagarajan, 2023). A recent report (CBRE, 2023) also revealed that hotels were the real estate class with the highest average carbon footprint (96 kg.CO₂e/m²), among 10 studied asset classes (leisure lodging, healthcare, high street retail, shopping centres, hotels, offices, retail warehouses, cold warehouses and warm warehouses) with a combined average carbon footprint of 80 kg.CO₂e/m². A study on energy performance of hotel buildings (Arenhart et al., 2024) listed building characteristics, economics, social and environmental factors as contributors to hotel energy use. In (Arup et al., 2021), it is further reported that Net Zero in the hotels sector would require a reduction of CO₂ emissions by 66%-90% between 2030 - 2050, per room, against a 2010 baseline, to forestall the forecast growth in hotel rooms translating to a corresponding increase in carbon emissions.

The foregoing suggests that hotels have peculiar environmental, financial, social operational and regulatory context that affects their energy demand and carbon emissions. Hence, the existing metrics for tracking energy efficiency, and monitoring decarbonisation progress and the cost of net zero are normalised on a room-night basis resulting in conflict with the floor- area - normalised metrics traditionally used for building sector regulations and standards. These constraints are in the following three (3) domains:

- a. **Net Zero Targets and Operational Data:** Net zero requires information on the targets and limits of energy efficiency, carbon emissions, renewable energy share

and operation of the specific building, including occupancy and the maintenance and replacement lifecycle of active systems. Considering that most existing hotels were commissioned before the current era of climate-awareness, the use of complex room-night normalisation to define net zero targets/limits is constrained by incompleteness or unavailability of required data.

- b. **Modelling and Simulation of Regulated and Unregulated Loads:** energy and cost models require construction and operational characteristics, occupancy profile and behaviour, building use class, meteorological parameters (including future weather files), varying energy and power generation mix, and energy cost data, including projections of future energy costs. The existing net zero metrics are derived from regulated loads and give baseline information about the operation of the building energy system, but true net-zero requires modelling and simulation of unregulated loads, to test and quantify the impact of EEMs. The modelling, dynamic simulation, and verification of a representative hotel model from geometrical, meteorological, operational and occupancy data, affords the use of profiles that are derived from actual operational data to account for uncertainties associated with plug loads, and occupant energy behaviour are normalised to floor area.
- c. **Timelines for Monitoring Energy Efficiency, Decarbonisation and Climate Change:** NZB entails progressive, incremental improvement of energy efficiency, carbon emissions reduction, and increase in renewable energy share of a building across stated timelines, under the constraints imposed by climate change and the required resilience in the building energy system. In existing buildings, additional considerations about retrofit strategies (one-go or stepped) affect the timelines for monitoring progress on net zero. Net zero metrics that are normalised on a room-night basis would be complicated to use for monitoring net zero across future timelines, compared to floor-area normalised metrics which are based on simple floor area data.

1.3 AIM AND OBJECTIVES OF THE STUDY

The study aims to investigate the feasibility of operational net zero in an existing UK hotel building typology, develop energy, carbon and cost metrics, and compute benchmark targets and limits of energy efficiency, carbon emissions, and LCOE for

proofing net zero claims in UK hotel typologies. The aim of the study will be achieved through the following objectives:

1. Identification of suitable case study typology for the energy audit and research.
2. Critical literature review of the metrics for quantifying net zero variables in the context of commercial building typologies; energy performance, energy efficiency, renewables and integrated energy systems.
3. Collection of the following datasets for the case study: Architectural and construction drawings, 2022 Electricity consumption and cost, 2022 Natural gas consumption cost, UK macroeconomic data and capital and operational cost of rooftop solar-PV, Lithium-ion battery, natural gas boiler and converter technologies.
4. Extraction of TMY “.epw” weather files for the case study location, for baseline year (2022), interim period (2030 – 2035) and 2050 PPT year under SSP2-4.5 future climate scenario.
5. Baseline physics-based whole-building energy performance modelling and calibration of case study according to 2006 UK Building Regulations Part L2.
6. Simulation of calibrated baseline model under SSP2-4.5 future climate scenarios, UK Future Buildings Standard (2025), selected EEMs, and analysis of energy performance and carbon emissions.
7. Modelling and sizing of rooftop solar-PV generation for the case study.
8. Coupling of solar-PV generation (6 and 7 above) to develop the microgrid model using baseline techno-economic and environmental variables, and constraints applicable to the site and location of the case study.
9. Simulation and optimisation of microgrid model to identify the “least cost system”.
10. Computation of benchmark operational NZ targets and limits of the EUI, CEI and ECI for stepped retrofit between baseline year (2022) and 2050.

1.4 RESEARCH QUESTIONS

1. Is operational net zero feasible for existing hotel typologies in the UK under the PPM and UKNZCBS frameworks?

2. Under an SSP2-4.5 future climate scenario, what is the impact of passive and active EEMs on the EUI of a typical UK hotel typology and how do these compare to existing benchmark targets of operational net zero EUIs?
3. In the context of changing meteorological and macroeconomic conditions, and projected decarbonisation of the UK electricity mix, what are the benchmark targets and limits of energy, carbon and cost metrics for operational Net Zero in a typical hotel typology?

1.5 SIGNIFICANCE AND NOVEL CONTRIBUTIONS OF THE STUDY

The characterisation of a Net Zero Hotel is done using sector-specific metrics, normalised on a “room-night” basis and articulated in the “Net Zero Methodology for Hotels” (Greenview, 2021). The main categories of metrics are (a) Whole-hotel GHG accounting metrics (Scope-1,2 &3 emissions), (b) Carbon-intensity metrics (carbon per occupied room, carbon per available room), (c) Operational metrics (Laundry and linen metrics; energy and water per kg of linen washed, food and beverage operational metrics; cooking fuel use, refrigeration loads, kitchen exhaust/ ventilation energy, and wellness and leisure metrics that track energy use for pools, spas, saunas and steam rooms (Arenhart, et al., 2022). Unlike conventional NZB metrics that are normalised with floor area, NZH metrics are normalised on a “room-night” bases, making them unsuitable for statutory compliance monitoring required under the BRUKL2. Hence, there is need to develop metrics that are verifiable with easily-available data such as floor area. The foregoing context highlights the significance of the study in three (3) main ways:

- ❑ The results of energy performance, CO₂ emissions and energy system optimisation obtained for current and future climate scenarios would assist hoteliers and developers of service buildings in planning optimal energy efficiency retrofits and microgrids to maximize carbon savings.
- ❑ The case study is located on a university campus, the Paris Proof approach and whole-building calibrated building energy performance modelling, simulation and parametric analysis could serve as a viable tool to support the climate ambitions of HEIs.
- ❑ The sizing of solar-PV generation and integration to the microgrid could be applied to model building integrated energy systems in any part of the world. The

hierarchical application of passive, active and renewable retrofit measures to investigate net zero for the case study typology represents a pathway to sustainability in the hospitality sector.

In view of the foregoing, this work intends to make novel contribution by integrating construction, meteorological, energy consumption, and cost data in dynamic models to develop benchmark limits of net zero operational metrics; total EUI (kWh/m²/yr), CEI (kg.CO₂/m²/yr), and ECI (£/m²/yr) suitable for application as a reference resource for planning the decarbonisation of operational energy in hotel typologies and inclusion in the body of evidence for the UKNZCBS. The emphasis of this work on existing buildings is underpinned by the nexus with sustainability in the built environment, and reports that they currently account for approximately 90% of the global building stock of 2020 – 2030 (Blum, 2023).

1.6 SCOPE OF THE STUDY

The unit of analysis in this study is a mid-rise, concrete-framed 3-star hotel typology with a commercial load profile. The main parameters in the study are energy efficiency, renewable energy uptake and carbon emissions and the following secondary datasets were used in the study:

- 1) Time-series (half-hourly and hourly) electricity consumption (Appendix-1A) obtained from actual metered values at the case study.
- 2) Representative retailer invoices for electricity (Appendix-1H) and natural gas (Appendix-1I) consumption.
- 3) Occupancy data for 2017 – 2022 obtained from hotel owner (Appendix-1J).
- 4) Kitchen and boosted water consumption obtained from case study owner, Appendix-1K and Appendix-1L, respectively.
- 5) Architectural, mechanical, electrical, lighting and plumbing design extracted from “Architect’s Design Statement” of the case study (Appendix-1O).
- 6) Lighting Design of case study (Appendix-1P).
- 7) General Arrangement drawing of case study plantroom (Appendix-1Q).
- 8) Projected UK Electricity emissions factors till 2100 (Appendix-1R).

The case study is located within a temperate oceanic (Cfb) climate zone, and the load profile is typical to hotels, having 3 peaks during the day. Hence, the methodology can be utilised on any building typology while the benchmark EUI, CEI and ECI results are

indicative for typical UK 3-star hotels. The work involves physics-based building energy performance modelling and calibration, and rooftop solar photovoltaic (solar-PV) generation modelling and simulation. In addition, the solar-PV model is coupled to a microgrid model to investigate the technical, environmental and economic performance of the hybrid energy system at the case study. Hence, corresponding metrics to measure technical, environmental and economic performance are developed and indicative benchmark values are computed to inform the feasibility or otherwise of operational net zero in the building typology. The results of this study are interpreted relative to; (a) UKGBC-PPM, (b) UKNZCBS, and (c) CHSBI benchmarks.

The research, policy and practice literature on net zero hotels contains methodologies and case studies of the contribution of control and behavioural measures, refurbishments and replacement strategies for reduction of embodied energy and carbon, and compensation of residual carbon with quality certified offsets. However, these aspects are outside the scope of the present study and are not reported.

2.0 LITERATURE REVIEW

A survey of 106 policy, practice and research literature revealed growing criticism of the existing energy certificates system, as unsuitable for monitoring net zero in buildings. The review aimed at establishing the state-of-the-art approaches for quantifying energy, carbon and cost intensity and identifying gaps to be addressed in development of robust, fit-for-purpose operational net zero metrics and, benchmark limits/targets for buildings. The definitions of net zero, measurement metrics, benchmark targets/limits, and the impact of identified independent, dependent and mediating variables were evaluated on the basis of the standard requirements that net zero metrics for buildings should be simple, within the control of the building owner, complemented by other policies that incentivise energy efficiency, and be developable from verifiable data within a short time. In addition, net zero metrics should encourage electrification, not require high upfront costs to implement, reflect local circumstances of building typology, climate, carbon intensity of the electricity grid, and should have a clear compliance path. The literature was evaluated along the following themes; Net Zero Context, Net Zero Frameworks, Building Energy Simulation Tools, Simulation Calibration Standards, Empirical Benchmarking Approaches, Solar Resource and Modelling Methods, Microgrid Techno-economic Optimisation, and Uncertainty and Sensitivity Methods. The independent and mediating variables on Net Zero Buildings and the factors that determine whether, or not, net zero can be achieved (independent variables) formed the core of sensitivities and uncertainties (dependent variables); total energy consumption, total carbon emissions and cost of energy. In the studied case of an existing hotel, on which this review is based, the cost motive does not support outright re-design and reconstruction to achieve net zero so building orientation is excluded from the sensitivity factors. The review informed the adoption of benchmark net zero metrics. The summary of review of 122 literature, outlines the research gaps on the metrics for building energy efficiency, carbon emissions and energy cost, and informed the research questions, research design, methodology and methods used in this work. Despite the review of the impact of physiological and behavioural factors on energy consumption, and by implication, emissions and energy cost on the respective intensities, the whole-building modelling approach adopted in this study precluded the determination and analysis of space comfort temperatures and occupant energy epidemiology, as they were outside the scope of this study.

2.1 NET ZERO CONTEXT

The development of net zero buildings took the trajectory of rise in prominence of environmental issues within the UN and the global consciousness about climate change. In the first 2 decades of its existence, the UN actions on the environment were mainly concerned with the adequacy of known natural resources for economic development of members and were executed through the WMO leading to the convenance of the first UN Conference on the Human Environment in Stockholm Sweden in 1972. This coincided with the period of the global energy crisis of the 1970s, when rising energy prices and supply-side uncertainties in the global energy system provoked interest in building energy efficiency and renewable energy as means to energy security and cost saving. At the time, passive strategies for zero carbon buildings were predominant mainly in the USA and Europe.

In the period leading to the establishment of the IPCC in 1988, the WCED, also known as the “Brundtland Commission” was set-up in 1983, to formulate a global agenda for adoption of long-term environmental strategies for achieving sustainable development by the year 2000 and beyond. In furtherance of this, the 1987 Brundtland Report of the WCED titled “Our Common Future”, defined “sustainable Development” as “...development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). The report laid the foundation for modern sustainable development practices and policies, emphasising the integration of environmental and developmental goals to address climate change, resource management and social equity. The task of the IPCC was to assess the science related to climate change and update policy makers with the regular scientific assessments on climate change, its implications and potential future risks, in addition to proposing adaptation and mitigation strategies. The IPCC produces five-yearly comprehensive assessment reports from the 3 working groups. Working Group 1 (WG -1) focuses on the physical science basis of climate change, Working Group 2 (WG -2) addresses impacts, adaptation and vulnerability, while Working Group 3 (WG – 3) deals with the mitigation of climate change. In addition to the main assessment reports, the IPCC also publishes special reports on specific topics. The IPCC Sixth Assessment Report -IPCC AR-6 (Calvin *et al.*, 2023) was released in 2023 for the Sixth Assessment Cycle (2015 – 2021) and highlighted substantial changes in the climate system and the urgent need for action.

In 1992, the UN Conference on Environment and Development in Rio de Janeiro, Brazil birthed the UNFCCC with the mandate to stabilize atmospheric concentrations of GHGs at a level that would prevent dangerous anthropogenic interference with the Earth Climate System. In March 1995, COP-1 was held in Berlin and adopted the “Berlin Mandate” (COP-1, 1995). The Mandate acknowledged that commitments under the UNFCCC were insufficient to effectively mitigate global warming and initiated a two-year negotiation process aimed at establishing protocols or other legal instrument for reduction of GHGs beyond the year 2000. As an outcome of the negotiations from the “Berlin Mandate”, the Kyoto Protocol was adopted in 1997 to set binding emissions reduction targets for the 37 industrialised economies and the European Union aimed at reducing overall GHG emissions by 5% against the 1990 levels over an initial 2008 – 2012 commitment period. The developments between 1992 and 2002 coincided with the US-DOE NREL origination of HOMER Pro™ software as part of the program “Village Power”, to assist with rural electrification in developing countries.

A second commitment period (2013 – 2020) was agreed in December 2012 under the “Doha Amendment”. The Protocol placed the burden of responsibility for the current high levels of GHG in the atmosphere on developed countries under the principle of “common but differentiated responsibility and respective capabilities”. In addition, the Protocol offered three market-based mechanisms for meeting the emissions reduction targets; International Emissions Trading, Clean Development Mechanism (CDM) and Joint Implementation (JI), encouraging GHG abatement to start from the developing world, where it is most cost-effective. The mechanisms are source-agnostic, as they are only concerned with the reduction of the Assigned Amount Units (AAUs) from the atmosphere by respective parties, irrespective of source. Additional benefits of the mechanisms are the stimulation of green investment in developing countries and inclusion of the private sector in the endeavour to reduce and steady GHG emissions. Furthermore, the mechanisms make the possibility of long-term economical “leap-frogging” (skipping the use of older, dirtier technology for newer, cleaner infrastructure and systems).

Emissions trading allows countries that have emission units to spare – emissions permitted them but not “used” – to sell this excess capacity to countries that are over their targets. Since carbon dioxide is the principal greenhouse gas, it is tracked and traded as a commodity in the “carbon market”. Transfers and acquisitions of these units are tracked and recorded through the Registry Systems under the Kyoto Protocol

and an “International Transaction Log” ensures secure transfer of emission reduction units between countries. As of 2024, the International Carbon Action Partnership (ICAP, 2024), reported that there are 36 ETSs in operation globally in jurisdictions that represent 58% of global GDP, covering 9.9 GtCO₂e (over 18% of global GHG emissions). The CDM allows a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol to implement an emission-reduction project in developing countries to earn saleable Carbon Emissions Reduction (CER) credits, each equivalent to one tonne of CO₂ which can be counted towards meeting Kyoto targets. The CDM became operational in 2006 as the first global, environmental investment and credit scheme of its kind, providing a standardised emission offset instrument, CERs. A CDM project activity might involve, for example, a rural electrification project using solar panels or the installation of more energy-efficient boilers. The CDM stimulates sustainable development and emission reductions, while giving industrialised countries some flexibility in how they meet their emission reduction or limitation targets. A CDM project must provide emission reductions that are additional to what would otherwise have occurred. The projects must qualify through a rigorous and public registration and issuance process. Approval is given by the Designated National Authorities and public funding for CDM project activities must not result in the diversion of official development assistance. The CDM Executive Board reported that 7800 projects were registered in the first and second commitment periods representing 2.156 billion CERs (CDM-EB, 2021) and that beyond 2020, the CDM will be integrated with the Sustainable Development Mechanism (SDM) under the Paris Agreement.

The Paris Agreement, adopted in December 2015 at the 21st Conference of the Parties (COP-21) in Paris, France required both developing and developed nations to reduce their greenhouse emissions (in the commitment period of 2025 – 2030) to prevent the average global temperature from rising more than 1.5 °C above pre-industrial levels. The Agreement further required each Party to prepare, communicate and maintain successive NDCs of actions for decarbonisation of end-use sectors and build resilience and adaptation to the impacts of rising temperatures. Consequently, carbon neutrality targets were set by multilateral bodies, countries, regions, cities, companies and professional institutions resulting in the increase of competitive low-carbon solutions such as NZCBs. In the years leading to, and after, the Paris Agreement, technical

advancements and reduction in costs of renewable energy technologies led to their increased integration in building energy systems to achieve net zero goals. These developments impacted the cost of energy consumption, maintenance and operation of buildings, and the return on the investment in energy efficiency measures and renewable energy installations. These impacts necessitated rigorous appraisal of investments in NZBs to assess the environmental impact (how the investment will contribute to reducing carbon emissions and achieving sustainability goals), financial viability (costs, potential savings, and returns on investment), regulatory compliance (to ensure that the project meets local and international environmental regulations) and risk management (to identify and mitigate technological, market and regulatory risks associated with the investment).

Net Zero Definitions and Strategies

“Net Zero” is the state when the GHGs emitted into the atmosphere are offset by actions that remove an equivalent amount, resulting in zero net increase in atmospheric GHG levels. “Net Zero” originated as a scientific term implied in the Paris Agreement to encourage parties to achieve a balance between anthropogenic emissions, by sources, and removals of GHGs, by sinks, and is now a construct to govern the temperature goals set by the Paris Agreement” (Fankhauser *et al.*, 2022). “Net Zero” is defined and operationalised as “Net Zero Carbon”, “Net Zero CO₂” or “Carbon Neutrality” in contexts that emphasise carbon emissions (Carrillo Pineda and Faria, 2019), while “Net Zero Emissions” is used where the climate enforcer encompasses all GHGs (Green and Reyes, 2023). The related term “Climate Neutrality” is used when anthropogenic activities are balanced with removal of residual CO₂ emissions and do not result in a net effect on the climate system.

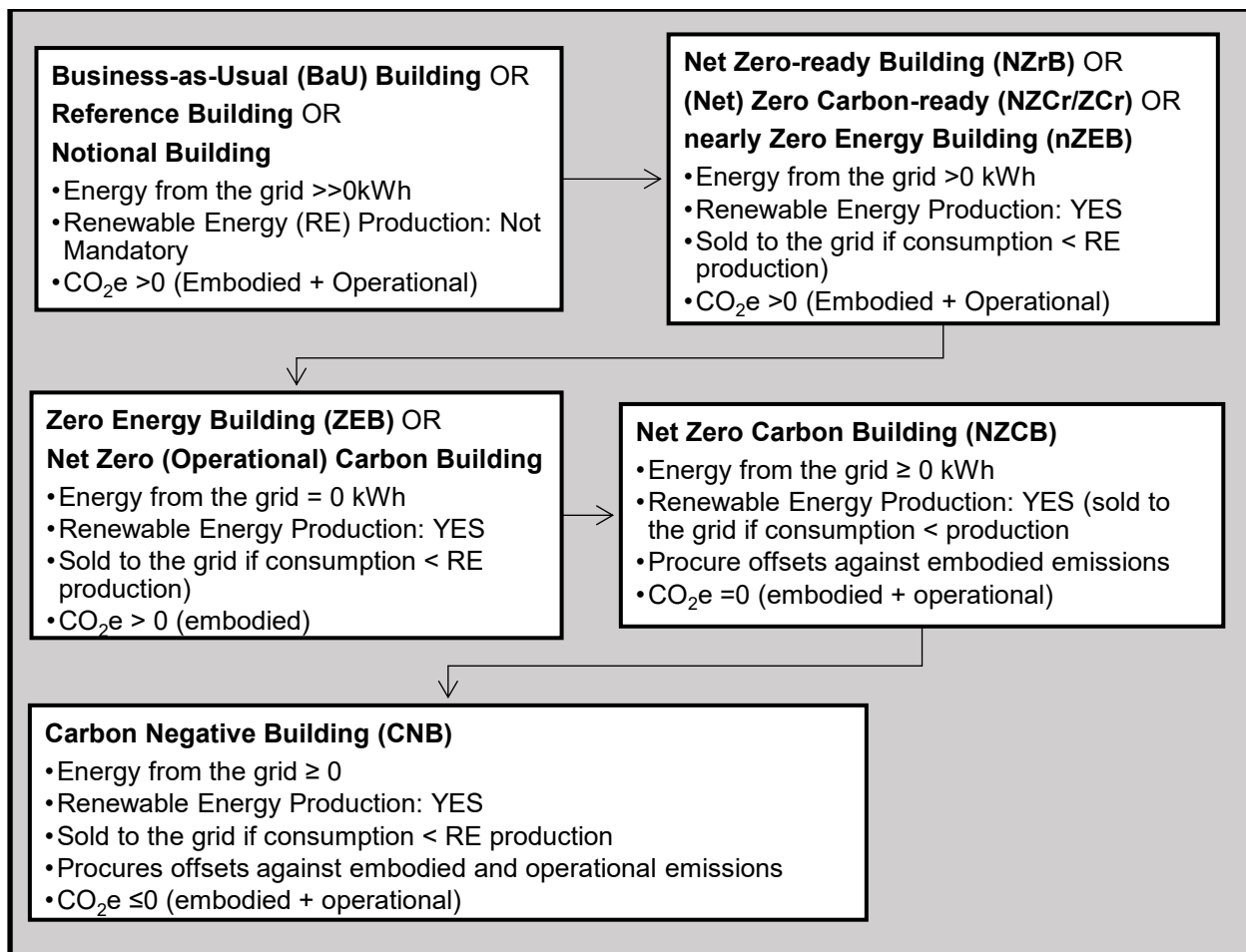


Figure 2.1: Classification and Net Zero Progression of Buildings. Prepared on the basis of grid Energy Performance, RE production, carbon emissions and procured offsets.

In the buildings sector, climate neutrality is characterised as “nearly Zero Energy Buildings” (nZEBs), also known as “Zero Energy Buildings” (ZEBs) or “Net Zero Energy Buildings” (NZEBs), and “Net Zero Carbon Buildings” (NZCBs), with the progression of buildings through the energy, carbon and renewable energy boundaries as shown in Figure 2.1. In (Hill et al, 2020), NZCB is defined as a building in which there is “a reduction in the demand for energy and materials to a level that can be met solely by sources that do not emit GHGs”. A different categorisation of NZEBs into 4; Net Zero Site Energy Buildings, Net Zero Emissions Buildings, Net Zero Source Energy Buildings, and Net-Zero Cost Energy Buildings highlighted the importance of delivered energy, primary energy, CO₂ Emissions and Energy Cost metrics for achieving the Net Zero balance (Marszal et al., 2011). All the NZB pathways reported in the literature; (a) “CIBSE Carbon Hierarchy”, (b) “Paris Proof Methodology (PPM)”, (c) “ARUP Route to Net Zero” and (d) “UKGBC Framework”, entail energy efficiency

improvement and utilisation of renewable energy resources and verified offsets to balance residual demand.

Net Zero Buildings: Net Zero Energy and Net Zero Carbon

The definition of an NZEB as a building where the total sum of energy used annually is approximately equal to the total sum of the renewable energy produced on site is implied in definitions provided by (Sartori, et al., 2010; Robert & Kummert, 2012; Parkin, et al., 2020; Kilkis, 2022; Lou & Hsieh, 2024). In existing buildings, NZEB is achieved by renovation, retrofitting or refurbishment; the process of upgrading or renovating existing structures to enhance their aesthetics, functionality, energy efficiency buildings and/or safety. The British Standards Institution (BSI) defined retrofits as the process of modifying existing buildings to improve energy efficiency and reduce energy consumption and carbon emissions through installation of new technologies or features such as insulation, energy-efficient lighting and renewable energy systems. A quantitative approach to the definition of renovations and retrofits in buildings (Joyce et al., 2013) reported that they must be achieved using specific strategies and specifications and should result in at least 50% reduction in overall energy consumption of the building.

In a review of case studies (Ibrahim et al., 2024), NZEB retrofitting measures were categorised into “non-adjustable parameters affecting building energy performance” and “energy retrofit measures”. The former comprises climate (equatorial, arid, warm temperate, snow and polar), based on Köppen classification, and occupancy. Energy retrofit measures consist of passive or building envelope retrofit measures, active measures that replace inefficient devices with low energy-consumption alternatives, and renewable energy retrofits. An observed gap in the study is that out of over 50 cases reported, only residential, office and educational typologies were covered. Non-residential hospitality typologies, such as hotels, were not included in the study.

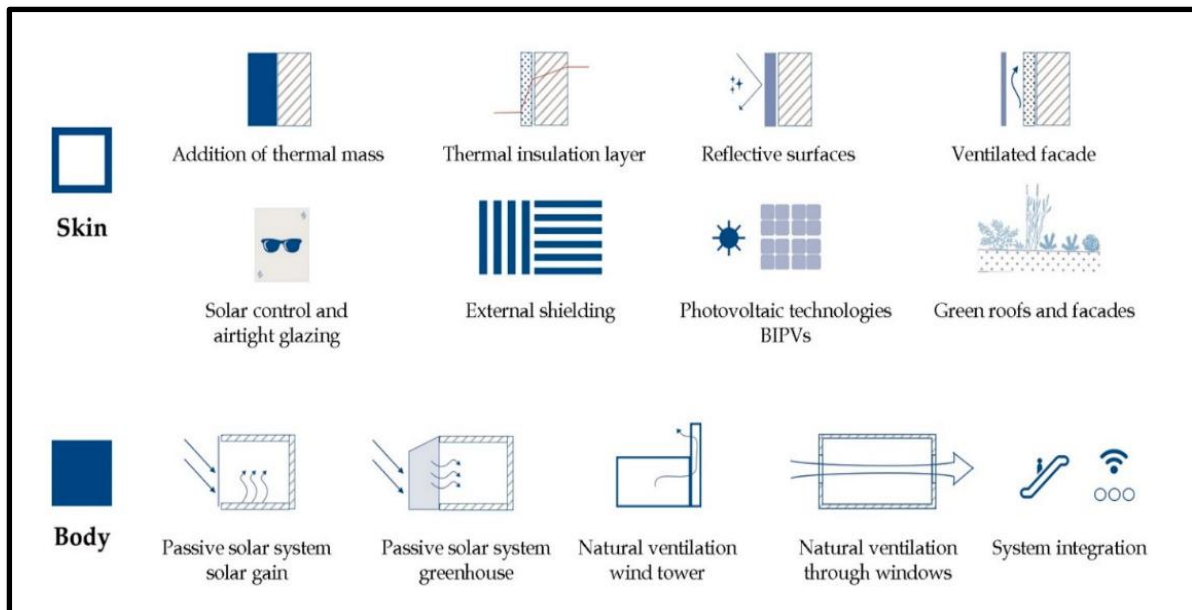


Figure 2.2: Scope of Skin and Body Retrofits (Pan, et al., 2023)

An asset-level classification scoped retrofits into “skin” and “body” strategies (Pan, et al., 2023), as presented in Figure 2.2. However, the PAS 2038 (BSI-PAS 2038, 2021) specification details the scope of retrofit for non-domestic buildings greater than 500m² GIA, and PAS 2035 applies to all buildings with less than 500m² GIA. The UKNZCBS framework goes further to specify EUI limits for “Stepped” and “One-Go” retrofit of existing buildings of all typologies between 2025 – 2050.

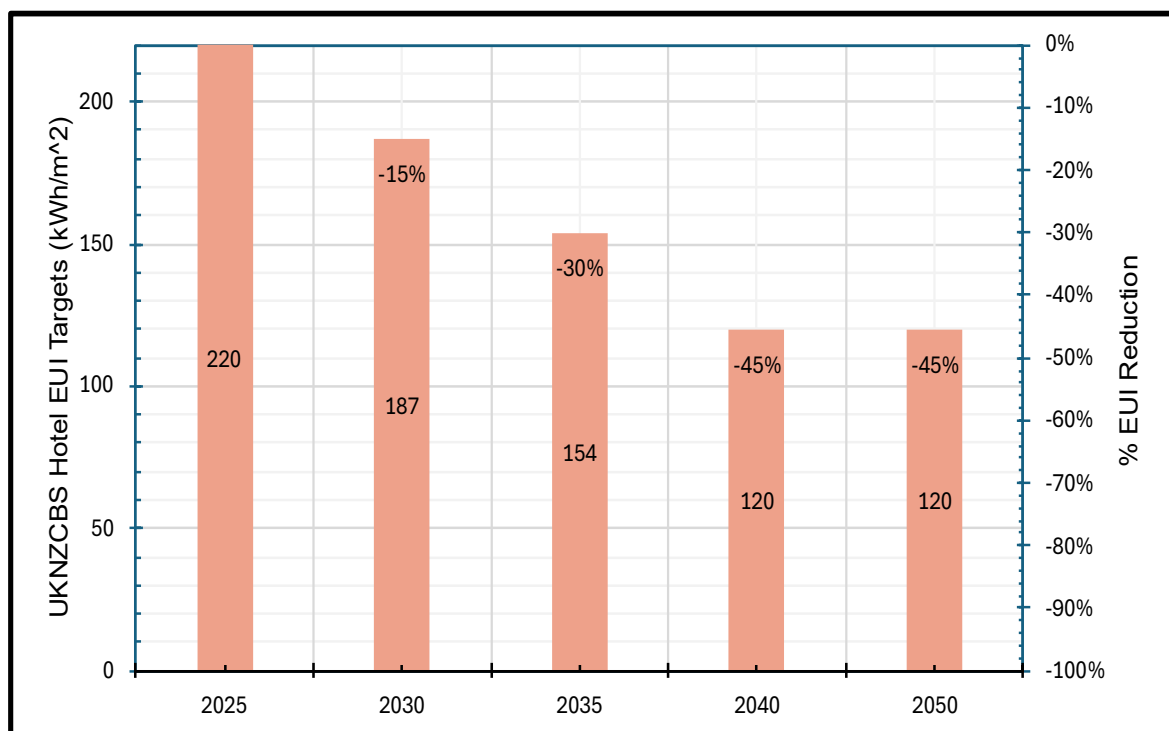


Figure 2.3: UKNZCBS Hotel EUI Limits for Stepped Retrofit

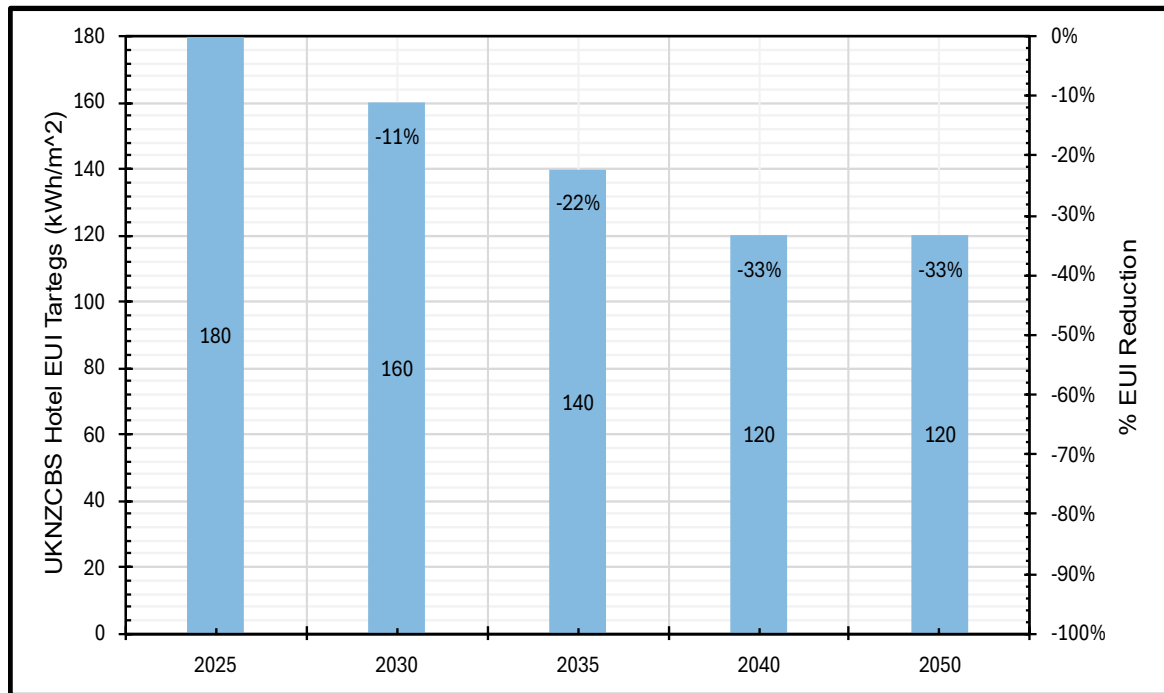


Figure 2.4: UKNZCBS Hotel EUI Limits for “One-Go” Retrofit

As presented in, The EUI limits for hotel typologies in stepped (Figure 2.3) and “One-Go” (Figure 2.4) retrofits shows that the requirement for operational NZH is 45% and 33% EUI reduction respectively

The analysis and interpretation of the results would confirm whether (or not), NZ is attainable from the reduction in EUIs from the base year, through the interim period , to 2050, for a hotel typology. Furthermore, the on-site renewable electricity generation target for operational NZ applicable to all buildings, other than single family homes and single-storey storage and distribution typologies, is 40kWh/m² of GIA per year for all other typologies located in Middle and North England. In interpreting the results of solar-PV model simulation, the RE output is evaluated against the UKNZCBS target

The reviewed strategies and specifications for retrofit did not reflect the impact of digitalisation; the application of the capacity of digital technologies to effectively collect, transmit, process and store huge data, and quickly identify patterns or problems, simulate scenarios, and test solutions virtually. However, a review concluded that the application of different digital technologies across the building lifecycle, (Asif, Naeem and Khalid, 2024) is a key success factor for reduction of energy and carbon intensity. Traditionally, NZEB has focused on new designs despite the need to reduce energy and carbon intensity of existing buildings.

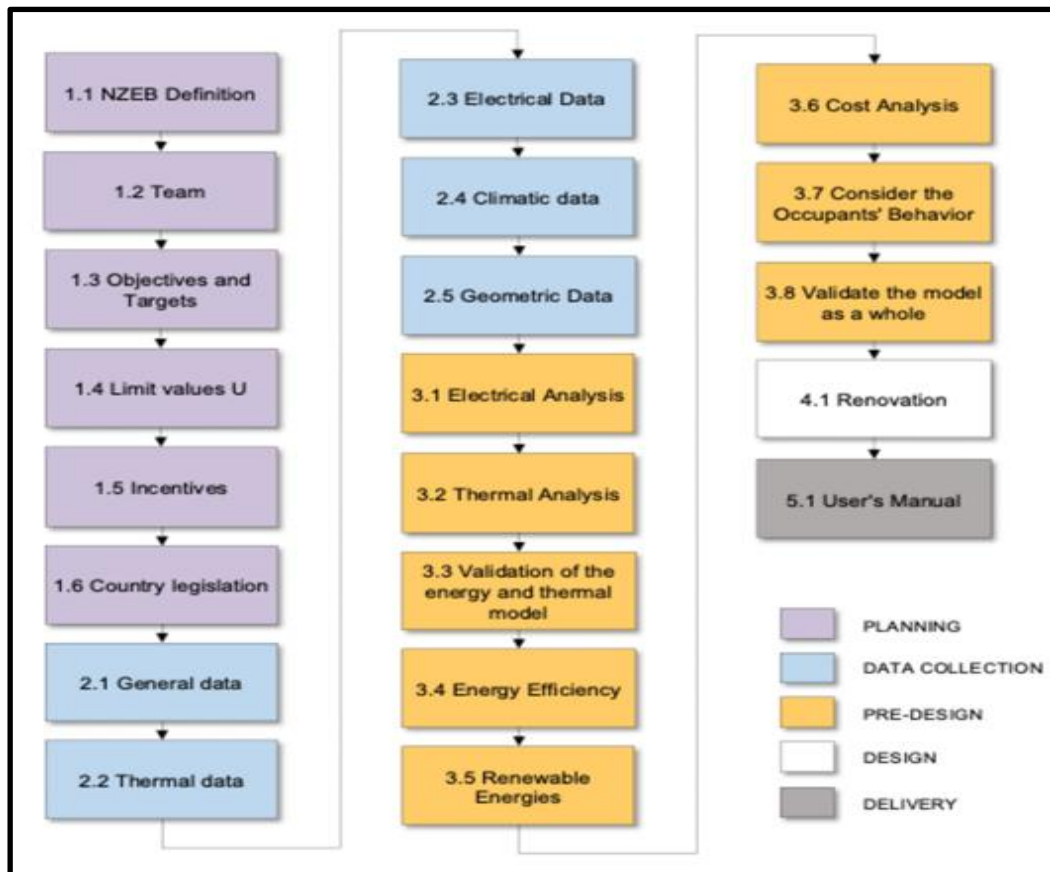


Figure 2.5: Guidelines for NZEB Interventions (Andrade et al., 2025)

In this regard, methods for transforming existing buildings to NZEB were reviewed (Andrade et al., 2025) and a set of typology- and climate-agnostic guidelines derived comprising organisational, statutory, social, and technical factors that must be considered and the data requirements necessary for execution of an NZEB (Figure 2.5). The review observed that there was low research activity on the impact of occupant behaviour on energy consumption, post-occupancy evaluation and long-term energy performance monitoring. Furthermore, there was overemphasis on solar PV as the on-site renewable energy source. The validation of the guidelines on particular case studies is a gap that remains to be explored.

Net Zero Carbon Buildings (NZCBs)

The UKGBC defines NZCB as the condition achieved “when the amount of carbon emissions associated with a building’s embodied and operational impacts over the life of the building, including its disposal, are zero or negative”. At the global level, the WGBC in partnership with a network of 75 Green Building Councils and industry partners set out a series of hierarchical, mutually-reinforcing principles (WorldGBC, 2023) and programmes that, when applied in an integrated manner, will guide

governments and policymakers in enacting policies, legislations and regulations that will deliver transformative action and the desired impact required to reach the goals of the Paris Agreement. The WGBC provides support to governments on regulation, information and incentivisation of each principle. The adoption of NZCBs at scale is driven by legislative, economic, market, cultural and industry factors and they vary according to jurisdiction and typology. Globally, key legislative measures for the uptake of NZCBs are reported in (Tirelli & Besana, 2023) and include; implementation of building energy codes (with requirements for energy efficiency, renewable energy integration and carbon reduction), enactment of climate change framework laws with specific provisions for the building sector, performance-based standards and international agreements. However, Ohene et al., 2023 reported that emerging economies are lagging in development of NZCB legislation and policies.

In the UK, the measures for NZCBs include a system of EPCs, Minimum Energy Efficiency Standards (MEES), UK Future Buildings Standard, Performance-based Ratings, UK Heat and Buildings Strategy and Financial Incentives (Cross, 2021). The WGBC also developed the Net Zero Carbon Buildings Commitment (NZCBC) with the goal of halving the emissions from the building and construction sector by 2030 and reaching total decarbonisation by 2050. There are currently 35 Green Building Councils (GBCs) participating in the programme, 18 certification schemes and 856 buildings have been certified by GBCs as operating at Net Zero (WorldGBC, 2023; WorldGBC-ANZ, 2023). The NZCBC advocates for existing buildings to reduce their energy performance and eliminate emissions from energy and refrigerants, removing fossil fuel use, and where necessary, compensate for residual emissions. New developments and major renovations are required to be highly-efficient and powered by renewables, with a maximum reduction in embodied carbon and compensation of all residual upfront emissions. The vision of the NZCBC is to outline strategies to be adopted by signatories to the Commitment to address carbon emissions throughout the building lifecycle using the following best practices:

- ❑ Commit assets, new developments and major renovations under direct control to reduce (and compensate where necessary) all operational and embodied carbon emissions by 2030

- ❑ Disclose and assess of annual asset and portfolio operational energy demand and carbon emissions, as well as whole life embodied carbon emissions according to EN 15978 or another accepted national standard.
- ❑ Implement actions with key milestones to achieve maximum reduction of operational carbon emissions, increased energy efficiency and renewable energy uptake, and for embodied carbon, achieve maximum emission reductions in upfront, in-use and at the end-of-life.
- ❑ Verify enhanced energy performance and reduced carbon emissions from operational carbon, the prevention strategies, Whole Life Carbon Assessment calculations, offsets and progress towards Net Zero embodied carbon assets and portfolio.
- ❑ Advocate for wider emissions reduction by acting as a catalyst through core organisation activities for further action within respective supply chains

The NZCBC approach to reduction of operational carbon entails prioritising consumption reduction and energy efficiency, supply of remaining demand from on-site or off-site renewable energy sources, offset of residual emissions with high quality, credible offsets and electrification. On embodied carbon, the NZCBC emphasises renovation over new developments, evaluation of designs to determine upfront carbon reduction on a whole lifecycle basis, avoidance of future embodied carbon during and at the end of life, and compensation of residual carbon emissions with high quality and credible offsets. Among the 176 signatories to the NZCBC are several UK organisations, accounting for about 7.2 million t.CO₂. Considering that the 2024 UNEP Emissions Gap Report (Olhoff et al., 2024) stated that the 2030 and 2035 mitigation potential of buildings based on current policies and the 1.5°C trajectory is 3.2 Gt.CO₂e and 4.8 Gt.CO₂e, respectively, more NZCBs need to be achieved for the sector to reach Net Zero by 2050.

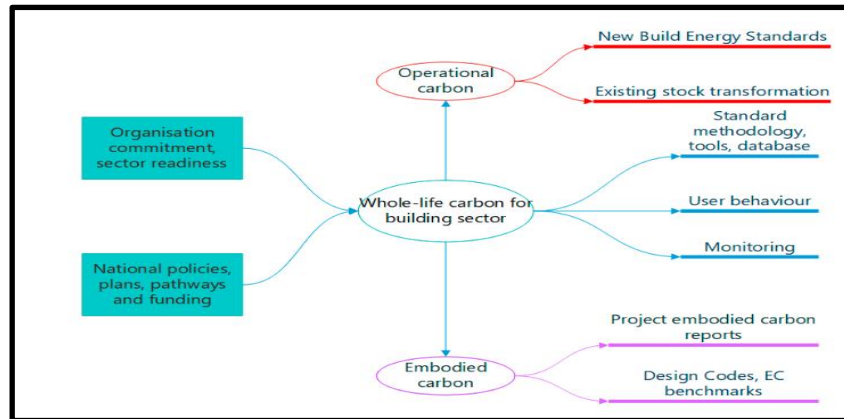


Figure 2.6: National NZCB Policies and Organisational Commitments

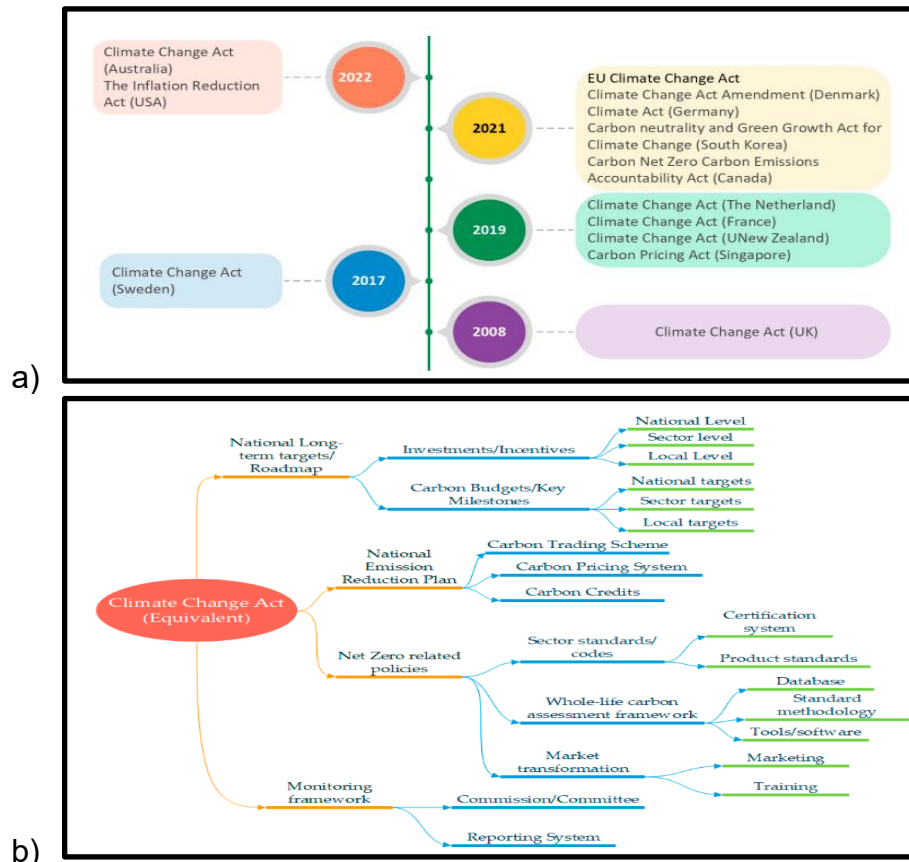


Figure 2.7: Climate Change Legislation in Developed Countries. (a) the timelines and (b) the elements or actions under the legislations.

Several countries have established net-zero targets to reach carbon neutrality, and some countries are making significant progress, while others are lagging when initiatives and policies on NZC in respective jurisdictions are mapped against the components of NZCB policies and actions as presented in Figure 2.6. An evaluation of the status of countries on carbon-neutrality presented the timelines and elements of climate change legislation in the developed countries (Figure 2.7).

There are also significant barriers constraining the uptake of NZCBs at scale, such as high upfront costs of design and construction, lack of awareness and expertise complicated by shortage of skilled sustainability professionals, and inadequate or absence of necessary legislative, policy and regulatory frameworks to enforce energy efficiency and carbon reduction standards. There are also challenges with high cost and complexity of integrating new technologies such as smart grids and energy storage systems, limited access to financing especially in developing countries, low market demand for NZCBs as consumers and businesses are unwilling to pay a premium for the NZCB, cultural factors associated with resistance to change and preference for traditional building methods.

The paucity of supporting infrastructure such as renewable energy systems and waste management technologies also retards the development of NZCBs at scale. Globally, several strategies are applied to reduce energy performance, such as increasing energy efficiency, reducing carbon emissions (operational and embodied), offsetting residual carbon. In addition, metrics and benchmarks to evaluate the effectiveness of the measures on attainment of NZCBs are impacted by various drivers and barriers.

2.2 NET ZERO FRAMEWORKS

Net zero frameworks refer to the structured approaches adopted by organisations, governments and multilateral entities, and applied singly or in combination, to balance GHG emissions by specified target dates (2050 in most cases). The frameworks aim to align individual actions with the 1.5 °C trajectory envisaged under the Paris Agreement. The frameworks reported in literature define the pathways and strategies required to reach Net Zero Carbon emissions by a target year and were broadly classified into policy and sector-specific (institutional) frameworks. The former refer to pathways underpinned by the work of the IEA and UNEP and adopted in the climate and net zero legislation and policies of countries, and multilateral and professional organisations. The latter relate to science-based approaches that guide organisations in setting targets for reducing emissions to reach net zero (by 2050 in most cases) and managing climate risks. In (Dursun & Alkurt, 2025) the imperative of achieving net zero through deep decarbonisation is emphasised despite differences in the amount, speed and timing of carbon emissions among countries due to the principle of “Common but differentiated responsibilities”, and among sectors due to the diversity in access to, and cost of technologies.

The existing policy frameworks include the ISO Net Zero Guidelines (ISO-IWA 42, 2022) for policy making by governments and the Net Zero Investment Framework (NZIF) which is used by investors to ensure decarbonisation of the economy by aligning existing investment portfolios with the goals of the Paris Agreement and increasing investments in the range of climate solutions that enable the energy transition. Institutional frameworks from professional bodies and multilateral entities such as WGBBC, are domesticated in respective jurisdictions by the local networks of the entities. An example is the UK Net Zero Carbon Buildings Framework (UKNZCBF), an adaptation of the WGBBC Net Zero Commitment principles (WorldGBC-ANZ, 2023) to the UK. The UKNZCBF advocates reduction first; reduction of energy demand through efficiency measures before considering offsetting. In addition, UKNZCBF recommends that buildings must achieve net zero carbon for operational energy; balancing the energy used in heating, cooling, lighting and other operations with onsite renewables or verified off-site renewables, in addition to reduction of embodied emissions through sustainable materials and construction processes.

In addition, professional bodies and government authorities such as the UKGBC, CIBSE, and the Greater London Authority (GLA) also defined Net Zero trajectories in form of the “Net Zero Commitment”, the CIBSE Carbon Hierarchy, the GLA Plan, and the PPM pioneered by the Dutch Green Building Council. PPM defines the trajectory of energy performance targets required for commercial buildings to reach Net Zero in 2050 through a 60% reduction in “whole building” EUI between a baseline year and 2050 (Paris Proof Year). Further to this objective, the UKGBC target recommended a minimum OR (grade B40) in the interim period (2030 – 2035) for commercial buildings that target to reach Net Zero by 2050. The framework of the Paris Proof approach was originally developed to align office buildings with the Paris Agreement’s goals but is now applied to other typologies..

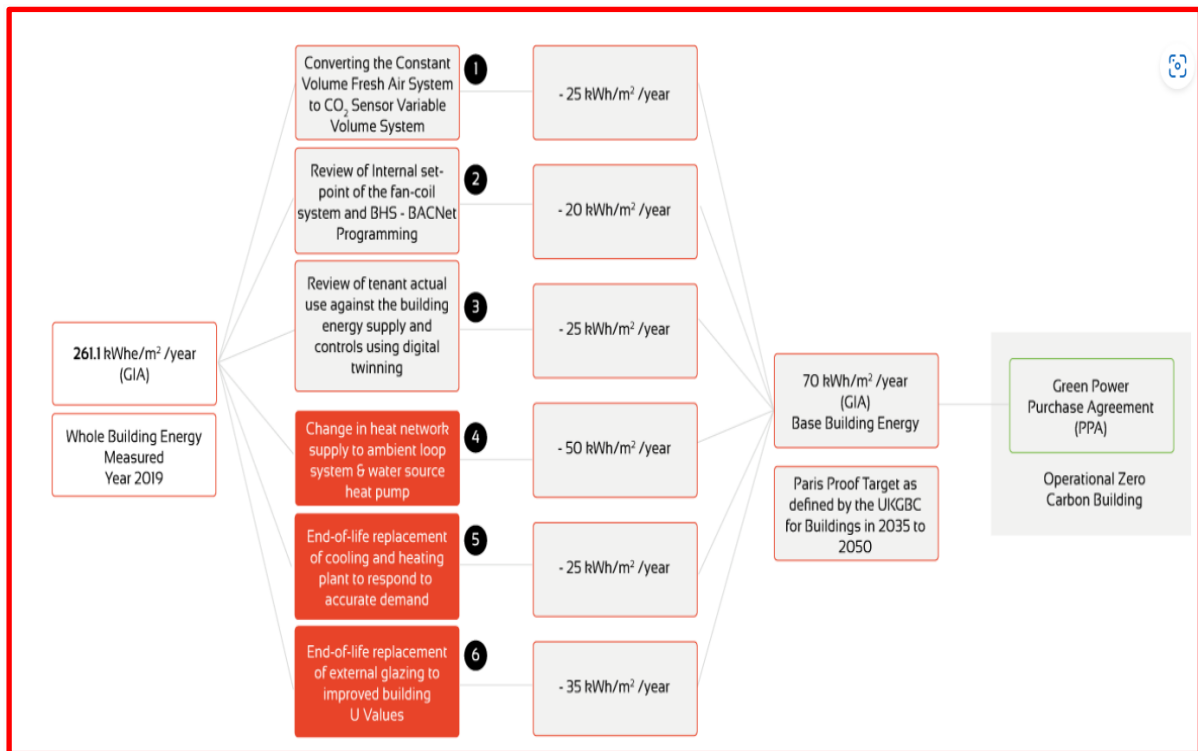


Figure 2.8: Case Study Application of PPM(Kings Cross Estate London).

The PPM was applied to “Kings Cross Estate” London using the pathway in Figure 2.8 and envisages to reduce the EUI from 261 kWh_e/m²/year to 70 kWh_e/m²/year of the GIA between 2021 and 2050.

Net Zero Initiative (Dugast, 2020), which provides companies with a methodology to organise climate action and maximise contribution to global carbon neutrality, Examples of institutional trajectories and net zero target dates are the Brunel University of London (2040), Radisson Hotels Group (2050), Accor Hotels Group (2050) and the Federal Republic of Nigeria (2060). The Net Zero framework specific to the hotel industry, outlined in the net zero methodology for hotels (Greenview, 2021) comprises (a) measurement of extant energy use to create a baseline for measuring net zero progress, (b) delineation of emission boundaries; Scope-1 (direct emissions), Scope-2 (indirect emissions from purchased electricity), and Scope-3 emissions (indirect emissions from related offsite activities), (c) development of decarbonisation pathway of five-yearly milestones, (d) implementation of EEMs, (e) onsite renewable generation or purchase of verified offsite renewable offsets, and (f) carbon offsetting. The EnB provides a quantitative reference for objectively tracking EnP savings and EE improvements, over a definite period, before and after implementation of EnP actions and EEMs.

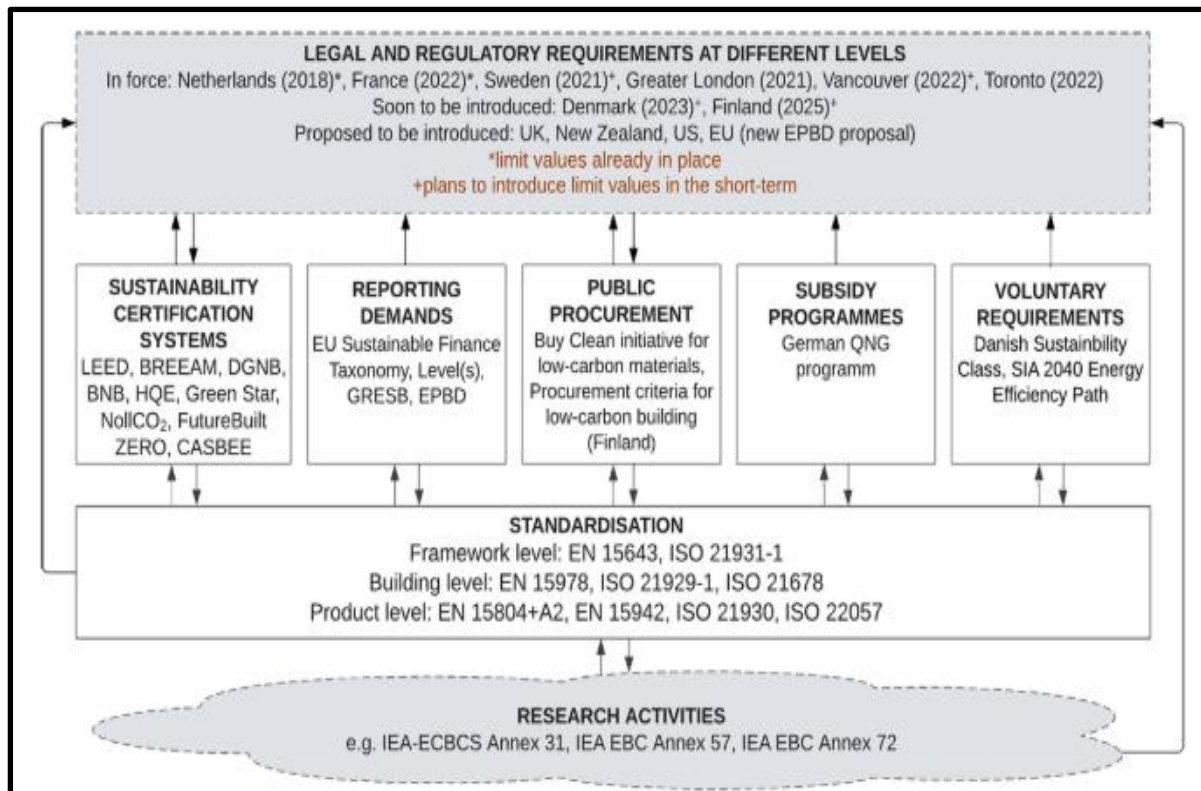


Figure 2.9: Summary of Developments on Embodied Emissions (Lützkendorf & Balouktsi, 2022)

The infographic of the regulatory, standardisation and research activities on embodied carbon emissions (Figure 2.9) shows that regulatory requirements, standards and research evidence exist, and are being developed, to expand and improve the certification systems, reporting obligations, public procurement policies, subsidy programmes and voluntary requirements for reduction of embodied carbon emissions. Several approaches for characterising and reducing building operational emissions are outlined in the literature. A study of energy consumption and carbon emissions of a cluster (GIA of 159079 m²) comprising residential (47%), commercial (14%), hotel (3%) and office (36%) building typologies reported 11431 t.CO₂ operational carbon emissions, about 29% of which was from the hotel typology with EUI of 232 kWh/m²/year and GIA of 4881m² (Ji & Jones, 2017). As the study was done at a location with a cooling-dominated climate, the result revealed that commercial, office and hotel typologies consume more energy on cooling than heating, while residential typologies are consuming more energy for heating than cooling.

Table 2.1: Extract of Sectors and Subsectors covered in the UKNZCBS

Sector	Subsectors that may exist within this sector
Commercial Residential	Student Residences, Care Homes
Culture and Entertainment	Performance (e.g., theatre, cinema, opera house), Collection (e.g., library, visitor centre, museum, gallery), Archives
Data Centres	Low-Utilisation (<50% utilisation of m ² of IT space), High-Utilisation (≥50% utilisation of m ² of IT space)
Healthcare	Acute Trust, Care Trust, Community Trust, Mental Health & Learning Trust, Ambulance Trust
Higher Education	n/a
Homes	Single Family Homes, Flats
Hotels	n/a
Offices	General, Call Centres, Trading Floors
Retail	Supermarket, High Street Units & Department Stores, F&B Without Catering (i.e. only cold/hot drinks or cold food, no on-site kitchen), F&B With on-site Catering (e.g., restaurant, pub, fast food with on-site food preparation / catering), Landlord Areas (only used as part of Commercial Centres / Shopping Centres), Warehouse
Schools	Early Years, Primary, Secondary including Special Educational Needs (SEN)
Science and Technology	n/a
Sport and Leisure	Dry, Wet, Fitness
Storage and Distribution	Unconditioned, Conditioned, Cold Store

The foregoing review and other published literature show that in the UK, the policy and institutional net zero building frameworks are being harmonised under the UKNZCBS to reach a unified definition of Net Zero and specification of standardised, performance metrics of limits and targets for building energy demand, carbon emissions, and renewable energy share. The three intensity metrics-EUI, CEI and ECI- are interrelated but focus on different priorities. EUI prioritises the “Fabric First” approach to reduce energy demand and is the primary metric for both the UKGBC-PPM and UKNZCBS frameworks, regardless of mode of generation. Buildings with the same EUI could have different CEIs, as the metric depends on the carbon intensity of the source of energy supply to the building. Hence two buildings, one using natural gas and the other renewable-powered heat pump could have the same EUI, but the former would have a higher CEI than the latter. The ECI metric is influenced by market prices and peak demand charges for energy. Introduction of the ECI metric in this work is a new dimension as the existing net zero frameworks (UKGBC and UKNZCBS) do not include this metric.

Building Energy Performance and Efficiency

Building energy consumption refers to the total amount of energy used to maintain the building services and ensure an acceptable level of indoor acoustic, visual and thermal comfort for performance of the use functions in the spaces of the building. The main reasons for high energy consumption in buildings are the significant proportion of existing “energy inefficient” buildings constructed when energy efficiency regulations were sparse, and the rapid increase in building floor area (IEA, 2021b). Net Zero in buildings is impacted by the Primary Energy (PE) mix (the combination of all energy sources; fossil fuels, renewables, nuclear energy) and the Energy Efficiency Rating (EER) of the building and its systems. A higher EER implies that the building uses less energy to achieve the same or higher level of comfort or functionality. To account for conversion inefficiencies and enable comparison of building energy consumption in the same units (e.g. kWh) across different typologies and energy mixes, conversion factors (published annually in the UK by the DESNZ and DEFRA) are applied to convert PE to Final Energy (FE). The performance rating evaluates the PE and EER for a building by comparison with corresponding benchmark or standard values for a similar (notional or reference) building. The performance rating encompasses metrics for energy consumption and efficiency of systems and is an indicator of compliance with specified codes and sustainability schemes.

Energy Performance (EnP) represents the amount of energy used while Energy Efficiency is the ratio between an output of performance, service, goods or energy, and an input of energy (BS-EN:15900, 2010; BS- ISO: 50001, 2018). The EnP of a building is the measure of the energy used over a period, usually a year, compared to a benchmark value, the Energy Baseline (EnB). Energy Performance Indices (EnPIs) are used to evaluate and monitor energy performance in buildings. EnPIs are quantitative metrics (values, ratios or models) that are accepted as representative of the energy performance and by which the performance improvement, in the form of an Energy Performance Improvement (EnPI) value, can be demonstrated. The quantifiable factors that significantly affect the EnPI and account for Significant Energy Use (SEU) are called “Relevant Variables” and the changes in these variables are accounted for through a process called Normalisation. Hence, an energy efficient building is defined as one which “provides the required internal environment and services with minimum energy use in a cost effective and environmentally sensitive

manner” (Cheshire, 2012). The identification and selection of EnPIs, EnBs and relevant variables, including the Normalisation process, are given in (BS ISO 50001, 2018) and (BS ISO 50006, 2023).

In the UK, the energy performance of new residential buildings is assessed using the Standard Assessment Procedure (SAP) to generate Energy Performance Certificates (EPCs). SAP is based on typical occupancy patterns of dwellings and demonstrates compliance with Part-L1 of the UK Building Regulations (BRUKL). A simplified version RdSAP (Reduced Data Standard Assessment Procedure) adopts a dataset with several assumptions to produce EPCs for existing buildings. In non-residential buildings, the SBEM is used to produce EPCs for buildings less than 1,000 m² GIA, and Display Energy Certificates (DECs) for GIA equal to or greater than 1,000m².

The effect of building design, insulation, climate change, and EER on PE consumption (cooling and heating demand) was studied by several scholars. An evaluation of the effect of different design strategies on heating and cooling demand, and PE use for an apartment building (Tetty, et al., 2016) reported that application of design improvements based on the Passivhaus 2012 and the Swedish BBR 2012 resulted in up to 19-34% reduction in operational PE use, compared to the “as built” PE consumption of 71.6 kWh/m². This result conveys valuable information on the significance of design in reducing PE consumption but cannot be generalised to other building typologies with different load profiles.

In a study of the effect of insulation thickness on PE demand, (Jie et al., 2018) reported that the annual heating demand decreased with insulation thickness while the annual cooling demand remained nearly unchanged with increasing insulation thickness for the case study of a multi-apartment building located in a climate zone with distinct summer and winter, hence the generalisability of the results to similar building typologies located in other climate zones. In terms of the effect of climate change, (Gordić, et al., 2019) reported a 35.7% reduction in heating demand and a five-fold increase in cooling demand for public buildings in Serbia but the future climate scenario was not specified. In (Sadati, 2023) an RCP8.5 future climate scenario projected a 42% rise in cooling load, 36% drop in heating load and 10.5% increase in EUI between the contemporary period and 2079 based on a study of Mediterranean hotels. The study used an RCP8.5 future climate scenario which is not reflective of the

global efforts at reducing building energy consumption and increasing building energy efficiency through implementation of energy codes.

Heating Ventilation and Air Conditioning (HVAC)

HVAC systems in buildings are essential to guarantee energy efficiency and occupant comfort through optimal design strategies, choice of energy conservation methods and use of renewable energy technologies. A five-step HVAC design process for NZEB comprising building load analysis, including HVAC technology selection, energy modelling, system selection and control optimisation is presented in (Tejani et al., 2022), alongside the thermal comfort strategies; 1) passive solar design, 2) thermal mass utilisation, 3) natural ventilation, 4) smart HVAC controls and 5) occupant feedback and adjustment. In (Bruning, et al., 2021), HVAC energy consumption is linked to the cooling and heating loads imposed on the building through the orientation, building envelope, lighting system and appliance loads.

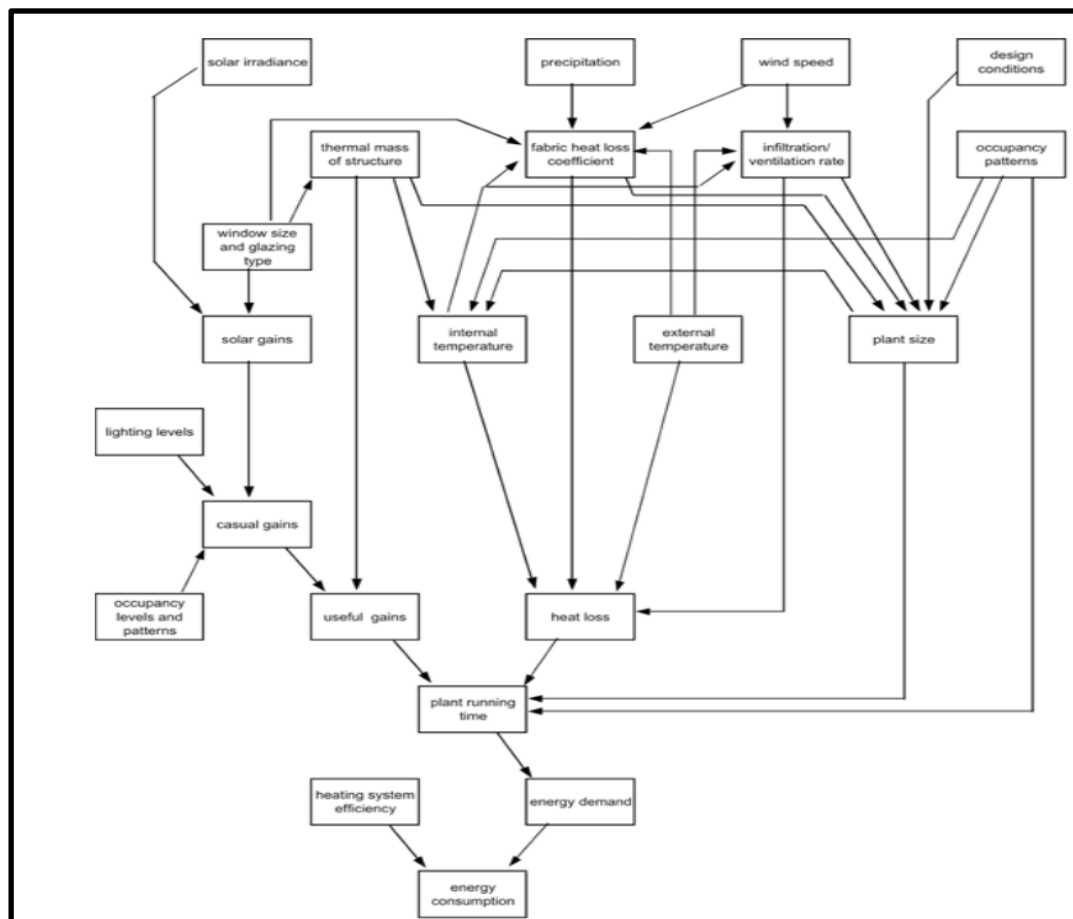


Figure 2.10: Parameters that Influence Space Heating Energy Consumption (Day, 2006)

HVAC systems are estimated to account for approximately 40% of final energy consumption and up to 35% of carbon emissions in commercial buildings. Weather-related energy consumption contributes significantly to energy bills and emissions in heating-dominated climates and is influenced by several interrelated parameters (Figure 2.10). The large number of variables necessitates the use of full dynamic thermal simulation (Day, 2006) to reliably estimate energy consumption (heating and cooling) and CO₂ emissions.

Thermal Comfort and Comfort Scales

Thermal Comfort is defined as the condition of the mind that expresses satisfaction with the thermal environment, based on the equilibrium between heat gains from metabolic activities in the human body and heat losses from the body to the environment (ASHRAE 55, 2010; Jankovic, 2024b). In building energy studies, space temperature is the indoor air (dry-bulb temperature) while indoor thermal comfort encompasses additional parameters to dry-bulb temperature; mean radiant temperature, air speed, humidity, metabolic rate, and clothing insulation. Considering the diverse variables involved, thermal comfort is characterised by the operative temperature – a weighted average of air and mean radiant temperatures that indicates the human perception of warmth or coolth in the space. The combination of indoor environmental, and individual, factors are quantified in comfort scales which dictate temperature set-points, comfort bands, and HVAC energy consumption.

Table 2.2: Summary of Scales used in Thermal Comfort Research

Scale	Parameters	Remarks
ASHRAE 55	Air Temperature, Radiant Temperature, Air speed, Humidity, Clothing and Activity level	Emphasises the balance between factors influencing thermal comfort and provides guidance for different indoor environments. Based on PMV and PPD indices to predict thermal comfort levels.
EN16798-1 (2019)	Same as ASHRAE 55	Based on use of PMV and PPD to predict thermal comfort levels.
HSE Thermal Comfort	Air Temperature, Radiant Temperature, Air movement,	UK Guidelines for thermal comfort in workplaces. Requirement is for thermal

Scale	Parameters	Remarks
	Humidity, Clothing and Metabolic rate	comfort to be maintained for at least 80% of occupants.
Adaptive Comfort Model (CIBSE TM-52)	Outdoor temperature, Indoor temperature, Adaptive behaviours	Based on occupants' ability to adapt to varying temperatures based on thermal history and expectations.
Fanger's Comfort Equation	same as ASHRAE 55	Uses empirical data for detailed thermal comfort analysis and design
ASHRAE-7 (Bedford) Comfort Scale	Air Temperature, Radiant Temperature, Air movement, Humidity, Clothing and Metabolic rate	Based on subjective responses to thermal sensations characterised by the scale and descriptors in Table 2.3.

The summary of scales used in thermal comfort research, adapted from (Nicol, 2013) is presented in Table 2.2. The comfort scales are used to define comfort bands and set-points where a percentage of occupants are deemed thermally-satisfied. These bands are described with Comfort Descriptors and form the foundation of subjective thermal assessment.

Table 2.3: ASHRAE-7, Bedford Comfort Descriptors and Numerical Equivalents

ASHRAE-7 Comfort Scale		Bedford Comfort Scale	
+ 3	Hot	7	Much too hot
+ 2	Warm	6	Too warm
+ 1	Slightly Warm	5	Comfortably warm
0	Neutral	4	Comfortable
- 1	Slightly Cool	3	Comfortably cool
- 2	Cool	2	Too cold
- 3	Cold	1	Much too cold

The main categories of Comfort Descriptors (thermal sensation and thermal acceptability descriptors) are shown in Table 2.3. The latter capture the occupant's perceived thermal state and are prominent in the ASHRAE 7-point scale, ranging from "cold" (−3) to "hot" (+3). These descriptors underpin the PMV model and are embedded in ASHRAE 55 and ISO 7730 (Ortiz, et al., 2017). Acceptability Descriptors such as "acceptable", "just acceptable", "unacceptable" or the Bedford scale's range of "comfortable" to "much too warm or cold" introduce an evaluative dimension by expressing whether the condition is satisfactory rather than describing how warm or

cool an occupant feels in the space. In comparison, acceptability descriptors embed normative judgement and are more directly aligned with design and policy outcomes, as against the subjectivity linked to thermal sensation descriptors. A class of descriptors used in adaptive thermal comfort – preference descriptors (“prefer warmer”, “no change” or “prefer cooler”) is also reported in (Nicol & Humphreys, 2002) and capture the direction of desired thermal adjustment. Comfort Descriptors directly inform comfort bands and HVAC set-points, and their interpretation has energy demand implications hence narrow comfort bands result in increased energy use while wider bands are associated with reduced HVAC demand (Afram & Janabi-Sharifi, 2016). Hence, comfort descriptors quantify comfort and impact on the energy performance of the building. Researchers have reported the relationship between thermal comfort, comfort descriptors and energy performance in several building typologies, climatic contexts and occupancy scenarios.

Physiological and Behavioural Frameworks of Net Zero

Physiological factors describe the responses of the human body to the indoor environment and determine comfort expectations and adaptive actions. In (Dear & Brager, 2001), it is demonstrated that preferred temperatures often diverge from neutral sensation temperatures, especially in naturally ventilated buildings. Preference descriptors therefore reveal behavioural adaptation and expectation effects that sensation descriptors alone cannot capture, and their inclusion in adaptive comfort models, now codified in EN 16798- (2019), reflects a shift toward occupant-centred interpretations of comfort. A review of indoor thermal comfort temperature range and related behavioural adaptations (Arsad et al., 2023) reported that indoor thermal comfort temperature range varies from 15.0 to 33.8 °C, depending on factors like climate, ventilation mode, building type, and age of occupants, and that listed clothing adjustment, fan usage, air conditioning usage, and opening windows as primary adaptive behaviours. The review submitted that the elderly population had the broadest range of indoor thermal comfort temperatures compared to other age groups and attributed this to physiological debility that reduces the ability of older people to detect and respond to thermal stresses, longer experience with acclimatisation and adaptation to broader thermal comfort range, and impairment of thermoregulatory mechanisms, such as sweating and vasodilation, with ageing.

In hotels, the effect of physiology and human behaviour on net zero could be significant as guests often have high expectations on energy-driven services, which conflicts with the incentive to conserve energy. Studies show that Thermal comfort reduces the need for mechanical heating and cooling, hence lowering energy consumption and GHG emissions. In the context of Net Zero, Behavioural Factors are the pattern of human actions and habits that significantly influence energy demand, carbon emissions and cost of energy. Behavioural factors

2.3 BUILDING ENERGY SIMULATION TOOLS

The US-DOE described Building Energy Modelling (BEM) as a physics-based software simulation of thermal loads, building energy use, and building system responses using inputs such as the building use function and operations, geometry, occupancy schedules, thermostat settings and weather data. BEM is applied in HVAC and control design, architectural design, retrofits, building performance rating and building stock analysis. The 3 approaches to BEM are “White-Box Modelling (WBM)”, “Black-Box Modelling (BBM)” and “Grey-Box Modelling (GBM)”. In WBM, variables such as insulation, heat transfer and ventilation are applied in energy equations to solve the heat and mass balance inside a building. In BBM is time-series statistical assessments and machine learning of rules are used to evaluate and estimate the building energy utilisation, using Artificial Neural Networks (ANN), Support Vector Machine (SVM) and statistical regression. GBM is a hybrid of WBM and BBM, and it uses simplified models to estimate the value of baseline energy use as a function of numerous interdependent internal and external factors such as envelope materials, mechanical and electrical systems, solar orientation, climate, occupancy, and equipment schedules. WBM and GBM are achieved with tools such as EnergyPlus™, DOE-2™ and TRNSYS™, and require calibration with historical energy consumption or cost data to improve accuracy of the models. In the UK, there are 29 benchmark categories of buildings, adjusted for weather and occupancy (Field et al., 2008). The weather adjustment improves the accuracy of the Operational Rating and is done automatically within the approved software, using the relevant degree-day data for the assessment period. The list of approved software (last updated in August 2018) is available at: [Approved software for the production of non-domestic Energy Performance Certificates – GOV.UK \(www.gov.uk\)](https://www.gov.uk/government/publications/approved-software-for-the-production-of-non-domestic-energy-performance-certificates)

A Building Energy Simulation Tool (BEST) enables the evaluation of energy impacts across these dynamic interrelated systems. BESTs are applied in design of energy efficient buildings and optimisation of active systems, prescriptive and performance compliance with codes and standards, energy performance certifications and energy retrofits thereby supporting the analyses that inform energy efficiency policies and programs. The practice of estimating modelling input data due to lack of, or incomplete, detailed and high-resolution information about building geometry, envelope properties, HVAC systems, controls, occupancy and schedules, especially in existing buildings is a challenge with using BESTs. In (Mahmoud, et al., 2020), it is explained that this situation arises from the slow uptake of building energy modelling in early-stage design by Architects. This lack of, or incomplete data, leads to propagation of uncertainties through the simulation, resulting to variabilities in the predicted energy use. A review (Yu, et al., 2022) identified human (occupant behaviour and thermal comfort), building (envelope parameters and HVAC system) and weather (historical and future weather) factors as the main sources of uncertainty in the prediction of building energy consumption. Hence, deterministic simulation outputs that do not account for the effect of uncertainties could give a false sense of accuracy. A related challenge with BESTs is the dependence of the accuracy of calibration and validation of models on user-judgement, the time required for calibration and the computational cost of calibrating complex models, all of which could make well-calibrated models produce widely-divergent predictions of energy savings.

In (Desai, 2019), energy modelling tools were partitioned into those for residential building applications such as Beopt™, commercial building uses (eQuest™, OpenStudio™), and related non-building energy modelling tools; RETScreen™ for modelling renewable energy technologies, energy efficiency and conventional combustion technologies, PVWatts™ for estimation of energy production and Cost of Energy of grid-connected solar-PV systems, SAM™- System Advisor Model (behind-the-meter solar-PV systems), and HOMER™ (modelling and optimisation of conventional electrical generation microgrid with high renewable penetration), all of which were the state-of-art software at the time of the presentation. A review (Pan,et al., 2023) reported that BESTs could be classified into five areas spanning the different stages and levels that they are applied; (1) tools for performance-driven design for

new buildings and retrofits,(2) tools for model-based operational performance optimisation, (3) tools for integrated simulation using data measurements for digital twins, (4) tools that support urban energy planning and (5) tools for modelling building-to-grid (B2G) interaction for demand response, but the choice of tool for modelling, and the confidence level of simulation outcomes is dependent on several factors.

On the basis of modelling objective, required fidelity, flexibility and representation of HVAC and control systems, building energy simulation software of two broad categories; EnergyPlus® and Modelica®. The former is a domain-specific, physics-based, whole-building simulation engine that uses predefined component models and quasi-steady-state heat balance method to predict loads, HVAC performance and annual energy usage and has been validated in ASHRAE Standard 140 making it widely-adopted for research and operational analysis (Crawley et al., 2001). EnergyPlus® is limited to compliance modelling, design assessment and operational energy analysis because its modelling scope is constrained to the library of available objects. In contrast, Modelica® is an equation-based, object-oriented modelling language that enables multi-domain, fully-dynamic simulation of thermal, fluid, electrical and control systems using first principles (Wetter, et al.,2011) and allows customisation of HVAC and control systems using IBPSA libraries. EnergyPlus® supports standardised, repeatable building simulations whereas Modelica® enables high-fidelity system-level modelling using custom equations, dynamic behaviour and control. An EnergyPlus®-based simulation engine was selected in this study because the scope was whole-building simulation.

A directory of Building Energy Simulation Tools lists IESVE™ and DesignBuilder™ among software with whole-building simulation capability for commercial buildings. IESVE™ integrates compliance, daylighting, HVAC, LCA and costing modules within a unified commercial interface making it widely-used in the UK for TM54 Building Regulations compliance assessments and Building in a singles commercial interface (IESVE-BPM, 2023) while rapid early-stage modelling is preferred in DesignBuilder™ (Attia et al., 2012). The current study focused on investigating energy and carbon reduction across passive and active elements of an existing building to determine viable net zero pathways, hence IESVE™ was selected for its contextual suitability.

2.4 SIMULATION CALIBRATION STANDARDS

Calibration is the process of modifying or fine-tuning the inputs to a model to correct the output so that it closely matches the actual performance. Energy models are calibrated to reconcile the systematic mismatch between simulated and measured energy performance and to enhance the credibility of models for decision-making. Calibration uses empirical data to constrain model behaviour and improve alignment between design intent and actual operational performance, thereby enabling a more accurate estimate of baseline consumption, evaluation of the impact of EEMs and avoidance of systematic over- or under-estimation of energy savings (Raftery, et al., 2011). Calibration, supported by sensitivity analysis enables the identification of parameter combinations that satisfy the goodness-of-fit criteria. In addition, calibrated simulation is a recognised approach for whole-building measurement and verification with specified statistical thresholds that calibrated models must meet when used to support energy and carbon savings claims and investment decisions. Overall, Calibration assumes that the unobserved/latent parameters are responsible for the discrepancy between simulation and measured output. In a recent review of 50 papers on “calibration of building energy models”, (Chong, et al., 2021) showed that weather parameters were the most common observed inputs used for calibrating Building Energy Models (BEMs), followed by, in order, Infiltration Rate, HVAC Fluid Temperature and Flowrate, Equipment and Lighting Electricity, Supply Air Flowrate, Occupancy and material properties. Therefore, depending on the objective of the calibration, the most influential parameters affecting the specific outputs concerned are selected for fine-tuning to create a match between the two data sets, improve transparency, reduce uncertainty, and ensure models are fit for the intended purpose irrespective of the calibration standard or platform adopted for the model.

Energy model calibration is mainly based on ASHRAE Guideline 14 and the International Performance Measurement and Verification Protocol (IPMVP). In ASHRAE Guideline 14, statistical goodness-of-fit metrics (NMBE and C_v RMSE) are used as benchmarks for model acceptance particularly in retrofit and, measurement and verification (ASHRAE-14, 2023). In IPMVP, four standard measurement and verification options – A through D- that differ in measurement scope, data intensity, cost and accuracy are applied to select an appropriate measurement and verification approach for the model. In (Webster et al., 2015), the scope of each option is

described, with Option-D specified for calibrated computer simulation of component or whole-building energy consumption to determine energy savings. In addition to ASHRAE Guideline 14 and IPMVP, the IEA Energy in Buildings and Communities (IEA-EBC) programme annexes 58 (Strachan et al., 2016) and 71 (Kersken & Strachan, 2021) provide methodological and contextual guidance for model calibration, validation, and uncertainty analysis. Technically, energy model calibrations rely on EnergyPlus™-based platforms that are increasingly adopting probabilistic and reduced-order modelling techniques to address uncertainty and scalability limitations.

In spite of the documented utility of energy model calibration, it remains methodologically challenging. A major limitation arises from incomplete and uncertain observational data as calibration is sometimes performed with coarse data that constrains model parameters and masks their internal dynamics. The uncertain inputs in energy models- infiltration rates, internal gains, occupancy schedules- undermine confidence in the physical interpretation of their meanings due to non-identifiability and equifinality, whereby multiple parameter sets can satisfy accepted goodness-of-fit criteria while representing different physical realities. Calibration also risks overfitting to historical conditions, producing models that reproduce past energy performance but perform poorly under changing climate, occupancy or EEMs. There are several documented works on alternatives to, and proposed solutions to overcome the challenges with energy model calibration.

2.5 EMPIRICAL BENCHMARKING APPROACHES

Benchmarks are standard reference values for comparing the measured performance attribute(s) of a device, process, facility, or organization to itself, its peers, or established norms, with the goal of informing and motivating performance improvement. Empirical benchmarking is the systematic comparison of parameters using actual observed data to evaluate the relative performance of systems against peers or defined reference standards. Empirical benchmarking is data-driven, relies on measured or disclosed evidence, and compares prior performance and measurable commitments to produce relative assessments. Hence, as inferred in the UK Infrastructure and Projects Authority Benchmarking Guidelines (UK-IPA, 2018) a benchmarking approach is considered empirical if it uses observable input data, is based on comparative logic; peer benchmarking (system versus system), system versus of average of systems, and system versus external reference standard. In

addition, the approach must be replicable (deliver the same outcome when the same rules and data are applied). Empirical benchmarking enables accountability, comparability, supports regulatory enforcement and supervision, and exposes gaps between commitments and outcomes. Benchmark categories are the major functional groupings that provide an indication of the energy performance of a building in relation to applicable typological characteristics such as space usage, operating schedule, building services, occupancy, etc.

Empirical benchmarking contrasts to model-based benchmarking which compares simulation outputs to standard building models, as in the “Notional Building Concept” of the UK-NCM. It also differs from Normative Benchmarking and Asset-Rating, which entail compliance with energy codes, and theoretical performance, respectively. Examples of model-based benchmarking is in CIBSE TM 46 (Field et al., 2008), which gives EUI and emissions benchmarks for 29 asset categories, with hotels having $EUI_{el} = 105 \text{ kWh/m}^2$, $EUI_{th} = 330 \text{ kWh/m}^2$ and carbon emissions benchmarks of $120.5 \text{ kgCO}_2/\text{m}^2$ based on 2008 grid emission and PEF. The values in CIBSE TM-46 have a practical knowledge gap because current improvements in efficiency of energy conversion technologies and reduction in grid carbon intensity resulted in significant deviation between corresponding current and previous values. Furthermore, the CIBSE-TM46 values did not disaggregate the building categories into respective features, hence there are overlaps in borderline values of EUI when assets within the same category are evaluated at finer granularity. Normative benchmarking is exemplified in the benchmark data collated as part of the UKNZCBS which characterises best-practice operational energy performance EUI of $54 - 123 \text{ kWh/m}^2/\text{yr}$ based on GIA for 3-Star hotels (Anderson et al., 2024) and EUI reduction from $180 - 120 \text{ kWh/m}^2$ between baseline and PPT year, for achievement of net zero. The CHSBI is also a normative benchmark based on a detailed categorisation of hotels according to star-level and whether they are resort- or non-resort hotels. CHSBI indicates that 3-star hotels in London UK (Ricaurte & Jagarajan, 2024), have mean carbon emissions and EUI of $45.03 \text{ kgCO}_2/\text{m}^2$ and 240 kWh/m^2 , respectively. Asset Rating benchmarks occur in two distinct areas in the UK; energy performance of buildings and financial and investment. The foregoing benchmarks have a theoretical gap as the metrics fail to address the cost of energy, a key enabler of energy equity in the “Energy Trilemma” of security, accessibility and affordability, and sustainability.

This work introduces a novel metric, the “Energy Cost Intensity, ECI (£/m²)” as an indicator of the affordability of energy along the Net Zero Trajectory.

Metrics and indicators are quantitative, qualitative or binary variables that can be measured or calculated to quantify performance, quality or other attributes to enable evaluation and judgement based on standards (BS ISO 50006, 2023). In the context of building energy and carbon performance, (Bannister & Hinge, 2006), recommended that empirical benchmarks of buildings should be based on the median of the parameter of interest. In addition, the authors emphasised the need to define Normalisation Factors (corrected to appropriate parameters) as “a common basis of comparison that allows the efficiency-related issues (such as poor plant, maintenance or operation) to be differentiated from primary factors (such as building size) or operational factors (such as hours of servicing)”. The authors advised that when normalising for the issue of size, relevant variables that are linked to the productive function of the building of the building should be used. As an example, hotels should be characterised in terms of beds rather than floor area, as it is the beds in both cases that are associated with production, rather than the floor space. This normalisation approach does not align with the floor-area normalisation that specify the energy and carbon metrics for monitoring regulatory compliance. Therefore, the use of floor-area normalised metrics for benchmarking net zero is adopted in this work to overcome this limitation.

The imperative to improve energy efficiency towards Net Zero, and proof net zero claims motivated research on applicable metrics in many jurisdictions and across building typologies, especially considering the effect of climate change. The divergence in site and source EUI reported for buildings located in cities across North America, Asia and Europe (Parkin, et al., 2020) indicated that site EUI is a more acceptable metric than source EUI. In buildings, net zero metrics are quantitative measures applied to assess and track the energy consumed, carbon emissions and renewable energy uptake to enable achievement of net zero (NZE or NZC) in 2050, compared to benchmarks. Four main metrics are identified; energy efficiency, electrification, renewable electricity and GHG emissions metrics and it is recommended (USEPA, 2022) that metrics should be selected to ensure energy efficiency, simplicity (each metric to measure one variable), focus on actions that are within the control of building owners, encourage efficient electrification, and be

aggressive with a clear compliance path. Furthermore, metrics should be applicable to all buildings in the typology, not require costly investments in new equipment and services, and reflect local factors such as climate, occupancy schedules and patterns and carbon intensity of the electricity grid. These measures ensure that verifiable data is available for applying the metrics and that there is a standard normalisation approach.

In the UK, benchmarking gained prominence under the EPBD, as part of the DEC scheme, which mandatorily required a DEC to be produced for public buildings with floor areas greater than 500 m² that are frequently accessed. The OR on a DEC is based on the comparison of actual consumption of a building to the benchmark energy performance of similar typologies. The UKNZCBS defined two types of operational energy metrics for different building sectors and sub-sectors; Pass/Fail (Mandatory) and Reporting metrics, and used a hierarchical framework to categorise buildings and spaces as sectors and sub-sectors with sectors indicating the main use functions that are $\geq 70\%$ of the building NIA, and sub-sectors being servant areas of the building that are $\geq 10\%$ of NIA and have different use functions from the master typology (Anderson et al., 2024). In this sense, mixed-use buildings are classified as those with several areas $\geq 10\%$ of NIA and having different use functions.

The robustness of empirical benchmark categories was observed to be skewed towards higher electricity consumption and lower fossil thermal energy consumption due to changes in energy use of building typologies and climate (Bruhns, et al., 2011), necessitating investigation of the factors that compromised the robustness of the benchmarks and interrogation of the benefits and limitations of existing benchmarking methods. Two broad fundamental empirical benchmarking approaches, top-down and bottom-up, were identified. The former refers to the formulation of benchmarks using the overview of a building, without details of the sub-systems, while the latter entails specification of lower-level system information to enable a more precise overview of the building. In (Hong et al., 2013), the Top-down approach was used to benchmark the energy performance of 14000 primary and secondary schools in England and Wales using descriptive statistics to derive typical and good practice benchmarks and Artificial Neural Networks based on an analysis of the factors that contribute to energy consumption.

An application of the Top-down benchmarking approach in commercial buildings is the Cornell Hotel Sustainability Benchmarking Index (CHSBI), an existing standardised metrics and framework for assessment of environmental, social and economic performance of hotels to enable improvement towards reaching the certification standards of the hospitality industry. In addition to the identified drawback of being a statistical approach that relies on robust and up-to-date data (Hong et al., 2013), the CHSBI does not have the cost metric despite its importance in the decarbonisation planning and decision process of hotels.

In (Burman et al., 2014), Building Physics and Aggregated End-use Bottom-up Benchmarking approaches were applied to four secondary schools in the UK to demonstrate their utility, merits and limitations. Building Physics method uses mathematical equations to estimate a building's energy use based on its physical properties and operating conditions. This can establish a baseline for energy performance, but accuracy depends on the quality of input data and user expertise, while the Aggregated End-use Method calculates energy use by identifying and estimating contributing factors for each end-use. This can help diagnose performance issues but has limitations in predicting total energy use accurately. An example of Aggregated End-use Method is the UK ND-NEED initiative which links building characteristics, with data of actual electricity and gas consumption to provide comprehensive data on energy use and intensity in non-domestic buildings across building sizes and typologies with the aim of enabling evidence-based policy making on energy efficiency and decarbonisation. This study, benchmarked baseline energy consumption against the "Non-domestic National Energy Efficiency Data Framework-2022" (Hemingway, 2022) energy intensity values; electricity (111 kWh/m²) and gas consumption (242 kWh/m²). A practical bottom-up benchmarking approach is also provided in CIBSE:TM63 (Jain et al., 2020) and specifies the data requirements for calibration; 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. In addition, CIBSE TM-63 provides guidelines for simulation and calibration of building energy performance in the operational phase.

In summary, the foregoing review of Top-down and Bottom-up benchmarking approaches highlighted that the former is driven by econometric and technological

data, making it easier empirical and easier to apply at scale. However, and despite its usefulness for benchmarking stock-level net zero targets, the Top-down approach lacks causal insight. On the other part, Bottom-up benchmarking is physics-based with high physical detail and despite its utility in design-stage net zero retrofit analysis, it suffers from the limitations of calibration uncertainties and generalisability of results. Hence, a hybrid of both methods is applied in this study to maximise the benefits in identifying and improving energy efficiency of commercial buildings.

2.6 SOLAR RESOURCE AND MODELLING METHODS

The solar resource refers to the energy that can be harnessed from the sun building and utility-scale photovoltaic (solar-PV) and solar thermal technologies (CSP) systems. The integration of solar resources to existing buildings is motivated by orientation and location, roof condition and structure, energy profile, local climate and weather conditions, storage solutions, regulatory and permitting requirements, financial constraints, and aesthetics. The radiation emitted by the sun (at an effective surface temperature of approximately 5800K) is distributed over a wide range of wavelengths and is referred to as “solar spectral power distribution” or “solar spectrum”. The extra-terrestrial spectrum which includes ultraviolet, visible, and near-infrared radiation (wavelength range from 200–4000nm) is used in engineering applications on earth because 99.2% of the energy from solar radiation is concentrated in this region (Gueymard, 2018), hence the sustained interest in the solar resource for building applications. The environmental benefits, reduction in capital costs over the last decade and low maintenance and operation costs, despite the challenges of variability, intermittence and its low energy density ($1.5 \times 10^{-6} \text{ Jm}^{-3}$) compared to oil (4.5 EJ Jm^{-3}) also endeared solar systems to building applications. Case studies of application of BAPV and BIPV to different building typologies in 6 climatically-diverse locations, (Kong et al., 2023), reported appreciable reductions in (EUI), despite the significance of factors such as building surface area to volume ratio, window-wall ratio, glass Solar Heat Gain Coefficient. The variation and intermittence of the solar resource at any location on the Earth’s surface is determined by astronomical parameters that define solar radiation and the amount that is recorded at terrestrial observatories.

Astronomical Parameters

The relevant astronomical parameters are; (1) Earth-sun distance, (2) declination angle, (3) hour angle, (4) Geographical coordinates/ latitude (5) sun elevation (6) solar azimuth angle (7) Day Length, and (8) Sunshine Duration. The parameters are used in transposition and decomposition models of solar radiation. The Earth-sun distance is the mean of the distance between the position of the Earth and the focus of its elliptical orbit as it revolves around the sun and varies between 144 – 154 million km on 21 December and 21 June respectively. Declination angle (δ°) is the angle between the rays of the sun and the plane of the equator and varies between $+23.5^\circ$ to -23.5° , due to the tilt of the Earth's axis relative to the orbital plane.

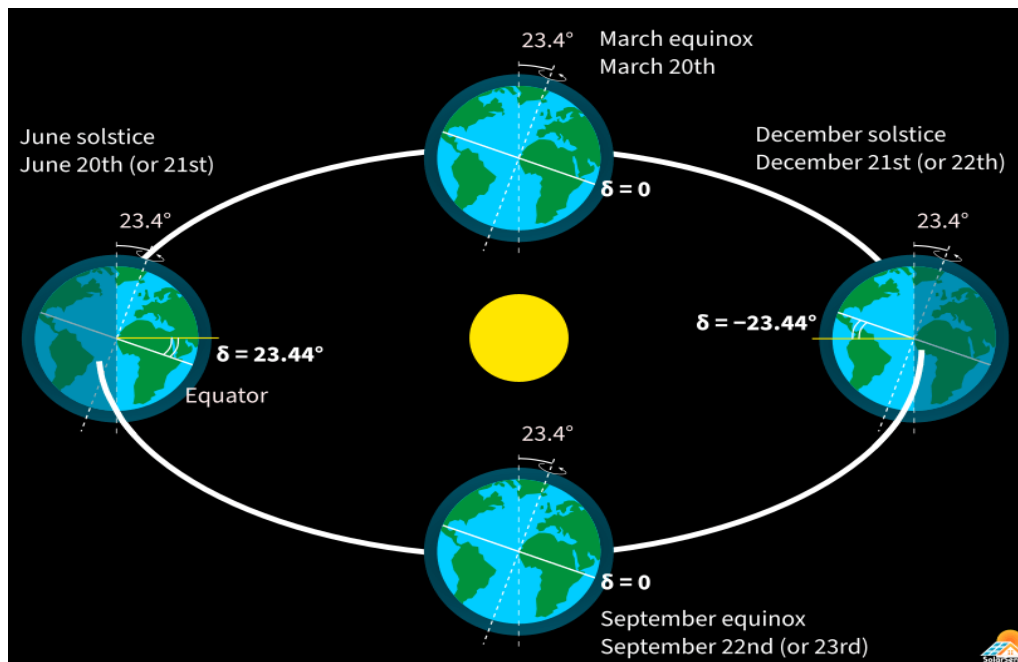


Figure 2.11: Maximum and Minimum Value of Declination Angle (SolarSena, 2021)

The maximum and minimum values of " δ " and the corresponding seasons are shown in Figure 2.11. Summer (June) solstice occurs around 21st June when " δ " ($=23.5^\circ$) and the sun is directly overhead at the Tropic of Cancer, marking the start of summer (longer days and shorter nights) in the Northern Hemisphere. When " δ " is 0° , around March 21st and September 21st, and the length of day and night is nearly equal worldwide. It is the beginning of spring and autumn in the Northern and Southern Hemisphere respectively. The calculation of " δ " using equation 2.1, given by (Cooper, 1969) assumes a circular orbit but is accurate for practical engineering purposes because it gives values of the same order when corrected for the elliptical effects.

$$\delta^0 = -23.45^\circ \times \cos\{0.986 (j + 284)\} \quad 2.1$$

where

j is the day number of the year ranging from 1 on January 1 to 365 on 31 December

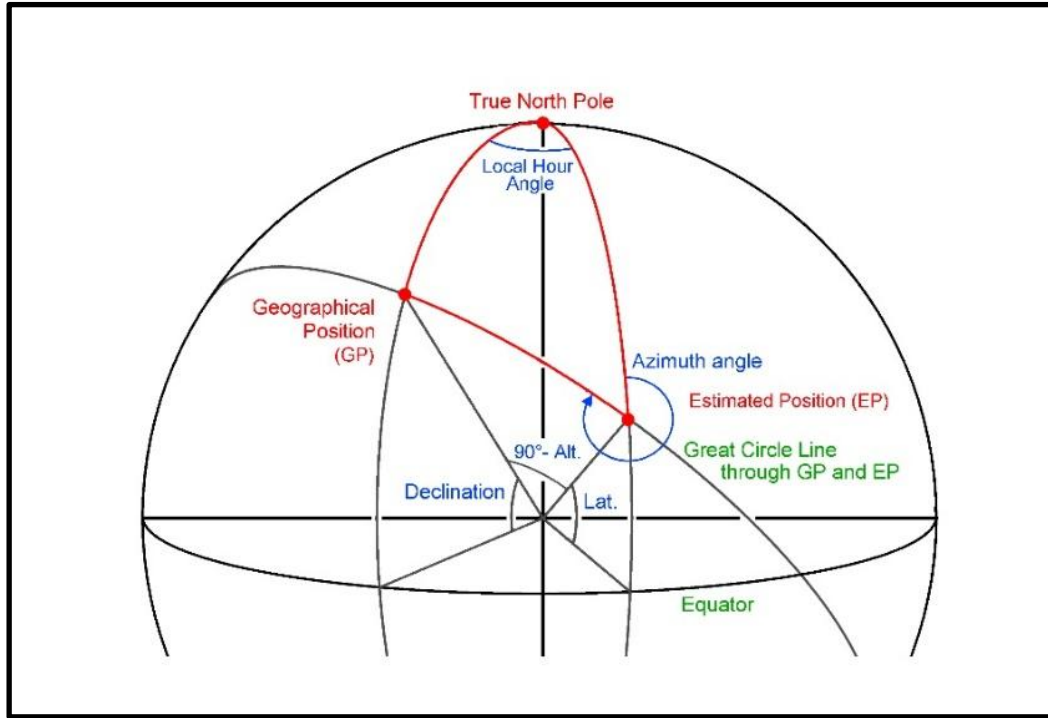


Figure 2.12: Declination, Azimuth, Latitude and Hour Angles (SOURCE: 54eoffrey-kolbe.com)

The astronomical parameters relevant for modelling the solar irradiance reaching the earth's surface; declination, hour angle (ω^0), also called Local Hour Angle, (LHA), azimuth, latitude and altitude are shown in Figure 2.12. The LHA is the angle between the great circle passing through the vertical plane at a place, and another great circle passing through the sun centre (equation 2.2), and it enables definition of the true solar time, T_{sv} , from equation 2.3:

$$\omega = 15 (12 - T_{sv}) \quad 2.2$$

$$T_{sv} = T_l - DT_l + (D_{hg} + E/60)/60 \quad 2.3$$

$$E = 450.8 \sin(2\pi j/365 - 0.026903) + 595.4 \sin(4\pi j/0.352835) \quad 2.4$$

where, " T_l (h)" is the local time, " DT_l " is the difference between local and standard time, " D_{hg} " is the time difference (advance of 4 min per degree), and "E" is the value obtained from the equation of time (equation 2.4). The Sun Azimuth (ψ^0) is the angle between the North direction and the point on the horizon directly below the sun, measured

clockwise from the North. It is a function of “ δ ”, “ h ” and “ ω ”, and is calculated using equation 2.5:

$$\psi = \sin^{-1}\{\cos(\delta) \cdot \sin(\omega) / \cos(h)\} \quad 2.5$$

The sun elevation “ h^0 ” is the angle between the horizontal plane and the sun direction and has a value of ($h=0$) at sunrise and sunset, varying between 90° (zenith) and -90° (nadir). Sun elevation is calculated using equation 2.6:

$$h = \sin^{-1}\{\sin(\varphi) \cdot \sin(\delta) + \cos(\varphi) \cdot \cos(\delta) \cdot \cos(\omega)\} \quad 2.6$$

where, “ φ (degrees)” is the latitude, “ λ (degrees)” is the longitude. The day length, “ S_j (hours)” is calculated using equation 2.7

$$S_j = 24\{1 - \cos^{-1}(\tan(\delta) \cdot \tan(\lambda)) / \pi\} \quad 2.7$$

Sunshine duration, S_e (hours) is given by equation 2.8:

$$S_e = \frac{2}{15} \cos^{-1}(-\tan(\varphi) \cdot \tan(\delta)) \quad 2.8$$

The solar altitude, “ α^0 ”, refers to the angle of the sun above the horizon at a specific location and time, and is given as:

$$\alpha = 90^\circ - |\varphi - \delta|$$

At sunset and sunrise ($\alpha = 0^\circ$) and at solar noon, the sun reaches the maximum altitude.

Extraterrestrial Solar Irradiance

In photovoltaic applications, ESI refers to solar irradiance available in space, usually measured at the interface of space and the Earth’s atmosphere and Terrestrial Solar Irradiance (TSI) is the portion of solar irradiance received on earth. Hourly ESI (I_0) is calculated by equation 2.9

$$I_0 = \frac{12 \times 3.6}{\pi} I_{SC} E_0 \times \left\{ (\sin \varphi \cos \delta) \times (\sin \omega_2 - \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} (\sin \varphi \sin \delta) \right\} \quad 2.9$$

where, “ E_0 ”, the Eccentricity Correction Factor originally given by (Spencer, 1971) as:

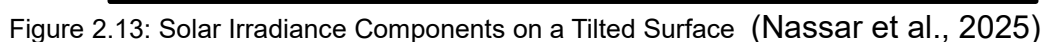
$$E_0 = 1.000110 + 0.034221 \cos \Gamma + 0.001280 \sin \Gamma + 0.000719 \cos 2\Gamma + 0.00077 \sin 2\Gamma \quad 2.10$$

where “ Γ ” is the day angle in radians. A simpler form of equation 2.10, suitable for engineering applications is given by (Duffie, et al., 2020) as:

$$E_0 = 1 + 0.0033 \cos\left(\frac{2\pi j}{365}\right) \quad 2.11$$

$$I_H = I_d + I_b \quad 2.12$$
$$I_H = I_{bN} \cos \theta_z + I_d \quad 2.13$$

$$I_d = CI_{bN} \quad 2.15$$

$$\theta_z = \cos^{-1}(\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \omega)$$


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Furthermore, the annual energy production for parabolic trough plants was found to decrease by 10% for every 10° increase in latitude in the Northern Hemisphere and about 14% in the Southern Hemisphere due to reduced irradiance during winter. DHI is the solar radiation from the sky dome, not including DNI, that has been scattered by clouds, aerosols, and other atmospheric constituents available on a horizontal surface, as measured by a shaded pyranometer with a 180° field of view.

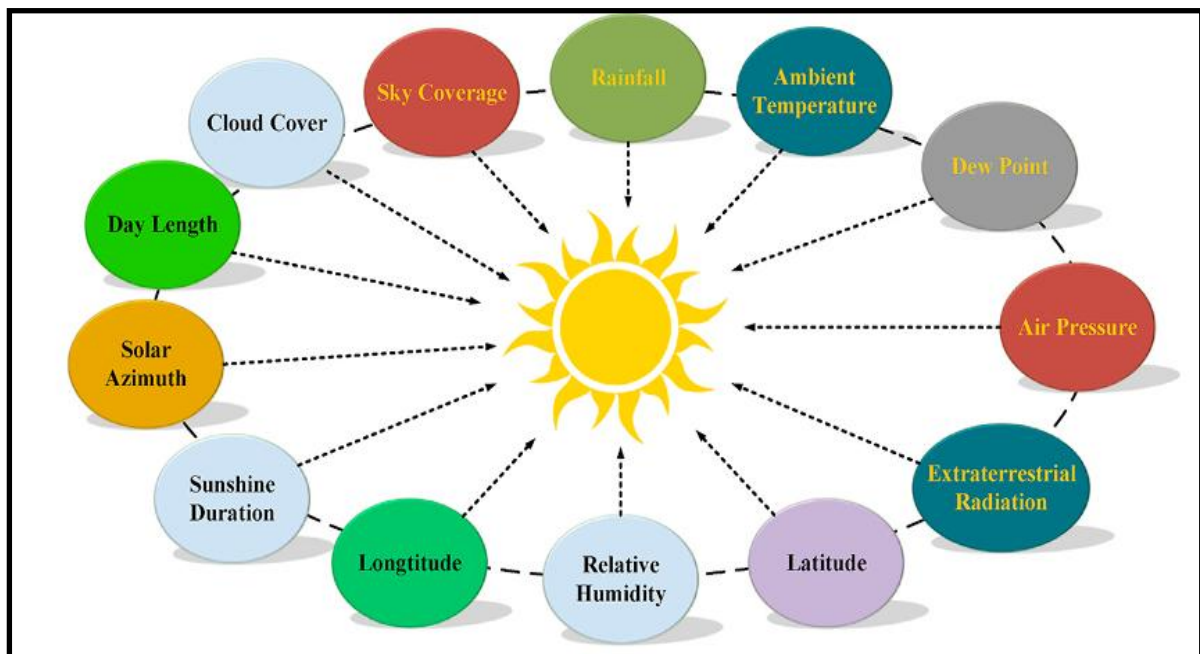


Figure 2.14: Inputs for Solar Radiation Modelling (Gürel et al., 2023)

In the context of building photovoltaic generation, solar radiation models, using the input parameters in Figure 2.14, enable the calculation of electricity generation capacity of solar cells, modules, and arrays at a particular location. A recent review (Gürel et al., 2023) identified four types of solar radiation models; (1) empirical (based on measured data), (2) time series (leverage historical data to forecast future trends), (3) Artificial Intelligence – AI (leverage machine learning algorithms to analyse vast amounts of data and generate models of improved accuracy), and (4) hybrid models that combine two or more approaches.

In summary, three fundamental components of solar radiation at the Earth's surface are required for solar-PV yield assessment and bankability of solar-PV projects (Kleissl, 2013; Good, 2024): (1) DNI, (2) DHI, and (3) GHI. There is appreciable research activity on the impact of DHI on solar-PV yield and optimal solar resource potential when sizing rooftop arrays under the constraints imposed by environmental and meteorological parameters. The estimation of electrical and thermal energy

generated by a solar-conversion system is underpinned by a two-stage modelling framework comprising irradiance decomposition and transposition using underlying SDM and STM formulations, respectively.

Solar Radiation Decomposition and Transposition Models

Solar irradiance decomposition and transposition form the core link between meteorological observations and engineering performance metrics and there is a growing body of literature that ascribes the solar modelling uncertainties to the interaction between decomposition outputs and transposition formulations under variable sky conditions. Solar decomposition is important because the mostly-used anisotropic transposition models and solar-PV devices require DNI and DHI separately, while most measurements provide GHI alone. Hence, decomposition enables the separation of GHI into DNI and DHI for modelling angle of incidence effects, assessment of tracking system performance and representation of anisotropic sky behaviour.

A Solar Transposition Model is used to convert measured or estimated GHI to POA irradiance (monofacial modules) and RPOA irradiance (bifacial modules) to enable the estimation of PV yield and solar-PV modelling in CSP and solar-PV projects. The process involves decomposition of GHI into DHI and DNI, transposition of DHI and DNI onto the tilted surface using geometry and sky-distribution assumptions, and addition of the impact of ground-reflected irradiance (albedo) to the model.

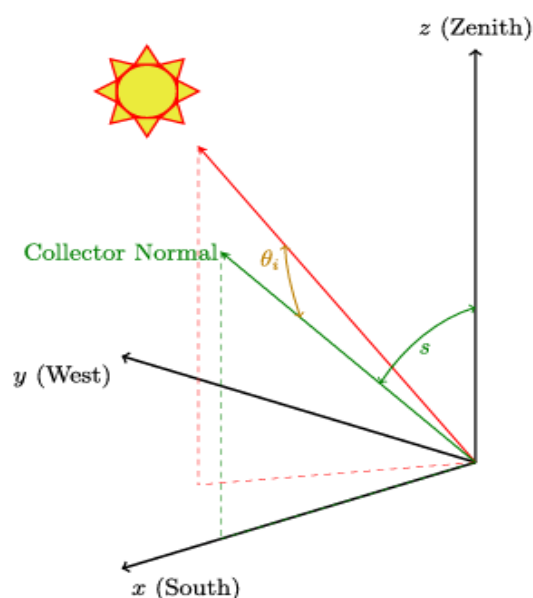


Figure 2.15: Solar Transposition Geometry

There are two broad categories of Solar Transposition Models; Simple Transposition Model (STM) also called Isotropic Solar Model (ISM) and, Sky Diffuse Model (SDM) which is also called Anisotropic Diffuse Model (ADM). As presented in the work of (Kamphuis et al., 2020) and others, solar transposition geometry shown in Figure 2.15 is expressed in general form as:

$$POAI = POAI_d + POAI_{u,sky} + POAI_{u,ground} \quad 2.16$$

Equation 2.17 gives $POAI_d$ as:

$$POAI_d = DNI \cos \theta_i \quad 2.17$$

$$\cos \theta_i = \cos \beta \cos \theta_z + \sin \beta \sin \theta_z \cos \psi \quad 2.18$$

On the assumption of isotropic irradiance, diffuse and ground-reflected transposition factors are respectively accounted as:

$$R_d = (1 + \cos \beta)/2 \quad 2.19$$

$$R_r = 1 - R_d = (1 - \cos \beta)/2 \quad 2.20$$

The equivalent mathematical expressions for equations 2.19 and 2.20 are:

$$R_d = \cos^2 \left(\frac{\beta}{2} \right) \text{ and } R_r = \sin^2 \left(\frac{\beta}{2} \right), \text{ respectively.}$$

Isotropic models assume uniform distribution of diffuse radiation across the sky dome and are characterised by equation 2.20. The formulation of the typical ISM (Liu and Jordan model) reported in (Liu & Jordan, 1961) is denoted as:

$$R_d^{LIU} = \frac{(1 + \cos \beta)}{2} \quad 2.21$$

There are several literature on the origin, geometrical basis of the Isotropic Solar Model (ISM), the validity of equations 2.19 and 2.20, and the appropriate boundary conditions when spatially integrating the sky irradiance. Regardless, ISM is still widely used in solar-PV modelling despite it being unrealistic (Kamphuis et al., 2020), with the formulation of other STMs differing by the modelling of R_d . An Anisotropic Diffuse Model (ADM) or Sky Diffuse Model (SDM) refers to non-uniform sky illuminance and is dependent on sky conditions (clear sky, partly cloudy/variable, and overcast/cloudy conditions), characterised by the “Clearness Index or Cloudiness Coefficient, “k”. An

adaptation of the “King and Buckius” model by (Ideriah, 1981), was used for calculation of GHI on a horizontal surface for the year 1977, using for ($k = 1.0$ and 0.75) in a tropical location (Ibadan, Nigeria). The result showed that for ($k = 0.75$; cloudy sky conditions), the deviation from measured data was less than 15%.

The assumption of isotropic sky conditions in the Liu and Jordan transposition model (Liu & Jordan, 1960), was modified in the subsequent Hay and Davies model (Hay and Davies, 1980), and Perez models (Perez et al., 1988), which assumed anisotropic and hybrid approaches to estimate the components of GHI. In (Xie & Sengupta, 2016), it is reported that the performance of the Perez model gives the best consistent agreement between surface and POA irradiance because it considers anisotropic distribution and diffuse radiation. In spite of the existence of anisotropic sky conditions in reality, necessitating the generation of STMs as improvement of the Liu and Jordan Model (equation 2.21), an IEA report (Forstinger et al., 2023) based on a validation study of radiation models with high quality ground-based GHI measurements from 129 stations worldwide, showed higher deviations in DNI than GHI, confirming the generalisability of solar-PV yield estimation with GHI. A novel Risk Index Theory (RI) introduced by (Nassar et al., 2025) assessed the risk associated with varying the tilt angles for the eight most-referenced transposition models; (1) Klucher, (2) Skartveit and Olseth, (3) Bugler, (4) Perez, (5) Ma and Iqbal, (6) Hay, Davies Klucher and Reindl (HDKR), and (7) Hay. The result for 133 locations in the Northern Hemisphere showed there was increased risk of lower yield as the tilt angle approached vertical and recommended unique tilt angle intervals for all the studied sites.

Consequent on its isotropic formulation, the Liu and Jordan model introduces systematic, non-random errors as the assumption of uniform distribution of diffuse sky radiation across the sky is actually unrealistic, particularly under clear and partly-cloudy sky conditions. The errors are quantified as MBE (or NMBE) and RMSE (or C_v RMSE) to measure the systematic bias between model predictions and measured values (over- or under-prediction) and accuracy and variability of outcomes, respectively. MBE is often normalised as a percentage of the mean measured value. An $MBE > 0$ implies systematic over-prediction, $MBE < 0$ means there is systematic under-prediction, and an MBE of approximately zero suggests little or no bias, but errors may still exist. In (Yang, 2016) computer codes and experimental data were used to predict and evaluate solar radiation on inclined surfaces for 26 transposition

models across 18 case studies from four locations; (a) Lat. 44.05°, Long. -127.07°, Altitude 150m, with Albedo (b) Lat. 39.74°, Long. -105.18°, Altitude 1829m, with Albedo (c) Lat. 53.15°, Long. 8.17°, Altitude 40m, without Albedo and (d) Lat. 1.30°, Long. 103.77°, Altitude 40m, without Albedo. Model performance comparison using linear ranking (NRMSE) and Diebold-Mariano pairwise hypothesis testing showed that the top four families of models are: Perez, Muneer, Hay and Gueymard.

Solar decomposition models introduce errors due to the effect of climate zone, aerosol load, cloud type and season on the empirical relationships between “k” and diffuse fraction (k_d). In (Berrizbeitia, et al., 2020), a high correlation (R-squared values ranging from 0.87 – 0.93) was reported between the monthly-averaged hourly values of “k” and “ k_d ”, for 3 latitude ranges (13-20 °N, 20-42 °N and 50 – 58 °N). Several practice literature and market report up to 8% error from inaccurate estimation of diffuse fraction. Hence, (Hofmann & Seckmeyer, 2017) validated solar-PV models with Baseline Surface Radiation Network data from 28 geographically and climatologically diverse locations and recommended the use of irradiance decomposition models with maximum DHI in solar-PV yield estimation. The sensitivity of modelled PV yields to the choice of decomposition and transposition models is particularly significant to the UK context due to high latitudes (50 – 60° N), a temperate maritime climate, high proportion of diffuse irradiance (> 60%), frequent overcast and intermediate sky conditions ($1.5 \geq k > 0.6$), and low solar elevation angles, especially in winter. In (Muneer, 2007), a comparison of MRM (v1-3), Erbs, Orgill-Hollands, Reindl and ASHRAE decomposition models concluded that the high values of “ k_d ” in the UK makes MRM and Erbs models more stable as errors in diffuse fraction estimation tend to partially offset over long time horizons. Hence, the UK Climate Impacts Programme validated the MRM model using irradiance data for 3 locations in the UK to make future climate projections (Tham, et al., 2009).

The choice of transposition model to be used in the UK is based on comparison of transposition models benchmarked against the Perez model across regions that are climatologically equivalent to the UK. In this regard, the validation of 140 models using over 25 million, 1-minute data points from 54 stations across 7 continents (Gueymard & Ruiz-Arias, 2016) recommended ENGERER2 and SUEHRKE models because both integrate with the workflow of Perez model, with the latter having a bias of less than 10% and RMSD less than 30% in temperate zones. As calibrated models in one region

exhibit reduced performance elsewhere, it is imperative to predict solar yield with decomposition and transposition models that are suitable for the project location. The implication is that Perez transposition model is the benchmark for solar-PV yield estimation, hence its choice for use in this work.

An important consideration in utilisation of the solar resource is the tool selected for planning, modelling, simulation and optimisation of photovoltaic systems prior installation. A survey of practice literature reveals the capability requirements for these tools as; 3D site modelling, shading analysis, energy yield estimation, electrical design, financial analysis and proposal generation are connected in a single workflow in a solar-PV design software tool. In (Rakholiya & Neumann, 2026), reported an evaluation of eight major solar-PV modelling platforms across seven criteria; simulation accuracy and validation, feature depth, electrical design and single-line diagram generation, proposal and sales integration, pricing transparency and value, learning curve and onboarding time, and market coverage and compliance. The authors stated that other tools were validated against Pvsyst™ because it was the benchmark for accuracy due to its certification by NREL, DNV and independent engineering firms. HelioScope™ is cheaper than Pvsyst™, has high simulation depth and validated by DNV to within 1% of Pvsyst™ under similar assumptions. In addition, HelioScope™ generates single line diagrams from electrical design and is cloud-based, which translates to a shorter learning curve of hours to days, as against Pvsyst™ which takes weeks. In the context of the present study which required modelling rooftop solar-PV generation for estimating onsite renewable energy share, the accuracy of HelioScope™ sufficed for its selection.

2.7 MICROGRID TECHNO-ECONOMIC OPTIMISATION

The US-DOE and the International Electrotechnical Commission (IEC) defined a Microgrid (MG) as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act a single controllable entity with respect to the grid”, and can work in tandem with conventional large scale power grids (macrogrids) that are energised from large power plants, or operate in island mode (McGrath & Gomstyn, 2024). In addition to the ability to operate in island and grid-connected modes, microgrids facilitate the integration of renewable technologies and Distributed Energy Resources (DERs), thereby reducing transmission losses and energy costs.

The increasing application MGs to provide power in remote areas, guarantee reliable power supply to critical infrastructure and, enhance energy efficient and sustainable technologies in commercial and industrial facilities necessitated research on approaches to increase the value proposition. This is more so as independent and centralised energy systems are transitioning to decentralised and distributed architecture and technologies, motivated by technical, economic, and environmental sustainability.

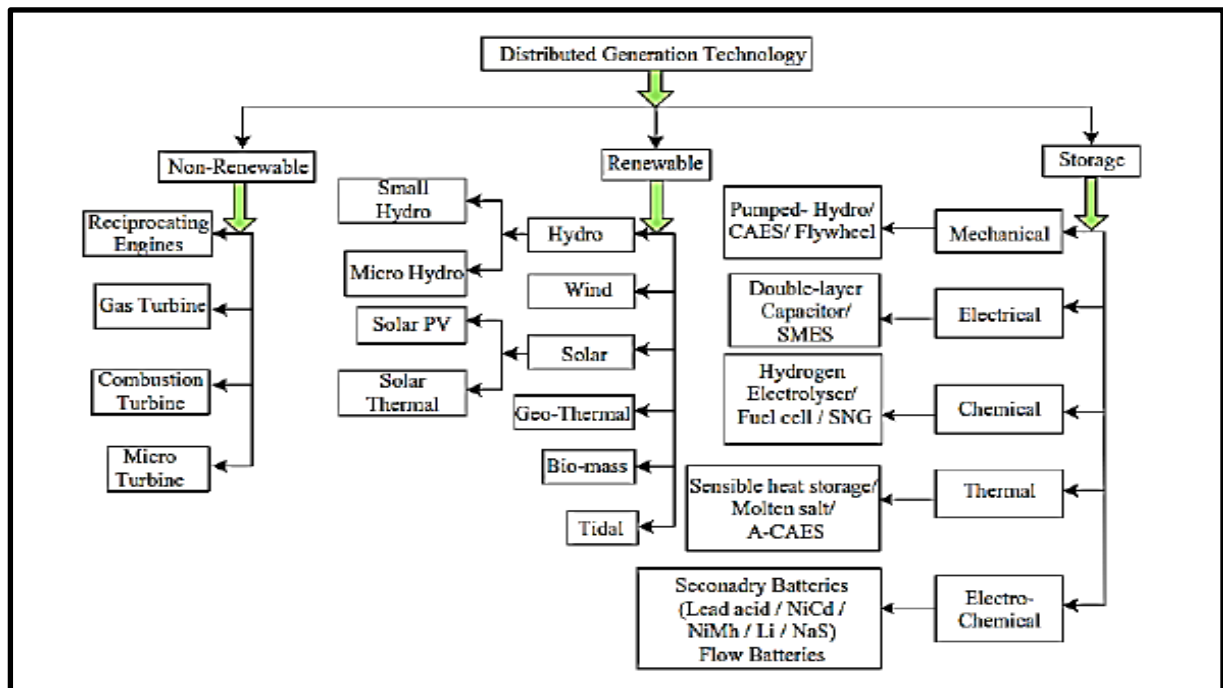


Figure 2.16: Classification of Distributed Generation Technologies (Khetrapal, 2020)

A classification of distributed generation technologies (Figure 2.16), shows options of non-renewables, renewables and storage that can be hybridised in building microgrids to reduce energy intensity, emissions and cost in furtherance of net zero objectives.

Hotel Microgrid Case Studies

There are several hotel microgrids reported in practice literature. In (Hotel Energy Solutions, 2011b), eleven successful, case studies are reported across Europe but none in the UK. Specifically, there are no studies that report performance of hotel microgrids using measured data on energy generation, demand, emissions, and energy cost. In (Vourdoubas, 2024), an outline of the roadmap for net zero hotels included decrease of energy use, increased energy efficiency, use of renewables instead of fossil fuels, and offsetting the remaining carbon emissions. The author also highlighted renewable energy options and energy saving approaches in hotels. The

sustainability and renewable energy approaches proposed included solar-PV, green roofs, solar thermal systems, wind turbines, biomass, geothermal fluids, CHP, fuel cells, heat pumps, district heating. The author concluded that net zero hotels were technically and economically feasible, without providing any empirical data to validate the use of the listed approaches, nor did the study present the theoretical or contextual basis for selection of the recommended renewable energy options.

An earlier study used HOMER® and HYBRIDS® to compare diesel generator-only, renewable energy supply-only, and renewable energy supply/diesel hybrid technologies, and hence the feasibility of individual options supplying a stand-alone 100+ bed hotel in Australia (Dalton, et al., 2009) and concluded that a hybrid diesel/renewable energy source configuration provides the lowest NPC result, Payback of 4.3 years, and resultant renewable fraction of 76%. In comparison to the diesel generator-only configuration, NPC is reduced by 50% and GHG emissions by 65%. The results indicated that wind energy conversion systems (>1000 kW), rather than photovoltaics, are the most economically-viable renewable energy supply option for large-scale operations, as they are more efficient and economical than multiple small-scale systems (0.1–100 kW). In spite of the similarity of results from HOMER® and HYBRIDS®, with HYBRIDS® producing on average slightly higher NPC than HOMER®, the modelling and resulting data from the analysis indicate that RES is technically feasible and economically viable as a replacement for conventional thermal energy supply for large-scale tourist operations. The absence of a detailed design of the renewable energy generation (solar and wind) for the case study created the methodological gap which should be investigated by using renewable system sizing tools to estimate the renewable energy potential of the studied site. Furthermore, an empirical gap was created which requires further investigation because the performance of the microgrid was not validated with actual operational data.

The considerations for selection of options for microgrid modelling include price, capability for system resiliency studies, energy arbitrage modelling, peak-shaving or load response analyses, probability- of -exceedance analysis (P50/P90), reliability coverage reports, utility tariffs and complex rate analysis. A survey (Rituraj et al., 2024) conducted by the IEA on available software tools for optimising microgrids compared HOMER Pro™ and iHOGA PRO+™ on 22 quantitative and qualitative criteria and recommended that selection of software should be based on criteria

that apply to the needs of the project. The commercial microgrid investigated in the current study is grid-connected and is conceived on the basis of site-specific meteorological and economic data, with solar-PV generation and battery storage system, characteristics which inform the selection of the software for modelling and optimisation.

Features					
	SAM	Reopt	DER_VET	HOMER	XENDEE
Resiliency Studies		✓	✓	✓	✓
Peak-Shaving / Load-Response			✓	✓	✓
Reliability / Coverage Probability			✓	✓	✓
Energy Arbitrage Modeling				✓	✓
P50/P90 Analysis	✓				✓
Easy, Complete Reporting	✓	✓		✓	✓
Site-Specific Weather Data			✓	✓	✓
System Optimization		✓	✓	✓	✓
Web-Based Software		✓			✓
Free / Open-Source	✓	✓	✓		
Utility Rates / Incentives Included				✓	✓
Traditional Generation (diesel, gas, coal, etc.)	✓	✓	✓	✓	✓
Available Financial Models					
	SAM	Reopt	DER_VET	HOMER	XENDEE
Residential & Commercial (behind-the-meter)	✓	✓	✓	✓	✓
Residential & Commercial (front-of-meter)	✓	✓		✓	✓
Power Purchase Agreements (PPAs)	✓			✓	✓
Available Renewable Sources					
	SAM	Reopt	DER_VET	HOMER	XENDEE
Solar PV	✓	✓	✓	✓	✓
Battery Storage	✓	✓	✓	✓	✓
Thermal Storage		✓	✓	✓	✓
Wind	✓	✓	✓	✓	✓
Hydropower				✓	✓
Solar Water Heating	✓	✓			✓
Fuel Cells	✓			✓	✓
Geothermal Power	✓	✓		✓	✓
EV Charging			✓	✓	✓

Figure 2.17: Microgrid Modelling Software Comparison Matrix (Zoucha, 2022)

In Figure 2.17, a summary decision matrix for microgrid software options outlines the features, financial models, and renewable resources that inform the choice of HOMER Pro™ for this work. The technical capabilities, financial models and renewable sources of the study align with the capabilities of HOMER® (energy arbitrage modelling, system optimisation, utility rates/ incentives, traditional generation, behind-the-meter commercial, solar PV, and battery storage).

2.8 UNCERTAINTY AND SENSITIVITY METHODS

Sensitivity analysis (SA) and uncertainty analysis (UA) have become central to building energy modelling (BEM) because they expose how uncertain inputs (weather, occupancy, envelope, systems, controls) propagate to key outputs such as annual energy use, peak loads, and overheating risk. A recent review (Roka et al., 2025) show a rapid growth in SA/UA applications, from single-building studies to urban building stock models and machine-learning-based surrogates. UA quantifies how uncertainty

in inputs propagates in outputs, expressed as probability distributions, confidence intervals, and exceedance probabilities. On its part, SA decomposes the output variability to identify which inputs matter most, guiding data collection, calibration, design optimisation, and decision-making.

In (Rivalin et al., 2018), it is reported that SA comprises local, global and screening methods. In local methods, one parameter varies at a time and the others are set, an example being differential sensitivity analysis methods implemented in a BESTs. Global methods quantify the influence of the parameters on their whole variation range to determine their impact on the output, ordering them by their level of importance. Examples are linear regression methods (Pearson, Spearman, SRC-Standard Regression Coefficient, and PRCC-Partial Rank Correlation Coefficient), and Variance Decomposition Indices (Sobol). Screening Uncertainty Analysis methods cover all the input space to determine the most influential inputs qualitatively with a few simulations, an example of which is the Morris method.

UA methods consist of Monte Carlo, Latin Hypercube Sampling, Quasi-Monte Carlo, Importance Sampling, Directional Sampling, FORM-First Order Reliability Method, and SORM- Second Order Reliability Method. Similarly, a review of UA methods (Tian et al., 2018) discussed 3 main forward UA approaches for building energy assessment; Monte Carlo Sampling-based Simulation, (b) Non-sampling Methods, and (c) Non-Probabilistic Methods, including Interval Analysis, Fuzzy Theory, and Dempster-Shafer Evidence Theory. The authors recommended that the choice of UA method should depend on the purpose and specific application of the building project, as well as the availability of data and computational resources.

The utility and flexibility of building energy models for design, retrofit and policy evaluation depends on UA-SA workflows because they reveal the true variabilities in model parameters, identify the influence parameters, and provide confidence intervals and probability distributions to avoid reliance on point estimates. Hence UA-SA workflows transform the modelling process from a deterministic prediction exercise into a rigorous and transparent framework. Regardless, (Roka et al., 2025) reported several challenges associated with UA-SA workflows such as computational cost, generic default characterisation of key inputs (infiltration, internal gains, occupancy schedules, and control strategies), limitations on transferability of UA-SA workflows due to variation of important parameter values and ranges with climate zone, building

typology, and regulatory context parameter importance, absence of robust empirical distributions to characterise occupant behaviour and controls, among others. A recent review of 50 papers (Chong, Gu and Jia, 2021) on “calibration of building energy models” showed that weather parameters were the most common observed inputs used for calibrating building energy models, followed, in order, by Infiltration Rate, HVAC Fluid Temperature and Flowrate, Equipment and Lighting Electricity, Supply Air Flowrate, Occupancy and Material Properties.

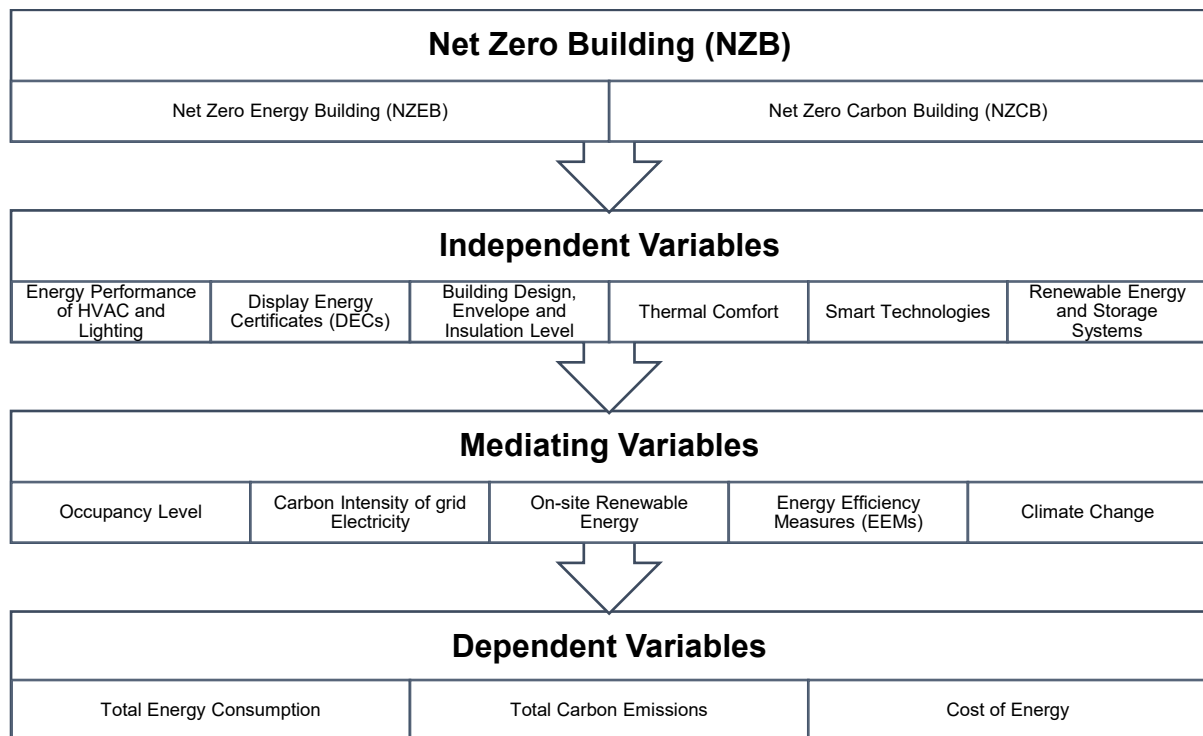


Figure 2.18: Net Zero Building Sensitivity and Uncertainty Review Framework

A survey of several literature reveals the net zero context of UA-SA in mid-range UK hotels, is influenced by independent and mediating variables (Figure 2.18) encompassing highly uncertain operational inputs such as occupancy schedules (guest arrival/departure patterns, seasonal variation), with structural uncertainties; internal gains (lighting, equipment, and occupants), infiltration and ventilation rates, domestic hot water demand profiles, weather variability (including future climate scenarios), and model-form uncertainties like HVAC control strategies, especially guest-room set-point overrides. In whole-building energy simulation, global SA methods are used to rank influential parameters while UA adopts probabilistic sampling to generate distributions of outputs, enabling risk-based interpretation of energy performance and compliance margins.

Several studies used UA-SA workflows to investigate aspects of energy performance, carbon emissions and energy cost in commercial buildings. In (Rivalin et al., 2018), the aim of identifying a consumption threshold for an Energy Performance Contract on a 40,000 m² office building in Nantes, France was studied by coupling thermal simulations with various UA-SA methods. The study compared screening and differential sensitivity methods to reduce the number of inputs, analysed various uncertainty analysis methods to set an appropriate energy consumption threshold, and identified the most critical contributors to energy levels through sensitivity analyses in various input spaces, to create the measurement plan, select an appropriate optimal computation time budget and expected accuracy. The study outlined the process for execution of the UA-SA workflow and reported a consumption threshold of 115 MWh and a coefficient of variation of the desired Confidence Interval of 0.1.

Building Occupancy

Building occupancy refers to the number of people that occupy a building and the way they use the space. It is characterised by the occupant density (number of people per unit area of the building), occupancy patterns (the times and durations when people are present in the building) and usage types (the activities and functions performed by the occupants). Annex 66 of the IEA Energy in Buildings and Communities (IEA-EBC) project (Yan & Hong, 2018) defined energy-related occupancy as the Boolean value (0 or 1) representing the state of an occupant (or occupants) being in a space. The report identified that occupant behaviour impacts energy use and comfort and also provided data collection guidelines for deterministic and stochastic modelling of occupant behaviour, choice of occupant behaviour simulation models and integration with building performance simulation programs. A report of 32 case studies (Andrews et al., 2017) covering different residential and commercial typologies and climate zones showed that occupancy accounts for between 15 – 50% variation in building energy performance. Furthermore, occupancy patterns affect energy consumption in whole-building and specific service scenarios at urban and building scale (Ren *et al.*, 2024). In another study (Dong & Andrews, 2009), sensor data of monitored energy behaviour in a room was used to validate an EnergyPlus™ model and 30% energy savings were reported. The implication of occupancy pattern and positioning on energy consumption in a library case study (Wang & Shao, 2017) reported that 26.1% energy savings were possible from removal of identified sources of energy waste.

There are a few studies reported on the effect of hotel occupancy on energy consumption. In the case study of an occupancy-based energy auditing model of a hotel in Singapore (Yi Tuan & Lu, 2016), occupancy rates (50% - 73%) over a one-year period, were used for calibration of, and forecasting with, hotel energy models. The results showed that with increasing occupancy, there is a direct relationship and good correlation between actual and estimated energy consumption. In studying occupancy on hotel energy consumption across seasons, (Gao & Zhang, 2011), the energy consumption of a “unit utilising room” of a hotel in Dalian China was used as proxy indicator of the hotel’s energy consumption. A “unit utilising room” is a functional space within a building designed for various practical purposes and typically includes areas for laundry, storage and other tasks. The study demonstrated that for occupancy ratios between 50% - 100%, the total energy consumption was always highest in winter (50.6% higher than in summer) and lowest in spring and autumn (63.5% less than in winter), confirming that there is variation in energy consumption with changing season. In spite of the foregoing, the gap in the literature is that studies on the effect of occupancy on energy consumption in UK hotels, especially in the context of climate change and net zero, are required.

Energy Performance Certificates

The EPC is an official document that evaluates and classifies the energy consumption of a building and rates the energy efficiency on a scale from least-efficient (G) to most-efficient (A). In addition, EPCs identify the building, energy characteristics (heating, cooling, hot water systems, insulation and building materials), recommendations for improvement of energy efficiency and date of issue. The assessment process of EPCs enables identification of areas of energy efficiency improvement and measures to optimise energy consumption and reduce carbon emissions. In addition to being a regulatory requirement for sale and rental of properties, EPCs enable the deployment of energy efficient and sustainable technologies resulting in financial savings. The introduction of the Energy Performance of Buildings Directive (EU-EC-91-EPBD, 2002) and subsequent recasts, energy efficiency is linked to the energy ratings of appliances and the guidance from EPC assessments (Anđelković et al., 2021), such that, regardless of the diversity in methodologies, input data, assessment processes, metrics/outputs used and assessor protocols across Europe (Jenkins et al., 2024), EPCs were contemplated for measuring net zero in buildings.

Cognisant of the shortcomings of measuring Net Zero with EPCs, the UK-CCC proposed a reform of the Energy Performance of Buildings (EPB) framework as part of the sixth carbon budget (UK CCC, 2020, 2022). In addition, a consultation was launched in 2024 to reform the EPB framework to a new system that produces EPCs with metrics that are easy to understand and relate to the energy performance of a building and similar typologies. In addition, the new framework aims for EPCs that contain measures to lower energy bills, reduce carbon emissions and support the NZ goals of the Government (MHCLG & DESNZ, 2024) as stated in an earlier communication to the UK parliament (Deben, 2023) which proposed different headline and secondary metrics for energy cost, carbon emissions, energy performance, fabric performance, heating system type and smart readiness for residential and commercial building typologies. Furthermore, a case study of hotels in the Mediterranean region, (Sadati, 2023), projected a 42% rise in cooling load and 36% drop in heating load by 2079, under an RCP8.5 future climate scenario. The use of Representative Concentration Pathways (RCPs) in this study implies that the impact of socio-economic factors (population growth, economic development and technological progress) was not considered, necessitating further studies that use Shared Socioeconomic Pathways (SSPs) to explore the impact of GHG emissions and climate change on hotel energy consumption. The factors that affect reviewed literature identified the parameters that are relevant to the metrics being proposed in the EPC reforms, but the benchmark values of the metrics for proofing future Net Zero claims in respective building typologies need to be defined.

Envelope Insulation Level

The building envelope refers to the outer shell of the building that separates the interior from the external environment and comprises the external walls, roof, windows and doors, foundation and, air and vapor barriers. The defining characteristics of envelope insulation are the Thermal Conductivity, λ (W/m.K), a measure of the ability of the material to transfer heat, and the R-value ($\text{m}^2\cdot\text{K}/\text{W}$), the measure of the ability of insulation material to resist heat flow, and the Thermal Transmittance or U-value ($\text{W}/\text{m}^2\cdot\text{K}$). CIBSE Guide-A: 2021 (Cheshire, 2012) gives “ λ ”, U- and R- values for common building materials. The non-linear increase in R-values with increase in thickness of insulation necessitated research to optimise the thermal conductivity and thickness of insulation materials as a comfort and sustainability imperative. In (Raza,

Farhan and Abu-Jdayil, 2024) it was reported that lignocellulosic waste could be employed directly as thermal insulation or repurposed as a filler within thermoplastics and thermosets to achieve $\lambda \leq 0.2$ W/m.K, and 30-50% replacement of the polymer content with renewable material. The energy savings from the application of three envelope insulation materials; polyurethane foam, rock wool and resin-bonded fibre board studied by (Alla et al., 2021) for an apartment block typology showed that thermal insulation has a higher impact on winter heating and slightly affects the summer cooling requirement. In addition, the effect of thermal conductivity on energy consumption, heating and cooling loads for different climate conditions showed that the application of 10 -12 cm Expanded Polystyrene (EPS) or stone wool improved energy efficiency while energy consumed and cost reduced (Sari & Aksoy, 2024). The work of (Mohamed & Mansour, 2020) reported a 30% improvement in energy efficiency, and reduction of CO₂ emissions, for a hotel typology in Egypt by changing the orientation and thermal insulation in a DesignBuilder™ model. In spite of the interest in the impact of envelope insulation on energy efficiency, there is paucity of studies on the effect of thermal conductivity on energy consumption, energy efficiency and cost of energy in UK hotel typologies.

Lighting

Lighting refers to the effect observed from the part of the electromagnetic spectrum (wavelength 380nm – 780nm, frequency 430 – 790 THz) that also enables photography and human vision. Light is produced by incandescence; when a material is heated to a high temperature, luminescence; release of energy from (chemical reactions-chemiluminescence, living organisms-bioluminescence, flow of electric current through a material- electroluminescence (e.g. Light Emitting Diodes) and photoluminescence (e.g. fluorescent and phosphorescent materials). Light is also emitted from the flow of electric current through a gas to excite the atoms (Gas discharge), fracture, rubbing or scratching of crystals (triboluminescence) and black bodies (the sun and incandescence). In buildings, lighting refers to the deliberate use of artificial light and fixtures (luminaires) or natural light (sunlight) to achieve visual comfort or aesthetics and impacts the energy consumption of buildings. Several accounts report that between 15% - 21% of building energy consumption is attributable to lighting.

On-site Renewable Energy Supply and Storage

Renewables are energy resources that are derived from natural sources and are continually replaced within the human timescale (Dehouche & Kolokotroni, 2017). Renewable energy is obtained from the sun (solar), moving wind, flowing or falling water (hydro), organic materials (biomass), heat from the earth's interior (geothermal), and oceans from waves, tides and temperature differences in seawater. It is recognized that reduction of building energy consumption towards NZ requires two synergistic approaches; implementation of energy efficiency measures to reduce energy demand and offset of the balance from onsite renewable generation or increase of share of renewables in the grid. In existing buildings, the selection of renewable energy resources for the Building Integrated Energy System (BIES) is driven by factors such as availability of renewable resources on, or near the site, availability of renewable energy technology, characteristics of the energy profile to be offset by renewables, cost of energy purchased from the grid, availability of incentives for offsetting the installation cost, impact of extant local regulations and willingness to preserve or alter existing architectural features (Hayter & Kandt, 2011).

Onsite renewable energy generation reduces the reliance on fossil fuels, hence decreasing GHG emissions. In addition, generating power close to the point of use reduces transmission losses and improves overall efficiency. Furthermore, technological advancements in renewable energy generation, storage and energy management solutions are providing cost-effective and efficient systems to enhance sustainability. The introduction of codes, standards and policy incentives (tax credits, grants, subsidies, etc) for increasing the renewable energy share towards NZBs, is aimed at overcoming the upfront costs and regulatory challenges constraining increased uptake of on-site and off-site renewables. The location of the conversion process from primary to delivered energy (Marszal et al., 2012) differentiates on- and off-site Renewable Energy Sources; the latter being conversion processes located outside the boundary of the property and the former referring to conversion processes within the property boundary or having the same ownership with the building. In the UKNZCBS (Anderson et al., 2024) the requirement is that "NZC Aligned Buildings" should have 40 kWh/m² minimum onsite Renewable Energy Sources (on-site RES). Several scholarly works, practice reports and policies on optimising onsite and offsite

Renewable Energy Sources (on-site and off-site RES) and storage solutions are documented.

In (González-Mahecha et al., 2018) a single objective optimisation of Feed-in Tariff (FiTs), cost of renewable technologies and purchase price of grid electricity to minimise the total economic cost was validated by testing six scenarios on an integrated energy system (solar-PV, wind turbine and storage) in a case study high-rise multi-apartment cluster in Lisbon, Portugal. The results showed that the lowest total economic cost occurred when the cost of technologies decreased by up to 50% - 75% compared to the base case. Furthermore, the total economic cost was highest when peak tariffs were implemented for periods of peak electricity consumption, even with decreased cost of technologies. However, the study did not consider the effect of different load profiles, occupancy and meteorological conditions on the energy consumption and hence, the energy cost.

A related requirement for on-site RES is the use of an Energy Storage System (ESS) to store excess energy for future consumption, balance supply and demand, integrate variable and intermittent renewable energy sources, and provide ancillary services (frequency regulation, voltage support, and black start capability). ESSs are also used for managing the cost of energy through load shifting and peak shaving; cheaper off-peak energy is stored and used during peak periods when energy is expensive. In microgrids, availability of suitable energy storage systems improves the overall efficiency and ensures seamless islanding events during the switch between grid-connected and islanded modes. In (Smdani et al., 2022), it is stated that ESSs are characterised by Power Density (also known as specific power or volume power density) and Energy Density. Power density is the amount of power an ESS can deliver per unit volume or mass (W/kg , W/m^3 or W/litre), the volume of the ESS being the whole volume including the energy storage component, peripherals and associated structures, and the inverter scheme. To enhance their performance, NZBs require various technologies and approaches to energy storage such as Thermal Energy Storage (TES), Hydrogen Energy Storage (HES), and Hybrid Energy Storage which combine different storage technologies.

TES relates to the technologies for transfer and storage of heat energy that is mainly produced from solar radiation or the transfer of coolth from the environment to maintain thermal comfort in a space. In (Deka & Szłęk, 2022), it is reported that TES is

implemented in walls, floors and ceilings, tanks inside the buildings, underground tanks, suspended ceilings, ventilation, PV systems and external facades as sensible heat storage, latent heat storage or thermochemical storage. Furthermore, TES is classified on the basis of heat convection mode (active and passive TES), on the basis of materials used (Sensible Heat Thermal Energy Storage-SHTES, Latent Heat Thermal Energy Storage-LHTES, and Thermochemical Heat Storage-THS). The advantages and opportunities in the use of TES for NZBs are reported but studies on application to hotel typologies are non-existent.

BES provides the capability to preserve balance in energy consumption under uncertainties of the power system thereby ensuring flexibility, availability of backup power, and frequency regulation and voltage stability. Furthermore, BES facilitates Demand Response (DR) through reduction of peak demand and enablement of Time-of-Use (ToU) tariffs and enable the integration of the building energy system with renewable energy sources. In (Li et al., 2023), the effective parameters (system applicability, and optimisation methods, objectives and constraints) for optimal coupling of solar PV from single buildings and clusters to BESs were reported for two types of BES. The first stores electricity from the PV system and the grid and is set to achieve peak shifting and peak load regulation. The stored electricity is not sold to the grid. The second system has all the features of the first system, and in addition, electricity can be sold to the grid to realise price arbitrage. The authors did not validate the findings with actual cases studies, a literature gap that needs examination.

Grid Electricity Carbon Intensity

Grid carbon intensity ($\text{g.CO}_2/\text{kWh}$) is a measure of the amount of CO_2 emissions produced per kWh of electricity generated. This means that higher carbon intensities are associated with higher proportions of fossil energy in the PE mix and vice versa. Hence the grid intensity of electricity delivered in a building determines the carbon footprint. In this sense, the carbon footprint of a building that relies on carbon-intensive grid electricity would be higher even if it were energy-efficient. In addition, the effectiveness of renewable energy systems in net zero is enhanced with decreasing grid intensity. Energy storage and management strategies for net zero are also driven by grid carbon intensity as systems have to be developed to align consumption of stored renewable energy with periods of high grid carbon intensity. The foregoing highlights the imperative of predicting grid carbon intensity to establish the time-to-use

stored renewable energy or grid electricity to enable effective demand-side energy management for actualising NZBs.

The studies reported on grid carbon intensity projections are mostly day-ahead forecasts and have different objectives. In (Lowry, 2018), a half-hourly day-ahead forecast for management of HVAC energy demand showed a 20% reduction in carbon emissions. A multi-day grid carbon intensity forecasting approach (“CarbonCast”) to generate a 96-hour forecast of grid carbon intensity using Artificial Neural Network Machine Learning (ANN-ML) techniques was validated with historical carbon intensities averaged over a week for 13 regions across the US, Europe and Australia (Maji, Shenoy and Sitaraman, 2023). The approach gave an average mean absolute percentage error of 9.96%, when compared to other state-of-the-art forecasting methods. In spite of the existence of applied research on carbon intensity and energy management, case studies of the long-term effect of grid carbon intensity on Net Zero in commercial typologies are non-existent.

Cost of Energy in Buildings

The energy costs in buildings encompass the operational and maintenance costs of the infrastructure for energy services in the building. The cost of energy to operate the services in a building is linked to the viability of energy efficiency measures required to achieve reduction of energy consumption and carbon emissions.

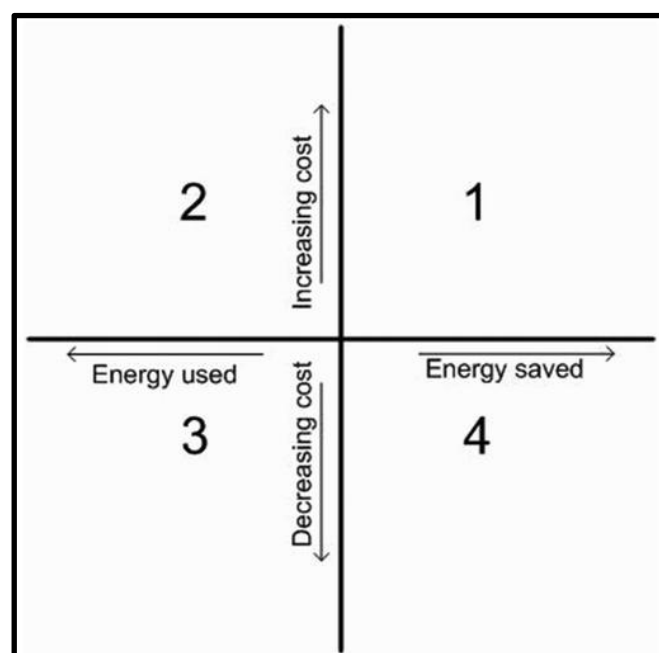


Figure 2.19: Decision Trade-off Quadrant for Building Energy Projects (Torcellini, Pless and Leach, 2015)

High energy costs stimulate the adoption of energy-efficient and renewable technologies while the adoption of these technologies is challenging in a low energy cost regime. Consequent on the foregoing, (Torcellini, et al., 2015) developed an approach to create low-energy buildings without additional construction costs, using the trade-off quadrant in Figure 2.19, with EEMs in quadrant-1, hence the best energy saving measures are closest to the positive abscissa. Decisions which relate to the features of the building and yield additional costs and negative impact on energy use are in quadrant-2. The use of low-efficiency equipment saves money but wastes energy (quadrant-3). Quadrant-4 (decreased costs and increased energy savings) is recommended because the building is optimised around energy and cost. An investigation of the operational performance of five (5) Net Zero Energy houses in Australia (Alam et al., 2024), showed the payback on embodied carbon of 13.1 t.CO_{2e} for each house was between 4 to 9 years, depending on the operational carbon, but achieving net zero cost in the houses required lower operational energy costs and higher feed-in tariff.

The cost of Net Zero retrofits is also an area of research interest considering the quantum of existing buildings that must undergo deep renovations and retrofits for the climate neutrality goals to be achieved. A recent lifecycle assessment, based on the lifecycle stages and boundaries of BS EN 15978 (Figure 1.4), was done on a historic commercial building in the USA (Hu, 2023). The LCCA evaluated three (3) levels of cost to determine the effectiveness of energy performance over a 60-year lifespan. The level-1 cost (based on the reference year energy demand of 54 kWh/m²/year) was 18% of the Lifecycle Cost (LCC), the level-2 cost (based on target energy performance of 44 kWh/m²/year) was 12% of LCC and level-3 cost (to meet the nearly net zero goal of offsetting 20 kWh/m²/year energy use through solar-PV panels) was 5% of the LCC. In the hotel sector, a typical five-star UK hotel case study (Salem et al., 2020) was used to analyse the post-retrofit energy performance and identify the representative cost-optimal primary energy consumption level for hotels. However, the cost-optimal primary energy consumption level of 193.59 kWh/m²/yr is not representative of lower-star (1 to 4-star) hotels because (Arenhart et al., 2024) presented that there is significant and positive correlation ($r=0.58$, $p<0.0001$) between the hotel star-level and energy consumption.

Climate Change

Climate is defined as the statistical description of weather in terms of the mean and variability of near-surface variables such as temperature, precipitation, and wind patterns, typically over a period of 30 years, as recommended by the World Meteorological Organization (WMO). The IPCC described “change in climate” as changes in the mean and/or variability of the near-surface properties, identified from statistical tests for at least a decade, and the distinction between natural and anthropogenic climate change was given by the UNFCCC. The main mechanism of impact of climate change on buildings is the shift in energy use either through decrease in heating or increase in cooling loads (de Wilde & Coley, 2012). Hence, research is focused on enabling the adaptation of existing and new buildings to current and future changes in energy performance and Indoor Environmental Quality (IEQ). The investigation of the impact of climate change on building energy performance is mediated by Urban Heat Island (UHI) effect and reliability of available microclimate data. Similarly, IEQ is impacted by the presence of air pollutants in infiltrating outdoor air, and higher indoor temperature and humidity.

The UHI effect refers to the phenomenon where urban areas experience significantly higher ambient temperatures than adjoining rural areas due to anthropogenic activities, sparse vegetation and dense infrastructure. An analysis of 11 studies on the impact of ambient temperatures on the peak electricity demand (Santamouris et al., 2015) reported that for each degree of ambient temperature rise, there was a corresponding increase of between 0.45% and 4.6% in peak electricity load and actual increase in electricity demand of between 0.5% and 8.5%. This is consistent with the conclusion that cooling load and overheating hours would increase, and heating load would decrease in future, reported in (Kolokotroni et al., 2012) following IESVE™ simulation of a typical office building across (East – West) of London.

The increase in building energy consumption due to UHIs causes uncertainties in Building Energy Simulation (BES), which can be minimized by coupling BES models with the microclimate (Kyriakodis, et al., 2019), the microclimate being the specific meteorological conditions of temperature, humidity, wind and precipitation at the building location, influenced by topography, vegetation, water bodies and human activities.

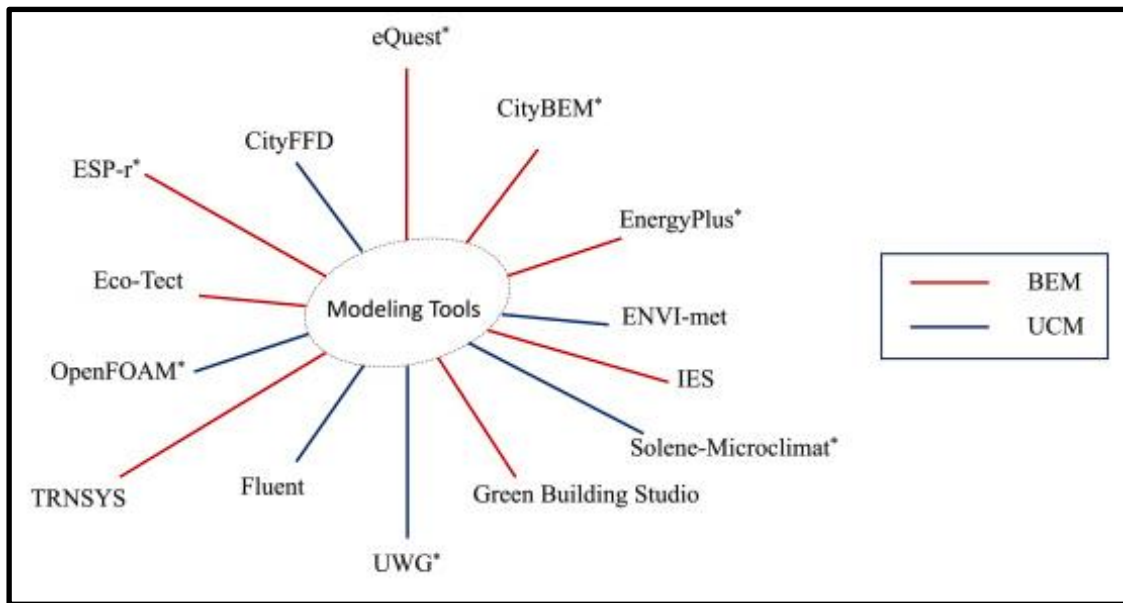


Figure 2.20: BES and Urban Microclimate Modelling Software Platforms (Sezer et al., 2023)

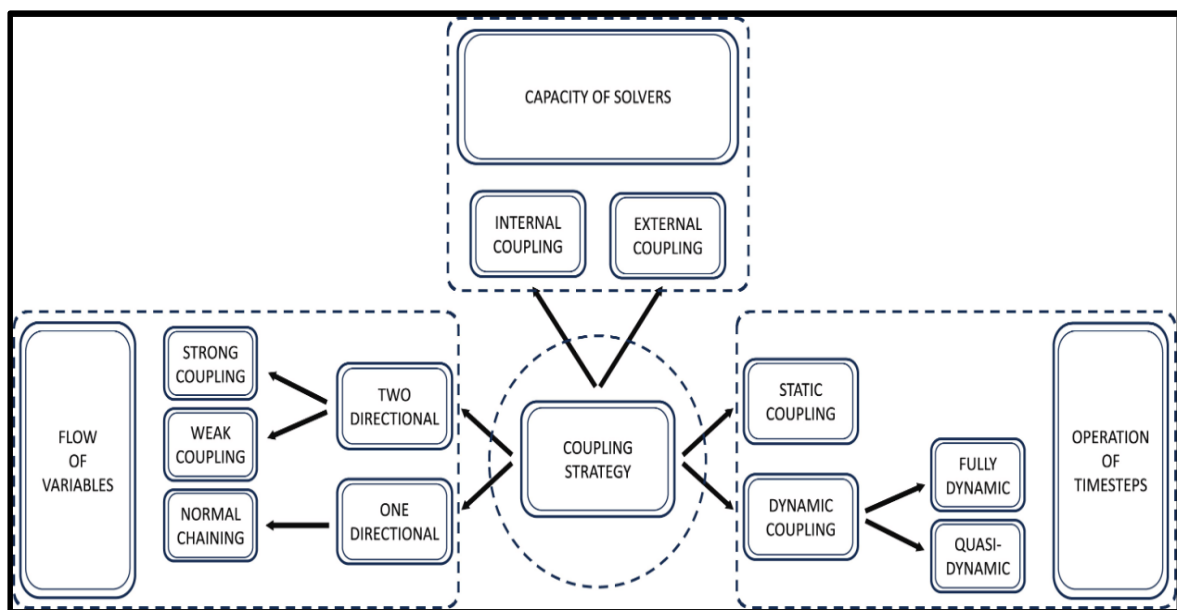


Figure 2.21: Classification of Coupling Strategies (Sezer et al., 2023)

A survey of coupling strategies (Sezer et al., 2023) showed the BES and microclimate modelling software in Figure 2.20 and classification of coupling strategies as presented in Figure 2.21. Coupling strategies are “the formulation of various domains and dependent variables in which the domains cannot provide results while remaining distinct from each other”, implying rapid exchange of information and variables between different computational engines to solve the model. The use of historical data for DSTM is increasingly considered inaccurate for estimating the future performance of buildings, especially those with lifetimes exceeding 30 years (Dickinson & Brannon,

2016). Hence, the use of future weather files for DSTM would be more representative of the impact of climate change on building Energy Performance and emissions. A concern with use of Future Weather Files stems from the inherent uncertainty with respect to accurately matching future weather files with actual future climate upfront. This necessitates the risk management approach of using more than one set of files to design and size cooling and heating systems for new and existing buildings respectively.

2.9 DISCUSSION AND SUMMARY OF LITERATURE REVIEW

The review evaluated 106 research, practice and policy sources along the main themes of building energy simulation, solar-PV generation and microgrids, in the context of their application to the definition of Net Zero metrics in commercial building typologies. In the review of definitions and context of net zero, practice, empirical and theoretical gaps associated with the absence of measurable actions for quantifying energy efficiency, decarbonisation and cost efficiency (Green & Reyes, 2023), and non-verification of strategies and claims with actual data or case studies (Sartori, et al., 2010; Hill & Hunziker, 2023) was attributed to the dominance of qualitative research designs and content analysis. Furthermore, the sources reviewed on net zero metrics and benchmarks had evidential and empirical gaps because the impact of changes in future meteorological and macroeconomic conditions on the cost of energy, and hence, operational net zero were not considered. In addressing these gaps, the actual construction and operational data of a case study 3-star hotel located within the oceanic (Cfb) climate was used to develop novel operational net zero metrics (CEI and ECI) based on the UKGBC and CIBSE Net Zero frameworks.

The review of applications of renewable energy in existing buildings (Hayter & Kandt, 2011), and in the context of NZEBs (Ahmed et al., 2022) revealed a dominance of solar-PV applications in dwellings and commercial buildings. In the context of the UKNZCBS, with pilot version released in 2024 (Anderson et al., 2024), and the final version to be released in the last quarter of 2025, the mandatory operational net zero requirement of at least 40kWh/m² implies the use of solar irradiance decomposition and transposition models that maximise yield and bankability of the project. The reviewed research and practice literature adopted quantitative approaches to investigate the efficacy of decomposition and transposition models. In using HelioScope™ tool for modelling solar-PV generation at the case study, the

methodological and practical knowledge gaps inherent in the reported sources was addressed because the Perez transposition and MRM decomposition models, which are suitable for commercial loads and London sky conditions respectively, were applied to renewable energy generation in a UK hotel typology.

The review of case studies of use of Building Energy Simulation Tools and methods in prescriptive and performance-based scenarios, building performance optimisation (Pan, et al., 2023), and in consulting practice (Shahcheraghian, et al., 2024) all reported a preference for BESTs running on the EnergyPlus™ simulation engine for energy-related BEM and optimisation of energy consumption and CO₂ emissions, mainly in residential and commercial (office and educational) building typologies. The sources reviewed acknowledged microgrids as enablers of net zero through user-level integration, conversion, storage and output of energy vectors to meet load requirements. In the context of net zero as a futuristic concept that integrates energy efficiency and renewable energy, developing the measurement metrics and benchmarks to proof Net Zero requires coupling the BEM and renewable energy model onto a microgrid model, simulation with, and optimisation under, changing macroeconomic conditions, meteorological variables and grid carbon intensity. The application of this approach in the current study develops the ECI metric and benchmark cost of energy at which NZ is feasible in a 3-star hotel typology located in London, UK. In this sense, the study addresses methodological and theoretical gaps that would enrich the UKNZCBS and ND-NEEDS database.

3.0 RESEARCH DESIGN, METHODOLOGY AND METHODS

The overarching framework for operational net zero buildings aims to reduce carbon footprint by achieving a balance of energy consumption, site renewable generation and grid interaction at optimal cost. This study uses secondary architectural, construction, operational and meteorological data of a case study UK hotel to analyse energy demand, onsite renewable energy generation and grid decarbonisation under macroeconomic and meteorological sensitivities to develop appropriate metrics, and calculate representative benchmarks, for measuring and proofing net zero in hotel typologies. In this sense, the reduction in energy and carbon intensity, and increase in renewable energy share to progress buildings to net zero can be objectively measured and known, independent of external perceptions. This ontological position, combined with the use of empirical data and calibrated energy models to compute the energy, carbon and cost metrics underpins the quantitative research methodology used.

The methodology adopted in this work comprises three steps. First a baseline dynamic thermal model of the case study for the base year (2022) was created in IESVE™. Other than the UKNZCBS providing allowing for discretionary selection of baseline year, 2022 was selected because it represents the year of recovery to normal occupancy of the hotel, post-COVID 19. Regardless, to ensure representative occupancy data that accommodates sensitivities to occupancy, energy demand and emissions, the average occupancy for 2022, 2023, and 2024 was used to create occupancy profiles for the Building Energy Model. The timestep and day-to-day variabilities applied to the electrical and thermal load exported from IESVE™ to HOMER-Pro™ for microgrid optimisation was an additional provision to ensure the results of this study are representative of the energy use and emissions for a wide range of occupancies.

The baseline IESVE™ model was simulated with contemporary (2020) “.epw” TMY weather files generated from Meteotest®-Meteonorm™ API. The dynamic simulation model of the hotel was calibrated, using one year of measured electricity data from the hotel’s BMS, to ensure that predicted energy use reflects the hotel’s as-operated performance. Electricity data was used to calibrate the model because policy and practice literature (e.g. the UK-NEEDS) are based on electricity consumption. The benchmarks in ASHRAE Guideline 14 for hourly calibration, NBME and C_vRMSE of $\pm 10\%$ and 30%, respectively were targeted. The calibrated model achieved hourly

NMBE (4.75%) and C_v RMSE (12.6%), meeting ASHRAE Guideline 14 thresholds, and demonstrating strong agreement at hourly resolution. Detailed residual analysis was not conducted to characterise the remaining mismatch between measured and simulated performance. However, the study acknowledges that these residual calibration errors represent irreducible uncertainty arising from behavioural variability, imperfect HVAC control representation, infiltration dynamics, and measurement noise. They provide essential inputs for predictive uncertainty quantification and form the baseline for the multi-building validation framework, enabling cross-building comparison of model accuracy and identification of systematic versus building-specific modelling issues.

The interim case model (Model-2.0) was generated by simulation of the calibrated baseline model with 2030 future weather file generated from Meteotest®-Meteonorm™. Furthermore, the interim model was simulated with 2050 future weather file to generate Model-3.0 (PPT model). In each model, CIBSE TM-52 comfort analysis was performed to check for overheating. The impact of the future climate and EEMs on energy performance and emissions was estimated singly for each model; 1.0, 2.0, and 3.0, and then aggregation of the impact of EEMs across the timelines of the EEMs was done in a stepped retrofit strategy based on the “Fabric First Principle”.

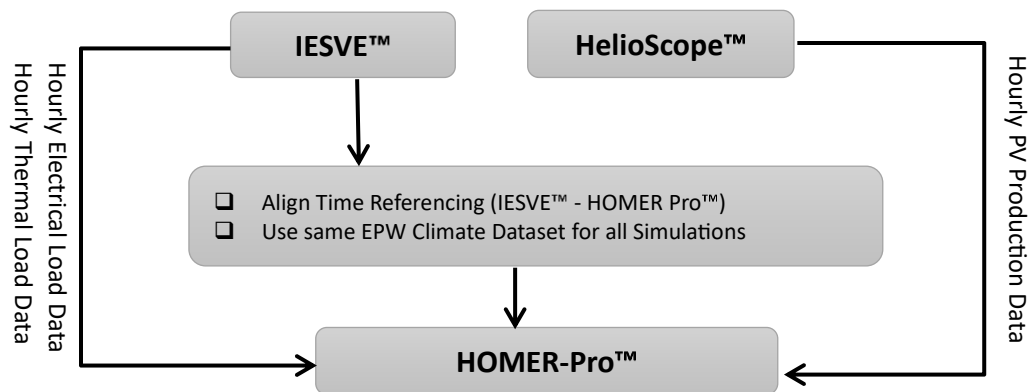


Figure 3.1: Data Transfer Scheme across the Modelling Platforms

In the second part of the methodology, a rooftop solar-PV generation model was developed in Helioscope™, from commercially-available solar-PV module and inverters according to the safety requirements of RC-62 standard and the technical specifications of the UK-MCS. The data transfer across the modelling platforms, which constitutes the third part of the methodology, is depicted in Figure 3.1. The time referencing of electrical and thermal loads were converted from the half-hourly

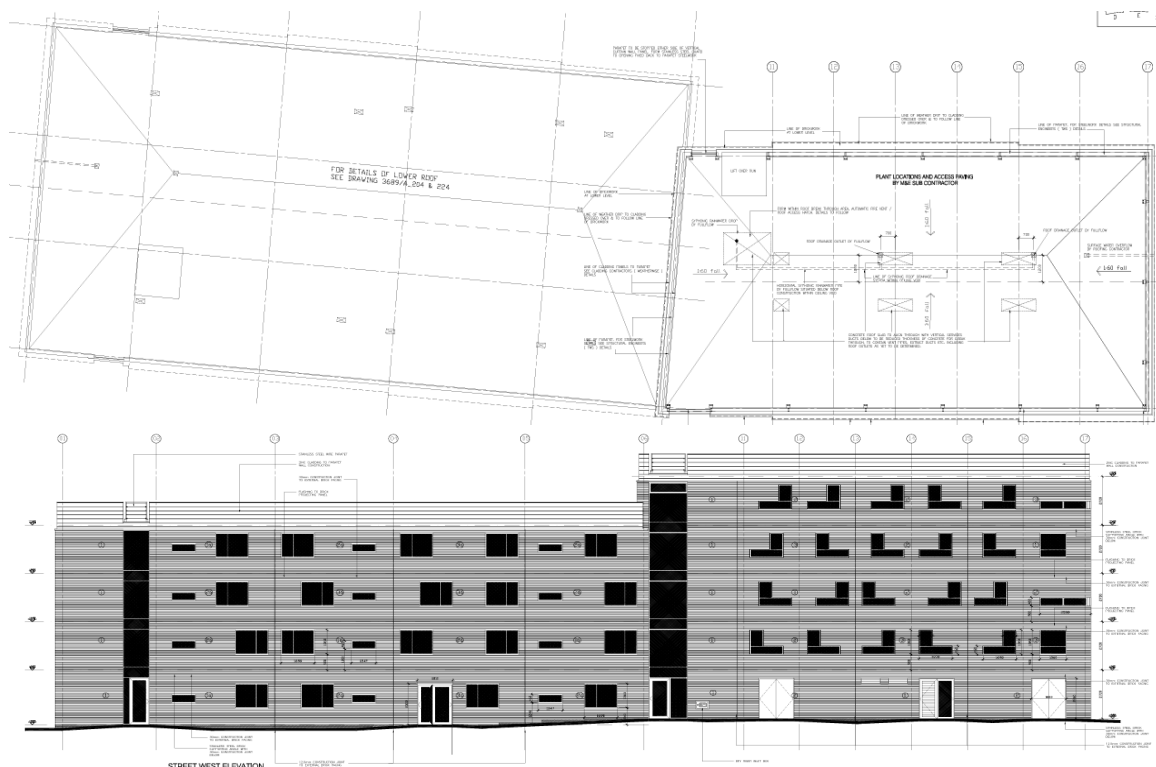
resolution IESVE™ format to the hourly resolution format, in a spreadsheet, to be compatible with HOMER-Pro™, before export to HOMER-Pro™. System-generated timestep and daily variabilities of 10% and 20% respectively were applied to the loads to add sensitivity. In summary, the Data Transfer Scheme shown in Figure 3.1 uses standardised data structures, validated simulation engines and controlled import and export workflows to ensure consistency and energy balance as data is transferred across the 3 simulation platforms.

The solar-PV resource was also coupled to HOMER-PRO™ to create a microgrid model based on technical, economic and environmental variables, and constraints existing at the site and applicable to the study location. Consistent with the decarbonization framework of the PPM and the CIBSE “Carbon Hierarchy”, of applying renewable energy sources after implementation of energy conservation and efficiency measures. The IESVE™ model is used to determine the overall electrical demand, HelioScope™ determines the solar-PV supply, and HOMER-Pro™ optimises the mix energy mix to give the system with the least LCOE. The microgrid was simulated with empirical technical, cost and environmental data and under optimised conditions for minimum cost of energy and carbon emissions. The results obtained from this methodology and the ensuing analysis are detailed in chapter 4.0.

3.1 IESVE™ BUILDING ENERGY MODEL FRAMEWORK

The case study is located on the campus of Brunel University London (Lat. 51.53, Long.0.47W) in West London, South-East of England (Koeppen-Geiger Climate zone -Cfb). It was designed and constructed between 2003 – 2007, commissioned in 2008 and has an organic (irregular) form, as shown in

Figure 3.2, comprising two (2) joined quadrilaterals, the North-side (NS) and South-side (SS), oriented at N21°E, with a total footprint of approximately 800 m². The case study is bounded by natural vegetation and a flowing river to the East, an adjoining building to the south, a road to the North and concrete pavement to the West. This case study was selected for three (3) main reasons: (i) energy and cost data are available (ii) the documents on building construction are available for modelling for development of the energy model, and (iii) there is a 2040 Net Zero ambition by the property owner. The Energy Performance data was obtained from the BMS via the Energy Manager® platform. A non-intrusive survey of the hotel was conducted and , energy end uses were identified. In addition, severe overheating of the case study in



summer was reported.

Figure 3.2: Roof Plan (top) and West End Elevation (bottom). Extracted from Architectural Drawings. The North-side (sitting on 3 Floors) and South-side (sitting on 4 Floors) are on the Left and Right ends of the West End Elevation, respectively.

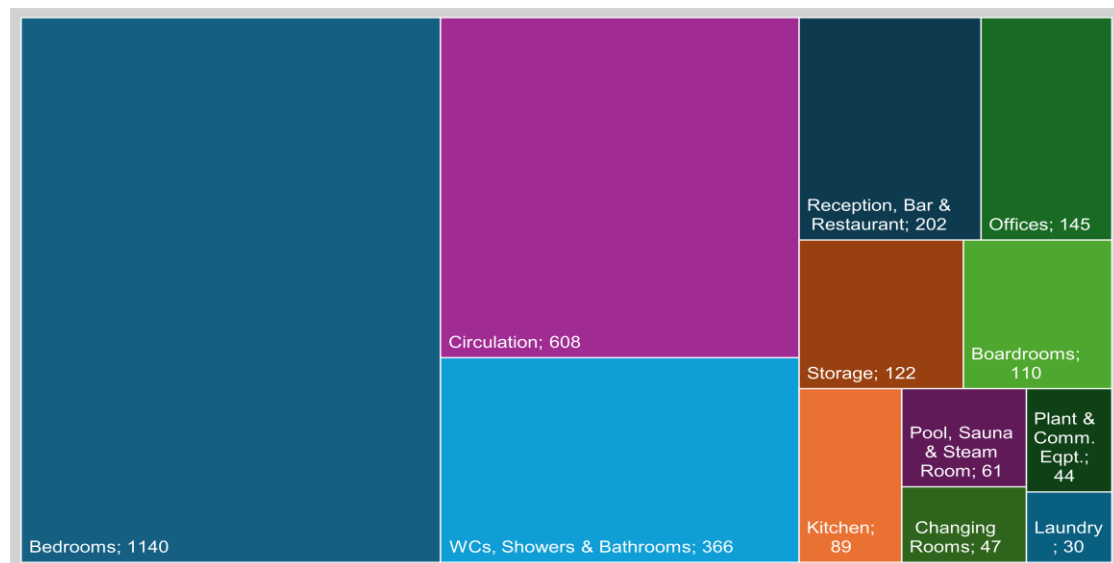
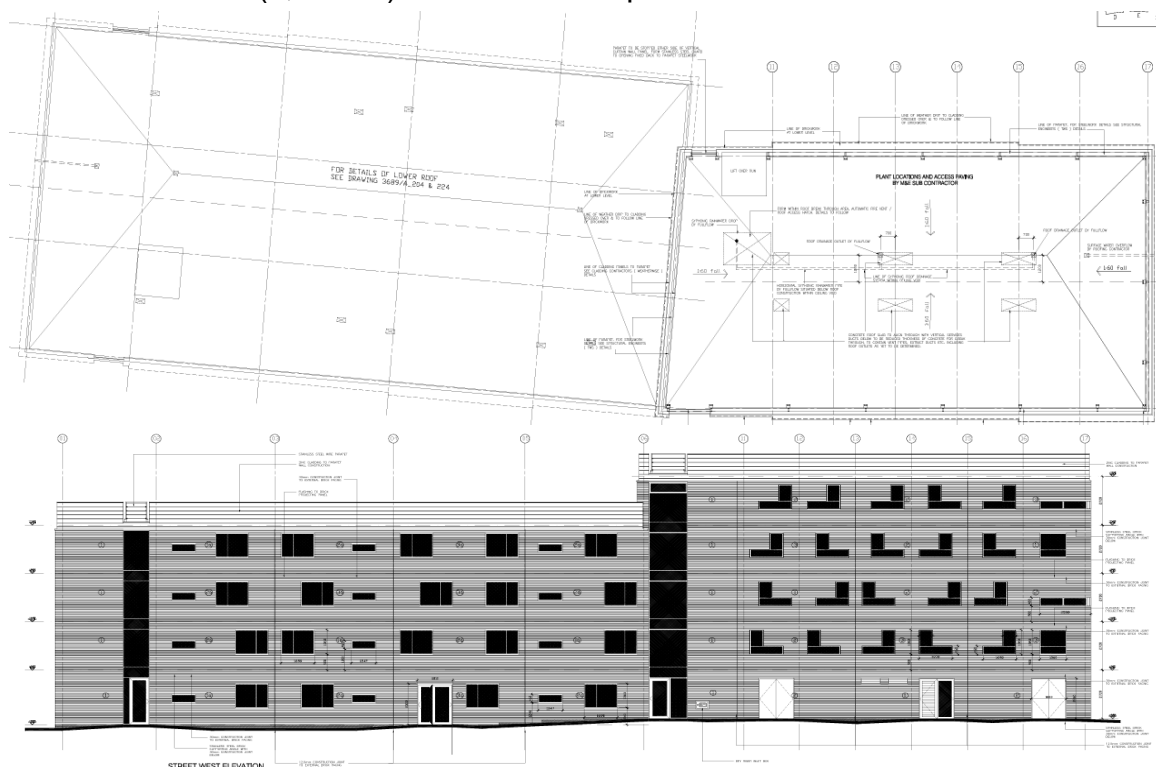


Figure 3.3: Treemap of Floor Area Distribution (m²) of Conditioned Spaces

The total floor area (2,964m²) of conditioned spaces is distributed as shown in the tree



map in Figure 3.3. The boxes contain the names and floor area of each space category. The building is connected to the utility grid for supply of electricity, gas and water. It is also connected to the central sewage system. The respective electricity and gas retailers to Brunel are EDF and Corona Energy. Electricity is supplied via a Star

(Y) 400V/230V MV/LV metered feeder to power services such as lighting, plug loads, lifts and the mechanical ventilation system (fans and air handling units). Heating of domestic spaces, spa whirl pool is provided from a natural gas-fired condensing boiler system installed in 3 X 100% configuration (3 units are installed with each unit sized to meet 100% of heating load and the other 2 units providing redundancy).

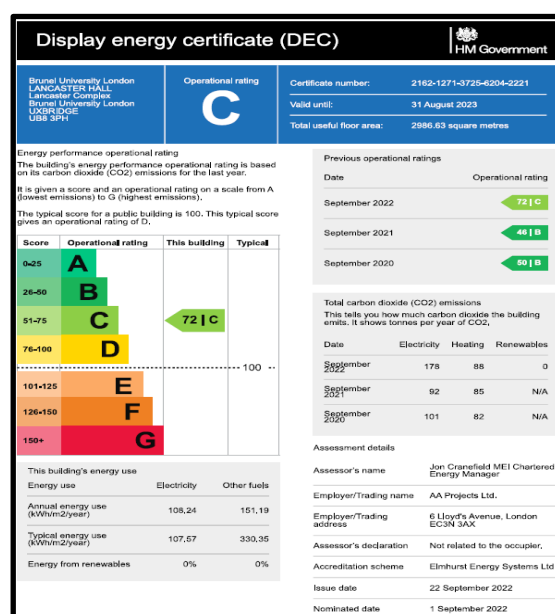


Figure 3.4: DEC of Case Study for the Base Year of 2022

The DEC of the case study building for the base year, 2022 (Figure 3.4) shows an Operational Rating (OR) of 72 (Grade C). A typical building will achieve an Operational Rating of 100, which places it on the boundary between Grades D and E. The “OR” is calculated according to (CIBSE:TM47, 2009) as:

$$\text{OR} = (\text{Building CO}_2 \text{ Emissions} / \text{Building Floor Area}) \times (100 / \text{Typical CO}_2 \text{ Emissions per Unit Area}) \quad 3.1$$

The DEC also shows separate performance indicators and benchmarks for annual use of electricity and of fuel or heat.

Target Energy Performance, Emissions and Energy Cost

The DEC is a certificate that incorporates a numerical indicator of performance, “Operational Rating”; the ratio of actual measured energy use of the building over a year to a benchmark figure for buildings of that type. It also gives the historical energy performance data for the preceding two years, if available, summary information about the energy used by the building, and a “Recommendation Report” which states the measures for improving the energy performance of the building. Since 1st October

2008, DEC's are a mandatory requirement under the Energy Performance of Buildings (Certificates and Inspections), England and Wales, Regulations 2007 for public buildings with GIA greater than 1000 m² (CIBSE:TM47, 2009; Lewry *et al.*, 2014). In the PPM and UK-CB6 frameworks for net zero, the goal is to achieve incremental reductions of 60% and 78% (or minimum DEC Rating of B+) in EUI and carbon emissions respectively by 2050.

Table 3.1: Baseline, Interim and PPT EUIs for CS and Good Practice UK Hotel

EUI (kWh/m ²)	Baseline	Interim Targets		Paris Proof Target
	2022 – 2025	2025 – 2030	2030 – 2040	2050
Good Practice UK Hotel	340	255	190	135
Case Study Hotel	259	195	145	104

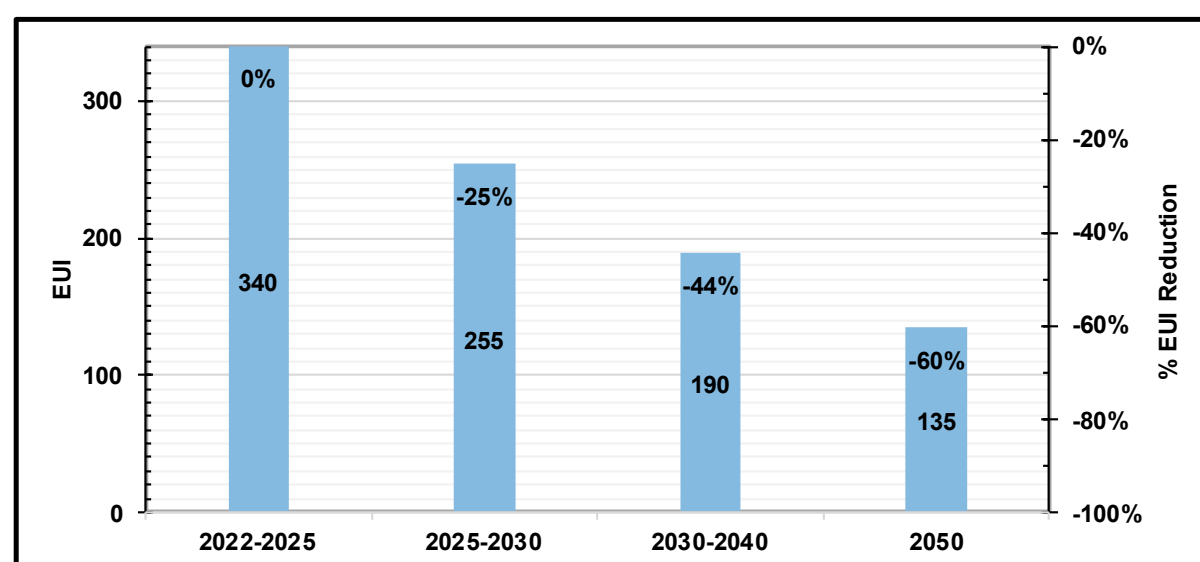


Figure 3.5: EUI (kWh/m²) Targets for NZ in Good Practice UK Hotels

As an illustration of the PPM framework, the “good practice” EUI data for typical “good practice” UK hotels, extracted from CIBSE Guide F (Cheshire, 2012), and the extract from the 2022 DEC of the case study hotel (Figure 3.4) are presented in Table 3.1 showing the baseline, interim target and PPT, for the PPM Net Zero framework in Figure 3.5 for a “good practice UK hotel”.

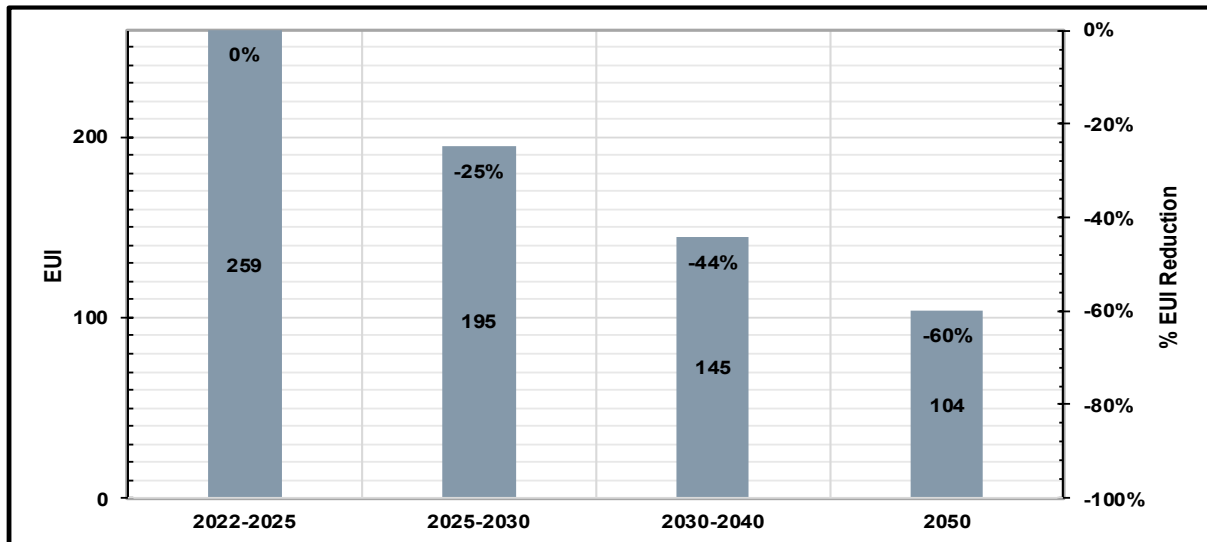


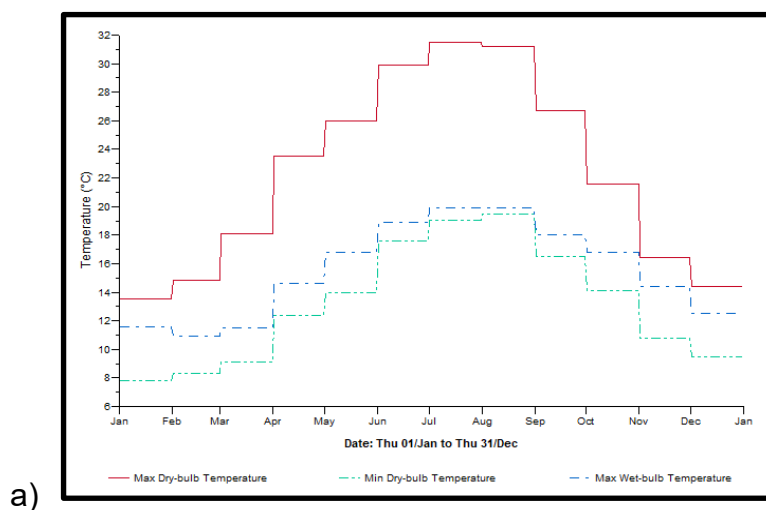
Figure 3.6: EUI (kWh/m²) Targets for Net Zero in the Case Study

In Figure 3.6, it is shown that based on the 2022 DEC of the case study, the condition to reach net zero by 2050 is a 60% reduction of baseline EUI by 2050, through interim periods; (a) 2025 -2030, 25% EUI reduction and (b) 2030 -2035, 44%, hence the governing model of this study is equation 3.2:

$$EUI_{PPT} = 0.4EUI_{Baseline} \quad 3.2$$

3.2 BASELINE AND FUTURE WEATHER

Design weather data are derived from climate statistics for heating and cooling load calculations, typically in HVAC design and includes data on; (a) dry and wet bulb temperatures (°C), (b) wind speed (m/s) and direction, (c) solar radiation (W/m²), (d) humidity (%), © degree days, and (f) extreme temperature percentiles.



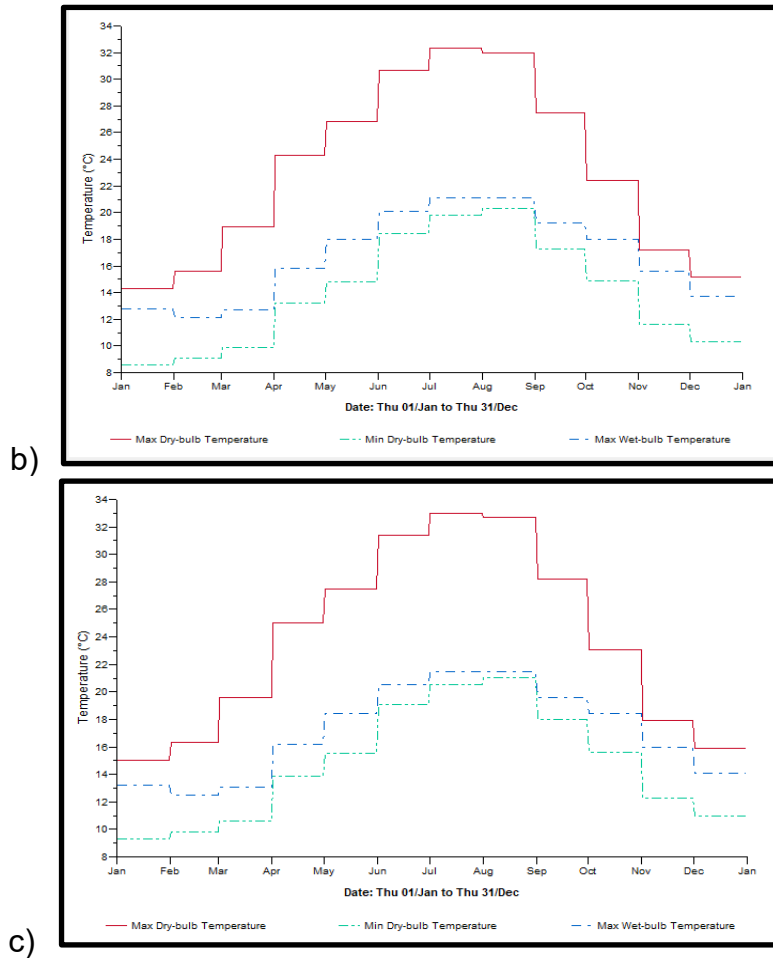


Figure 3.7: Plots of Design Weather Data used in BEMs for 2022, 2030, and 2050

The design weather data used in the model was selected from IESVE®-ApLocate™ module, based on ASHRAE®-database v7.0™ for location 37720 (London Heathrow, UK), with annual percentile for heating loads design weather (99.6%) and monthly percentile for cooling loads design weather (0.4%). The respective parameters used in the BEMs of the baseline, 2022 (Figure 3.7a), 2030 (Figure 3.7b), and 2050 (Figure 3.7c) are; outdoor winter design temperature (-2.30°C , -4.80°C , -4.10°C), dry-bulb temperature, (31.5°C , 32.30°C , 33.00°C), and wet-bulb temperature, (19.9°C , 21.10°C , 21.50°C). Simulation weather data is used in energy modelling and dynamic performance simulation. They are formatted as hourly time-series data, usually for a full year (8760 hours). EnergyPlus™ (.epw), NREL™, and Climate.OneBuilding.org™ are common sources.

The baseline model was simulated with contemporary (2020), instead of 2022 weather file because both years are of temporal proximity to each other, and the meteorological conditions are assumed to be the same. Similarly, EnergyPlus™ (.epw) future weather files generated from Meteotest®-Meteonorm™ version 8.2.0 software, based on

SSP2-4.5 future climate scenario, were used to simulate building energy performance during the interim year (2030) and the PPT year (2050). The types of simulation weather data are; (a) TMY, which represents weather conditions based on historical data, (b) AMY, which is real data for a specific year, (c) TRY, similar to TMY, used in Europe, and (d) Climate Zone data which is aggregated data for particular climate zones. The detailed table of values of the contemporary and future weather data is in Appendix -3A: CONTEMPORARY AND FUTURE WEATHER PARAMETERS.

. The simulation weather data generated from Meteonorm™ is constructed as a TMY file from the following data: (1) 2001 -2020 radiation parameters, (2) 2000 – 2019 temperature, dew point temperature, wind, precipitation and days with precipitation parameters (Remund *et al.*, 2023). The weather files are of high quality and accuracy because the RMSE in interpolation of monthly radiation and temperature values is 7% and 1.3°C respectively. Furthermore, the uncertainty of yearly values of global horizontal irradiance, direct beam irradiance and outside temperature used in the model are 3%, 7% and 0.5°C respectively. The discrepancy in average total radiation based on historical (1961-1990) and contemporary (2000 – 2019) meteorological data is less than 3%.

3.3 THERMAL COMFORT SETTINGS

Thermal comfort is defined as the condition of the mind that expresses satisfaction with the thermal environment, based on the equilibrium between heat gains from metabolic activities in the human body and heat losses from the body to the environment (ASHRAE 55, 2010; Jankovic, 2024b).

Table 3.2: ASHRAE/Bedford Comfort Descriptors with Numerical Equivalents.

ASHRAE Comfort Scale		Bedford Comfort Scale	
+ 3	Hot	7	Much too hot
+ 2	Warm	6	Too warm
+ 1	Slightly Warm	5	Comfortably warm
0	Neutral	4	Comfortable
- 1	Slightly Cool	3	Comfortably cool
- 2	Cool	2	Too cold
- 3	Cold	1	Much too cold

Table 3.2 shows ASHRAE and Bedford Comfort Scales with the descriptors usually used in thermal comfort research.

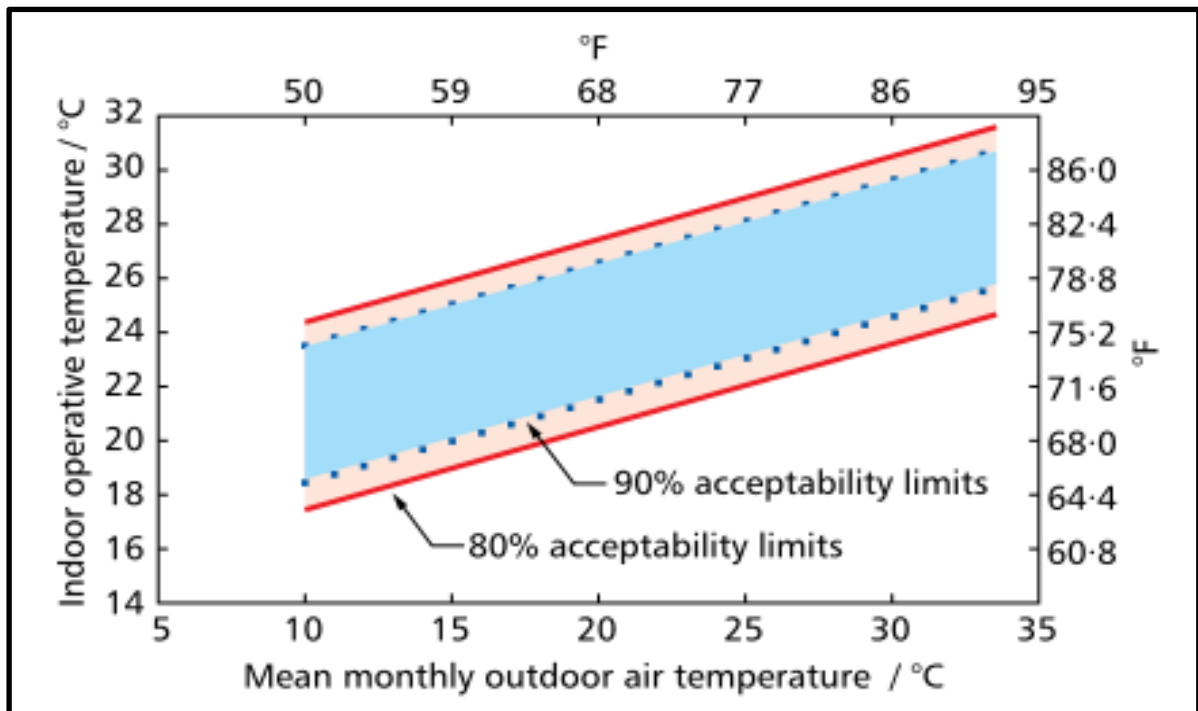


Figure 3.8: Operative Temperature Ranges for Naturally-conditioned Spaces (Nicol, 2013)

The overheating assessment of the spaces in the case study was based on the CIBSE Adaptive Comfort Model (similar to ASHRAE Comfort Scale), with acceptable operative temperature range for naturally-conditioned spaces in free-running buildings as shown in Figure 3.8, with an acceptable operative temperature range of 17 – 31 °C (80% acceptability limit) and 18 – 29 °C (90% acceptability limit).

Table 3.3: Applicable Comfort Temperature Ranges for Free-running Buildings

Category	Explanation	Suggested acceptable range / K
I	High level of expectation (only used for spaces occupied by very sensitive and fragile persons)	± 2 K
II	Normal expectation (for new buildings and renovations)	± 3 K
III	A moderate expectation (used for existing buildings)	± 4 K
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)	> 4 K

The case study is modelled as a “Category II” building, based on the CIBSE classification for free-running buildings (Table 3.3). The setpoints are within the values recommended for adaptive thermal comfort requirement for naturally-conditioned

spaces; 90% acceptability of “T_{op}” (maximum 10% PPD), as defined in the chart of “T_{op} (°C)” shown in Figure 3.8. The criteria for assessment of thermal comfort and overheating in the UK is described in CIBSE TM52 (Nicol, 2013), which recommends a maximum acceptable temperature of 3°C above the comfort temperature, given as:

$$T_{\text{comf}} = 0.33T_{\text{rm}} + 18.8 \quad 3.3$$

where “T_{rm} (°C)” is the exponentially-weighted running mean of the daily mean outdoor air temperature. Exponential weighting of “T_{rm} (°C)” applies larger weighting to recent temperature values when measuring time-series outdoor temperatures and is given by equation as:

$$T_{\text{rm}} = (1 - \alpha)(T_{\text{od}-1} + \alpha T_{\text{od}-2} + \alpha^2 T_{\text{od}-3} + \dots) \quad 3.4$$

where, “α”, is a constant (<1) and “T_{od-1}, T_{od-2}, etc” are the respective daily mean temperatures for the previous day, the day before, and so on. As CIBSE recommends that existing buildings, such as the case study, should conform to “Category II” overheating limits of ±3°C, equation 3.3 becomes:

$$T_{\text{max}} = 0.33T_{\text{rm}} + (18.8 + 3) = 0.33T_{\text{rm}} + 21.8 \quad 3.5$$

where, “T_{max}” is the maximum acceptable temperature (°C).

The overheating assessment criteria are defined using the difference, ΔT, between actual operative temperature, “T_{op}”, in the space and the maximum acceptable temperature (equation 3.5). ΔT is rounded to the nearest whole degree.

$$\Delta T = T_{\text{op}} - T_{\text{max}} \quad 3.6$$

Hence, CIBSE TM 52 states that a room that fails any two out of the three criteria listed below is classed as overheated:

1. **Criterion 1: Hours of Exceedance (H_e):** in the period May to September inclusive, the number of hours that T_{op} > T_{max} by 1°K or more, shall not be more than 3% of occupied hours.
2. **Criterion 2: Daily Weighted Exceedance (W_e):** this criterion requires that “W_e” shall be less than equal to 6 in any one day, where:

$$W_e = \left(\sum h_c \right) \times WF$$

$$W_e = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) \quad 3.7$$

where the Weighting Factor, WF=0, if ΔT ≤ 0, otherwise WF = ΔT, and “h_{ey}” is the time (h) when WF =y. The criterion deals with the severity of overheating within any

one day, which can be as important as its frequency, the level of which is a function of both temperatures rise and its duration.

3. **Criterion 3: Upper Limit Temperature (T_{upp}):** The third criterion sets an absolute maximum daily temperature for a room, beyond which the level of overheating is unacceptable.

3.4 THEORETICAL FRAMEWORK OF BUILDING THERMAL MODELLING

IESVE®-Apache™ Simulation (ApacheSim™) is a dynamic thermal simulation tool that applies first principles to model the heat transfer within and around a building. Among the four classes of building models given by CIBSE: (1) steady-state, (2) dynamic, (3) simplified dynamic and (4) detailed dynamic models, ApacheSim™ qualifies as a detailed dynamic model because conduction, convection and radiation heat transfer processes for each building element is modelled at temporal resolutions as high as one minute and integrated with models of heat gains, air exchanges and plant to give then thermal conditions of the building over time intervals between a day and up to a year. The modelling and simulation principles outlined in the following sections are inspired from the works reported in (Underwood and Yik, 2004; IESVE, 2016; DLUHC, 2021; Beattie, 2023) and adapted to the current study.

The values of projected grid UK consumption-based, commercial sector average grid Carbon Intensity (CI) for the interim period and Paris Proof Target year were obtained from the outlook to 2100 applied to the baseline energy model described in section 0. The projected emissions factors comprise consumption- and generation-based “Long-run Marginal” and “Grid Average” emissions factors and include transmission and distribution losses, and losses due to power station inefficiency. The generation-based emissions factors measure GHG emissions per unit of final energy demand, long-run marginal emissions factors while the grid-average emissions factors are used for foot printing.

In this model, the grid-average, consumption-based public sector emission factors (2022=0.155 kg.CO₂/kWh, 2030 =0.049 kg.CO₂/kWh and 2050 =0.002 kg.CO₂/kWh) are used. The baseline values of Source/Primary Energy Factor for natural gas (PEF_{gas} =1.13) and electricity (PEF_e =1.501) used in the models were obtained from the publications of the “2022 Digest of UK Energy Sources-DUKES” and respectively regressed by 10% and 20% to account for expected improvements in energy

conversion technologies by the interim period (2030 – 2035) and Paris Proof Target Year (2050). Hence, $PEF_{gas} = 1.017$ in 2030, and 0.904 in 2050, while $PEF_e = 1.3509$ in 2030 and 1.2008 in 2050.

Heat Conduction and Storage

Predicting the energy consumption of a building and the design of space heating, cooling and air-conditioning systems requires detailed knowledge of the types, mechanisms and methods for quantification of the heat and mass (air and moisture) transfer processes through the building envelope.

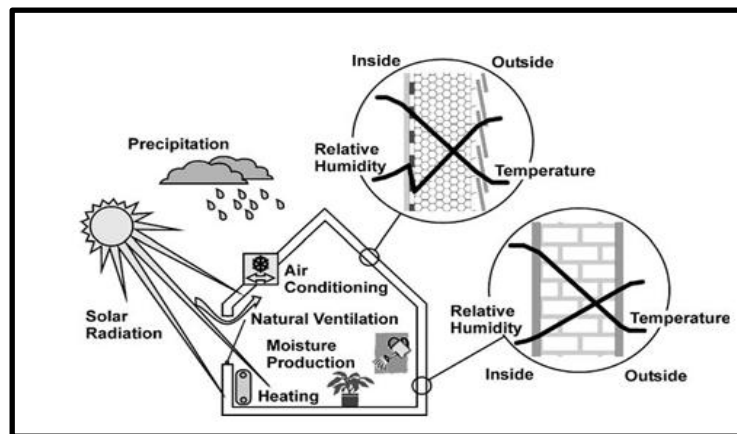


Figure 3.9: Conception of Whole-building Heat and Mass Transfer (Künzel *et al.*, 2005)

The graphical representation of whole-building heat and mass transfer (Figure 3.9), shows that heat, air and moisture transfer are coupled and interact closely with one another. Hence the state-of-the art in modelling, simulation and optimisation of building energy performance is to treat heat and mass transfer together. In IESVE™, heat conduction and storage in an envelope element without internal heat generation are modelled as in equations 3.8 and 3.9 respectively:

$$q'' = -\lambda \nabla T \quad 3.8$$

$$\nabla \cdot q'' = -\rho c \partial T / \partial t \quad 3.9$$

where, “ $T(x, y, z, t)$ ” is the Temperature ($^{\circ}\text{C}$) in the element at position (x, y, z) and time (t) , “ q'' ” is the heat flux vector (W/m^2) at position (x, y, z) and time (t) , “ λ ($\text{W}/\text{m}^2 \cdot \text{K}$)” is the Thermal Conductivity of the element, “ ρ (kg/m^3)” is the density of the element, and “ c ($\text{J}/\text{kg} \cdot \text{K}$)” is the specific heat capacity of the element. Hence, substituting equation 3.8 into 3.9, gives the general form of the heat conduction equation as:

$$\nabla \cdot (\lambda \nabla T) = \rho c \partial T / \partial t \quad 3.10$$

The heat storage in air masses within the building is modelled as:

$$Q = c_p \rho_a V dT_a / dt \quad 3.11$$

where, “Q (W)” is the net heat flow into the air mass, “c_p (J/kg.K)” is the specific heat capacity of air at constant pressure, “ρ_a (kg/m³)” is the air density, “V (m³)” is the air volume, “T_a (°C)” is the air temperature.

In IESVE®-ApacheSim™, conduction in each envelope element is assumed to be unidirectional in the direction of thickness of the element. In addition, the thermophysical properties of the envelope elements (λ, ρ, c) are assumed to be isotropic (uniform in all directions). Under these assumptions,

$$\begin{aligned} \partial T / \partial t &= \alpha \nabla^2 T = (\lambda / \rho c) \cdot \partial^2 T / \partial x^2. \text{ Therefore,} \\ \partial^2 T / \partial x^2 &= \frac{\rho c}{\lambda} \partial T / \partial t \end{aligned} \quad 3.12$$

Equation 3.12 is the general form of the Heat Equation. Appropriate boundary conditions are applied to close equation 3.12 under the assumption that heat flow at the boundary of the envelope element is continuous. In IESVE®-ApacheSim™, the boundary conditions for conductive elements of a building are determined from conditions in the internal or external spaces either side of the element. Where an adjacent room is rendered thermally-inactive, a reflexive boundary condition is applied; conditions on the far side are assumed to be identical to those on the near side. In this way, the thermal mass of the element is considered while the time-averaged heat transfer through it tends to zero.

In IESVE®-ApacheSim™, a finite difference approach is adopted in solution of equation 3.12. This involves first replacing the element with a finite number of discrete nodes at which the temperature will be calculated. Spatial discretisation of equation 3.12 gives:

$$\frac{T_{n-1} - 2T_n + T_{n+1}}{\delta_n^2} = -\{(\rho c / \lambda) \partial T / \partial t\} \quad 3.13$$

where, “T_n (°C)” is the temperature at the node, “δ_n (m)” is the local node spacing.

The nodes are distributed within the layers in such a way as to optimise the heat storage and conduction characteristics for the chosen time-step, subject to constraints imposed by the Fourier Number (Fo):

$$Fo = \{(\lambda / \rho c) \Delta / \delta_n^2\} \quad 3.14$$

where Δ, is the simulation time-step (s). Each layer may be assigned several nodes.

The objective of the retrofit is to minimise operational carbon emissions and energy performance while ensuring thermal comfort of the occupants. To achieve net zero, the reduction in energy performance entails reaching intermediate and Paris Proof Target values shown in Table 3.1. As the case study is an existing building, the fixed parameters that would necessitate alteration of the sub-structure or orientation of the building remain unchanged. The parameters/ variables considered in the retrofit are categorised into passive, active and renewable energy measures.

Air Gaps

The heat flow across air gaps (cavities) in opaque and transparent constructions are modelled as pure resistances. Hence,

$$Q = (T_1 - T_2) / R \quad 3.15$$

where, “Q (W)” is the heat flow across the air gap,” T_1 and T_2 (°C) are the temperatures of the surfaces adjacent to the air gap, “R” is the combined radiative/convective resistance of the air gap. The value of “R” is set as a parameter of the thickness of the cavity, and is given as:

$$R = \frac{1}{h_c + h_r} \quad 3.16$$

where, “ h_c ” and “ h_r ” are the convective and radiative heat transfer coefficients respectively.

Boundary Conditions

The boundary conditions for conductive elements of the building are determined by internal and external spaces either side of the element to maintain the continuity and stability of the simulation. In situations where the adjacent space is a void, a reflexive boundary condition is approximated where the conditions on the far and near sides are assumed identical. Hence, the thermal mass of the element is taken to account in the simulation and the time-averaged heat transfer through it tends to zero.

Air Mass and Furniture Modelling

The storage of heat in air mass in the room is described by equation 3.11. Heat storage in furniture is incorporated in the work because the case study is an existing operational hotel. The heat storage in furniture is modelled on the assumption that the temperature of the furniture approximates that of the air in the room. Under this assumption, the effective thermal mass of the air is increased by a Furniture Factor, f_r ,

defined as the factor by which the thermal capacity of the furniture exceeds that of the air in the room. Incorporating, f_f , into equation 3.11,

$$Q = (1 + f_f)c_p\rho_a V dT_a / dt \quad 3.17$$

Following the recommendations in (Underwood and Yik, 2004), all spaces with furniture, such as bedrooms is modelled with " $f_f = 1$ " and those without furniture such as toilets, corridors, lobbies and staircases are modelled with " $f_f = 0$ " (IESVE, 2016).

Convection Heat Transfer

Convection phenomena in the study are associated with the transfer of heat, and other physical quantities, as a result of the flow of air over building elements as a result of wind or mechanical ventilation (forced convection) or buoyancy effects (natural convection). Convective heat transfer is modelled as:

$$Q_{conv.} = K (T_a - T_s)^n \quad 3.18$$

where, " $Q_{conv.}$ (W/m^2) is the heat flux () from the air to the surface, " T_a ($^{\circ}C$) is the bulk air temperature, " T_s ($^{\circ}C$) is the mean surface temperature, " K " and " n " are coefficients. Convection at the exterior surfaces of the building is mainly wind-driven forced convection, modelled with a wind speed dependent heat transfer coefficient, " h_c ($W/m^2.K$)", calculated from McAdams' empirical equations (IESVE, 2016) :

$$h_c = 5.6 + 4.0v \quad (v < 4.88) \quad 3.19$$

$$h_c = 7.2v^{0.78} \quad (v \geq 4.88) \quad 3.20$$

where, " v (m/s) is the wind speed read from the simulation weather file. In the building energy models of this study, the system-generated values of exterior heat convection coefficient, calculated from linear interpolation, at the simulation timesteps, of the values in the weather file were used.

There are four convection models for internal surfaces: (1) CIBSE Simple (fixed convection coefficients for various elements and orientations, (2) CIBSE Variable (variable convection coefficients based on factors such as surface orientation, air-surface temperature difference, and mean room air velocity, (3) BS 15265 (similar to CIBSE simple, gives fixed convection coefficients for various elements and orientations) and (4) Alamdari and Hammond Convection Coefficients (AHCC), which were developed from empirical correlations, account for dynamic changes in temperature conditions and were used in the model. The AHCC coefficients also

approximate actual conditions of the presence of air movements generated by convection at adjacent surfaces or by ventilation. Hence, AHCC for vertical and horizontal surfaces for which the heat flow is upwards, is calculated from

$$h_c = \left[\{a(\Delta T/L)^{1/4}\}^6 + \{b\Delta T^{1/3}\} \right]^{1/6} \quad 3.21$$

where, “ h_c ” is the convective heat transfer coefficient, “ $\Delta T = |T_a - T_s|$ (°C)” is the absolute difference between the bulk air temperature, T_a , (°C) and the mean surface temperature, T_s , (°C), “ L ” is the characteristic length of the surface, which for a wall or window, equals the height of the space of which it forms a boundary and equals the diameter for horizontal surfaces, and “ a ” and “ b ” are coefficients. In vertical surfaces, $a=1.50$; $b=1.23$ and in horizontal surfaces with upward heat flow, $a=1.40$; $b=1.63$. In horizontal surfaces for which convective heat flow is downward, the convective coefficient is obtained from:

$$h_c = 0.6 (\Delta T/L^2)^{1/5} \quad 3.22$$

All values of AHCC are subject to a minimum of 1.0 W/m²K.

Heat Transfer by Air Movement

The air movements modelled for the case study are infiltration, natural ventilation and mechanical (auxiliary) ventilation. Infiltration is characteristic to only spaces that have adjacency with outside air. Mechanical ventilation is accounted by localised fans while natural ventilation, due to operation of fenestrations, occurs in every conditioned space in the model. The rate of heat transfer linked to a stream of air entering a space is given as:

$$Q = \dot{m}c_p(T_i - T_a) \quad 3.23$$

where, “ $\dot{m}$ (kg/s)” is the air mass flowrate, “ c_p (Jkg⁻¹·K⁻¹)” is the specific heat capacity of air at constant pressure, “ T_i (°C)” is the supply temperature of the air, and “ T_a (°C)” is the room mean air temperature. Air supply rates specified in air changes per hour (ach) are converted to mass flowrates using:

$$\dot{m} = \rho_{ref} aV/3600 \quad 3.24$$

where, “ ρ_{ref} (=1.2 kg/m³)” is the reference air density, “ V_r (m³)” is the room volume, and “ a (ach)” is the air change rate in the room.

The water vapour gain associated with the air supply contributes to the latent heat balance is given by:

$$w = \dot{m}(g_i - g) \quad 3.25$$

where “w (kg/s) is the water vapour gain, “g_i (kg/kg) is the humidity ratio of the supply air, and “g (kg/kg) is the humidity ratio of the room air. The humidity of the room air in the model is set to (30% - 70%), the acceptable range for thermal comfort.

Long-wave Radiation Heat Transfer

The emission and absorption of thermal radiation by building surfaces by virtue of their absolute temperature is an important heat transfer mechanism in buildings. The total radiation “W (W/m²) emitted by a plane surface of area, “A (m²)”, is:

$$W = \varepsilon A \sigma \theta^4 \quad 3.26$$

where, “ε” is the surface emissivity; ranges from 0-1; 0 (perfect reflector), 1 (perfect blackbody), “σ = 5.6697 x 10⁻⁸ W/m²K⁴” is the Stefan-Boltzmann constant, and “θ (K)” is the absolute temperature of the surface. The thermal radiation phenomena considered in the model are exchange of radiation between solid surfaces, and between gases and suspended particles in the air. In a pair of surfaces, the exchange of thermal radiation is characterised by a Shape Factor, F₁₋₂, the fraction of radiation emitted from surface of area (A₁) that reaches the surface of area (A₂). By a reciprocity theorem

$$A_1 F_{1-2} = A_2 F_{2-1} \quad 3.27$$

To reduce the computational effort, the CIBSE mean radiant temperature model is used in calculating the net radiant exchange between a surface and the space from:

$$Q_r = h_r (T_s - T_{MRT}) \quad 3.28$$

where, “Q_r (W)” is the net radiative loss from the surface, “h_r” is a surface heat transfer coefficient for exchange with the MRT node, “T_s (°C) is the surface temperature, “T_{MRT} (°C)” is the Mean Radiant Temperature of the space.

Casual Gains

Casual gains refer to the heat generated within a building from non-heating sources such as occupants, lighting, electrical appliances and other equipment. The values of internal gains used in the models were obtained from CIBSE Guide A (Parand *et al.*, 2021).

3.5 MODEL-1.0: BASELINE ENERGY PERFORMANCE

IESVE®) software for Building Energy Performance Simulation (BEPS) is licensed by Integrated Environmental Solutions (IES) Limited Glasgow, UK. IESVE® originated in the mid-1990s and was developed on the basis of shared content between different simulation tools. IESVE® contains different modules; ModelIT™ (creation of 3D geometrical models from 2D-CAD drawings and BIM data), ApLocate™ (editing weather and site location data), Apache™ (heating and cooling loads calculations, and energy simulation), ApacheHVAC™ (optimisation of HVAC), SunCast™ (solar analysis and shading), MacroFlo™ (analysis of infiltration and natural ventilation), RadianceIES™ (daylight simulation and lighting design optimisation), and VistaPro™ (analysis and visualisation of the results of one or more simulations and export of data and images to other software for analysis). IESVE® was selected because the same information can be shared among several simulation tools within the IESVE® to enhance efficiency (Jankovic, 2024a). In this study, only ModelIT™, ApLocate™, Apache™, RadianceIES™ and VistaPro™ modules were used.

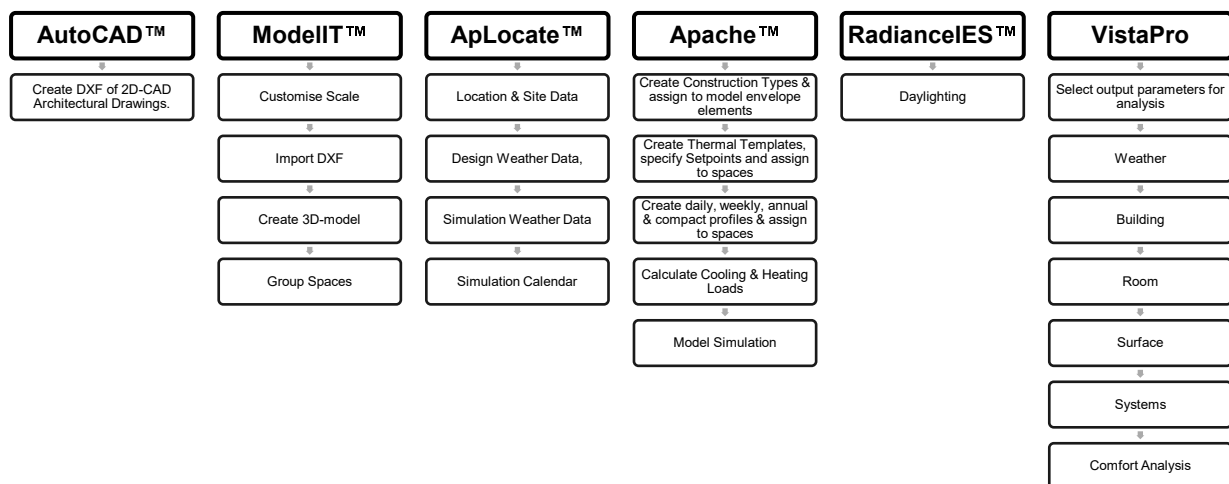


Figure 3.10: Process List Overview of the DSM Process Applied in the Study

The creation of the DSM comprised several sequential and iterative tasks as indicated in Figure 3.10. First, the 2D-CAD architectural drawings were converted to .DXF format and imported to the ModelIT™ module to create the 3D-geometrical model. The location and site data were updated, and simulation weather files were updated. Third, the building construction types (walls, floors, ceilings, windows and doors) using the section and detailed drawings. The defined construction types were assigned to

the respective elements of the building geometry. Thereafter, the use patterns (room conditions, internal gains, infiltration, ventilation and air exchange were defined. The energy system, including heating, is defined and assigned to respective spaces.

Construction and Thermal Input Data

The creation of a BEP model requires input of representative variables and accurate parameters to achieve a baseline model that approximates to the actual operation of the building and reduces the complexity of the calibration process (Raftery, Keane and O'Donnell, 2011).

Table 3.4: Fixed and Dynamic Model Input Parameters(IESVE, 2020)

Fixed Parameters	Dynamic Parameters
Site Plan drawings (incl. adjacent buildings and nearby objects)	Room Setpoints
Building Geometry Drawings (DXF Format): ☐ Site Plan Drawings ☐ Floor Plan Drawings ☐ Floor and Occupancy Layouts ☐ Elevation Drawings ☐ Section Drawings	Internal Gains
Construction Details ☐ U-values	Lighting Operating Schedules
Airtightness and Infiltration	Equipment Operating Schedules
Equipment Layout and Schematics	System Operating Schedules
Equipment Schedules and Specifications	Occupancy Profiles
Lighting Layout	Meteorological Data for case study location.
Plug Loads	Information from “Walk-through” Energy Audit

A summary of construction and thermal properties of the model and the sources of the data for the parameters used to create the baseline model are shown in Table 3.4. Variables refer to quantities that change with time and may be observed (measured or derived from available evidence or data) or unobserved (latent). Parameters (fixed or dynamic) are quantities that influence the output or behaviour of the model and are not time-varying values.

The Geometrical Model was developed from 2D-drawings exported in .DXF format to IESVE®-ModelIT™ module. Geometry consistency checks confirmed simulatability of the model, as there were no non-void zero volume spaces, non-planar surfaces, intersections, external holes, unmatched adjacencies, unmatched edges nor small surfaces for the 260 spaces in the model. Construction templates, created from construction properties of the envelope elements (fixed parameters) and thermal templates, created from thermal properties (dynamic parameters) of the spaces were

applied to the building energy model. As the building was designed in 2006 (BUL Estates. And MDL, 2006), the target U-values in the model are based on Part L2, of the 2006 UK Building Regulations (2006 BRUKL).

- ❑ External and internal surface resistance (R_{se} , R_{si}) obtained from Table 3.47 CIBSE Guide A (Parand et al., 2021).
- ❑ External (and internal) Solar Absorptance/ Solar Absorptivity (SA_e , SA_i), obtained from Table 15 (ASHRAE, 2021) based on Final Design Drawings (BUL-Estates. And MDL, 2006).
- ❑ External (and internal) surface emissivity (ϵ_1, ϵ_2), obtained from Appendix 3.A7 of CIBSE Guide A (Parand et al., 2021) and Table -3 (ASHRAE, 2021)
- ❑ Thermal Conductivity, Density (λ, ρ), Class B Engineering Bricks Technical Datasheet (Wienberger Class-B, 2020), Knauf Insulation Dritherm cavity slab datasheet (Dritherm-32, 2022) based on design specification, Drg. No. 3689-A209 (BUL-Estates. And MDL, 2006).
- ❑ Specific Heat Capacity, Vapour Resistivity, “ r_v ” Table 3.45 (Parand et al., 2021); Knauf Insulation Dritherm cavity slab datasheet (Dritherm-32, 2022) based on design specification, Drg. No. 3689-A209 (BUL-Estates. And MDL, 2006). And Table 3.45 of CIBSE Guide A (Parand et al., 2021)

Table 3.5: U-values of Envelope Elements in Base Case Model

Envelope Element	Base Case Model U-value (W/m ² .K)	BRUKL 2006 U-value (W/m ² .K)
External Wall	0.3507	0.35
Internal Partition	0.3507	0.35
Ground/ Exposed Floor	0.2509	0.25
Roof	0.1500	0.15 ^a
Internal Ceiling/ Floor	0.2503	0.25
Door	2.2038	2.2
Glazed Construction	2.2012 ^b	2.2

^a U-value for flat roof

^b The value is the Net U-value, excluding metal frame which occupies 15% of area.

Envelope Element	Base Case Model U-value (W/m ² .K)	BRUKL 2006 U-value (W/m ² .K)

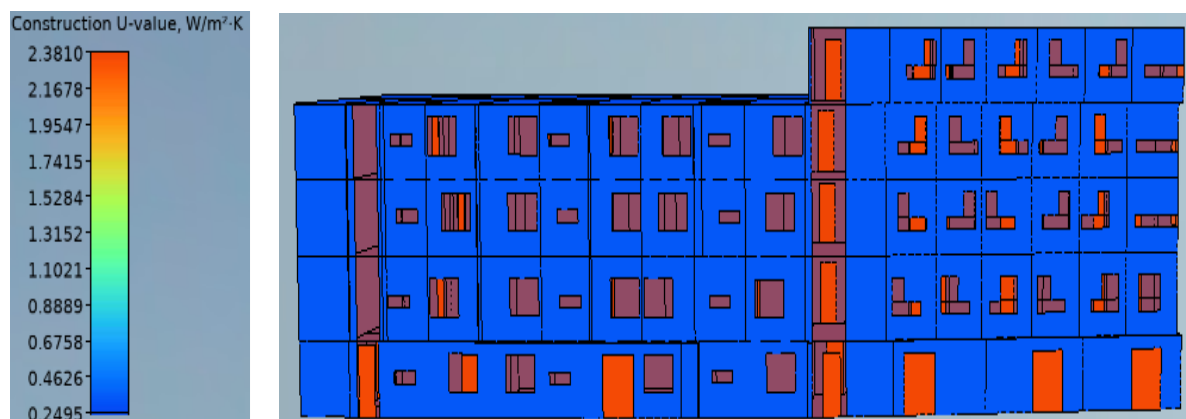


Figure 3.11: Model and U-value Variation up to a Maximum of 2.3810 W/m².K

The U-values of the 2006 UK Building Regulations- Part L (BRUKL 2006), summarised in Table 3.5, are used to model the base case envelope elements. The heat map of the variation of U-values between 0.2495 – 2.3810 W/m²K for the envelope elements of the model are shown in Figure 3.11.

Profiles

Profiles describe the time variation of thermal input parameters over a period, typically a year. The input parameters include operating schedule of plant equipment, power consumption, water consumption, casual gains and ventilation rates, natural gas consumption, occupancy, timing and degree of window opening and time varying set-points and supply temperatures (IESVE, 2020; IESVE-BPM, 2023). There are two (2) main types of profiles; absolute and modulating. In the latter, inputs are generated by altering time-series values between 0 and 1, while the former specifies the variation of physical variables with time, hence absolute profile values could have units. Profiles are organised in three (3) categories on the basis of pattern of variation of the parameter into daily, weekly or annual profiles. Daily profiles describe the variation of the parameter over a day while weekly profiles are assembled from daily profiles of a parameter to establish repeated pattern over the weeks of a year. In the BEPM of this study, occupancy, electricity consumption, natural gas demand, boosted water consumption and, kitchen water use was used to generate profiles. Profiles are used as proxy indicators of the variation of attributes that impact energy performance in the model. As an example, kitchen water consumption is used as a proxy indicator of occupancy in the kitchen.

Occupancy

Occupancy refers to the number of bedrooms occupied every night and is an indicator of the energy consumption in the bedrooms, bathrooms, toilets, and operation of cooling and extractor fans.

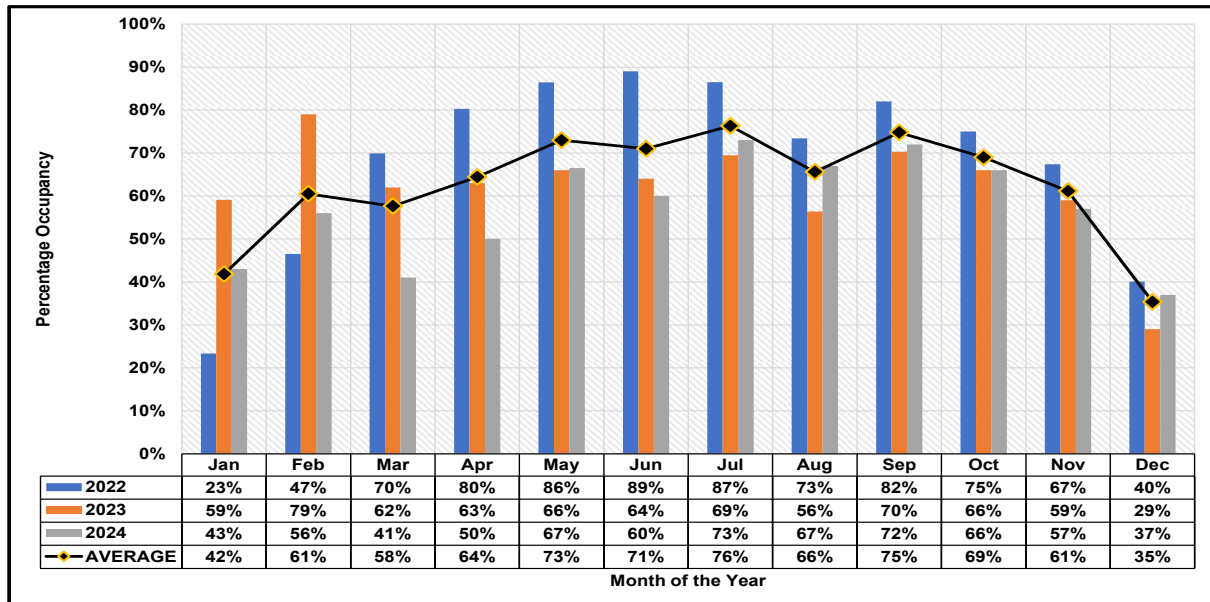


Figure 3.12: Clustered Bar Chart of 2022 – 2024 Occupancy Data (Appendix-1J: OCCUPANCY DATA OF CASE STUDY)

As shown in Figure 3.12, the occupancy rate of the case study in the baseline period was below the threshold of 75%, specified in the UKNZCSBS (Anderson et al., 2024), except for July and September, with occupancy rates of 76% and 75% respectively.

To ensure that the occupancy used in the model reflects stable operations of the case study, the occupancy of the case study for 2022, 2023 and January – August 2024 was obtained from the hotel management (Appendix-1J: OCCUPANCY DATA OF CASE STUDY) as summarised in Figure 3.12. In addition, occupancy data for September – December 2024 was estimated using the data for the last normal year of operation (2018), pre-COVID-19. The occupancy data for 2018 – 2024 was averaged and used to develop free form profiles that were used in the model. In addition, the electrical and thermal energy demand exported from IESVE™ to model the microgrid in HOMER Pro™ was subjected to timestep and day-to-day variabilities of 10% and 20%, respectively. This accommodates sensitivities of the energy system to occupancy variations.

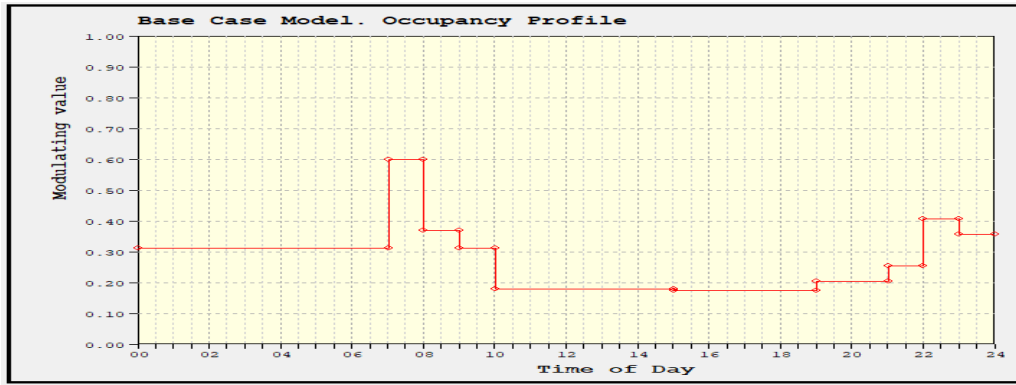


Figure 3.13: IESVE®-Apache™ extract of free-form occupancy profile

The average values of occupancy were used to create the free-form profile for the IESVE®-Apache™ module (Figure 3.13). In the UKNZCBS, the requirement is that Occupancy Rate “O (%)” for assessment of operational and carbon emissions shall be; (a) $\geq 80\%$ if the pass/fail metric is based on GIA, and (b) $\geq 75\%$ if the pass/fail metric is based on NIA. Furthermore, equation 3.29 gives “O (%)”:

$$O = (S_t / A_n) \times 100 \quad 3.29$$

$$S_t = S_1 + S_2 + S_3 + \dots + S_n$$

$$A_n = A_g - A_u$$

The UKNZCBS defined a separately occupiable space as an enclosed area within a building that could be occupied by different tenants or have different owners e.g., for apartment buildings, individual flats but excludes spaces that are used by multiple separately occupiable spaces (e.g., common areas including reception and circulation areas).

Electricity, Gas, and Boosted and Kitchen Water Consumption

The hourly-referenced values of electricity demand and, boosted and kitchen water consumption were obtained from the BMS platform “Energy Manager®” for the base year. An MS®-EXCEL™ Spreadsheet was used to compute the average value of each parameter (electricity and natural gas demand and, boosted and kitchen water consumption) at each timestep to generate absolute and modulating profiles. The modulating profiles function as control switches for the time variation of parameters between 0 and 1.

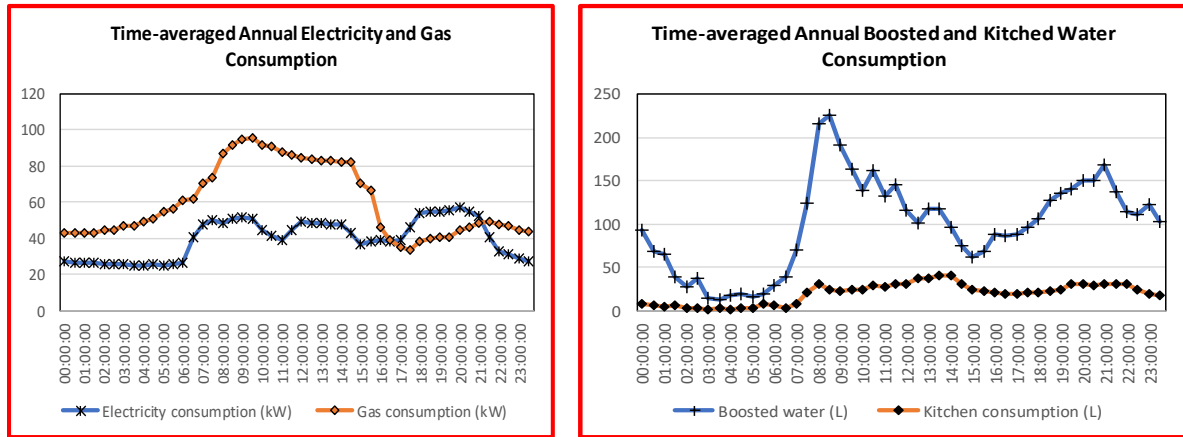


Figure 3.14: Time-averaged Electricity, Gas, Boosted and Kitchen Water Demand

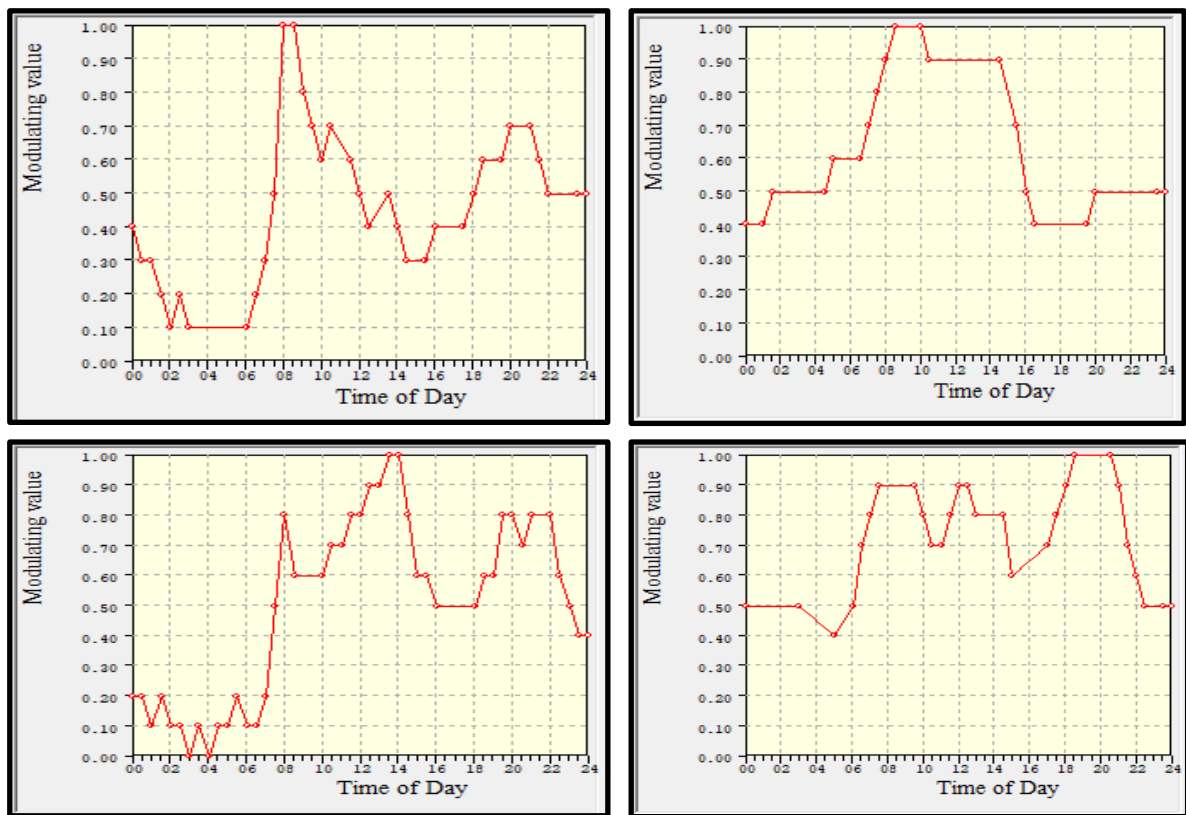


Figure 3.15: Weekly Profiles Associated to Annual FFPs for: Boosted Water (top left), Natural Gas (top right), Kitchen Water (bottom left) and Electricity (bottom right)

The modulating Free Form Profiles shown in Figure 3.14 and Figure 3.15 represent the annual pattern of timestep variation of the parameters, and the respective daily modulating profiles. The time-average values of each parameter; electricity and natural gas demand and, boosted and kitchen water consumption is obtained by averaging the values at 15-minute resolution over a year (Figure 3.14). In addition to the profiles described in the foregoing, some parameters are profiled as “ON

continuously” or “OFF continuously”. The daily modulating profiles are aggregated to weekly, monthly and annual Free Form Profiles in IESVE™.

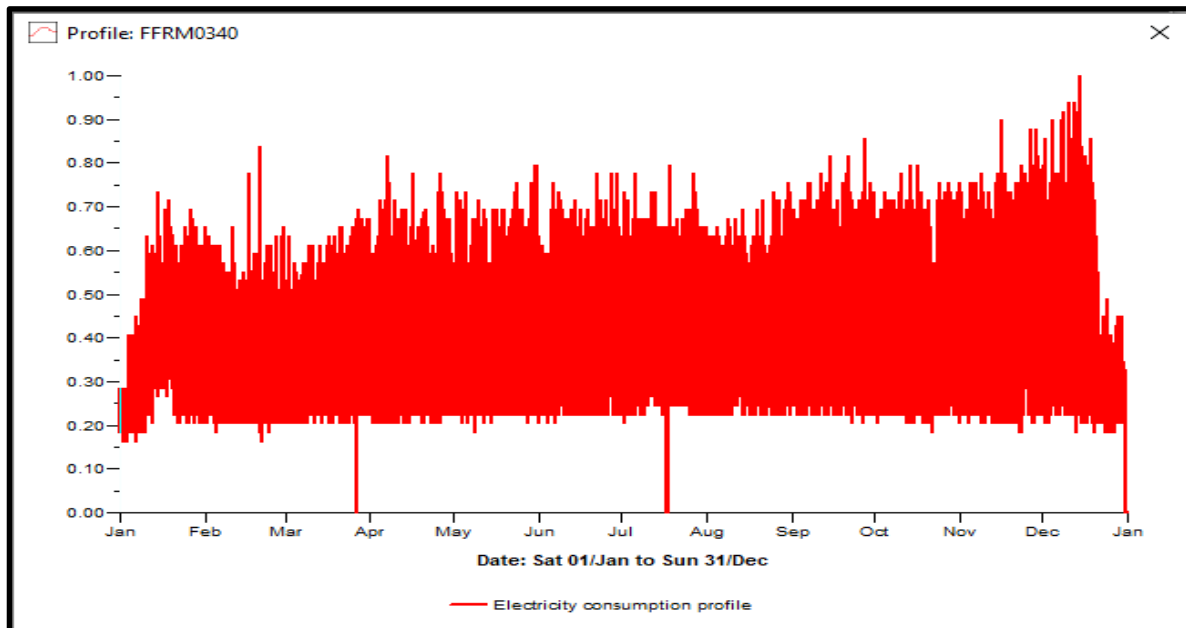


Figure 3.16: FFP of Electricity Consumption

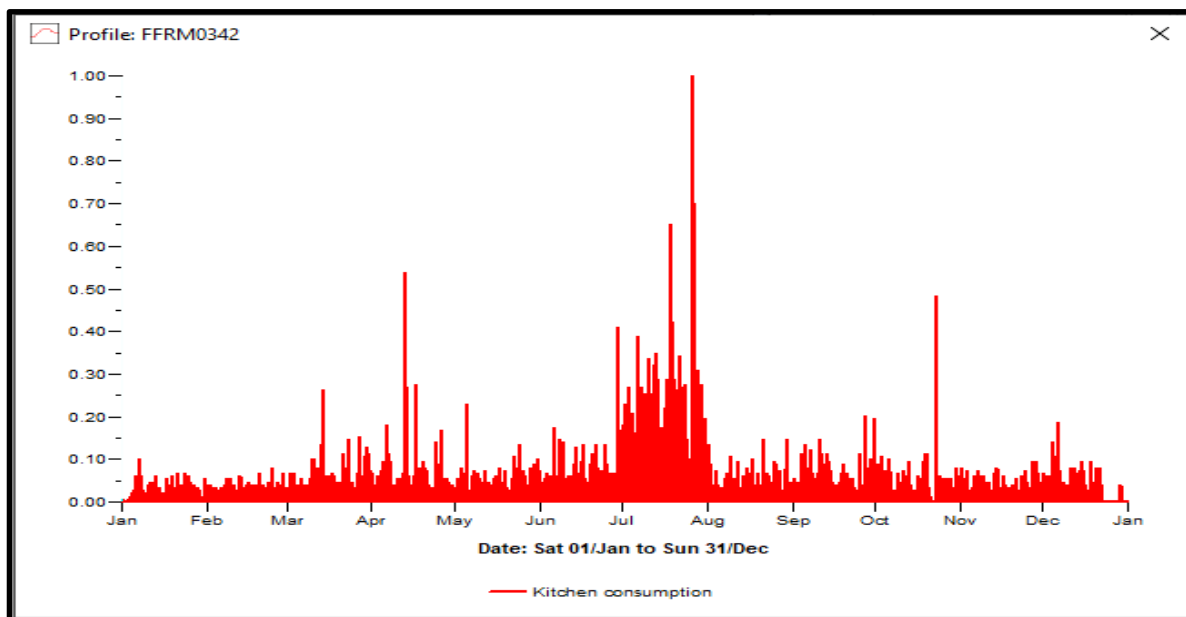


Figure 3.17: FFP of Kitchen Water Consumption

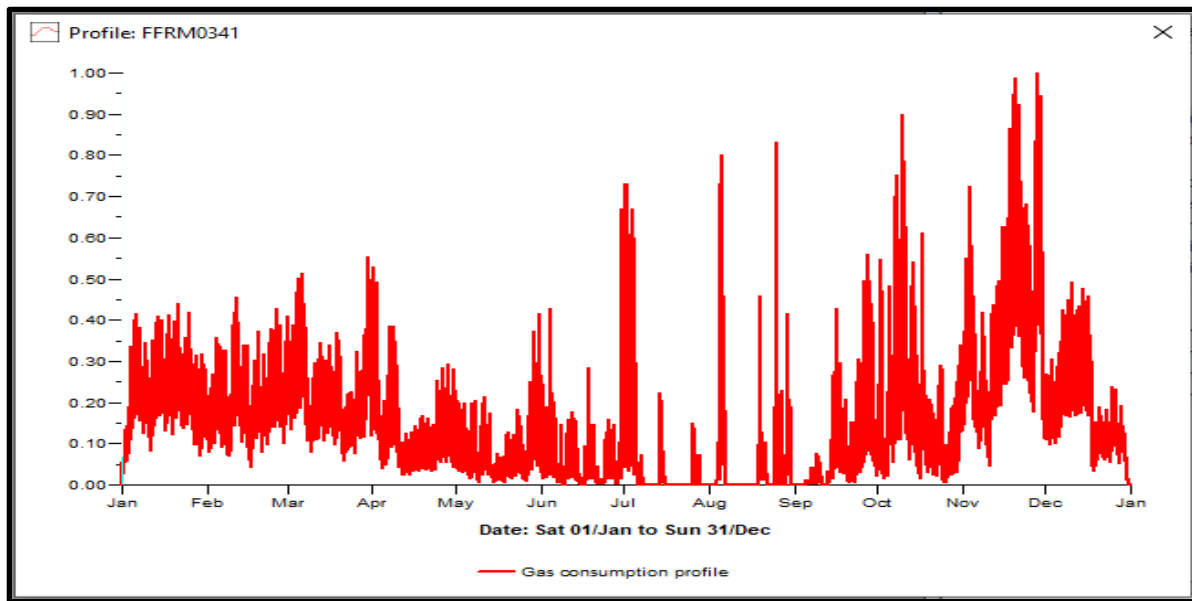


Figure 3.18: FFP of Gas Consumption

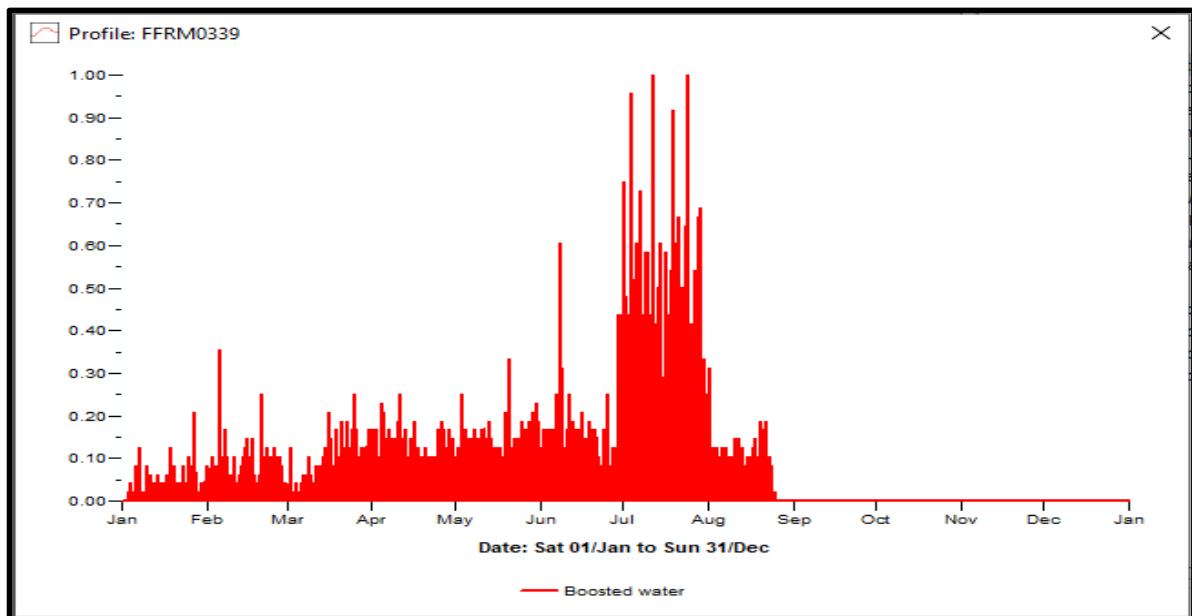


Figure 3.19: FFP of Boosted Water Consumption

The annual Free Form Profiles of the parameters (Figure 3.15 -Figure 3.19) show the timestep variation across the year and are used to characterise the pattern of variables in the model. As an example, the kitchen water consumption profile is a proxy indicator of kitchen occupancy pattern while boosted water consumption profile is used as an indicator of bathroom and toilet occupancy. Hence, each annual profile is linked to the corresponding daily, weekly, and monthly profiles to enable calculation of heating and cooling loads in the IESVE™ software. The modulated weighting greater than or equal to 0.5 are interpreted as “ON =1” and values less than 0.5 are classed as “OFF-0”.

Heating and Cooling Setpoints

The heating and cooling setpoints of 20°C and 27°C respectively were used in the model based on the heating and cooling setpoint data provided by the facility operator. In addition, the setpoints are within the 90% acceptability limit of operative temperature, “ T_{op} (°C)”, range for naturally-conditioned spaces (Figure 3.8) as defined in the intervals: (a) Heating: $18 \leq T_{op} \leq 23$ and, (b) Cooling: $24 \leq T_{op} \leq 29$ are in the acceptable range of thermal comfort.

IESVE®-Apache™ Systems

The IESVE®-Apache™ system model settings, input specifications and autosized parameters used in the energy simulation of each space are shown in **Error! Reference source not found.** The CS is modelled as a concurrent mixed-mode or hybrid ventilation building, defined as one which combines natural and mechanical ventilation, and/or cooling systems, with occupants having the choice to open windows when they choose (CIBSE Guide B2, 2016). The “systems” functionality in IESVE®-Apache™ is used to describe the characteristics of heating, domestic hot water, ventilation and air conditioning services to conditioned spaces. The inputs entered in the model are used to size heating and cooling loads, and to calculate fuel consumption and carbon emissions. There are three (3) parameters used to model heating and cooling systems; (a) Seasonal Coefficient of Performance (ScoP), (b) System Seasonal Energy Efficiency Rating (SSEER), and (c) Auxiliary Energy Value (AEV). ScoP (equation 3.30) is a measure of the proportion of delivered energy that is used by the heating system over a season.

$$\text{ScoP} = \text{HEFF} \times \text{HDE} \quad 3.30$$

ScoP takes the efficiency of the heat source (boiler), and the inefficiencies associated with distribution losses, energy of pumps, fans and controls. The Seasonal efficiency of heating (1.0890) was extracted from the datasheet (**Error! Reference source not found.**) of the heating generator (Remeha®-610 ECO™ boiler) with which the software generated the ScoP (0.9717) and HDE (0.8923) of the system.

In cooling systems, measures the energy used for cooling, relative to the delivered energy and includes chiller or cooling generator energy, distribution losses and fan and pump energy used for heat rejection. SSEER is given by equation 3.31:

$$\text{SSEER} = \left\{ \frac{(\text{SEER} \times \text{CDE})}{(1 + (\text{SEER} + 1)\text{HRP})} \right\} \quad 3.31$$

where, “SEER” is the “Seasonal Energy Efficiency Ratio” of the cooling generator, “CDE” is the “Cooling Delivery Efficiency” and “HRP” is the “Heat Rejection Pump and Fan Power Fraction”.

Evaluation of Calibration Metrics

The verification of the base case energy model against the baseline half-hourly electricity consumption Appendix-1A: TIME SERIES ELECTRICITY CONSUMPTION DATA was done using ASHRAE-14 protocol. The NMBE (%) and CvRMSE (%) are, respectively, calculated by implementing equations 3.32 – 3.33, in MS®-Excel™ spreadsheet, customised for the purpose.

$$\text{NMBE (\%)} = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{n \times \bar{y}} \times 100 \quad 3.32$$

$$\text{CvRMSE (\%)} = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}}{\bar{y}} \times 100 \quad 3.33$$

where, “n” is the number of data points. A value of 8760 hours, equal the number of hours in the base year was used. In calibration of monthly time-series data, n =12, “ $\bar{y}$ ” is the arithmetic mean of measured power consumption, “ y_i ” is the measured value of power consumption at each datapoint, “ $\hat{y}_i$ ” is the simulated values for each datapoint.

Table 3.6: ASHRAE-14 Calibration Acceptance Criteria

Index	Hourly	Monthly
NMBE (%)	± 10	± 5
CvRMSE (%)	30	15

The model verification requirements of NMBE and CvRMSE for calibration of hourly and monthly datasets in energy modelling under ASHRAE-14 protocol are presented in Table 3.6. The model calibration targeted to be within the hourly acceptance range (NMBE ± 10, CvRMSE 30%) and values of (NMBE=4.75%, CvRMSE=12.6%) were obtained. NMBE implies that at each timestep, the model tends to overestimate the electricity consumption by 4.75% relative to the average actual measured electricity consumption for the timestep, while the CvRMSE of 12.6%, indicates that the pattern

of electricity consumption predicted by the model represents the actual consumption pattern at the case study across different months.

Practice evidence and studies have shown that systematic and random differences remain between measured and simulated values of parameters, even when the ASHRAE-14 calibration of the model is within the acceptance threshold. However, as the models are within the calibration thresholds, the residual errors are small and negligible, for practical purposes. In addition, averaging effect from the normalisation of EUI and CEI with floor area further reduces the influence of the residuals. This is the reason the values of the benchmarks are usually expressed in ranges, that implicitly incorporate residuals.

3.6 ENERGY EFFICIENCY AND RESILIENCE MODELS

The successive application of EEMs to the baseline model, generated decarbonisation pathways for evaluation of energy and carbon intensity reduction required for attainment of net zero.

Model Codes and Descriptors	2022 Weather	2030 Weather	2050 Weather	U-value	LED	DD	AV
1.0: Base Case (2006 BRUKL)							
2.0: Do Nothing (2006 BRUKL)							
2.1: U-value							
2.2: LED							
2.3: DD							
2.4: AV							
2.1.2: U-value + LED							
2.1.3: U-value + DD							
2.1.4: U-value + AV							
2.2.3: LED + DD							
2.2.4: LED + AV							
2.3.4: DD + AV							
2.1.2.3: U-value + LED + DD							
2.1.2.4: U-value + LED + AV							
2.1.3.4: U-value + DD + AV							
2.1.2.3.4: U-value + LED + DD + AV							
3.0: Do Nothing							
3.1: U-value							
3.2: LED							
3.3: DD							
3.4: AV							
3.1.2: U-value + LED							
3.1.3: U-value + DD							
3.1.4: U-value + AV							
3.2.3: LED + DD							
3.2.4: LED + AV							
3.3.4: DD + AV							
3.1.2.3: U-value + LED + DD							
3.1.2.4: U-value + LED + AV							
3.1.3.4: U-value + DD + AV							
3.1.2.3.4: U-value + LED + DD + AV							

Figure 3.20: Summary of Dynamic Thermal Simulation Models

As shown in the matrix (Figure 3.20), 30 additional models were evaluated. The design weather data for simulating the base and future conditions was constructed by “inputting and updating” in the “Design Weather Data” tab of IESVE®-ApLocate™ module, the following meteorological parameters; (a) the lowest value of dry-bulb temperature as “Outdoor Winter Design Temperature”, (b) the maximum dry-bulb and, (c) maximum wet-bulb temperature. The detailed design weather parameters for each of the scenarios is shown in Appendix-3C, and the respective plots of maximum and minimum monthly dry-bulb, and maximum wet-bulb temperature is given in Figure 3.7. The heating and cooling setpoints (21°C and 27°C, respectively) selected in the climate resilience and energy efficient models are within a range of 18 – 22°C (heating) and 24 -29°C (cooling), as recommended for adaptive thermal comfort requirement in naturally-conditioned spaces; 90% acceptability of “Top” (maximum 10% PPD), shown in Figure 3.20. A “stepped retrofit” approach based on the “fabric first principle” was applied to establish the net zero pathway that offered the most EUI reduction and carbon savings. The values for respective years; 2022, 2030 and 2050 were obtained weather files generated in Meteotest®-Meteonorm™ (V8.1):

- ❑ **Model-2.0: “Do Nothing”- 2030 Climate Change Effect:** The base case model was simulated with 2030 future weather file under a “Do Nothing” scenario, with the following parameters; (a) grid CI=0.098 kgCO₂/kWh, (b) natural gas PEF=1.017kWh/kWh, and natural gas CO₂ emission factor = 0.21 kgCO₂/kWh.
- ❑ **Model-2.1: U-value Reduction (UK 2025 Future Buildings Standard, UK-FBS):** in addition to the conditions in Model-2.0, the U-values of the envelope elements were reduced to conform with the following specifications for new thermal elements in existing non-domestic buildings under the “UK-FBS 2025” (**Error! Reference source not found.**); (1) Flat roof =0.18 W/m².K, (2) Wall = 0.26 W/m².K, (3) Floors = 0.18 W/m².K, (4) Windows =1.6 W/m².K, and (5) Pedestrian doors = 1.4 W/m².K.
- ❑ **Model-2.2: LED Retrofit:** Further to the measures in Model-2.1, a lighting retrofit from Compact Fluorescent Lighting (CFL) to Light Emitting Diode (LED) lighting was implemented by reducing the lighting gains and lighting gain Diversity Factor (DF) in Model-2.1 by 30%. The percentage reduction applied is based on the average value obtained from trade information in the product datasheets of several UK consultancies and some lighting manufacturers.

- **Model-2.3: Daylight Dimming:** In addition, to LED retrofit, daylight dimming was implemented in all the naturally-lit spaces with common use functions (staircases, corridors, lobbies, kitchen). Using equation 3.34, daily fuzzy logic formula profiles for daylighting were created the sunrise and sunset times of each month of the year. The sunrise and sunset times for London (Table 3.7) were extracted from Table 2.13(g) of CIBSE Guide A (Parand et al., 2021).

$$Gt(e1,100,5) \& gt(igh, 35,5) \quad 3.34$$

interpreted as “at sunrise and sunset, lighting is dimmed when the illuminance on a working plane (e1) in the space is greater than 100 lux and Global Horizontal Solar Flux (igh) is greater than 35 W/m², and the transition of “e1” and “igh” occurs over a proportional bandwidth of 5 lux and 5 W/m² respectively. Weekly profiles are created by applying the same daily profile for a particular month to each day of the week. Hence, 12 weekly profiles are created for each month of the year, which are further used to create the annual profile. Virtual sensors are created in each space to monitor the illuminance in each space relative to the amount of daylight and trigger dimming of the lighting according to the fuzzy logic (equation 3.34). The software customisation of the sensor position is “middle of the space, facing up and at working desk height, (about 0.8m above the finished floor level)”. The sensors are first simulated in IESVE®-RadianceIES™ module and before simulation in IESVE®-Apache™, the RadianceIES™ option is checked to couple the sensor and thermal energy simulation. The annual profile is applied as a dimming profile on lighting gains in daylit spaces.

Table 3.7: Table of Sunrise and Sunset Times for London (Parand *et al.*, 2021)

Month	Sunrise Time	Sunset Time
January	07:52	16:30
February	07:02	17:25
March	06:01	18:14
April	04:51	19:06
May	03:58	19:55
June	03:40	20:23
July	04:06	20:07
August	04:53	19:13
September	05:42	18:04

Month	Sunrise Time	Sunset Time
October	06:31	16:58
November	07:26	16:05
December	08:01	15:55

- ❑ **Model-2.4: Adaptive Ventilation:** An adaptive ventilation strategy was implemented on all spaces with external windows in Model-2.3. Using equation 3.35, a fuzzy logic daily ventilation formula profile was created.

$$Gt(t_a, 23, 2) \& Lt(t_o, 23, 2) \& (t_a < t_o) \quad 3.35$$

The equation is interpreted as “when the room air temperature (t_a) is greater than, and the outside temperature (t_o) is less than, 23°C the windows will be opened provided the room air temperature is less than the outside air temperature, and the transition of “ t_a ” and “ t_o ” occurs over a proportional bandwidth of 2°C. The setpoint of 23°C and a bandwidth of 2°C were selected to keep the temperature range within the acceptable adaptive comfort temperature range shown in Figure 3.8. A weekly ventilation profile was created by applying the daily profile (equation 3.35) to each day of the week. The weekly profile was used to create an annual profile which was applied to the natural ventilation profile of the spaces with external windows.

- ❑ **Model-2.1.2: U-value + LED Retrofit:** the combined effect of the UKFBS-2025 and LED retrofit was simulated with the following parameters; (a) Model-2.1 U-values, (b) Model-2.2 lighting gains, and (c) 2030 weather file.
- ❑ **Model-2.1.3: U-value + Daylighting:** the combined effect of the UKFBS-2025 and daylight dimming-controlled lighting was simulated with the following parameters; (a) Model-2.1 U-values, (b) Model-2.3 dimming profiles, and (c) 2030 weather file.
- ❑ **Model-2.1.4: U-value + Adaptive Ventilation:** the combined effect of the UKFBS-2025 and adaptive control of window opening and based on external temperatures was simulated with the following parameters; (a) U-values in Model-2.1, (b) formula profiles in Model-2.4, and (c) 2030 weather file.
- ❑ **Model-2.2.3: LED Retrofit + Daylighting:** the combined effect of LED retrofit and daylighting was simulated with the following parameters; (a) Model-2.2 lighting gains, (b) Model-2.3 dimming profiles, and (c) 2030 weather file.

- ❑ **Model-2.2.4: LED Retrofit + Adaptive Ventilation:** the aggregate impact of LED retrofit and adaptive ventilation was simulated with the following parameters; (a) Model-2.2 lighting gains, (b) Model-2.3 dimming profiles, and (c) 2030 weather file.
- ❑ **Model-2.3.4: Daylighting + Adaptive Ventilation:** the aggregate impact of daylight dimming controlled lighting and adaptive ventilation was simulated with the following parameters; (a) Model-2.3 dimming profiles, (b) Model-2.4 ventilation formula profiles and (c) 2030 weather file.
- ❑ **Model-2.1.2.3: U-value + LED Retrofit + Daylighting:** the combined effect of U-value reduction, LED retrofit and daylight dimming-controlled lighting was simulated with the following parameters; (a) Model-2.1 U-values, (b) Model-2.2 lighting gains, (c) Model-2.3 dimming profiles, and (d) 2030 weather file.
- ❑ **Model-2.1.2.4: U-value + LED Retrofit + Daylighting + Adaptive Ventilation:** the combined effect of U-value reduction, LED retrofit and daylight dimming-controlled lighting was simulated with the following parameters; (a) Model-2.1 U-values, (b) Model-2.2 lighting gains, (c) Model-2.3 dimming profiles, and (d) 2030 weather file.
- ❑ **Model-2.1.2.3.4: U-value + LED Retrofit + Daylighting + Adaptive Ventilation:** the combined effect of U-value reduction, LED retrofit, daylight dimming-controlled lighting and adaptive ventilation was simulated with the following parameters; (a) Model-2.1 U-values, (b) Model-2.2 lighting gains, (c) Model-2.3 dimming profiles, (d) Model-2.4 ventilation formula profiles and € 2030 weather file.
- ❑ **Model-3.0: “Do Nothing”- 2050 Climate Change Effect:** The base case model was simulated with 2050 future weather file under a “Do Nothing” scenario, with the following parameters; (a) U-values based on BRUKL, 2006, (b) grid CI=0.002 kgCO₂/kWh, (c) electricity PEF = 2.63 (d) natural gas PEF=1.38 kWh/kWh, and € natural gas CO₂ emission factor = 0.1526 kgCO₂/kWh. The PEF is calculated as the ratio of primary energy demand for natural gas in 2050 (718TWh) to final energy demand for natural gas in 2050 (522TWh), which values are published, respectively, in Annexes “E” and “F” of the “UK Energy and Emissions Projections” (UK-DESNZ, 2024). The projections are based on existing and planned policies and assume high fossil fuel prices (High-FFP) and medium GDP.

- ❑ **Model-3.1: U-value Reduction- 2050 Climate Change Effect:** The base case model was simulated with 2050 future weather file under a “Do Nothing” scenario, with the following parameters; (a) grid CI=0.002 kgCO₂/kWh, (b) electricity PEF = (b) natural gas PEF=1.38 kWh/kWh, and natural gas CO₂ emission factor = 0.21 kgCO₂/kWh. The PEF is calculated as the ratio of primary energy demand for natural gas in 2050 (718TWh) to final energy demand for natural gas in 2050 (522TWh), which values are published, respectively, in Annexes “E” and “F” of the “UK Energy and Emissions Projections” (UK-DESNZ, 2024). The projections are based on existing and planned policies and assume high fossil fuel prices (High-FFP) and medium GDP.

3.7 THEORETICAL FRAMEWORK OF SOLAR-PV MODEL

The modelling and prediction of solar-PV yield is essential for maximum renewable share towards Net Zero. This study used the HelioScope™ model to size a rooftop solar-PV system for the case study. HelioScope™ is a controlled-access website, for simulating solar array output for a specific location under a range of technology, architecture and environmental assumptions.

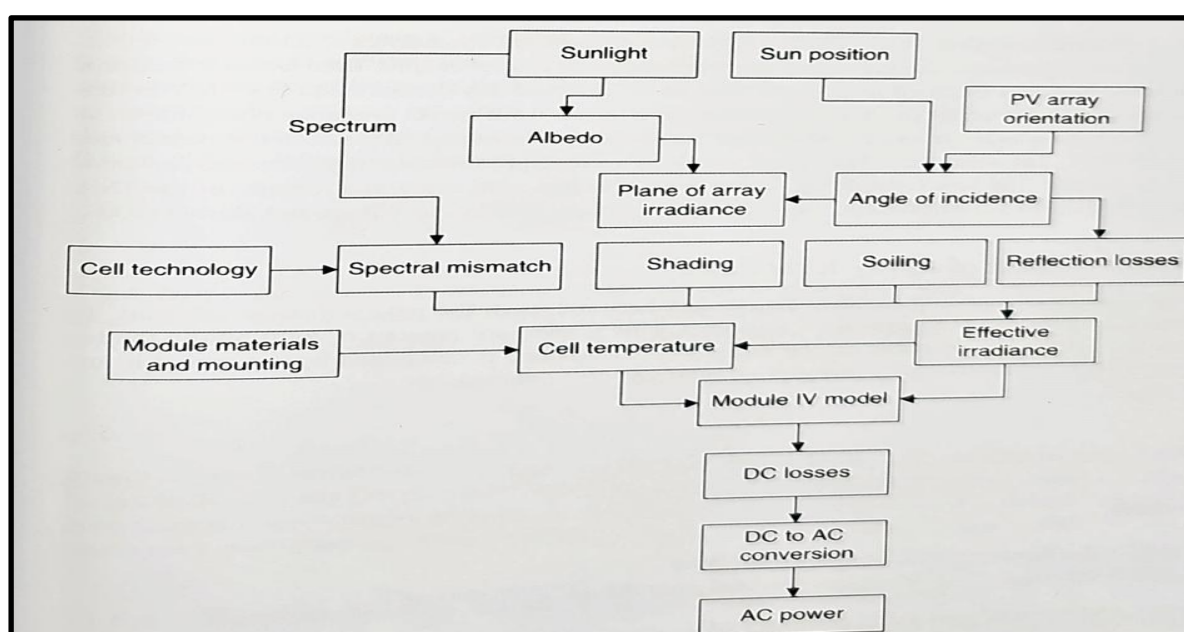


Figure 3.21: PV Performance Modelling Process for Grid-connected PV System (Stein, 2017)

The solar-PV modelling approach (Figure 3.21) shows the energy flow from the photon to AC power and the design process. The mathematical formulations, basis for selection of components, and parameters considered in the model are inspired from the works of (Gibbs, 2013; Guittet and Freeman, 2018; HelioScope Modeling 101,

2023). In addition, methodologies reported in (Stein et al., 2017; Yang, et al., 2020) were also adopted and adapted to develop the design process flowchart (Figure 3.23). The mechanical design encompassed the selection of a suitable type, number, orientation and configuration (spacing, tilt and azimuth) of PV module and array.

Module Selection and Orientation

The module selection considered the properties of sunlight, solar cells, modules and arrays that enable maximum solar-PV yield and optimal performance in commercial building typologies.

$$FF = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}} \quad 3.36$$

where, “ I_{mp} (A)” is the rated current, “ V_{mp} (V)” is the rated voltage, “ I_{sc} (A)” is the short circuit current, and “ V_{oc} (V)” is the open-circuit voltage.

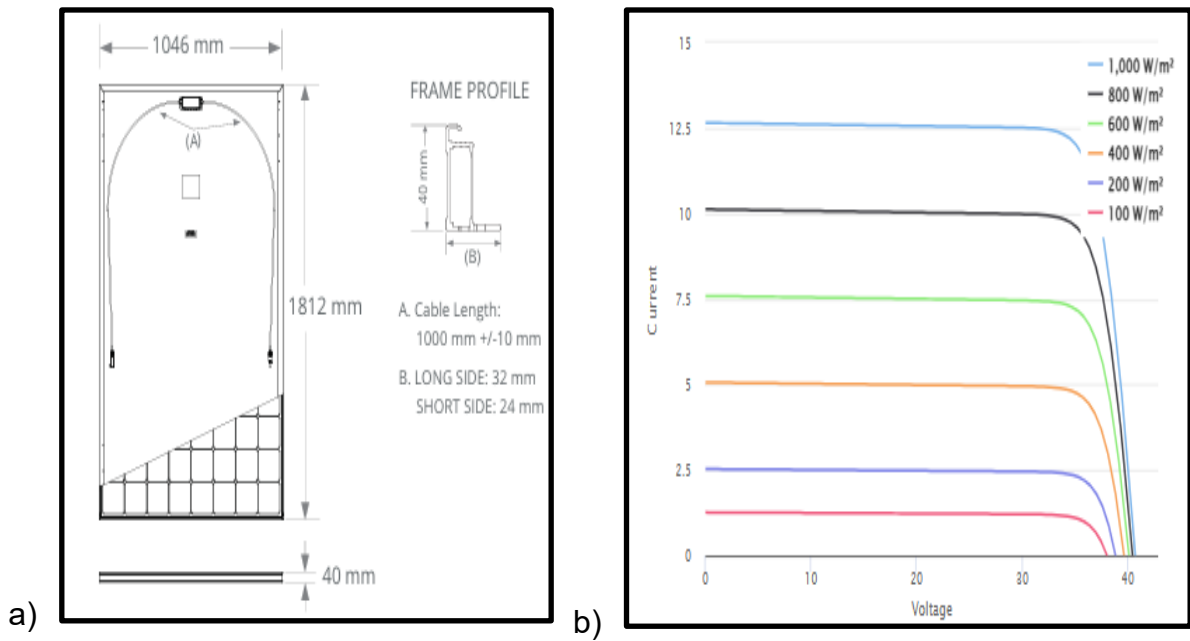


Figure 3.22: SPR-MAX3-420-BLK-R Module Specification Source: Sunpower Solar

The extract of the selected PV-module; “SunPower® Maxeon™ SPR-MAX3-420-BLK-R” specifications (Figure 3.22) datasheet are presented in Appendix -4C: DATASHEET OF MAXEON 420W BLK SOLAR PANEL. The Form Factor, the number of cells (112) and other parameters of the module are given in Table 3.8 and Figure 3.23, from which the Fill Factor ($FF=0.8$), is calculated using equation 3.36. The value of $FF=0.8$ is typical of monocrystalline silicon solar cells.

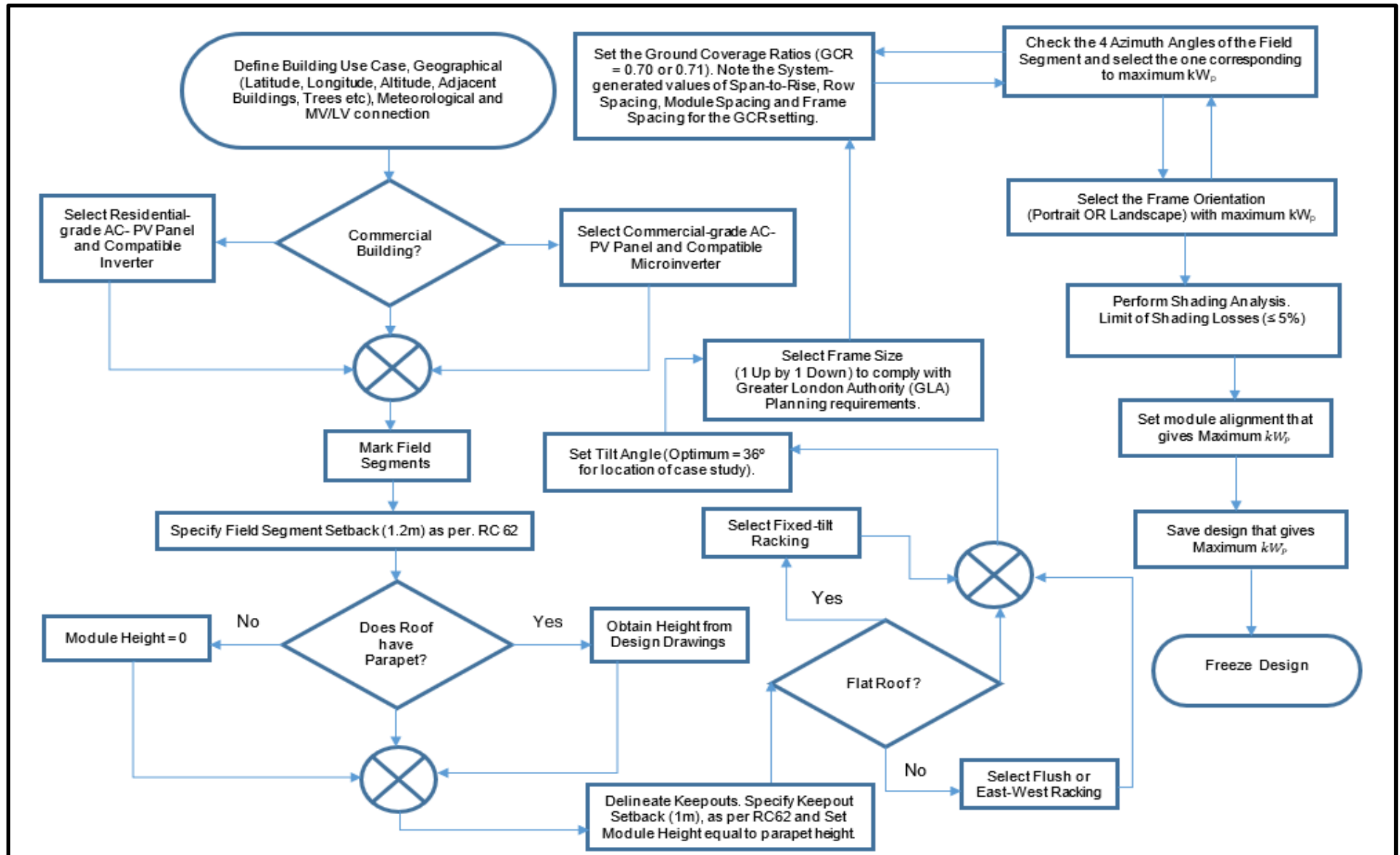


Figure 3.23: Flowchart of Solar-PV Design Process in HelioScope™

The procedure for sizing the solar-PV generation for the case study is outlined in Figure 3.23.

Table 3.8: Summary of SPR-MAX3-420-BLK-R Module Specifications

Variable/ Parameter	Value
STC Rating	420W
V_{mp}	35.6V
I_{mp}	11.62A
V_{oc}	40.7V
I_{sc}	12.65A
Panel Efficiency	22.2%
Number of cells in series	112

The module orientation, characterised by the tilt and azimuth angles, define the direction that the array is faced.

Solar Angle, Surface Azimuth and Module Tilt

The sun's angle in the sky at each hour of the year are required in the irradiance calculations to estimate the total amount of sunlight that reaches the modules. The PSA (Plataforma Solar de Almeria) Algorithm reported in (Blanco-Muriel et al., 2001) is used because it computes solar parameters; zenith distance, azimuth and direction vector of the sun with the least deviation when compared to previous algorithms; Cooper (1969), Spencer (1961), Swift (1976), Pitman & Vant-Hull (1978), Lamm (1981), and Michalsky (1988). HelioScope™ calculates the sun position by implementing the PSA algorithm with inputs of universal time and location (longitude and latitude) to give the outputs (azimuth angle, zenith angle and elevation angle). The azimuth is the direction on a compass that the module is oriented. The tilt is the angle of incline of the module, with zero degrees implying flat and 90 degrees corresponding to vertical. In the model of the case study, a tilt of 36° and azimuth of 191.821° were selected. The value of Azimuth is selected because sensitivity checks of solar-PV yield at various azimuths using a functionality of Helioscope™ showed that an azimuth of 191.821° gave the maximum PV yield at the location. The tilt of 36° was selected based on the world estimates of PV optimal tilt angles (Jacobson & Jadhav, 2018), which recommended 36° for the case study location.

Direct and Diffuse Irradiance and Transposition Modelling

The DNI or beam irradiance on a module is calculated based on the GHI and diffuse light from the weather file, along with the solar angle and module orientation angle.

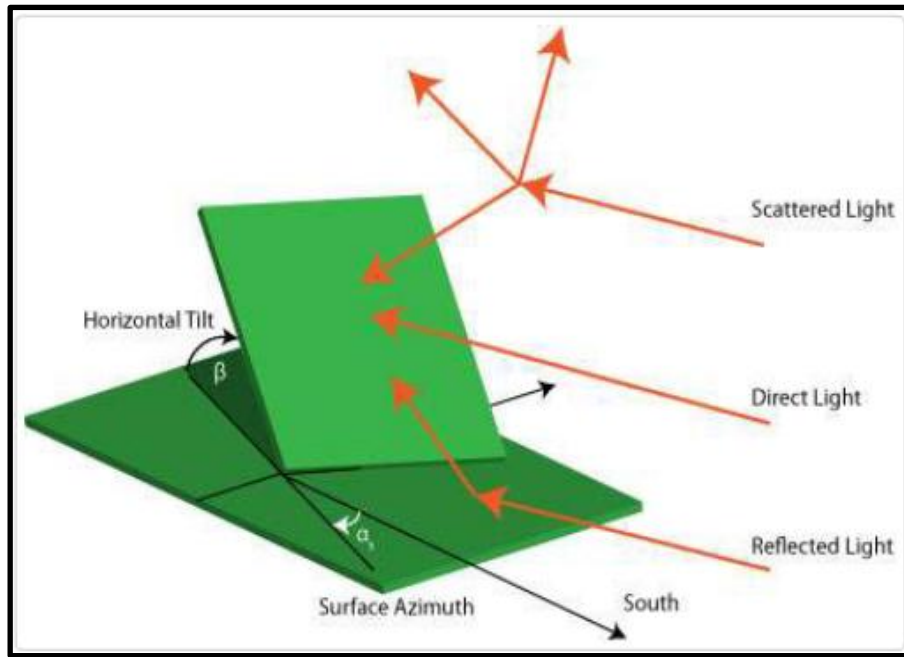


Figure 3.24: Solar Irradiance Components (HelioScope Modeling 101, 2023)

Helioscope™ first subtracts the diffuse irradiance from the GHI to obtain the DNI (Figure 3.24). Thereafter, the effective irradiance to the module is adjusted to factor the difference between the sun angle in the sky and the orientation angle of the module. This calculation is done for each module of the array. STMs are used to transpose the GHI into effective irradiance available to the module.

Plane of Array (POA) Irradiance

POA Irradiance (G_{POA}) is the total amount of sunlight reaching the top surface of the modules in the array. It is calculated by decomposing the Global Horizontal Irradiance into beam (E_b), sky-diffuse (E_{sd}) and ground-reflected (E_g) components. The formula for G_{POA} is given (Stein, 2017) as:

$$G_{POA} = E_b + E_{sd} + E_g \quad 3.37$$

$$E_b = DNI \times \cos AOI \quad 3.38$$

where “DNI” is the direct normal irradiance (W/m^2) and “AOI” is the angle of incidence of the “DNI” onto the module in degrees.

$$AOI = \cos^{-1}[\cos(\theta_z) \cos(\theta_T) + \sin(\theta_z) \sin(\theta_T) \cos(\theta_A - \theta_{A,array})] \quad 3.39$$

where, “ θ_z ” is the sun zenith angle in degrees, “ θ_A ” is the sun azimuth angle in degrees ($N=0^\circ$, $E=90^\circ$, $S=180^\circ$ and $W=270^\circ$).

Row-to-Row Spacing and Ground Coverage Ratio (GCR)

The spacing between the rows of modules in a rooftop array is important in the design because it determines the number of modules and the row-to-row shading. The Ground Coverage Ratio (GCR), the ratio of the total module area, divided by the total ground area of the array and typically ranges between 0.3 – 0.7 and is inversely-related to row-to-row spacing. Based on the results from a study of optimal GCRs for fixed-tilt systems for latitudes up to 75° and shading losses (Tonita et al., 2023), a GCR of 0.7 was used to limit the shading losses to less than 20%. The summary of mechanical inputs to the model is given in Table 3.9

Table 3.9: Mechanical Design Summary for Solar-PV Generation

Design Quantity/Parameter	Unit	Design Value	Remarks
Racking	-	Fixed Tilt Racking	The pitch of the roof is less than 10°.
Tilt	(°)	36	Optimum Tilt Angle for Greater London (Jacobson and Jadhav, 2018)
Module Height	m	1.1m	This quantity is limited by the height of the parapet (1.1m).
Azimuth	(°)	280.331	
Frame Size		1 Up x 1 Wide	The installation is roof-mounted
Orientation	-	Portrait (Vertical)	This orientation gives more yield than the Landscape (horizontal) orientation under the same design conditions.
Ground Coverage Ratio (GCR)		0.71	GCR should be less than 1 (HelioScope Modeling 101, 2023). The optimum value for monofacial PV modules ($\leq 5\%$ inter-row energy yield loss) is 0.70 -0.71 at locations with Lat. $\leq 75^\circ\text{N}$ (Tonita et al., 2023).
Row Spacing	m	1.184	-
Module Spacing	m	0.012 m	-
Span/Rise	-	1.0	-
Keepout Heights (m)		0.6 m	-
Setback (also Fire Setback)	m	0.8 m	-
Frame Spacing (m)	m	0.01	-
Alignment	-	Centred	-
Number of Modules	Assembly	108	-
Roof Area, less Keepouts	m ²	709.3	-
Peak Power	kW _p	45.4	-

Module Behaviour

The module behaviour refers to the characterisation of the current that a module can deliver at different voltages, showing the point at which power production is maximum.

The power production of a module is temperature dependent, and defined by the temperature coefficient, β_{module} (%/°C). At higher module temperatures, T_{module} (°C), the power production reduces, hence all coefficients are negative. The temperature (thermal) coefficient defines the rate at which the power and voltage change relative to the module cell temperature, T_{cell} (°C), other underlying factors being weather and design of the array. There are two options for cell temperature models; (a) Sandia, and (b) Diffusion. The value of “ T_{cell} ” is calculated from equation 3.40:

$$T_{\text{cell}} = T_{\text{module}} + \frac{E_{\text{POA}}}{E_0} \Delta T \quad 3.40$$

where, “ $E_0 = 1000 \text{ W/m}^2$ ” is reference irradiance. The calculated “ T_{cell} ” is then applied to calculate the module temperature coefficient. In the studied model, Sandia model was used because it is an empirical model, based on real-world experiments of outdoor PV arrays between 1991 – 2003 (King, et al., 2004). Hence,

$$T_{\text{module}} = E_{\text{POA}} \cdot (e^{a+b \cdot \text{WS}}) + T_a \quad 3.41$$

and

E_{POA} (W/m²) Solar irradiance incident on the module

T_a (°C) Ambient air temperature

WS (m/s) Wind Speed, measured at the standard meteorological height (10m)

As the solar-PV design is “open rack” and the module type is “tempered glass/cell/tempered glass”, “ $\Delta T = 3^\circ\text{C}$ ”, and representative values of “ $a = -3.47$ ” and “ $b = -0.594$ ” were selected from the values for different module constructions and mounting configuration (Table 3.10) and applied in the solar-PV model to calculate “ T_{module} ” at every timestep.

Table 3.10: Values of ΔT , “ a ” and “ b ” in Sandia Model (King, Boyson and Kratochvill, 2004)

Module Type	Mount	a	b	ΔT (°C)
Glass/cell/glass	Open rack	-3.47	-.0594	3
Glass/cell/glass	Close roof mount	-2.98	-.0471	1
Glass/cell/polymer sheet	Open rack	-3.56	-.0750	3
Glass/cell/polymer sheet	Insulated back	-2.81	-.0455	0
Polymer/thin-film/steel	Open rack	-3.58	-.113	3
22X Linear Concentrator	Tracker	-3.23	-.130	13

Electrical Design

The electrical design determines the powers and voltages at which the PV system will operate and can significantly impact the energy production. The modules are integrated with Enphase® IQ8P-72-2-BR microinverters, which specifications are extracted from the datasheet in (Appendix -4D) and presented in Table 3.11. The confirmation of microinverter compatibility is done using the ([IQ Microinverter compatibility calculator | Enphase](#)) tool. The compatibility check is based on the output parameters of the module being less than the corresponding parameters of the microinverter.

Table 3.11: Summary of ENPHASE IQ8P-72-2-BR Microinverter

Input (DC)		Output (AC); 50Hz Nominal Frequency	
Variable/ Parameter	Value	Variable/ Parameter	Value
Max. Input Power (P_{dcmax})	670W	Rated Power (P_{acf})	475W
Min./Max. Input Voltage (U_{dcmin}/ U_{dcmax})	16/65V	Power Factor	0.99
Rated Input Voltage (U_{dcf})	45.5V	Nominal Grid Voltage (U_{acnom})	230V
Min./Max. MPP Voltage (U_{mppmin}/U_{mppmax})	36/55V	Min./Max. Grid Voltage (U_{acmin}/U_{acmax})	184/276V
Max. Input Current (I_{dcmax})	14A	Max. Output Current (I_{acmax})	2.07A
Min. Input Voltage	16V	European Weighted Efficiency, η_{EU}	97.00%

Based on microinverter manufacturer's recommendation on the datasheet, a 2.5mm² copper cable was used in the model to connect the system AC run to the Point of Common Coupling (PCC) to the grid. The power loss (I^2R loss) and voltage drop were confirmed to conform with the limits imposed by IEC60364 and BS7671. The solar-PV simulation and, thermal and electrical loads from dynamic simulation of the BEM, are coupled into the microgrid model.

3.8 THEORETICAL FRAMEWORK OF MICROGRID MODEL

The microgrid is for the energy system of Lancaster Hotel and Spa, a 3-star non-resort hotel typology located approximately Lat. 51°N., Long. 4°W in London UK. The microgrid model was developed in HOMER-Pro™ software, by coupling the case study electrical and thermal loads obtained from IESVE™ simulation, and the site solar-PV generation to enable evaluation of the operational net zero metrics, and definition of benchmark values, from the simulation outputs.

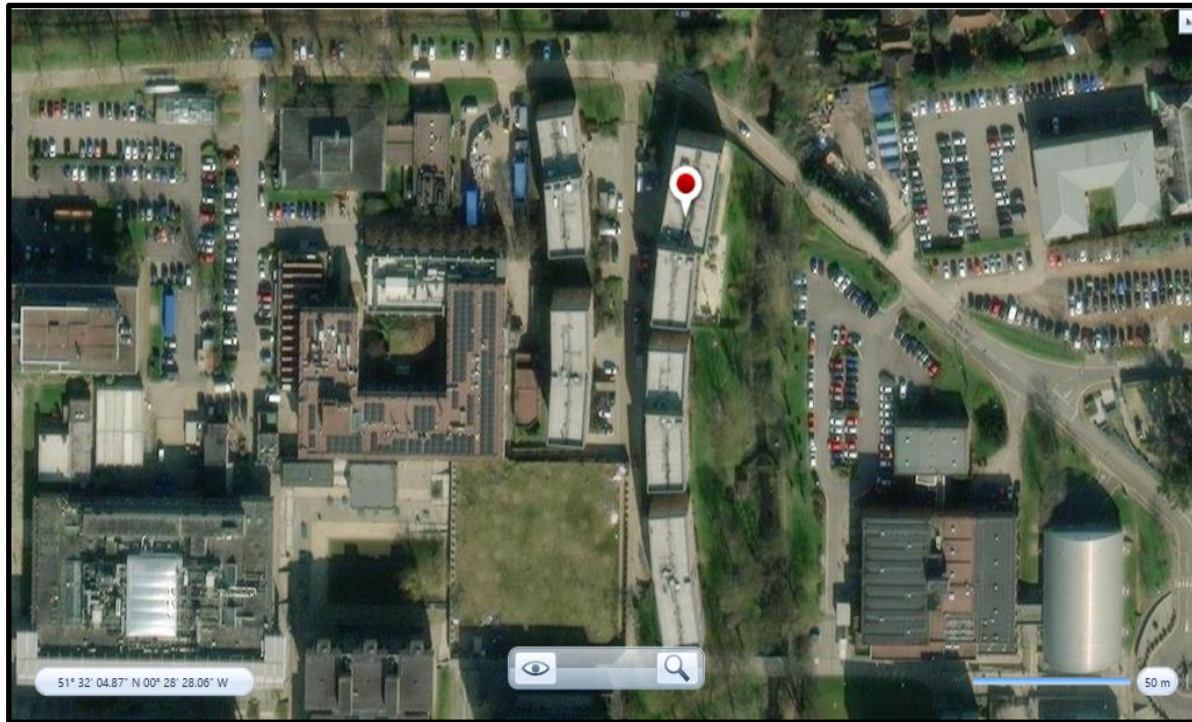


Figure 3.25: Neighbourhood View of Microgrid Site Extracted (SOURCE: HOMER Pro™)

The position of the case study is indicated by the position marker in the neighbourhood view (Figure 3.25). The model comprises a Grid Connection, Solar PV Generation (HelioScope™), Lithium-ion (Li-ion) Battery Storage, Natural Gas-fired Boiler, Electrical and Thermal Loads, and AC/DC Converter. The net zero metrics are; (a) Site Electricity Use Intensity, $SEUI_{el}$ (kWh/m²/year), (b) Thermal EUI, EUI_{th} (kWh/m²/year), (c) CEI (kgCO₂/m²/year), and (d) ECI (£/m²/year). The model was developed by customising the case study energy system to the existing meteorological conditions of the site, operating conditions of the active energy systems and the extant regulatory and economic factors in the UK energy market. HOMER-PRO™ simulates the energy system operation by making energy balance calculations for each of the 8,760 hours in a year. In each hour, the energy flows to and from each component is calculated to determine whether the system can meet the energy demand under the specified conditions and configuration (feasible) or not (infeasible). The software also estimates the cost of installing and operating the system over the lifetime of the project.

Two (2) types of variables (Sensitivity and Decision/Optimisation) are used to input arguments to parameters in HOMER-Pro®. Sensitivity variable is an input variable for which multiple values can be specified. Decision/ Optimisation variables are those whose optimal values are determined during the optimisation process, and which

arguments are passed to HOMER-Pro™ in the “Search Space” or the “HOMER Optimizer™” field, after which a separate optimisation procedure is performed for each specified value/ argument. The “Search Ranges” for grid parameters, boiler, converter, and battery were specified with the HOMER-Pro Optimizer™ function to enable a continuous search between an upper and lower limit. To avoid optimising the microgrid within a narrow, constrained search space, HOMER-Pro™ recommends a lower limit of zero and an upper limit that is much higher than the expected parameter size (HOMER-PRO, 2016) so that the optimal value of the parameter is not on the boundary of the space. In this study, an upper limit on Homer-Pro Optimizer™ was set between 200 – 400% to obtain values of parameters. Single simulation was used (as against multi-year simulation) as a trade-off for a simple methodology for calculation of the Net Zero metrics; simulation was run to generate feasible configurations which are extrapolated over the project lifetime. Furthermore, optimisation and sensitivity analysis algorithms in the software evaluate and compare the economic and technical merits of the different configurations, to sort the least cost system.

The following theoretical framework for the mi(Lambert, et al., 2006; HOMER-PRO, 2016; Lilienthal et al., 2018) and adapted to the peculiar macroeconomic, meteorological, load profiles, resource availability, technical components, and energy dispatch strategy of the case study. The details of the costs, technical parameters of components, resources and load profiles input to the model are presented in the following sections. The calculation of the operational net zero metrics; EUI_{el} , EUI_{th} , CEI and ECI is also presented. In the current study, the system with the lowest Net Present Cost (NPC) is used for evaluation of the metrics.

Microgrid Resources: Solar-PV Generation

The resources refer to any inputs external to the microgrid that are used to generate electric or thermal power to satisfy the loads. The solar resource used in the microgrid was modelled and coupled to the microgrid model using the “HelioScope™ Import” functionality in HOMER Pro™.

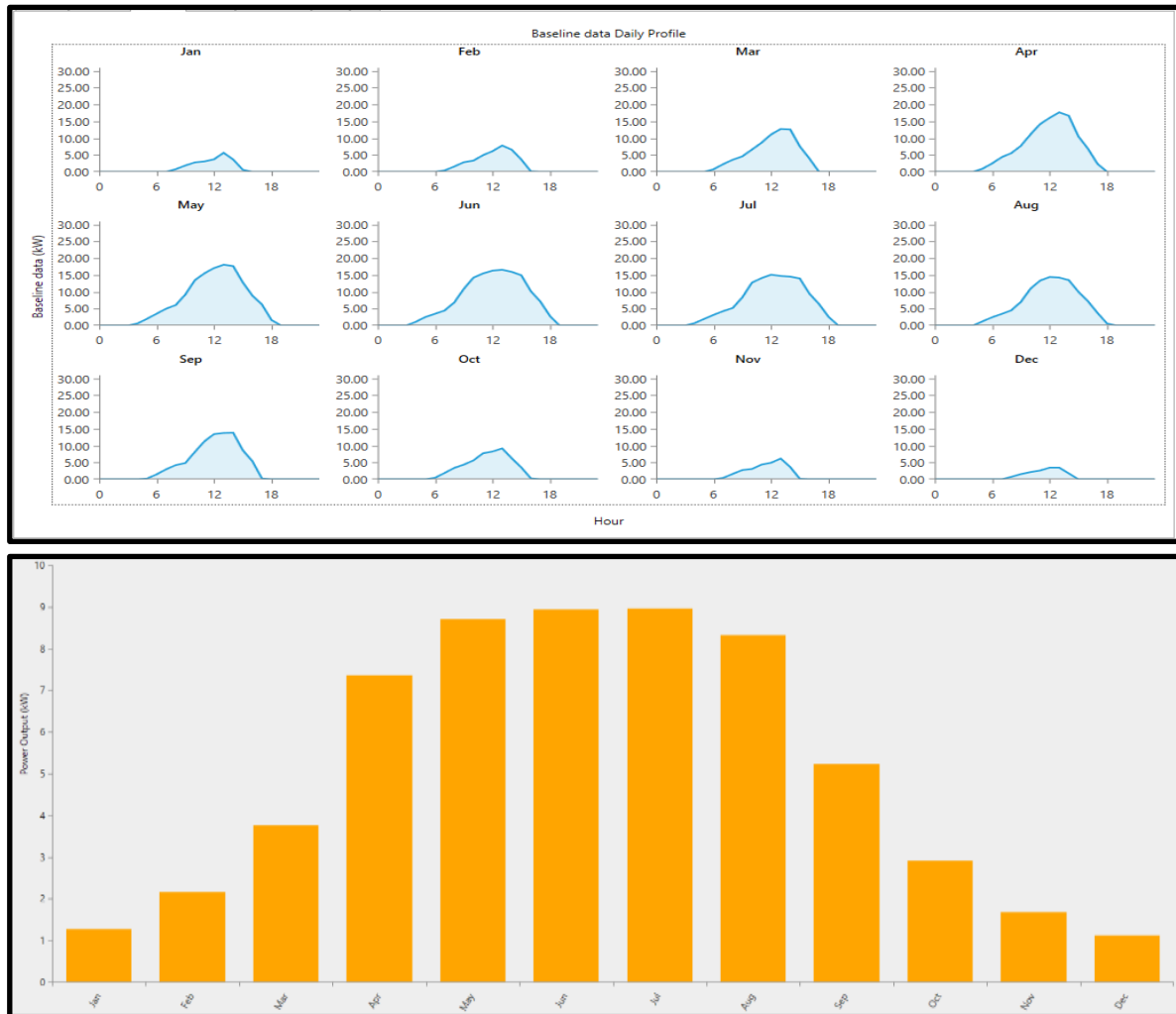


Figure 3.26: Daily and Monthly Solar-PV Profile

The baseline daily and monthly solar-PV profile is depicted in the microgrid model as shown in Figure 3.26.

Solar-PV System Sizing, Costs and Lifetime

The cost of installation of the 48.3kW rooftop solar-PV generation used in the microgrid model is based on empirical cost data obtained from the UK Microgeneration Certification Scheme (MCS) for solar-PV generation equipment (excluding battery storage), services for installation and connection to the electricity supply and Value Added Tax (VAT) in residential and commercial solar-PV systems (Table 3.12). Applying the mean value of £1355/kW for 2022/23 financial year as the unit capital cost, the capital cost of the solar-PV generation = $£1355 \times 48.3 = £65,446.5$. This value is used as capital cost of solar-PV in the HOMER-Pro™ model. Based on forecast cost reduction of 60%/MWh by 2040 and 59% by 2030, projected by Bloomberg Energy Finance (BENF) and IRENA, the “Replacement” cost is set at a conservative 70% of the capital cost (= $£45826.55$).

The coupled solar-PV generation is sized using the HOMER Optimizer™ functionality between “Upper =1” and “Lower =0”. This means that a solution with a fraction of, say 0.5 is sized at half (24.15 kW) the solar-PV capacity modelled in Helioscope™ (48.3 kW). The upper limit is set at 1 because the installation size is limited by the rooftop space.

Table 3.12: Solar-PV Installation Costs (£/kW): 2013 – 2024 (DESNZ, 2014)

Financial year	10-50 kW: Median (£/kW)	10-50 kW: Inflation adjusted median (£/kW)	10-50 kW: Mean (£/kW)	Consumer Price Index (CPI)
2013/14	1,332	1,350	1,391	98.6
2014/15	1,298	1,302	1,343	99.7
2015/16	1,212	1,210	1,252	100.2
2016/17	1,150	1,133	1,219	101.5
2017/18	1,074	1,030	1,152	104.2
2018/19	1,078	1,013	1,158	106.4
2019/20	1,023	946	1,085	108.2
2020/21	1,000	917	1,089	109.1
2021/22	1,016	898	1,132	113.1
2022/23	1,232	1,001	1,355	123.0
2023/24	1,376	1,059	1,502	129.9

A survey of UK trade data shows that the structure of solar-PV Operation and Maintenance solar-PV (O&M) costs for a lifetime of between 25 – 30 years comprises; (1) average cleaning costs = £9.5 per module, recommended twice a year (2) inspection and servicing of balance of plant components = £100 per visit. In the CS system, the lifetime is set at 28 years. The O&M cost is set based on commercial information in the UK. In the CS system with 115 modules, (**Error! Reference source not found.**), the annual O&M costs of £2385 used in the HOMER-Pro™ model is detailed as follows, (a) cleaning costs at £19/module = £2185, (b) inspection and servicing cost = £200.

Electrical Bus, Operating Reserve and Derating Factor

The solar-PV system is connected to the AC bus because the modules (“SunPower® Maxeon™ SPR-MAX3-420-BLK-R”) are integrated with microinverters (Enphase® IQ8P-72-2-BR) to allow for individual module optimisation by isolating each module such that failure on one module does not affect others. The Photovoltaic Derating Factor, f_{PV} , is set to 84% over the 28-year lifetime (3% per annum). The required operating reserve of the system is set to zero because it is connected a reliable grid,

with average annual Reliability = 99.999% (UKPN, 2024). Hence it is unnecessary to provide a safety margin against variability and intermittency of the solar-PV generation.

Microgrid Cost Structure and Benchmarks

The cost structure of the microgrid refers to the financial requirement for the key components. The US-NREL identified four main microgrid cost categories; (1) DERs (2) Controllers, (3) Infrastructure, and (4) Soft costs, following the analysis of 80 microgrids based on market segment and complexity levels.

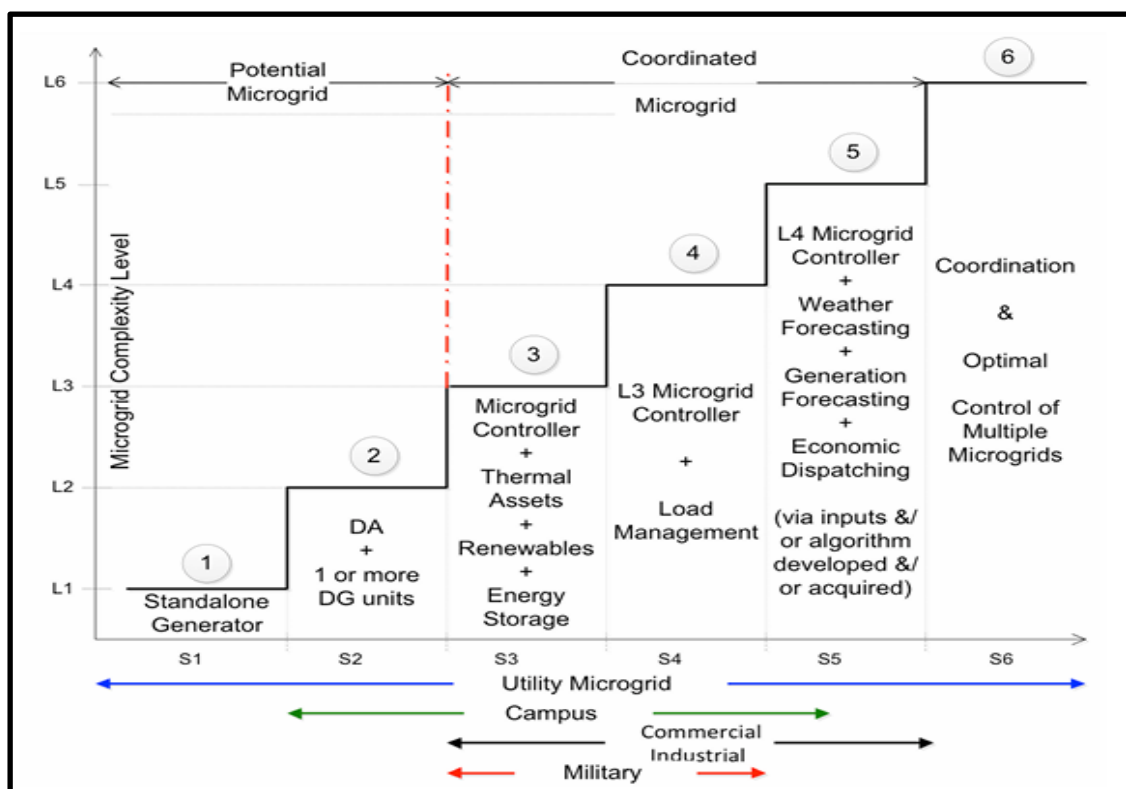


Figure 3.27: Microgrid Complexity and Market Segments (Giraldez *et al.*, 2018)

As shown in Figure 3.27, the NREL study categorised microgrids into 5 levels (L1-L5) in increasing order of complexity (function of the distributed energy resources in the microgrid, amount of renewable penetration, and presence of energy storage, control architecture and enterprise-level capabilities). The market segments include utility, campus, commercial, industrial, military and community microgrids. This, being among the few publications on microgrid cost data, it is used as a benchmark of the component costs in the microgrid model. The components refer to the parts of the microgrid that generate, deliver, convert or store energy. Applying the classification in Figure 3.27 and the US-DOE microgrid sizing guidelines (GDO, 2024), and presence

of the following features; (1) microgrid controller, (2) thermal assets, (3) renewables, and (4) energy storage, the CS microgrid is modelled as a 300kW (0.3MW) Level-3 (L3) commercial microgrid.

The benchmark component costs of the CS microgrid were obtained from the NREL data on component costs was obtained from Appendix -4I: NREL MICROGRID COST BENCHMARKS and the table of Interquartile Range (IQR) and mean normalised costs (\$/MW) of different levels of microgrids across the market segments for each complexity level.

Table 3.13: IQR and Mean MG Costs (\$/MW) by Complexity Levels (Giraldez *et al.*, 2018)

Level	IQR	Mean
Level 1	\$2,856,775–\$931,485	\$1,981,800
Level 2	\$4,870,648–\$2,178,975	\$3,462,685
Level 3	\$3,820,975–\$1,940,507	\$3,053,979
Level 4	\$5,142,510–\$3,727,321	\$4,436,563
Level 5	\$3,700,938–\$2,920,014	\$3,310,476

In Table 3.13, it is shown that for a 300 kW system, the estimated cost is = £2382 x 300 = £714631, which translates to a cost of £2382/kW (on an exchange rate of US\$1 = £0.78).

Table 3.14: Approximate Cost Breakdown of 300kW Case Study Microgrid

Cost Element per Component Cost by Level	NREL Cost Proportion	Cost (£)
Renewable Generation	30%	£214,389
Energy Storage	16%	£114,341
Controls	2%	£14,293
Conventional Generation	38%	£271,560
Additional Infrastructure	9%	£64,317
Soft Costs	5%	£35,732
Total Cost of 300kW Microgrid	100%	£714,631

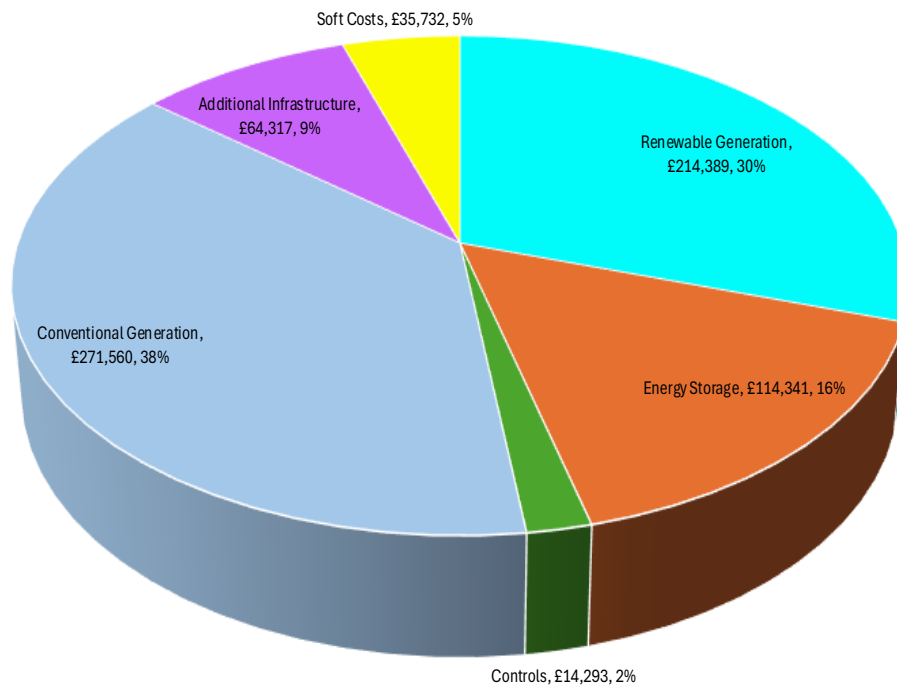


Figure 3.28: L-3 Total Costs per Component Cost for 300kW Microgrid

Based on the foregoing estimate, the cost breakdown of the case study microgrid is shown in Table 3.14 and the doughnut chart of the costs in Figure 3.28. The soft costs refer to the engineering, construction, commissioning and regulatory costs, incurred regardless of system size and architecture. The “system fixed capital cost” and “system fixed O&M cost” of the CS MG model are computed from the economic parameters.

Economic Parameters

In the “Project” tab of HOMER Pro™, there are four (4) additional parameters in the “Design” menu, calculated using a baseline electricity and natural gas cost of £0.24/kWh and £0.03/kWh respectively.

Nominal Discount and Expected Inflation Rates: Nominal discount rate, “ i (%)”, is the rate at which future cash flows are discounted to their present values, without adjusting for inflation, and represents the rate at which financing can be obtained for the project. The UK Green Book (HM Treasury, 2022) stipulates an annual discount rate of 3.5% for projects where the costs and benefits occur in the first 30 years, with a schedule of declining discount rates thereafter. Consequently, based on a lifecycle

of 28 years (between 2022 and 2050), a 3.5% Nominal Discount Rate is used. The inflation rate is the change in prices for goods and services over time and is measured using indicators such as the Consumer Price Index (CPI), Producer Price Inflation (PPI) and House Price Index (HPI). The projected change in energy costs from the baseline year (2022) to 2050 are modelled by entering sensitivity values of inflation rate, in unit increments, between 1-10%. These values are based on historical inflation rates published by the UK Office for National Statistics (UK-ONS, 2025) and the target inflation rate of 2% (BOE, 2025), set by the Bank of England. The real discount rate adjusts future cash flows to the present value, after adjusting for inflation and is used to convert between one-time costs and annualized costs. HOMER-Pro™ calculates the annual real discount rate (also called the real interest rate or interest rate) from the “Nominal discount rate” and “Expected inflation rate” inputs using equation 3.42. In this model, real discount rate ($i = 2.48\%$) was generated.

$$I = \frac{i' - f}{1 + f} \quad 3.42$$

where, “ i (%)” is the real discount rate, “ i' (%)” Nominal Discount Rate (the rate at which money could be borrowed), and “ f (%)” is the expected inflation rate. The real discount rate (2.48%) is less than the nominal discount rate (3.5%), consistent with the macroeconomic conditions applicable at the case study location.

System Fixed Costs: There are two (2) system costs modelled in the microgrid; (1) fixed capital costs “ $C_{cap, fixed}$ (£)” and (2) operation and maintenance (O&M) costs “ $C_{om, fixed}$ (£/year)”. The former is modelled as “soft costs”, and the latter is a recurring annual cost regardless of the microgrid size. The cost breakdown in Table 3.14 shows that “soft costs”, modelled as system fixed capital costs ($C_{cap, fixed} = £35732$) is used in the model. The system fixed O&M costs (“ $C_{om, fixed} = 0$ ”) because the O&M costs are included in the component windows.

Project Lifetime and System Costs: The project lifetime, R_{proj} (yr) is the length of time over which the costs of the system occur and is used to calculate the Annualised Cost (C_{ann}) from Net Present Cost (NPC), with the salvage value assumed to occur at the end of the project lifetime. The annualised cost of a component is the cost that were it to occur in equal annual instalments would give the same NPC as the actual cash flow sequence associated with that component. The annualised cost of a

component is modelled as a combination of the capital, replacement, maintenance and fuel costs, along with the salvage value and any other costs or revenues:

$$C_{\text{ann}} = \text{CRF}(i, R_{\text{proj}}) \cdot C_{\text{NPC}} \quad 3.43$$

where “ C_{NPC} (£)” is the Net Present Cost, “ i (%)” is the annual real discount rate and “CRF” is the Capital Recovery Factor, where:

$$C_{\text{NPC}} = \frac{C_{\text{ann,tot}}}{\text{CRF}(i, R_{\text{proj}})} \quad 3.44$$

and,

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad 3.45$$

where “ N ” is the number of years. The salvage value, S , is calculated as:

$$S = C_{\text{rep}} \frac{R_{\text{rem}}}{R_{\text{comp}}} \quad 3.46$$

where “ C_{rep} ” is the replacement cost of the component, “ R_{rem} ” is the remaining life and “ R_{comp} ” is the lifetime of the component. The Levelised Cost of Energy (LCOE) is calculated as:

$$\text{COE} = \frac{C_{\text{ann,tot}} - C_{\text{boiler}} H_{\text{served}}}{E_{\text{prim}} + E_{\text{def}} + E_{\text{grid,sales}}} \quad 3.47$$

where, “ C_{boiler} ” is the boiler marginal cost (£/kWh), “ H_{served} ” is the thermal load served (kWh/yr), “ E_{prim} ” and “ E_{def} ” are the primary electrical and deferrable load respectively, served by the system, annually.

Electrical and Thermal Loads

The Half-Hourly (HH) electricity consumption data for the base year (Appendix-1A: TIME SERIES ELECTRICITY CONSUMPTION DATA), was obtained from the BMS platform “Energy Manager®”. The system-calculated random day-to-day and timestep variabilities of 10% and 20%, respectively were applied to the imported baseline electrical loads to generate the scaled daily average load (2422.3 kWh/day), average load (100.93 kW), peak load (277.73 kW) and load factor (36%). Timestep and day-to-day variabilities are applied to the electrical loads obtained from the IESVE™ models to account for the uncertainties that arise from the impact of sensitivity variables such as inflation, occupancy rates, grid carbon intensity, energy efficiency

measures, climate change and renewable energy integration on energy consumption and CO₂ emissions over the study period (2022 – 2050).

Table 3.15: HOMER Pro™ Electrical Input Parameters

Parameters	Baseline	Scaled
Daily Noise (Day-to-day Random variability)	-	10%
Hourly Noise (Timestep Random Variability)	-	20%
Average (kWh/day)	955.12	2422.3
Average (kW)	39.8	100.93
Peak (kW)	109.51	277.73
Load Factor	36%	36%

Table 3.16: Summary of Baseline Electricity Load

Month	Annual Maximum (kW)	Day Average Maximum (kW)	Average (kW)	Day Average Minimum (kW)	Minimum (kW)
Jan	50.86	48.58	34.89	25.48	24.80
Feb	52.90	51.07	33.32	21.36	21.00
Mar	50.44	49.91	36.24	19.46	19.18
Apr	60.38	58.47	39.01	24.47	24.38
May	59.82	57.81	40.15	22.79	20.50
Jun	60.55	59.60	40.57	24.00	23.82
Jul	58.67	56.81	41.20	25.01	20.95
Aug	57.82	57.51	40.03	20.66	20.11
Sep	56.41	56.20	40.83	20.85	20.13
Oct	64.86	64.00	42.18	22.79	20.05
Nov	67.75	67.07	44.06	25.00	24.00
Dec	59.82	58.84	41.60	25.42	25.11

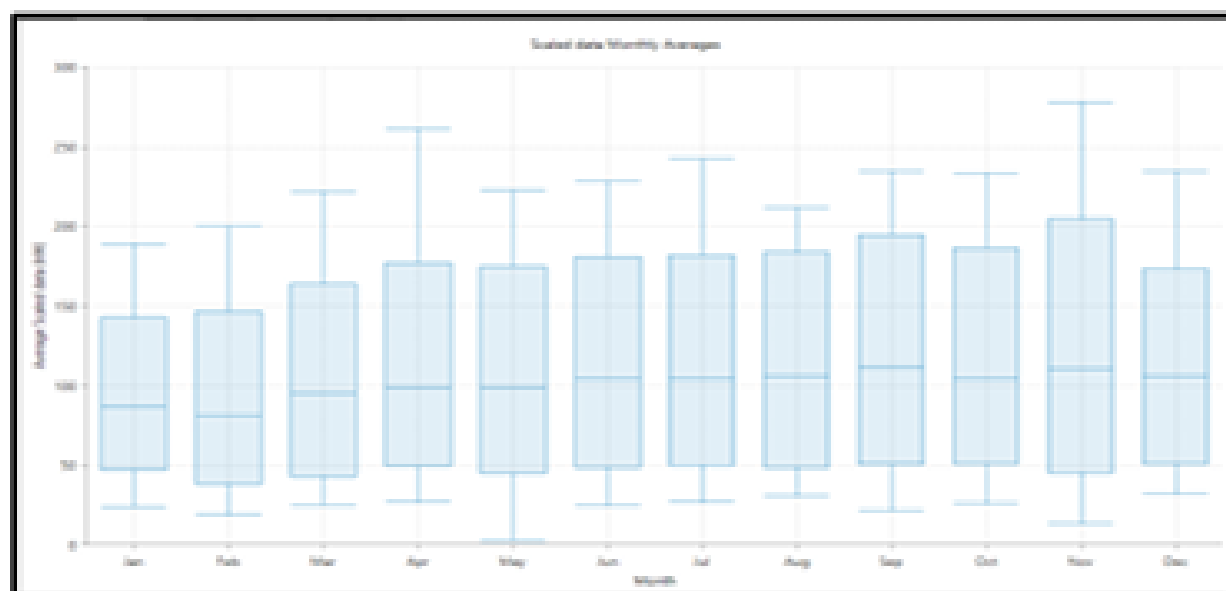


Figure 3.29: Extract of Box and Whisker Plot of Annual Electricity Consumption

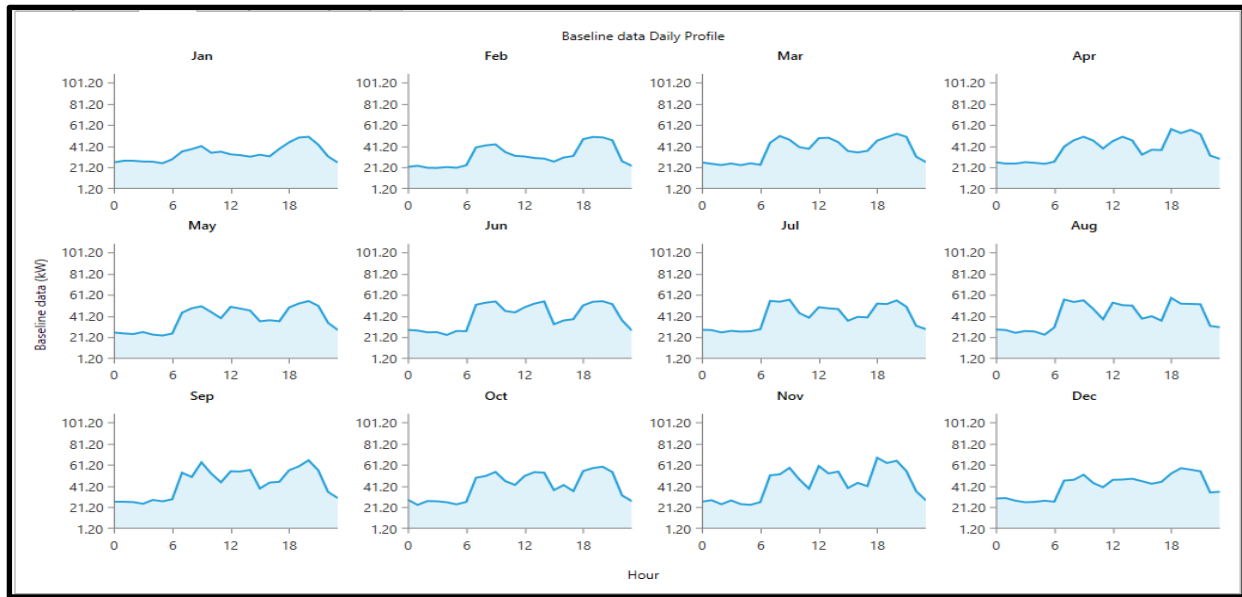


Figure 3.30: Baseline Daily Electricity Load Profile

The baseline daily electricity load profile (Figure 3.30) has two main peaks; (1) morning 6am – 8am, and (2) evening (6pm – 10pm).

Table 3.17: Summary of Baseline Thermal Load

Month	Annual Maximum (kW)	Day Average Maximum (kW)	Average (kW)	Day Average Minimum (kW)	Minimum (kW)
Jan	158.61	125.45	74.35	35.98	14.70
Feb	163.52	120.43	70.23	33.92	15.13
Mar	243.52	186.51	106.30	48.44	33.37
Apr	204.02	127.87	66.95	27.05	13.88
May	103.31	71.26	37.91	16.04	1.76
Jun	85.27	53.64	30.37	13.86	7.69
Jul	93.51	64.87	35.94	16.08	10.63
Aug	111.24	44.45	24.81	10.95	4.22
Sep	86.18	65.39	37.28	16.49	6.23
Oct	185.82	150.81	84.70	39.83	18.21
Nov	451.77	344.54	184.11	73.79	22.29
Dec	220.75	161.96	92.01	44.22	28.32

Table 3.18: HOMER Pro™ Thermal Input Parameters

Parameter	Baseline	Scaled
Daily Noise (Day-to-day Random variability)	-	0%
Hourly Noise (Timestep Random Variability)	-	0%
Average (kWh/day)	1687.4	2422.3
Average (kW)	70.31	100.93
Peak (kW)	299.92	430.53
Load Factor	23%	23%

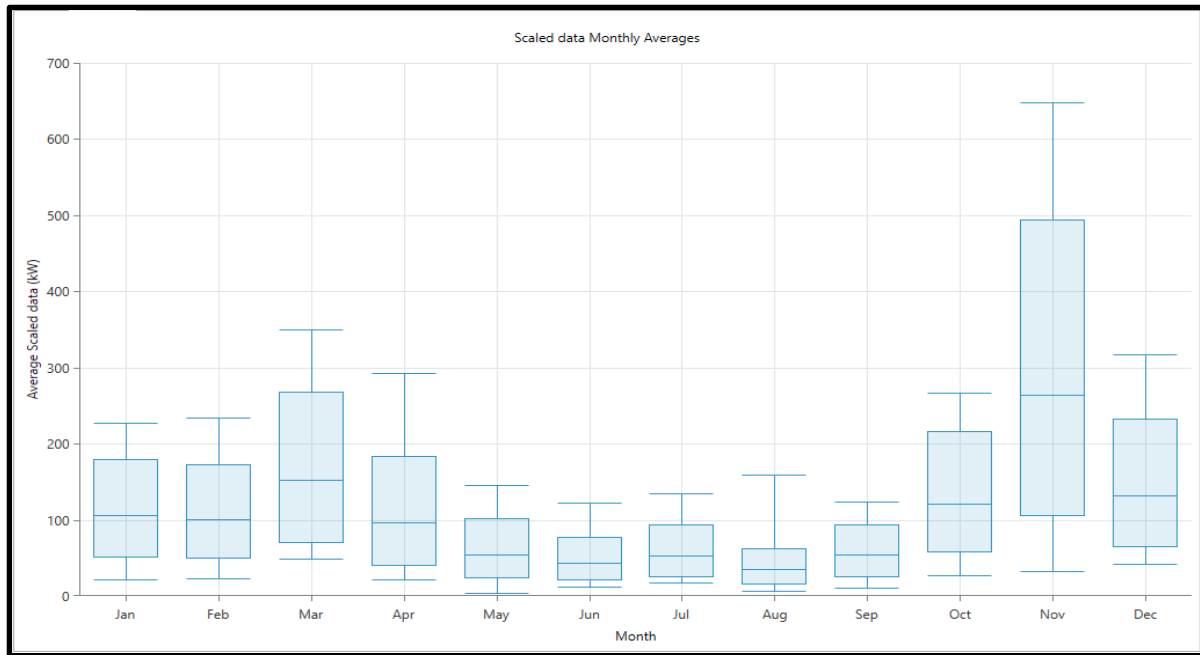


Figure 3.31: Extract of Box and Whisker Plot of Annual Thermal Load

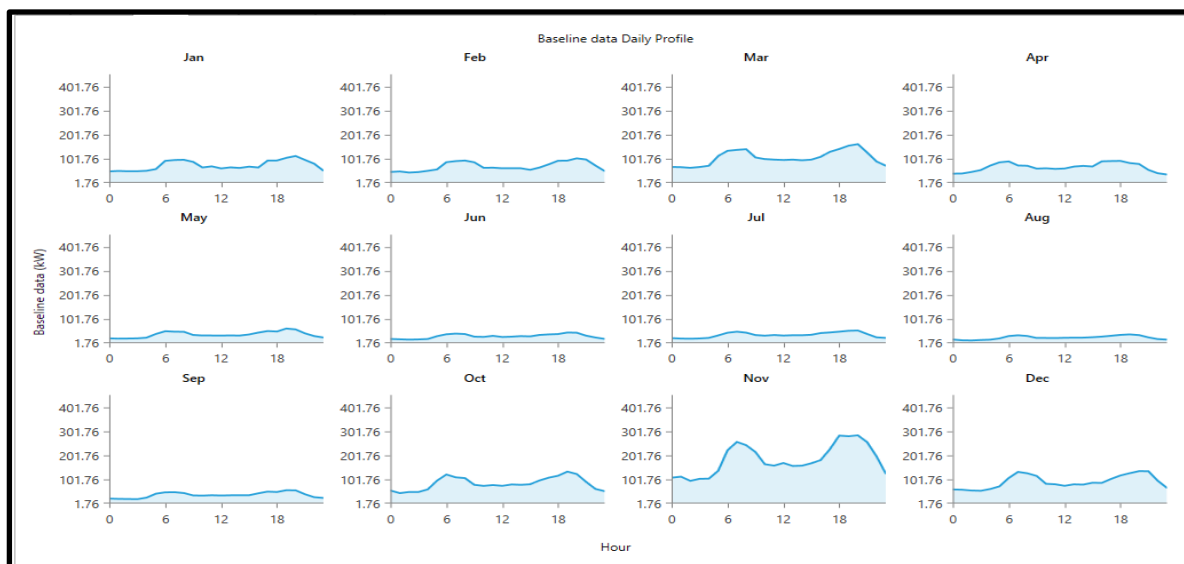


Figure 3.32: Baseline Daily Thermal Load Profile

The characteristics of the baseline thermal load are shown in Figure 3.32. The same timesteps were applied to the baseline loads to generate the case study baseline hourly thermal load profiles for each month of the year Figure 3.32.

Microgrid Components

A component is any part of the microgrid that generates, delivers, converts, or stores energy. The components used in the model are; (a) natural gas boiler (b) battery bank, (c) converter, (d) converter, (e) electricity grid, (f) PV modules, (g) Load Following (LF) controller.

Natural Gas Boiler

The boiler is modelled to meet unlimited thermal energy demand. The modelled boiler is a Remeha® 610-ECO™ (2X6 Sections) version, installed in the case study for central heating and indirect hot water production. The technical and efficiency information of the boiler (Table 3.19) is extracted from the datasheet (Appendix -2I: TECHNICAL DATA - REMEHA® GAS 610 ECO™ BOILER).

Table 3.19: Technical and Efficiency Data of Remeha® 610-ECO™ (2X6) Boiler

Characteristic	Unit	Value
Year of Manufacture	-	2005
Fuel	-	Natural Gas only
Boiler Control	-	Modulating
Nominal Output, P _n , (80/60°C)	kW	min: 87
	kW	max: 654
Nominal Input, Q _n (GCV/H _s)	kW	min: 101
	kW	max: 744
Nominal Input, Q _n , (NCV/H _i)	kW	min: 91
	kW	max: 672
NCV Combustion Efficiency @ 80/60°C	%	up to 99
NCV Heat to Water Efficiency @ 80/60°C	%	up to 98.5
Standing Losses (T _{average} = 45°C)	%	< 0.3
NCV Annual Efficiency	%	108.9
Inlet Pressure Gas (Boiler Running)	mbar	min: 17
	mbar	max: 100
Gas Consumption @ stp (298K and 1 atm)	m ³ /h	74
NO _x Emission (Class 5); <70	mg/kWh	60
Type Classification of Flue Gas Discharge	-	C33 ^a (closed flue)

The marginal cost of energy from the boiler is modelled as:

$$c_{\text{boiler,mar}} = \frac{3.6c_{\text{fuel,eff}}}{\eta_{\text{boiler}}\text{LHV}_{\text{fuel}}} \quad 3.48$$

where, “ $c_{\text{fuel,eff}}$ ”, is the effective price of the fuel (including the emission penalties) in £/kg, “ η_{boiler} ” is the boiler seasonal efficiency and LHV_{fuel} is the Lower Heating Value of the natural gas (MJ/kg). The average natural gas price for the baseline year, (2.89 p/kWh = 0.324 £/m³), obtained from Appendix-1H: TYPICAL ELECTRICITY INVOICE AT CASE STUDY, was used in the model. The historical (1988 – 2025) average inflation rates for gas and other fuels in the UK (Appendix -2F: INFLATION RATES: ELECTRICITY, GAS & OTHER FUELS) were applied to the model to account for future

^a The boiler is connected to a concentric or twin-pipe flue system with a vertical flue terminal. The air inlet and flue exhaust are in the same pressure zone (atmospheric).

price sensitivity. The natural gas price in the model was linked to the rates of inflation. The natural gas supplied to the boiler has the characteristics in Table 3.20.

Table 3.20: Characteristics of Natural Gas Supply and Boiler Emissions

Parameter	Unit	Value	Reference
Natural Gas Characteristics			
Calorific Value	MJ/m ³	39.8	Error! Reference source not found.
Correction Factor	-	1.025937	Error! Reference source not found.
kWh to MJ Conversion Factor	-	3.6	Error! Reference source not found.
Specific Gravity (s.g)	-	0.7	National Grid Specification
Boiler Emissions Characteristics			
Carbon monoxide	g/m ³	0.9044	
Unburned Hydrocarbons	g/m ³		
Particulate Matter	g/m ³		
Proportion of Sulphur converted to Particulate Matter	g/m ³	0.1	Limiting value in UK National Grid Gas Quality specifications.
Nitrogen Oxides (NO _x)	g/m ³	0.65	Calculated from the Correction Factor and Calorific Value.

The emissions parameters are estimated as follows:

- 1) Carbon monoxide (g/m³ of fuel):** the given combustion efficiency (Table 3.19) is 99% and the specific gravity of the natural gas (sg_{gas}) is 0.7. Taking the density of air ($\rho_{air} = 1.292 \text{ kg/m}^3$) at 273K and 1 atm (101.325 kPa). Hence, the density of natural gas is:

$\rho_{gas} = sg_{gas} \times \rho_{air} = 904.4 \text{ g/m}^3$. This means that 1g of natural gas occupies 0.0011 m³ at standard conditions. Therefore, for combustion of unit volume of natural gas at 99% combustion efficiency,

$$\text{Carbon monoxide emission} = 0.1\% \times 904.4 \text{ g/m}^3 = 0.9044 \text{ g/m}^3$$

- 2) Nitrogen Oxides (g/m³ of fuel):** the Class 5 NO_x emission value of 60 mg/kWh for the boiler is converted to g/m³ for modelling in HOMER-PRO™ as follows: Suppose V_{ng} (m³), is the volume of natural gas,

$$V_{ng} = \frac{\text{Energy (kWh)} \times \text{Conversion Factor (MJ/kWh)} \times \text{Correction Factor}}{\text{Calorific Value (MJ/m}^3\text{)}} = \frac{1 \times 3.6 \times 1.025937}{39.8} = 0.0928 \text{ m}^3/\text{kWh}.$$

$$\text{Therefore, } 60 \text{ mg/kWh has a specific volume} = \frac{0.06}{0.0928} = 0.65 \text{ g/m}^3.$$

- The parameters are derived at normal conditions of 20°C and 1 atm (101.325 kPa) because the pressure and temperature are outside the range of UK National Grid natural gas dewpoint specifications (-30°C to 10°C) for natural gas.

Battery Bank

The battery bank comprises one or more individual batteries capable of storing a defined quantity of Direct Current (DC) electricity at a fixed Round Trip Efficiency (RTE), and limits on how quickly it can be charged or discharged, the extent to which it can be discharged safely and the number of energy cycles that would pass through it before replacement.

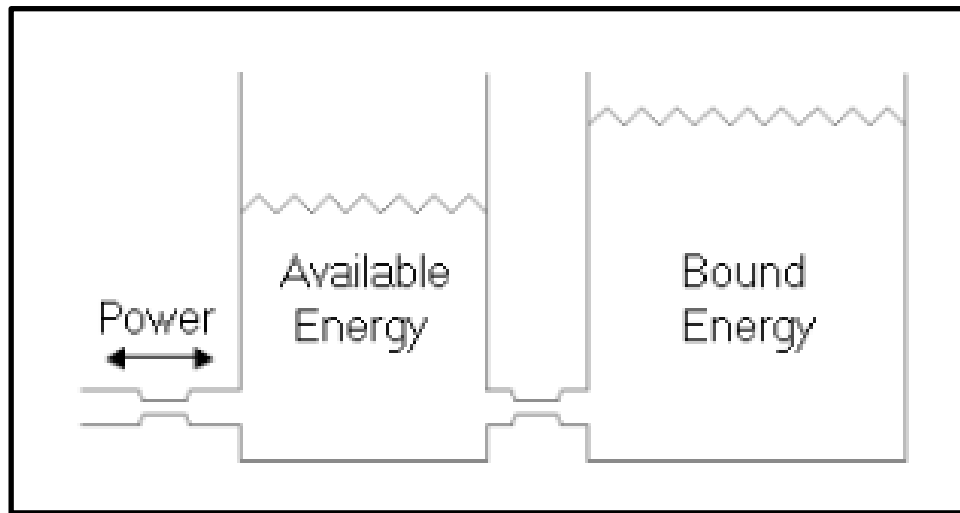


Figure 3.33: Schematic of Kinetic Battery Model (Manwell and McGowan, 1993)

The foundational basis of the model is the “Kinetic Battery Model”, Figure 3.33 described in (Manwell and McGowan, 1993) using 3 parameters; maximum theoretical storage capacity, $Q_{\max}$, capacity ratio, “c”, and the rate constant, k (h^{-1})

The total amount of energy stored in the battery, Q , is given as:

$$Q = Q_1 + Q_2 \quad 3.49$$

where, “ Q_1 ” is the available energy, and “ Q_2 ” is the bound energy. In modelling a storage bank of “ N_{batt} ” batteries, the maximum storage charge power, “ $P_{\text{batt},\text{cmax}}$ ”, is set equal to the least of 3 system constraints; the maximum amount of power that can be absorbed by the model (Figure 3.33), the maximum charge rate and the maximum charge current. The storage charge power associated with the maximum charge rate is given as:

$$P_{\text{batt},\text{cmax},\text{kbm}} = \frac{kQ_1e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \quad 3.50$$

where, “ Q_1 ” is the available energy (kWh) in the battery at the beginning of the timestep, “ Q ” is the total amount of energy (kWh) in the storage at the beginning of the

timestep, and “ Δt ” is the length of the timestep (h). The storage charge power, associated to the maximum charge rate is given as:

$$P_{batt,cmx,kbm} = \frac{(1 - e^{-\alpha_c \Delta t})(Q_{max} - Q)}{\Delta t} \quad 3.51$$

where, “ α_c ” is the maximum charge rate of the battery (A/Ah), and “ Q_{max} ” is the total storage capacity of the battery bank. The maximum battery bank charge power that can deliver the maximum charge current is given as:

$$P_{batt,cmx,mcc} = \frac{N_{batt} I_{max} V_{nom}}{1000} \quad 3.52$$

where, “ N_{batt} ” is the number of batteries in the storage bank, “ $I_{max}(A)$ ” is the maximum charge current of a battery, and “ $V_{nom}(V)$ ” is the nominal voltage of the battery. The maximum storage charge power is set to the least value calculated from equations 3.50 – 3.52, less charging losses, using the optimisation function:

$$P_{batt,cmx} = \frac{\text{MIN}(P_{batt,cmx,kbm}, P_{batt,cmx,mcc}, P_{batt,cmx,mcr})}{\eta_{batt,c}} \quad 3.53$$

where, $\eta_{batt,c} = \sqrt{\eta_{batt,RTE}}$ is the storage charge efficiency and “ $\eta_{batt,RTE}$ ” is the battery round trip efficiency, is the fraction of stored energy that can be retrieved, typically about 80% (HOMER-PRO, 2016). To account for multi-year degradation, the value of “ $I_{max}(A)$ ” is solved for each timestep using the “Modified Kinetic Battery Model” (Figure 3.34), described in (HOMER-PRO, 2016). At a given power output,

$$P_{out} = IV_{out} = V_o I - R_o I^2 \quad 3.54$$

Hence, “ $I_{max}(A)$ ” is calculated using 3.55 as:

$$I_{max} = V_o / 2R_o \quad 3.55$$

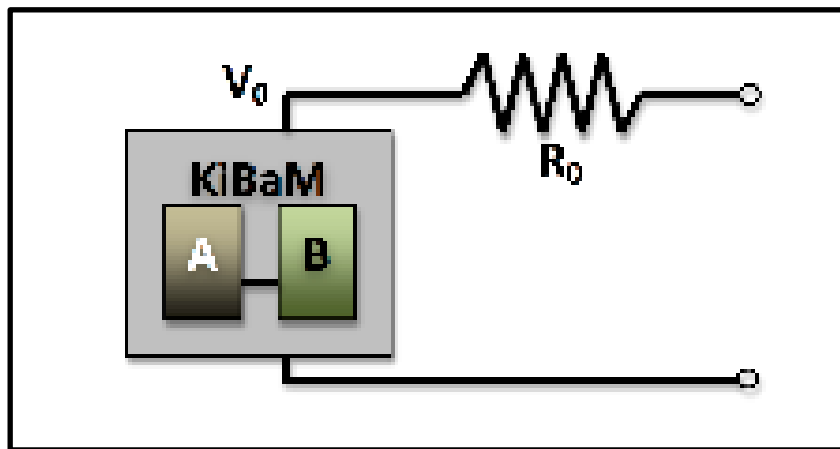


Figure 3.34: Schematic of Modified Kinetic Battery Model (HOMER-PRO, 2016)

The temperature of the battery was modelled by specifying the thermal conductance to ambient (W/K) mass of the battery (kg), and the specific heat capacity (1140 J/kg.K).

Converter

The microgrid system containing AC and DC buses and requires rectification of DC to AC and inversion of AC to DC in a converter. The ABB MGS100-40/27.6 converter (Appendix -4G: ABB MGS 100 CONVERTER DATASHEET) was selected by matching the AC and DC bus voltages to the converter AC input (3 x 400/230 V + N) and output (440 – 660V DC) respectively, compatible Li-ion batteries, maximum input current = 71A. The indicative capital and replacement costs were set at £800/kW, and the O&M costs are set at 5% of the capital costs. The choice of 5% is based on best-practice thresholds of industrial maintenance. The input parameters of the inverter and rectifier were set based on data from specification sheet (Appendix -4D: DATASHEET OF ENPHASE IQ8P MICROINVERTER); (a) Lifetime =15 years, (b) Inverter Efficiency =95%, (c) Rectifier Relative Capacity (80%), and (d) Rectifier Efficiency (95%). The rectifier relative capacity (%) is the rated capacity of the rectifier relative to the that of the inverter.

Utility Grid

The modelled microgrid is sized to operate in island and grid-connected modes. The excess electricity generated by the hybrid system is transferred to the utility grid when the load needed in the grid-connected mode. Hence, “ E_{ie} (kWh)”, the energy that is imported from (-ve) or exported to (+ve) the grid , is given by equation 3.56 (HOMER-PRO, 2016):

$$E_{ie} = \sum_{t_s=n_0}^N E_p(t_s) + E_s - L_r t \quad 3.56$$

where, “ E_s (kWh)” represents the stored electrical energy, “ L_r (kW)” denotes the demand of total load, “ t (hr)” is the running hour, “ t_s (hr)” is the sun hour, and “ E_p (kW)” is the output power from the solar-PV system at any timestep. The sale and purchase parameters, time-of-use (ToU) rates “ E_{ie} (£)”, also called “Red, Amber and Green (RAG)” rates (Table 3.21), demand charges, reliability and emissions parameters were defined using the “Scheduled Rates™” module. The ToU rates were linked to the rate of inflation.

Power Purchase Price and Grid Sellback Price

The “Power Purchase Price (£/kWh)” is the cost of buying electricity from the grid. On the electricity bill, this cost appears as “Distribution Use of System – DUoS”; the cost to cover O&M of the UK Electricity Distribution Network. DUoS comprise; (a) time-

based charges (Red, Amber and Green; RAG) rates, (b) “Supply Capacity” charges and, (c) “Standing Charge”. The model input arguments for this variable (Table 3.21) were obtained by addition of the Supply Component and the respective Distribution Components (Red, Amber, Green) of the Consumption Charge obtained from the detailed monthly electricity costs at the case study, and the sample invoice of the grid electricity utility (Appendix-1H: TYPICAL ELECTRICITY INVOICE AT CASE STUDY). Net metering was implemented in the model to operationalise the UK Smart Export Guarantee (SEG) scheme. The scheme price enables the electricity utility to pay for energy supplied by an independent low-carbon generator and applies to small-scale low-carbon generators with a total installed capacity of up to 5 MW, and up to 50kW for micro-CHP, (ofgem-SEG, 2019). The “Grid Net Excess Price (£/kWh)” variable was set to (£0.056/kWh) based on the rate quoted by EDF energy, the electricity retailer at the case study.

Table 3.21: Table of Consumption Charge with ToU Rates

Type of Charge	Component	Charge Description	Retail Rate (£/kWh)	HOMER Pro® Input (£/kWh)
Consumption	Supply	Energy Charge	0.110108	-
	Distribution	Red: Weekdays: 16:00 – 19:00	0.06206	0.1727
		Amber: Weekdays: 09:00 – 16:00 & 19:00 – 22:00	0.00647	0.1166
		Green: Weekdays: 00:00 – 09:00 & 21:00 – 24:00 Weekends: all day.	0.000029	0.1101

The following controls are applied to each of the RAG rates in the model according to the following justifications:

- a) **Red and Amber rates:** charging of battery from the grid, discharging of any battery, and sale of power to the grid from the battery are prohibited. As solar generation likely occurs at the CS between 06:00 -17:00hrs (Table 3.7), these rates are applied to control the cost of energy and maximise microgrid self-consumption.
- b) **Green rates:** sales from the battery to the grid is prohibited and charging of the battery from the grid is allowed during this period of low energy cost to maximise microgrid self-consumption and minimise cost of energy.

Sale and Purchase Capacities

The Sale Capacity is the maximum power (in kW) that can be sold back to the grid in each time-step while the Purchase Capacity is the maximum power that can be purchased from the grid in each time step and may correspond to the grid connection capacity. The model was designed for unlimited sale and purchase capacities.

Distributed Generation Costs

The UK power sector regulator (Ofgem) defined Distributed Generation (DG) as an electricity generating plant connected to a distribution network rather than the transmission network. HOMER Pro® required two (2) sensitivity variables (Interconnection and Standby Charge) to model DG Costs. Based on advice from the building owner, on experience from similar projects, the interconnection charge, ($C_{\text{grid,int}} = £1000$) was used in the model. The “Standby Charge, $C_{\text{grid,standby}}(£/\text{yr})$ ” is an annual fee charged by the utility for providing backup grid power for a grid-connected power system. In the UK, it is capped by ofgem every 3 months and varied between an average of £0.4534/day to £0.5137/day between 2022 and 2025, hence an indicative value of £200/yr was used in the model.

Demand Rates

This parameter represents the monthly fee charged by the utility on the peak demand (£/kW/month). The peak demand is monitored at short intervals and the highest peak during the billing cycle is used to calculate the demand charge. The value of demand charge used for the model is £0.4/kW, obtained from the representative electricity invoice for the case study (Appendix-1H: TYPICAL ELECTRICITY INVOICE AT CASE STUDY).

Reliability

The Reliability and Availability of the grid was modelled using the RIIO-ED1 formula:

“Revenue = Incentives + Innovation + Outputs for Electricity Distribution.

It was the price control framework set by UK-ofgem for the DNOs between 1st April 2015 – 31st March 2023, and focused on customer service, Reliability and Availability, safety, connections, environmental impact and innovation. The current phase, RIIO-ED2 began in April 2023 and will run till 2028. The RIIO-ED1 dataset (Table 3.22) of “Customer Interruptions and Minutes Lost: Electricity Distribution” published by the

UK-Ofgem, as an appendix to the Network Performance Report (ofgem-RIIO-ED1, 2021) was used in the model because as at the time of writing, reports under RIIO-ED2 were yet to be released. In HOMER-PRO™ outages are modelled as one or more-time steps when no electricity can be purchased from, or sold to, the grid. Consistent with industrial experience, outages can occur at any time of the day, month or year as scheduled (planned) or unscheduled (unplanned) outages.

Table 3.22: RIIO-ED1 Outage Data for 2019 -2020

Customer interruptions and minutes lost: Electricity distribution (RIIO-ED1)				
Distribution Network Operator (DNO)	Target for customers interrupted	Actual number of customers interrupted	Target average minutes lost per customer per year	Actual average minutes lost per customer per year
Electricity North West	46.90	28.00	42.10	32.90
Northern Powergrid	62.70	49.20	56.70	42.30
Western Power Distribution	62.60	43.70	42.80	29.60
UK Power Networks	54.30	35.40	43.70	29.80
SP Energy Networks	44.50	39.20	40.40	35.10
Scottish and Southern Electricity Networks	61.20	50.40	50.20	51.40
Industry Average	55.37	40.98	45.98	36.85

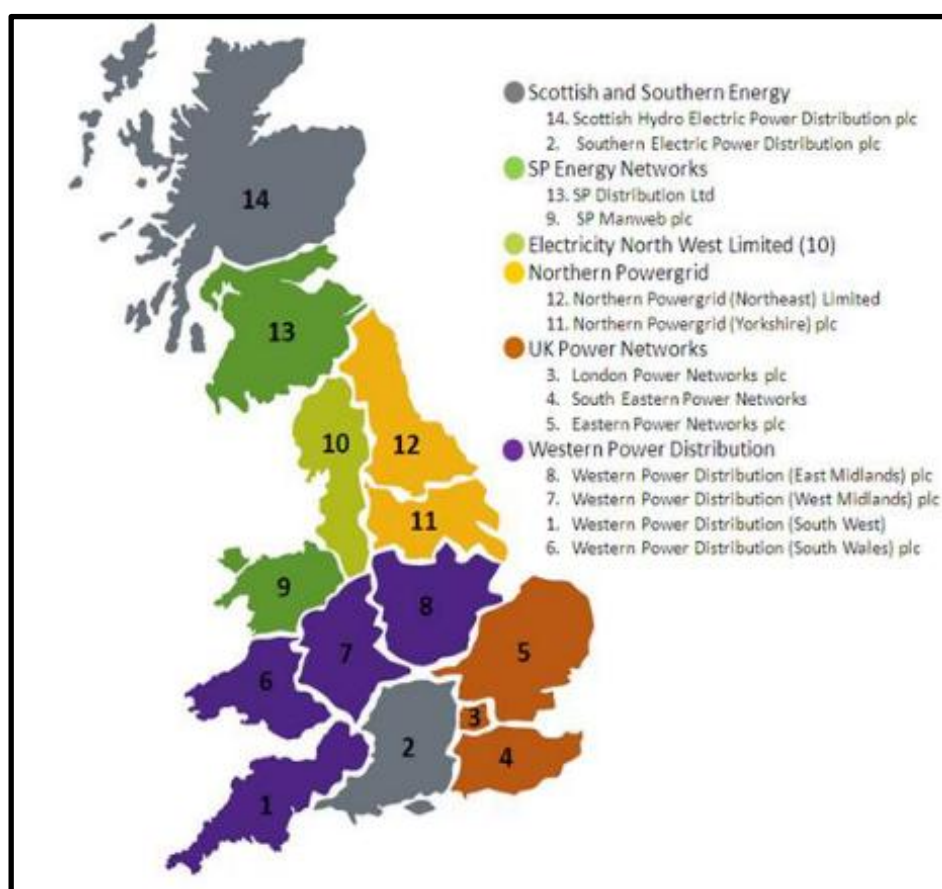


Figure 3.35: Map of UK DNOs and Coverage Area

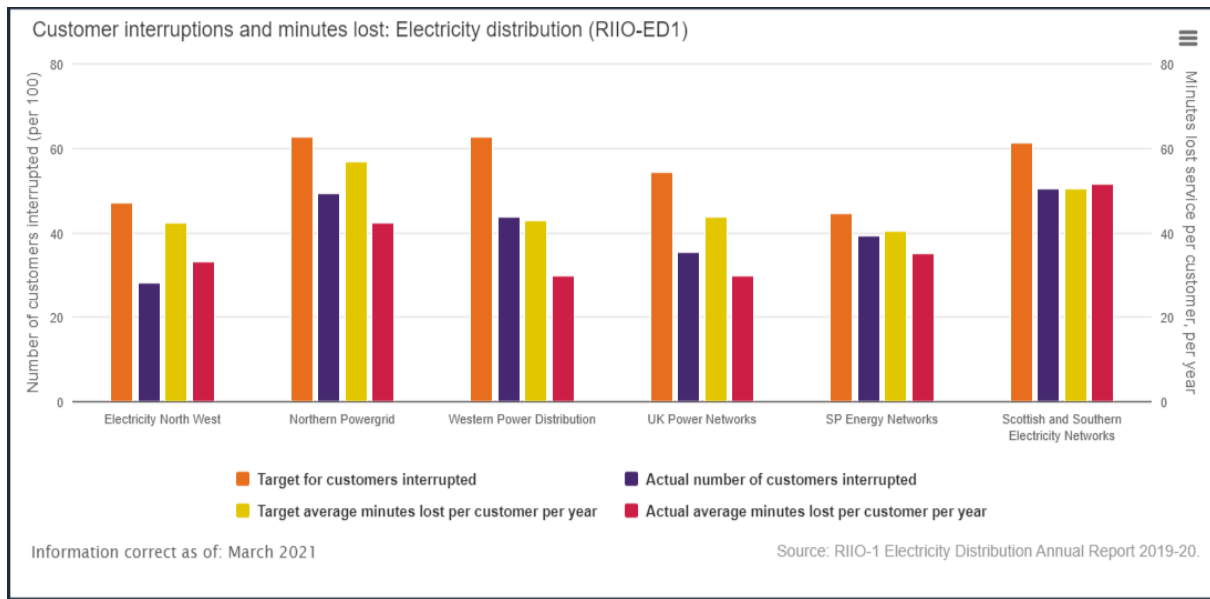


Figure 3.36: Bar Chart of RIIO-ED1 Dataset for 2019 -2020

The map and coverage of DNOs (Figure 3.35) shows “Scottish and Southern Electricity Networks” as DNO for the case study location. Based on the foregoing outage parameters applicable at the case study, the software algorithms calculate the following random outage parameters for (a) mean outage frequency of 60/year, (b) mean repair time of 0.84 hours and, (c) repair time variability of 15%. Outages are modelled as one or more timesteps which no electricity can be purchased from or sold to the grid.

Grid Carbon Intensity and Emissions Penalty

The sensitivity of grid electricity decarbonisation was accounted using the values of grid Carbon Intensity “CI (g/kWh)” between 2022 and 2050 (Appendix-1R: UK ELECTRICITY EMISSIONS FACTORS TO 2100) published by the UK-DESNZ. In addition, the related constraint, emissions penalty, was set at £0/tonne because there are currently no penalties in force.

Microgrid Dispatch

The microgrid dispatch model simulates hour-by-hour decisions on the individual components working together as a system such as the generators to operate and at what power level, the batteries to charge or discharge, and whether to buy from or sell to the grid. Modelling microgrid dispatch entails setting the operating reserve, specification of the control algorithm for dispatchable components, definition of dispatch strategy and prioritisation of loads. Operating (spinning) reserves are

essential for provision of a safety margin that ensures reliability and stability of the electricity supply against variability of electrical load and intermittency of renewable supply. Operating reserve is the difference between the operating capacity and the electric load. The model simulation aims to keep the operating reserve equal to or greater than the required operating reserve. As the system is connected to a very reliable grid, about 99.999% reliability, (Ofgem-RIIO-ED1, 2022), the operating reserve and annual capacity shortage are set to 1%.

Specification of the control algorithm requires determining whether the renewable (non-dispatchable) power sources can supply the entire electric load, required operating reserve, and the thermal load. The model uses a cost-based dispatch logic to select the combination of generators that can supply the load and the required operating reserve at the least cost. The controller enables specification of the dispatch strategy of the energy system during operation. In the Load Following (LF) strategy used in this model, when generators are required, they produce only enough power to meet the primary load. Lower priority objectives such as charging the storage bank or serving deferrable loads are left to the renewable power source. An LF strategy was used because renewable energy is integrated in the system. In addition, the LF controller is set to “allow diesel-off operation”, “allow generators to operate simultaneously” and “allow systems with generator capacity less than peak load”. The capital, replacement and O&M costs of the LF controller are set to zero to align the controller lifetime to that of the solar-PV array (28 years).

Microgrid Constraints

The Arguments in the “Constraints™” window allow definition of the conditions that the microgrid must satisfy so that all the systems that do not meet these constraints are discarded from the sensitivity and optimisation results of simulation. The main constraints are; (a) maximum annual capacity shortage (%), minimum renewable fraction (%) and (c) operating reserve.

Maximum Annual Capacity Shortage

It is defined (Lambert, et al., 2006) as the ratio of the maximum allowable capacity shortage fraction, “ f_{cs} (%)” to the total annual electric load, where:

$$f_{cs} = \frac{E_{cs}}{E_{demand}} \quad 3.57$$

and “ E_{cs} (kWh/yr)” is the total capacity shortage, and “ E_{demand} (kWh/yr)” is the total electrical demand. In the studied model, $E_{demand} = 2422.37 \times 365 = 884165.05 \text{ kWh/yr}$. As the microgrid is connected to the UK electricity network, with above 99% average Reliability (UKPN, 2024), incidents of “Unmet Load”, which occur when electricity demand exceeds supply are rare. Hence, the maximum annual capacity shortage is set at 1%, implying that at each timestep,

$$f_{cs} = \frac{1\% \text{ of Annual Electricity Demand (kWh)}}{\text{Total Annual Electricity Demand (kWh)}} = \frac{88416505}{884165.05} = 0.0001.$$

Minimum Renewable Fraction

The renewable energy fraction, “ f_{ren} ”, refers to the fraction of energy delivered to the load from renewable sources, given as:

$$f_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \quad 3.58$$

In the case study model, the following input sensitivity values of “ f_{ren} ” were set; (a) zero, corresponding to the base case where the case study has no onsite renewable sources, (b) values between 0-2%, in increments of 0.1%.

Operating (Spinning) Reserve

This is the surplus operating capacity that ensures reliability of supply in situations of sudden load increase or drop in renewable output. Further to the explanation on the high Reliability of the UK power network, to which the modelled microgrid is connected, the required operating reserve values are set as follows, based on timestep and day-to-day variability of load; (a) 10% of load in current timestep (b) 20% of annual peak load, and (c) zero percentage of solar-PV output.

3.9 CALCULATION OF OPERATIONAL NET ZERO BENCHMARKS

A workflow that entailed the export of values of electrical and thermal energy consumption at the case study from IESVE™ and also coupling of solar-PV generation from HelioScope™ to HOMER Pro™ was applied in the study. The values of energy consumption, carbon emissions and O&M from the least cost microgrid obtained from the simulation results described in the foregoing frameworks and equations 3.59 – 3.63 were used to calculate the EUI (average of EUI_{el} , and EUI_{th}), CEI and ECI for the optimal (least TNPC) microgrid.

$$\text{EUI}_{\text{el}} (\text{kWh/m}^2/\text{year}) = \frac{\text{Total Annual Electricity Consumption (kWh)}}{\text{GIA (m}^2\text{)}} \quad 3.59$$

$$\text{EUI}_{\text{th}} (\text{kWh/m}^2/\text{year}) = \frac{\text{Total Annual Electricity Consumption (kWh)}}{\text{GIA (m}^2\text{)}} \quad 3.60$$

$$\text{Total site-EUI (kWh/m}^2/\text{year}) = \frac{\text{EUI}_{\text{el}} + \text{EUI}_{\text{th}}}{\text{GIA (m}^2\text{)}} \quad 3.61$$

$$\text{CEI (kgCO}_2\text{/m}^2/\text{year}) = \frac{\text{Total Carbon Emissions (kgCO}_2\text{)}}{\text{GIA (m}^2\text{)}} \quad 3.62$$

$$\text{ECI (£/m}^2/\text{year}) = \frac{\text{Microgrid Operation and Maintenance Cost (£)}}{\text{GIA (m}^2\text{)}} \quad 3.63$$

The methodology adopted in this chapter, leading to the calculation of EUI, CEI and ECI metrics from equations 3.59 – 3.63 normalised total energy demand, carbon emissions and cost of energy to GIA and derived intensive indicators. The floor-area normalisation implies that the values are comparable across hotels of similar typology, urban context, star-rating, service level and meteorological situation, irrespective of geometrical size. The transferability of the metrics is reinforced by the identical energy- and carbon-intensive end-uses (space conditioning, domestic hot water, lighting, etc), operational patterns, and energy prices typical to hotels within the same typological grouping as the case study. In this context, the case-study was treated as a statistical sample from the population of comparable hotels. The methodology entailed application of timestep and day-to-day variabilities of 10% and 20% respectively to the modelled energy demand. In addition to accounting for uncertainties in energy and carbon performance, the variabilities accommodate intra-typology variations that may arise from application of the methodology detailed in this work to multiple sites. Consequently, the calculated EUI, CEI and ECI benchmarks are indicative for proofing operational net zero performance in mid-range (3-Star) UK hotels.

4.0 RESULTS AND ANALYSIS

This study aimed to investigate the feasibility of operational Net Zero in an existing UK hotel building typology, towards the development of energy, carbon and cost metrics, benchmark targets and limits of energy efficiency, carbon emissions, and LCOE. The benchmark values of EUI, CEI and ECI computed from the study are indicative for mid-rise, concrete-framed, mid-range (3-star) non-resort hotels with commercial load profiles located in London, UK. The benchmark values are driven by the following hotel-specific scenarios: (a) EUI: building design, occupancy level, weather, HVAC/DHW efficiency, hotel category/stars, guest behaviour and operational schedules, (b) CEI: energy sources (grid carbon factor, gas, diesel), renewable penetration, hotel amenities and policy conditions, and (c) ECI: energy tariffs, occupancy patterns, maintenance quality, generator use, PV/battery integration, and peak loads. Regardless, the methodology adopted lends itself to application for proofing of net zero claims in commercial and other building typologies.

4.1 FRAMEWORK FOR PRESENTATION OF RESULTS

The results that are significant to this study relate to the energy and carbon metrics (EUI and CEI) in the PPM framework of CIBSE and UKGBC, and the novel cost metric (ECI) introduced by this study. The results of the case study are interpreted in the contexts of EUI and emissions reduction defined in the following reference values:

- 1) OPTION-B Paris Proof Targets derived from the Technical Consultation on “Energy Performance Targets for Net Zero Carbon” Commercial and Office Buildings (UKGBC, 2020; Cohen et al., 2021).
- 2) The UKNZCBS EUI limits and targets for stepped retrofit of hotel typologies.
- 3) The CHSBI EUI limits for 3-star non-resort hotels.

The results were presented as follows to answer respective research questions:

- 1) **Baseline EUI:** were obtained from simulation of Model-1.0., which represents the building “as is”. The baseline EUI provides the reference point for comparing the changes in energy intensity resulting from application of EEMs, to enable Research Questions 1 and 2 to be answered.
- 2) **Future EIUs:** the changes in EUI, relative to the baseline, obtained from application of stepped energy efficiency retrofits and the impact of climate change are associated with; (a) impact of climate change in 2030 (EUI:2.0), (b) insulation

uplift (EUI:2.1), (c) LED retrofit (EUI:2.2), (d) daylighting (EUI:2.3), € adaptive ventilation (EUI:2.4), and (f) impact of climate change in 2050 (EUI:3.0). In addition to being a basis for the evaluation of energy intensity reduction, the future EUIs enable the comparison of energy and carbon intensities in the case study to the benchmark targets and limits defined in the PPM and UKNZCBS. This is required to answer Research Question 2.

- 3) **On-site Renewable Energy Intensity:** this is computed from the ratio of annual solar-PV production to the GIA of the case study. This parameter supports answering Research Question 1 as it enables evaluation of the adequacy of the UKNZCBS-stipulated renewable energy target of 40 kWh/m² for net zero.
- 4) **CEI and ECI Metrics:** these metrics support answering Research Question 3 because they are obtained from evaluating the impact of the following sensitivity variables; (a) grid Carbon Intensity (CI), and (b) “Expected Inflation Rate (%)”, on the following parameters of the lowest TNPC system; (a) O&M cost, (b) cost of energy, (c) renewable fraction, (d) maximum renewable penetration, and € CO₂ emissions.

4.2 SOLAR-PV PRODUCTION AND SYSTEM LOSSES

The modelling approach in Figure 3.21 and flowchart (Figure 3.23) were applied to generate the irradiance and system power calculations for each hour to project the energy production of the array over the 4,576 hours of sunshine at the case study location during the base year to give the main output parameters.

Table 4.1: Summary of PV System Output

Design Quantity/ Parameter	Unit	Design Value
DC Nameplate	kW _p	48.3
AC Nameplate	kW	40.1
DC/AC Ratio	-	1.20
Annual Production	MWh	43.8
Performance Ratio	%	75.5
Specific Yield	kWh/kW _p	906.1

As shown in Table 4.1, the system Performance Ratio (PR=75.5%) was obtained for the rooftop configuration studied. The PR is the ratio of the actual energy output of the system to the theoretical maximum energy output, taking account the losses. The value of 75.5% is marginal (very close to the IEA baseline benchmark of 75%) but is within the benchmark range (75% - 85%) for Europe (EU-SERENDIPV, 2020) and

average values quoted in several trade documentation. Assuming optimal azimuth and tilt angles, increase of the PR, and maintenance of the value above 75%, is an operational imperative that is impacted by environmental and technical factors such as temperature of the PV module, solar irradiance at the site of the installation, soiling, conduction losses, efficiency of PV module and inverter (or microinverter), hence the preference for available, higher efficiency commercial solar-PV modules with microinverters. An example is the Sunpower® Maxeon-7™ PV Module (24% Efficiency, 475W Nominal Power), released in November 2024, which is compatible with Enphase®-IQ8™ series microinverters. The combination of this module and microinverter would result to a higher PR under the studied conditions.

In addition, Specific Yield (kWh/kW_p), calculated as a ratio of the annual energy output (kWh) to the installed capacity (kW_p) characterises the performance of the system and normalises solar-PV energy production across regions, technologies and system sizes. The value of Specific Yield obtained from the model (906.1 kWh/kW_p) is within the average benchmark (960 kWh/kW_p , $\pm 5\%$ uncertainty) obtained from analysis of UK Government data on PV installations between 2014 – 2016 (Mason, 2016).

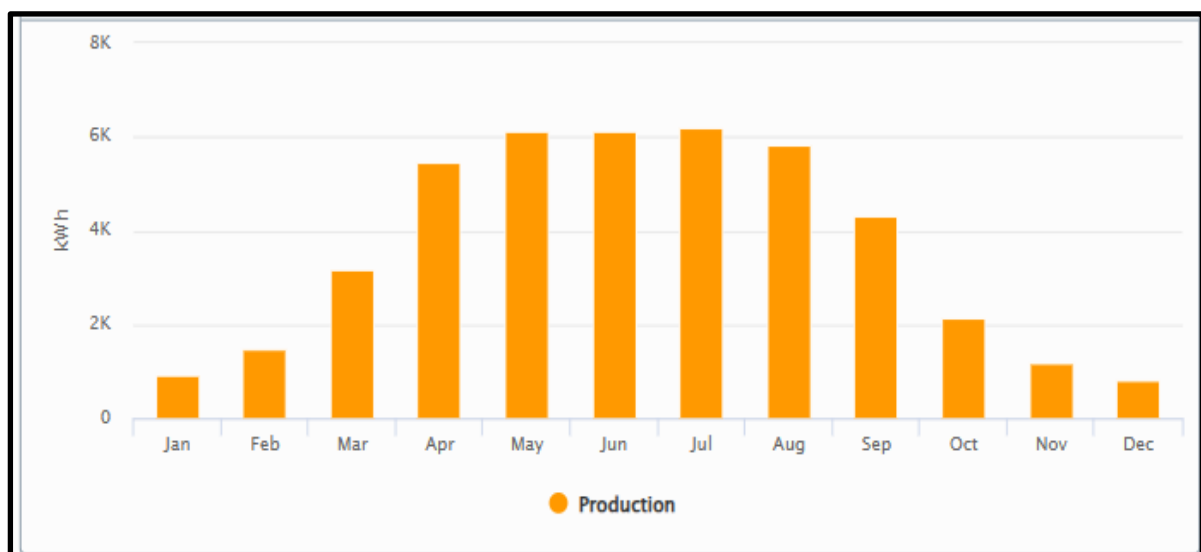


Figure 4.1: Model Solar-PV Production

The annual energy production of the solar-PV system (43.8 MWh) is presented in Table 4.1, with average peak value of 6 MWh (Figure 4.1.) in the spring -summer months between May – September, while minimum production averaged 2 MWh in the autumn-winter months (October - April).

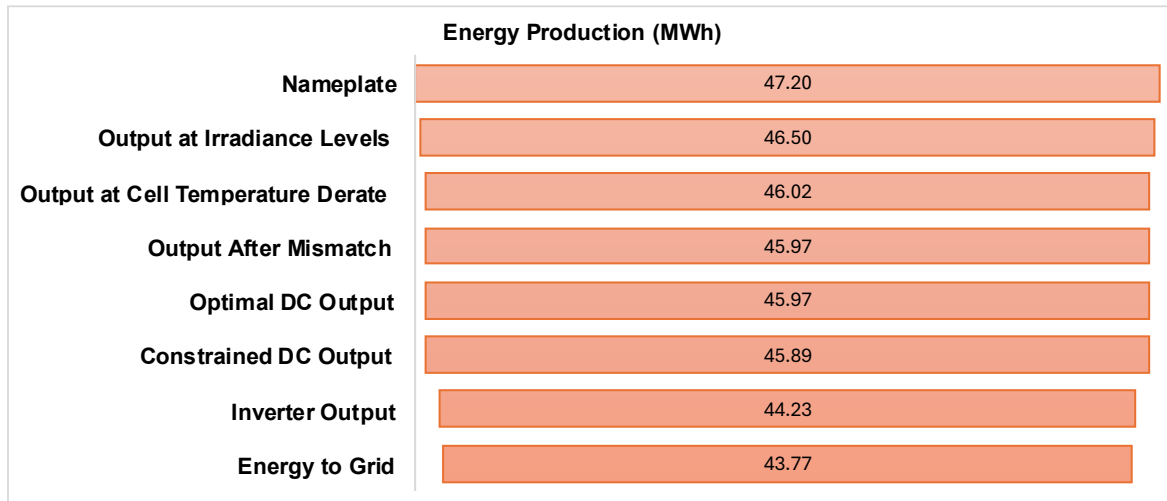


Figure 4.2: Energy Production Loss Tree for the Model

The system energy loss tree chart in **Error! Reference source not found.** shows the energy flow in the conversion of solar irradiance to grid energy and the losses at each stage, totalling 7% for the solar-PV modules in the modelled configuration.

Solar-PV Array Losses

The total system losses in the design (26.8%) comprise significant shading, reflection, soiling, irradiance, temperature, and inverter losses, as identified in the IEA Task-13 publication (French *et al.*, 2021) on solar-PV loss mechanisms.

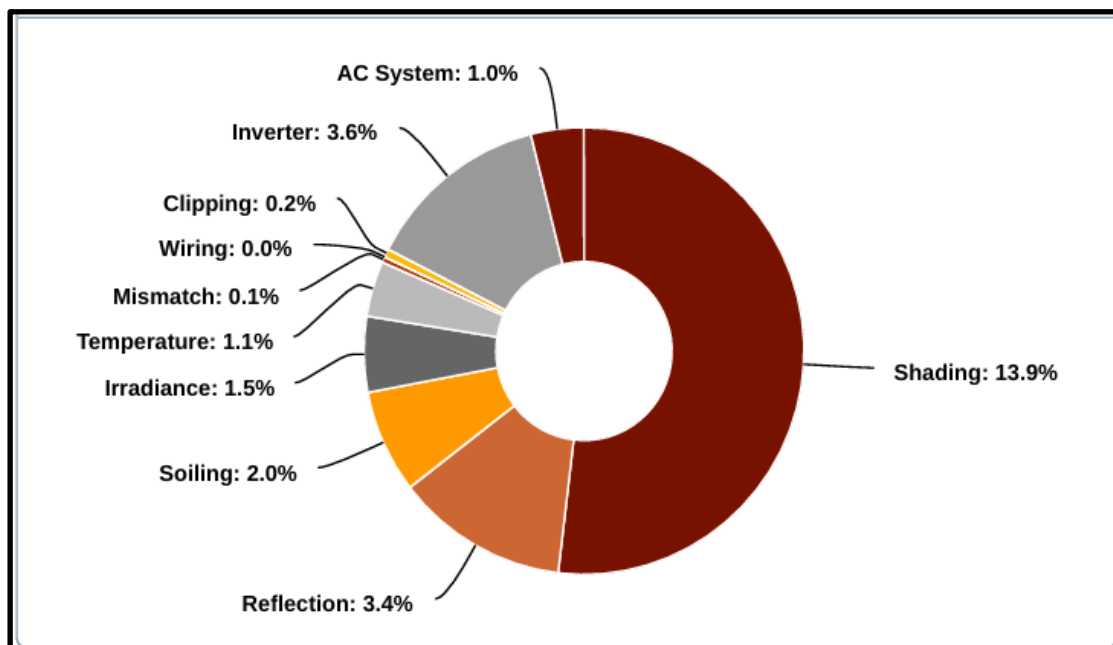


Figure 4.3: System Losses in Case Study PV Array

The pie chart of losses from the Helioscope™ model (Figure 4.3), shows that shading losses were dominant (13.9%). Several practice and research benchmarks estimate

5-15% shading losses as acceptable in commercial applications (Deline, et al., 2016; Ghaleb, et al., 2024; Neumann, 2026), with bankable losses within the 0-5% range, standard commercial threshold set at 5-10%, and shading losses greater than 10% likely to reduce financial viability. Soiling losses reported at 2% in this model account for average 4 – 7% (Schill et al., 2022) yield reduction globally, leading to significant operation and maintenance costs, and are forecast to increase with the growing influence of climate change. In the UK, a study (Solas et al., 2025) reported average annual soiling loss of between 0.5 – 3% depending on whether rainfall was considered a perfect, or 10%, cleaning agent. The 3.4% value of Reflection Losses (Figure 4.3) is within the range of 2.5 – 4% of annual POA irradiance, estimated for locations across the UK using standard Incident Angle Modifier (IAM) curves.



Figure 4.4: Shading Map of Case Study PV Array

The shading map of the array (Figure 4.4) shows that the modelled POA irradiance of all the modules was at least 77% (950 kW/m^2) of the rated value.

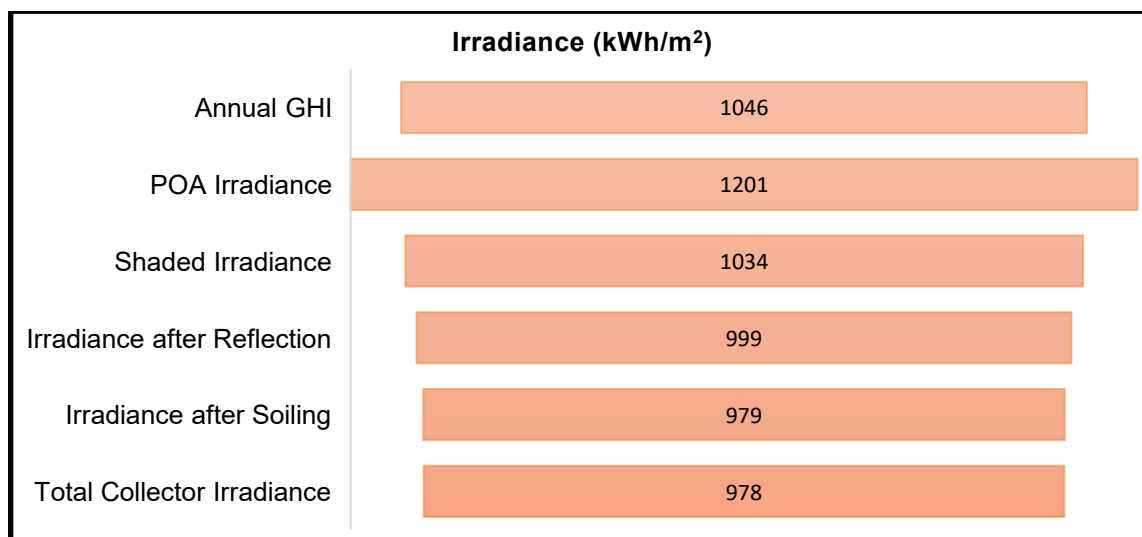


Figure 4.5: Irradiance Loss Tree for the Case Study

The Irradiance Loss Tree (Figure 4.5) shows the reductions in usable solar irradiance reaching the PV cells, compared to the theoretical irradiance available at the site.

The results of solar-PV modelling for the case study shows that the annual solar-PV yield of 43.8 MWh is about 4.5% of the electricity requirement of 884MWh. Hence, the solar-PV generated is below the target 40% renewable share envisaged in the PPM framework. In addition, the Renewable Energy Intensity of 14.8 kWh/m² at the case study is below the target of 40 kWh/m² specified in the UKNZCBS. These findings, though indicative, provide a basis for further interrogation of the renewable energy requirement for net zero as the limits appear too stringent for existing buildings in the absence of BIPV facades and windows, and the use of certified offsets.

In addition, though the dominance of fixed-tilt rooftop solar-PV for generation of onsite renewable generation is recommended in the UKNZCBS and supported by reasons ranging from cost-effectiveness and technical simplicity, the results obtained within the assumptions of the present study recommend ring-fencing of the parameters selected for estimation of solar-PV yield and computation of net zero metrics in commercial buildings in the UK as follows:

- a) **System Performance Ratio of not less than 75%:** This is supported by the state-of-the-art efficiency of modules, inverters and microinverters and the ongoing research to develop components with higher efficiencies.
- b) **The value of GCR (0.6 – 0.7):** and result to shading losses less than 15%. The selection of conductors for AC runs between the module to the central inverter and to the PCC (or microinverter and PCC) should, in addition to

complying with the power loss and voltage drop limitations of BS7671-18th edition and IEC60364, result to a maximum AC system loss of 1.5%.

- c) **Revision of the setback requirement from 1.2 m to between 0.8 – 1 m:** in RC-62 standard would increase the number of rooftop panels while still ensuring safety from fire hazard.

4.3 BASELINE ENERGY SIMULATION AND CALIBRATION

The base case energy consumption and emissions from BEM simulation ,Table 4.2, shows that 769MWh of energy was consumed, comprising 365MWh of electricity and 404MWh of natural gas.

Table 4.2: Base Case Monthly Energy Consumption and Emissions of CS

IES Virtual Environment 2024 Copyright © 2024 Integrated Environmental Solutions Limited.			Project File: Model-1.0. Base Case-2022.mit Sim File: Model-1.0. Base Case-2022 Weather File.aps 02/Mar/2025 Weather File: BUL-LH-IESVE-SSP2.4.5-RCP4.5_2022-hour.epw			
	Total energy (MWh)	Total electricity (MWh)	Total nat. gas (MWh)	Total CE (kgCO ₂)	Total nat. gas CE (kgCO ₂)	Total elec. CE (kgCO ₂)
Date	Model-1.0. Base Case-2022 Weather File.aps	Model-1.0. Base Case-2022 Weather File.aps	Model-1.0. Base Case-2022 Weather File.aps	Model-1.0. Base Case-2022 Weather File.aps	Model-1.0. Base Case-2022 Weather File.aps	Model-1.0. Base Case-2022 Weather File.aps
Jan 01-31	151.0826	30.9789	120.1037	31201	25222	5979
Feb 01-28	79.8986	27.9865	51.9121	16303	10902	5401
Mar 01-31	63.4755	31.0016	32.4738	12803	6820	5983
Apr 01-30	53.2642	30.0007	23.2636	10675	4885	5790
May 01-31	43.2794	31.0000	12.2793	8562	2579	5983
Jun 01-30	41.9072	30.0104	11.8968	8290	2498	5792
Jul 01-31	43.3025	31.0016	12.3009	8566	2583	5983
Aug 01-31	43.2782	31.0061	12.2721	8561	2577	5984
Sep 01-30	41.8994	30.0125	11.8868	8289	2496	5792
Oct 01-31	43.2644	30.9940	12.2703	8559	2577	5982
Nov 01-30	52.2730	30.0105	22.2625	10467	4675	5792
Dec 01-31	112.5194	31.0008	81.5185	23102	17119	5983
Summed total	769.4442	365.0036	404.4404	155378	84932	70446

In terms of proportions of electricity and natural gas consumption and associated emissions, the CS consumed 365MWh (47%) of electricity and 404MWh (53%) of natural gas (Figure 4.6a), and emitted a 85t.CO₂ and 71t.CO₂ from natural gas and electricity, respectively (Figure 4.6a).

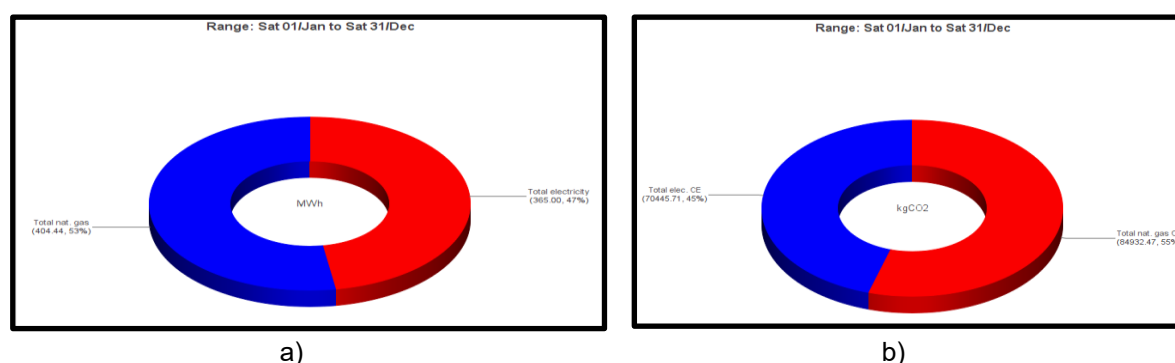


Figure 4.6: Model-1.0. Proportion of Energy and Carbon Emissions

The synopsis of the base case (Table 4.3) shows that minimum (43.24kW) and maximum (603.75kW) power consumption occurred in October and December, corresponding to summer and winter seasons, respectively. The peak power consumption in December-January was driven by winter heating demand, despite low average occupancy of 35% (Figure 3.12).

Table 4.3: Synopsis of Base Case Model

Variable Name	Type	Min. Val.	Min. Time	Max. Val.	Max. Time	Mean
Total Energy	Power (kW)	43.24	04:30,23/Oct	603.75	00:30,26/Dec	87.84
Total Electricity	Power (kW)	33.44	15:30,01/Jan	65.80	07:30,14/Apr	41.67
Total Nat. Gas	Power (kW)	7.01	03:30,01/Jan	565.46	00:30,26/Dec	46.17
Total CE	CO ₂ emission (kgCO ₂ /h)	8.5	04:30,23/Oct	126.1	00:30,26/Dec	17.7
Total Nat. Gas CE	CO ₂ emission (kg CO ₂ /h)	1.5	03:30,01/Jan	118.7	00:30,26/Dec	9.7
Total Elec. CE	CO ₂ emission (kg CO ₂ /h)	6.5	15:30,01/Jan	12.7	07:30,14/Apr	8.0

The monthly breakdown of electrical and thermal demand (Table 4.4) shows that heating and lighting comprise about 53% and 23%, respectively, of energy performance, both values of the same order of estimate, 60% and (15 -20%), respectively, reported for the UK hospitality sector (Carbon-Trust, 2018).

Table 4.4: Model-1.0:Monthly Heating and Lighting Performance

Month	Heating (MWh)	Heating Emissions (kg.CO ₂ /kWh)	Lighting (MWh)	Lighting Emissions (kg.CO ₂ /kWh)
Jan	120.1	25,702.6	15.3	2,955.3
Feb	51.9	11,335.8	13.8	2,669.3
Mar	32.5	7,300.3	15.3	2,955.3
Apr	23.3	5,350.6	14.8	2,859.9
May	12.3	3,059.5	15.3	2,955.3
Jun	11.9	2,963.6	14.8	2,859.9
Jul	12.3	3,064	15.3	2,955.3
Aug	12.3	3,058	15.3	2,955.3
Sep	11.9	2,961.5	14.8	2,859.9
Oct	12.3	3,057.6	15.3	2,955.3
Nov	22.3	5,140.4	14.8	2,859.9
Dec	81.5	17,599.7	15.3	2,955.3

The minimum and maximum electric power demand of 33.44 and 65.80kW correspond to periods of high and low average daylight hours, respectively, implying that electric power demand was largely driven by lighting. Based on the GIA of 2,964m² and electricity consumption of 365MWh, the electricity EUI ($EUI_{el} = 122 \text{ kWh/m}^2/\text{yr}$) is comparable to the range of electricity use intensities for hotels (90 -150 kWh/m²/yr) reported in the UK register of DEC's, and the thermal EUI ($EUI_{th} = 135 \text{ kWh/m}^2/\text{yr}$) is within the range, 120 – 250 kWh/m²/yr. To ensure that IESVE results are not artefacts of a particular weather year or an over-fitted calibration, the model was calibrated with

hourly gas and electricity data following ASHRAE Guideline-14 metrics. The confidence in the baseline thermal and electrical EUIs were achieved by the use of empirical construction data of the hotel to develop the IESVE™ construction types in the model. In addition, the actual operational data for average multi-year occupancy, boosted and kitchen water consumption, and Heating and Cooling Degree Day data for the location of the case study, were used to create daily weekly, annual and free form profiles for modelling occupancy of spaces with specific use functions, lighting, plug loads, infiltration, ventilation of the case study. Additional validation of the model with energy bills with energy to improve the credibility of the model could strengthen confidence in the baseline figures.

4.4 PHYSICS-BASED CALIBRATION OF BASE CASE MODEL

The results of electricity consumption predicted by the model, and the measured power consumption are presented in Table 4.5. Verification of the baseline model (Model-1.0) was done by hourly physics-based calibration against the measured time-series electricity consumption by calculating the NMBE (equation 3.32) and C_v RMSE (equation 3.33).

Table 4.5: Simulated and Actual Electricity and Gas (estimated) Consumption

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Simulated (MWh)	30.98	27.99	31	30	31	30.01	31	31.01	30.01	30.99	30.01	31
Measured (MWh)	26.05	22.47	27.31	28.20	29.60	29.30	30.83	29.96	31.43	31.25	32	31.04

The values of hourly calibration (NMBE=4.75%, C_v RMSE=12.6%) are presented in Table 4.6. NMBE implies that at each timestep, the model tends to overestimate the electricity consumption by 4.75% relative to the average actual measured electricity consumption for the timestep, while the C_v RMSE of 12.6%, indicates that the pattern of electricity consumption predicted by the model represents the actual consumption pattern at the CS across different months.

Table 4.6: Hourly ASHRAE-14 Model Verification Values

Index	Model Values	ASHRAE 14 Benchmarks
NMBE (%)	4.75	± 10
C_v RMSE (%)	12.6	30

NMBE and C_v RMSE are key indicators used for Measurement and Verification (M&V) in energy performance contracts, irrespective of energy profile, and there are case studies for sports stadia, manufacturing facilities, retail, and campus energy management in the UK. These indicators can be applied to benchmark energy and

carbon performance under the UK “Zero Carbon Services” (DESNZ and Jones, 2025) which aims to advise 600 British small businesses on energy and carbon savings and save £3 million on bills and reduce 2,700 tonnes of CO₂ emissions.

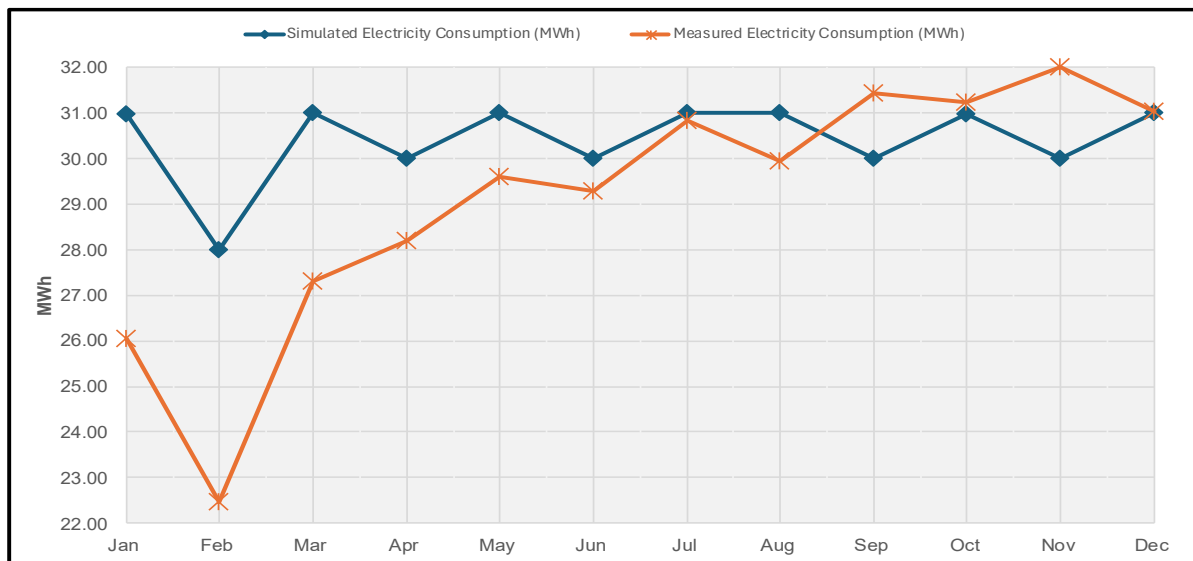


Figure 4.7: Plot of Baseline Simulated and Measured Electricity Consumption

The plot of simulated and measured electricity consumption (Figure 4.7), shows that the deviation of simulated electricity consumption from the measured value is greater than 10% between January and March. This may be attributed to the lower average occupancy (54%), compared to the other months with 67% average occupancy. Regardless of the deviations, the NMBE and C_vRMSE are within the ASHRAE-14 benchmarks for hourly calibration.

NMBE and C_vRMSE are key indicators used for Measurement and Verification (M&V) in energy performance contracts, irrespective of energy profile, and there are case studies for sports stadia, manufacturing facilities, retail, and campus energy management in the UK. These indicators can be applied to benchmark energy and carbon performance under the UK “Zero Carbon Services” (DESNZ and Jones, 2025) which aims to advise 600 British small businesses on energy and carbon savings and save £3 million on bills and reduce 2,700 tonnes of CO₂ emissions.

4.5 COMPARATIVE ENERGY AND CARBON PERFORMANCE

The energy and carbon performance of the BEMs is presented according to the “fabric first principle” in the stepped renovation/retrofit strategy for the study, in the following order; (i) base case (Model-1.0), (ii) 2030 climate change effect (Model-2.0), (iii) insulation uplift (Model-2.1), (iv) LED retrofit (Model-2.2), (v) daylighting (Model-2.3),

(vi) adaptive ventilation (Model-2.4) and (vii) 2050 climate change effect (Model-3.0). An overview of the CS heating and cooling load reports (**Error! Reference source not found.**) and energy reports (**Error! Reference source not found.**) indicates that electricity consumption is driven mainly by lighting, and thermal demand is mainly from natural gas. Consequently, the impact of climate change and EEMs in each model is evaluated in relation to the changes in electricity consumption, and thermal energy demand. In addition, as electricity emissions are influenced by the projected reduction in UK grid carbon intensity from a baseline value of 193g.CO₂/kWh to 2g.CO₂/kWh in 2050, the changes in emissions are evaluated on this basis.

Do Nothing Pathway: Impact of Climate Change

The successive simulation of the base model (Model-1.0) using baseline, 2030 and 2050 weather files represent the “Do Nothing” scenario as all the construction and thermal characteristics of the building are retained.

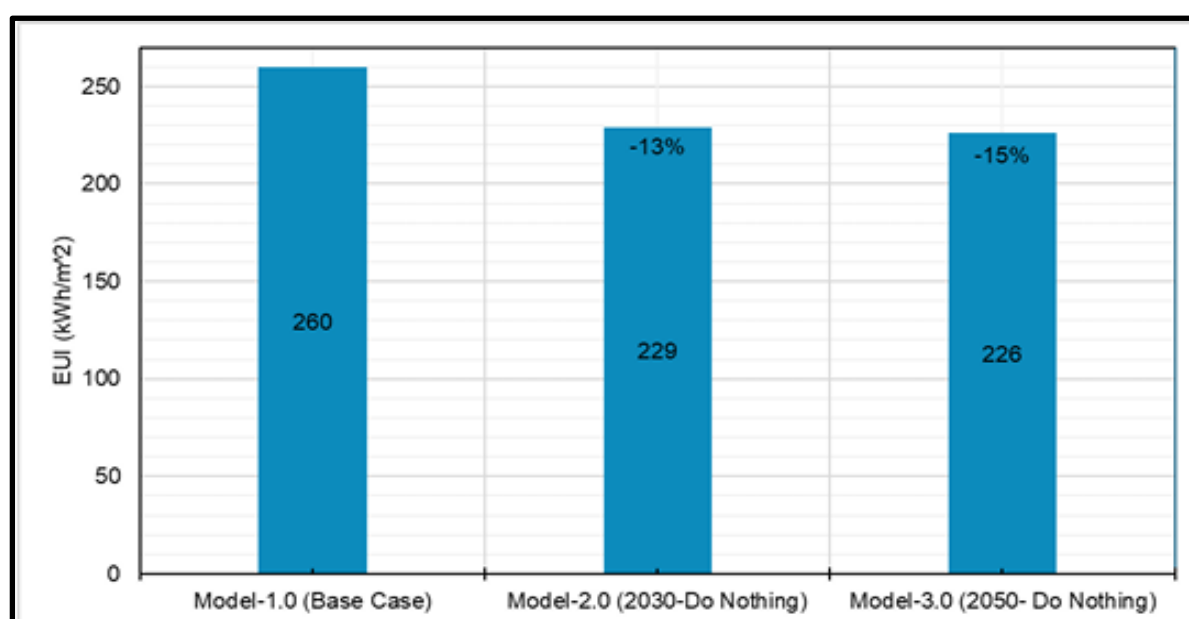


Figure 4.8: EUI Change in “Do Nothing” Pathway

As shown in Figure 4.8, the “Do Nothing” pathway shows that relative to the baseline, EUI decreases from 260 – 229 kWh/m² (13%) in 2030 and to 226 kWh/m² (15%) in 2050. Compared to the EUI benchmarks of the UKGBC and CIBSE net zero frameworks which require a 60% reduction in EUI between the baseline and 2050, this pathway does not achieve net zero for the building, justifying the implementation of measures for further reduction of the EUI towards net zero.

Table 4.7: Simulation Results of Energy Efficient and Climate Resilient Models

Models	Total energy (MWh)	Total electricity (MWh)	Total Nat. Gas (MWh)	Total CE (kgCO ₂)	Total Nat. Gas CE (kgCO ₂)	Total Elec. CE (kgCO ₂)	EUI (kWh/m ²)	% EUI Change (Relative to Base Case)	% CEI Change (Relative to Base Case) ²
1.0	769	365	404	155,378	84,932	70,446	259.60		
2.0	679	366	313	100,989	65,116	35,873	229.12	-13%	-54%
2.1	650	345	306	97,362	63,579	33,783	219.43	-18%	-60%
2.2	641	318	323	98,295	67,083	31,212	216.26	-20%	-58%
2.3	637	334	303	95,678	62,922	32,756	214.83	-21%	-62%
2.4	575	289	286	87,791	59,460	28,332	193.98	-34%	-77%
2.1.2	624	312	313	96,189	65,647	30,542	210.61	-23%	-62%
2.1.3	626	334	292	93,468	60,712	32,756	211.24	-23%	-66%
2.1.4	560	285	276	85,241	57,338	27,903	189.06	-37%	-82%
2.2.3	644	333	311	97,319	64,691	32,628	217.26	-19%	-60%
2.2.4	562	252	310	89,134	64,427	24,708	189.56	-37%	-74%
2.3.4	619	334	284	91,918	59,162	32,756	208.73	-24%	-69%
2.1.2.3	651	333	318	98,796	66,168	32,628	219.65	-18%	-57%
2.1.2.4	562	252	310	89,134	64,427	24,708	189.56	-37%	-74%
2.1.3.4	624	334	290	93,103	60,347	32,756	210.65	-23%	-67%
2.1.2.3.4	632	333	299	94,797	62,169	32,628	213.17	-22%	-64%
3.0	718	295	422	65,032	64,441	591	242.13	-7%	-139%
3.1	670	366	304	47,067	46,335	732	225.94	-15%	-230%
3.2	643	318	325	50,171	49,534	637	216.97	-20%	-210%
3.3	651	328	324	67,952	67,296	656	219.79	-18%	-129%
3.4	589	285	304	47,022	46,453	569	198.76	-31%	-230%
3.1.2	628	313	315	48,627	48,000	627	211.84	-23%	-220%
3.1.3	640	328	312	48,287	47,631	656	215.94	-20%	-222%
3.1.4	578	285	293	45,273	44,704	569	194.89	-33%	-243%
3.2.3	646	333	313	48,437	47,771	666	217.96	-19%	-221%
3.2.4	564	252	311	48,021	47,516	504	190.12	-37%	-224%
3.3.4	621	334	286	44,350	43,681	669	209.36	-24%	-250%
3.1.2.3	639	333	306	47,358	46,692	666	215.57	-20%	-228%
3.1.2.4	549	249	300	46,297	45,799	498	185.29	-40%	-236%
3.1.3.4	626	334	292	45,213	44,545	669	211.27	-23%	-244%
3.1.2.3.4	621	333	288	44,597	43,931	666	209.47	-24%	-248%

U-value Reduction, LED Lighting Retrofit and Adaptive Ventilation

This trajectory gave the highest EUI reduction of 40% (260-190-185 kWh/m²) from the baseline through 2030 to 2050. The pathway entailed renovation of the building to conform with the insulation requirements in the “UK Future Buildings Standard”, LED lighting retrofit, and adaptive ventilation.

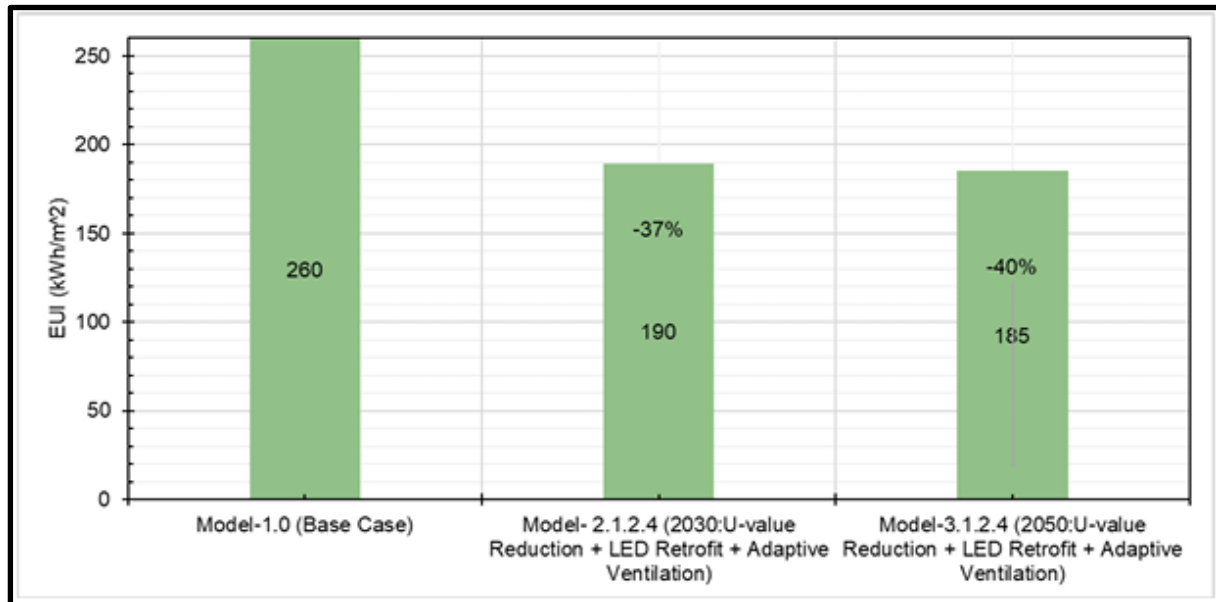


Figure 4.9: Absolute and Percentage EUI Change:1.0-2.1.2.4-3.1.2.4 Pathway

In comparison with the EUI of 220 kWh/m² for existing hotels stated in CIBSE TM46 energy benchmarks (**Error! Reference source not found.**), the baseline EUI obtained (260 kWh/m²) is of the same order. The proposed EUI reduction for UK hotels published based on a study by ARUP®, gleeds®, IHG® and Schneider® (Arup et al., 2021), based on the Paris Proof Methodology (PPM), the operational Net Zero framework adopted by UKGBC, CIBSE and RIBA, a 24.9% decrease in EUI by 2030, and 60% EUI reduction by 2050 is required to transform UK hotels to operational net zero, using a 2020 – 2025 baseline period. Relative to this benchmark, the 37% EUI reduction in the studied hotel meets the requirement for 2030 but will not achieve the net zero requirement in 2050 because the 40% EUI reduction is below the 60% requirement. In comparison to the UKNZCBS, the target EUIs in 2030 and 2050 for stepped retrofit of existing hotels to operational net zero are, 187 kWh/m² and 120 kWh/m², respectively as shown in Appendix-1D. While the EUI of 190 kWh/m² in 2030 about the same, the EUI of the studied hotel for 2050 exceeds the requirement by over 50%, implying that additional measures are required to achieve operational net zero

for this hotel on the basis of the UKNZCBS. In the context of the CHSBI, the EUI of a non-resort 3-star hotel located in London, UK is 240.18 kWh/m² while the benchmark emissions is 45.03 kgCO₂ (Appendix-1D), and the EUI is of the same order of magnitude as the baseline EUI of 290 kWh/m².

4.6 OVERHEATING AND THERMAL COMFORT

The focus of this study is on overall energy consumption, hence the detailed causes for overheating were not investigated in depth. However, an inspection of the overheating report of the 30 models developed in the study on the basis of “Category II-New Builds” (buildings with spaces that have an acceptable temperature range of $\pm 3K$) showed that in the baseline year, 180 out of the 215 occupied spaces were thermally comfortable met Criteria-1 and 3, out of the 3 comfort criteria, attaining a Percentage of People Dissatisfied (PPD) of less than 10%, as required by CIBSE TM52 (Nicol, 2013). In the same year, 45 spaces failed on another criterion in addition to criterion-2. In the future years, 2030 and 2050, all 215 occupied spaces failed on Criteria-1,2 and 3 suggesting the need for cooling to be provided for thermal comfort in the hotel as from, and beyond, 2030. In addition, it is proposed that measures such as shading and optimisation of heating and cooling setpoints would reduce incidents of overheating in the future periods (2030 – 2050) when the overheating risk in the occupied spaces is most severe.

4.7 MICROGRID SIMULATION AND OPTIMISATION

The HOMER Pro™ software works on the basis of the “SOS paradigm (Simulation, Optimisation, Sensitivity analysis)”, hence the results are presented in that order.

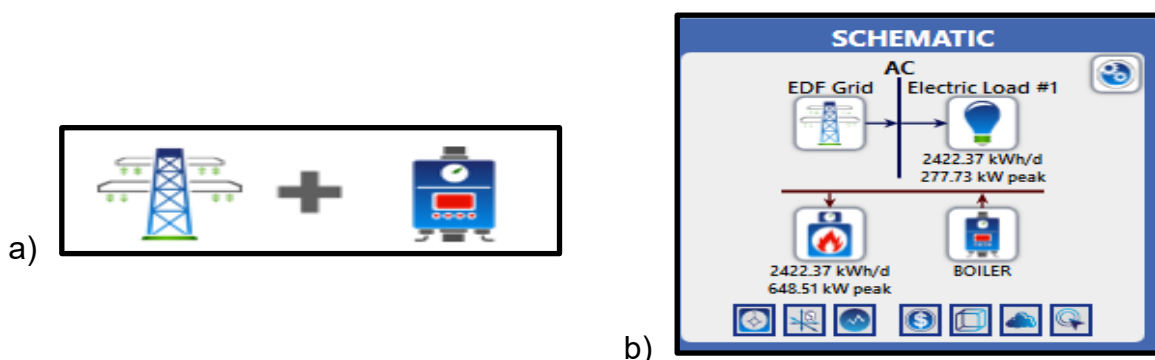


Figure 4.10: Schematics of Base Case Microgrid

The model inputs (section 0) generated 3,378,200 microgrid configurations for the lifetime of the project (28 years), with each system configuration simulated in hourly timesteps for 1 year (8760 hours). In the optimisation, 220 cases were evaluated to

select the most cost-effective way to meet the loads under the constraints imposed by 15,360 sensitivity cases. The base case system comprises the components of the energy system “as is” at the case study, described in section 0. It comprises the grid and boiler (Figure 4.10a), including the electrical and thermal loads, the energy control system, without renewable energy generation (Figure 4.10b) and has the lowest initial capital cost.

Proposed Microgrid

The proposed microgrid “Winning System” is the one that serves the loads at the lowest NPC from the most-optimal combination of resources, components and control. The NPC or Life-cycle Cost (LCC) of the microgrid is the present value of all the capital, operating and maintenance costs, less the present value of all revenues, over the lifetime.

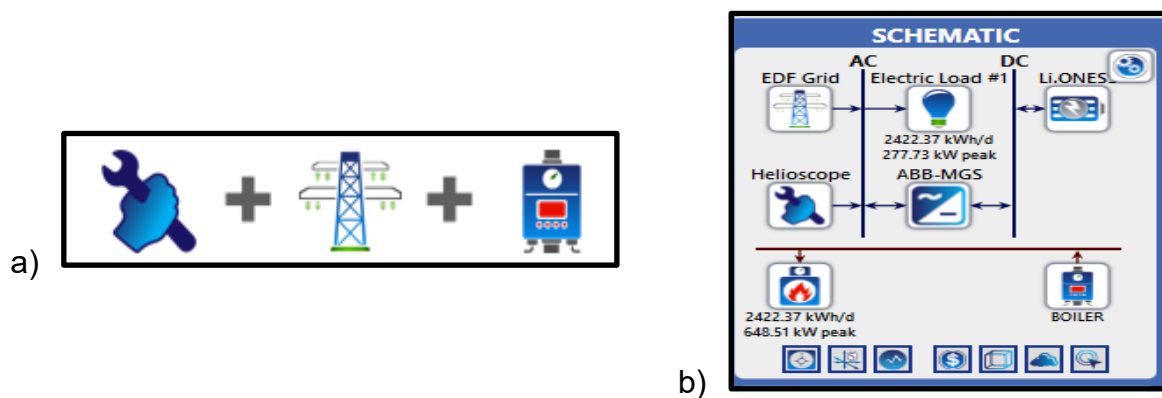


Figure 4.11: Schematics of Proposed Microgrid

The components of the proposed microgrid in Figure 4.11(a), comprising the electricity grid, boiler and solar-PV generation, converter, BESS, controller, and electrical and thermal loads are shown in Figure 4.11(b). The “Least Cost System (LCS)” is the optimal system that fulfils the load requirements for all the sensitivity variables; (a) relative rectifier capacity (%), (b) grid CI (g/kWh), (c) expected inflation rate (%), and (d) renewable fraction (%).

Table 4.8: Cost and Economic Summary of Base Case and Lowest Cost System

Parameters	Base Case	Lowest Cost System
Net Present Cost (M£)	3.18	3.07
Capital Cost (£)	35,732	102,199
O&M Cost (£/year)	90,614	85,542
LCOE (£/kWh)	0.168	0.159
Internal Rate of Return, IRR (%)	-	6.2
Return on Investment , ROI (%)	-	4.1
Simple Payback (yr)	-	13

Parameters	Base Case	Lowest Cost System
Discounted Payback (yr)	-	11.92
Present Worth (£)	-	109,698
Annual Worth (£/yr)	-	3,159

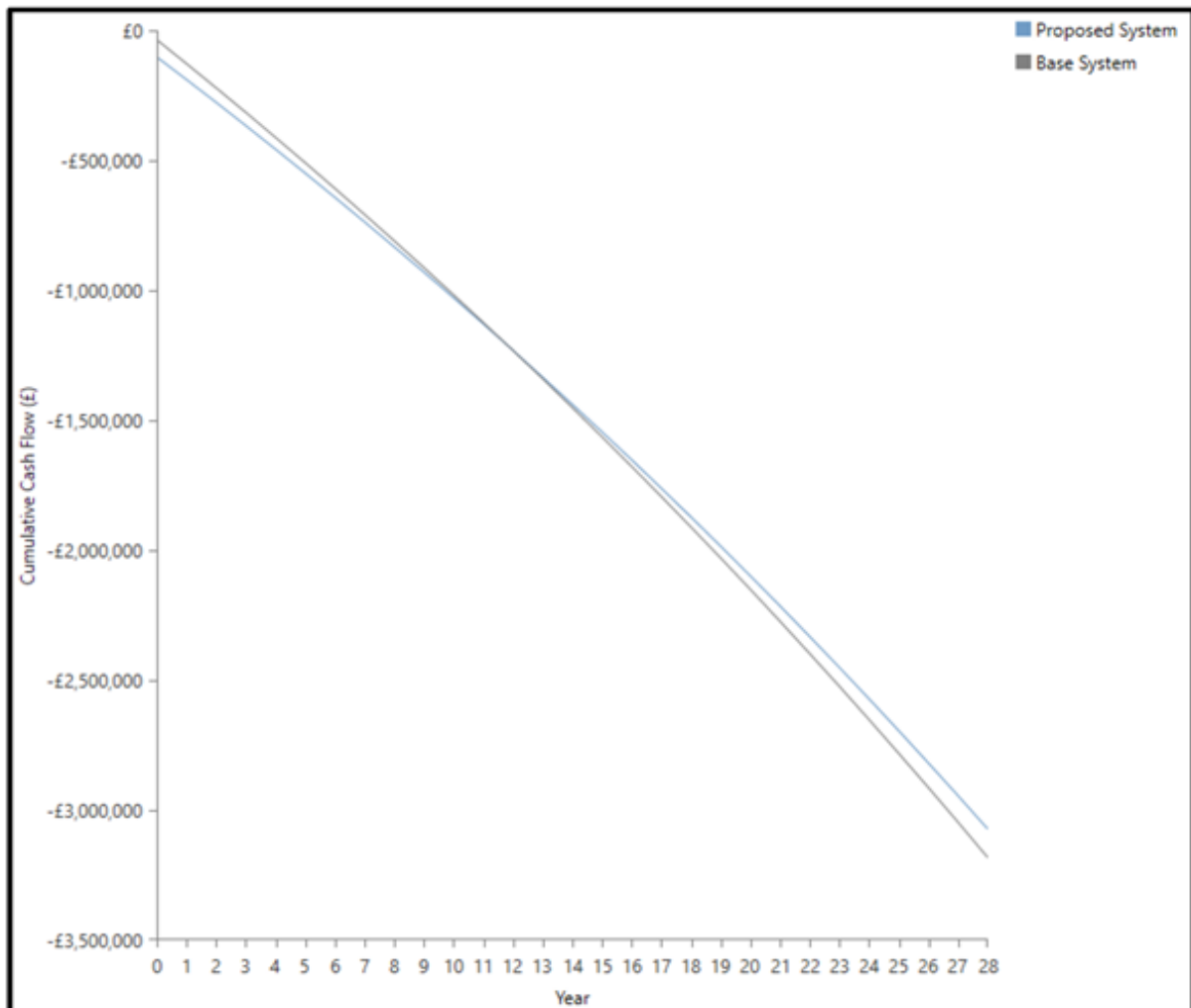


Figure 4.12: Cumulative Discounted Cash Flow of Baseline and Winning Systems

The cost and economic summary of the base case and LCS and plots of nominal and discounted cashflows of the LCS and base case systems are presented in Table 4.8 and Figure 4.12, respectively. The investment in the winning microgrid system breaks even in Year-12 and achieves a savings of £109,697 at the end of lifetime (28 years). The project appraisal parameters of the winning system will be evaluated against the UK and EU benchmarks for similar projects. Based on practice information, renewable energy projects in the UK are expected to have Internal Rate of Return (IRR) higher than the expected inflation rate (2-3%) published by the Bank of England (BoE). In Addition, a minimum Return on Investment (ROI) of 12% and Payback of not more

than 8 years are indicators of bankability of commercial-scale renewable energy projects in the UK.

Cost Summary and Cash Flow

The five (5) cost categories associated with the microgrid are capital, operating, replacement, salvage and fuel costs. The LCS is generated from an optimisation process involving two types of algorithms; (a) the original search algorithm that simulates all the feasible systems defined in the “Search Space”, and (b) the algorithm that searches the least cost system. Comparison of the aforementioned appraisal indicators with the values in Table 4.8 show that whereas the IRR (6.2%) is greater than the 2-3% expected inflation rate, the ROI (4.1%) is unattractive, considering the benchmark of 12%. Furthermore, the Payback of the winning system (13 years) exceeds the EU and UK benchmark of 8 years. Hence, the proposed microgrid is marginally viable despite the reduction in LCOE from £0.168/kWh to £0.159/kWh.

Electrical and Thermal Consumption

The energy performance of the microgrid shows that the monthly thermal energy demand in the summer months while peak demand is in the winter months.

Table 4.9: Electrical and Thermal Production and Consumption of Microgrid

		Description	kWh/yr	%
Electrical	Production	Grid Purchases	310,429	89.4
		Renewable Power Source	36,704	10.6
	Consumption	AC Primary Load	347,019	100%
		Grid Sales	114	0.0328
		Unmet Electrical Load	2,322	0.665
		Capacity Shortage	2,322	0.665
	Solar -PV	Renewable Fraction	3%	-
		Max. Renewable Penetration	100%	-
Thermal	Production	Remeha 610-ECO (2x6 sections)	884,165	100
	Consumption	Thermal Load	884,165	100

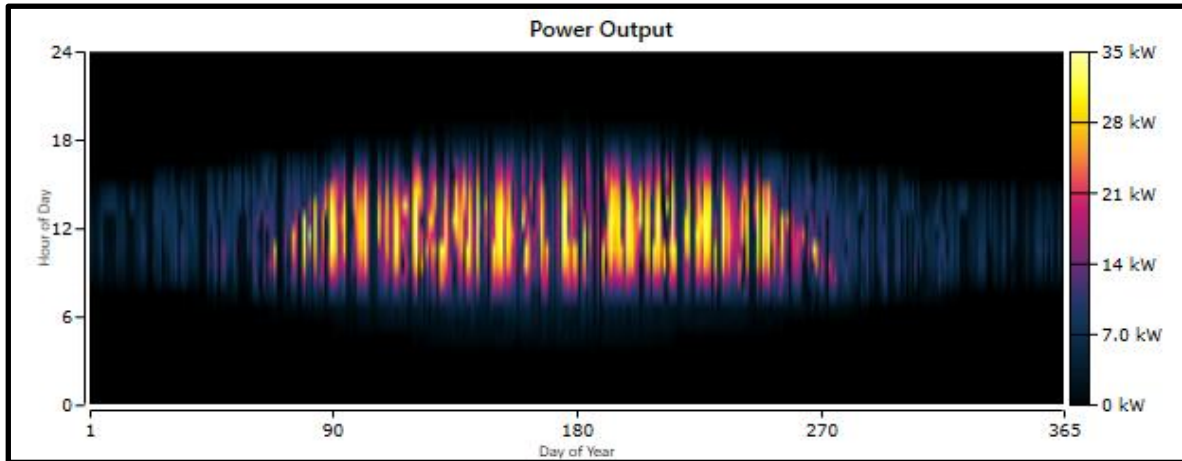


Figure 4.13: Heat Map of Electricity Production in the Microgrid

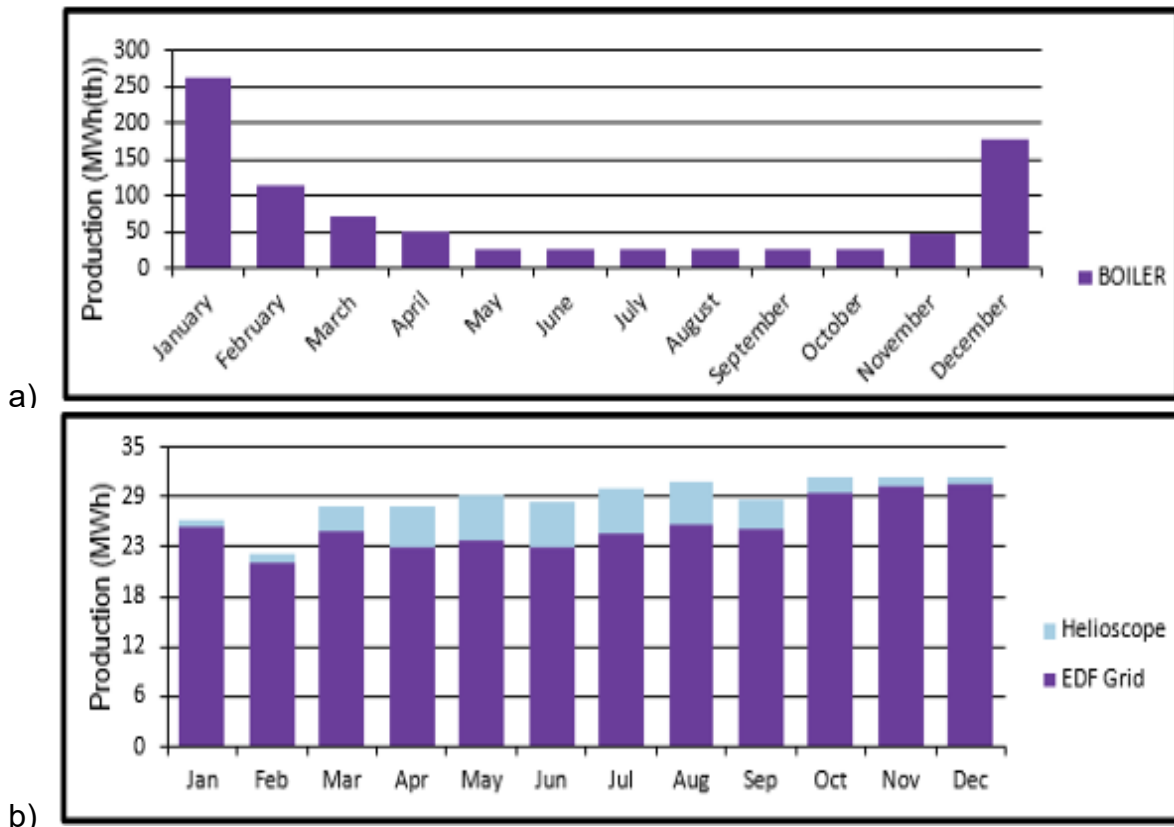


Figure 4.14: Electrical and Thermal Demand of the Winning Microgrid

As shown in Figure 4.14(a), the monthly thermal energy demand a) is less than 50 MWh between May – October and is highest in January at about 260 MWh.

The electrical and thermal consumption of the microgrid presented in Figure 4.14(b) and in Table 4.9 shows that electricity production in the microgrid, is from grid and solar-PV sources. The renewable power source is an energy-based metric that quantifies the amount of renewables produced and consumed in the simulation given

as the ratio of the total renewable production to the load. The maximum renewable penetration is a peak value obtained from the ratio of renewable output and load.

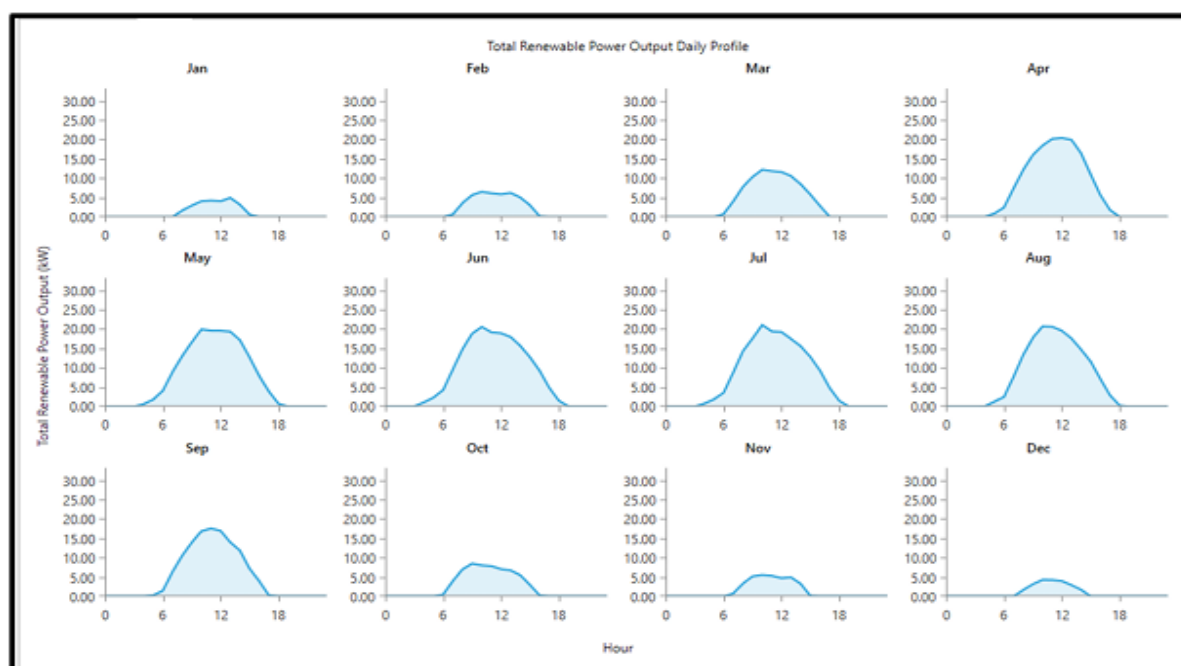


Figure 4.15: Total Renewable Power Output Daily Profile

Table 4.10: Specification of Solar-PV Generation in the Microgrid

Quantity	Value
Rated Capacity	1.0
Mean Output (kW)	4.19
Mean Output (kWh/d)	101
Minimum Output (kW)	0
Maximum Output (kW)	33.1
Hours of Operation (hrs/yr)	4,283
Capacity Factor (%)	12.6
Total Production (kWh/yr)	36,704
Levelised Cost (£/kWh)	0.116

As shown in Solar-PV generation (Helioscope™) contributed to the power mix in all the months of the year. The daily profile of renewable output in Figure 4.15 shows a peak of 20 kW around noon between April and August and falls to about 5 kW between November – February.

Grid

The Alternating Current (AC) primary load served by the winning system (Figure 4.6.6 and Table 4.6.3) has 3 daily peaks, representative of commercial load profiles. The annual energy purchased from the grid is 310,428kWh (Figure 4.6.7a) while 114kWh is sold to the grid (Figure 4.6.7b). It is expected that improvement in the cost of energy

paid to independent generators under the UK Smart Export Guarantee (UK-SEG) scheme would enhance grid exports.

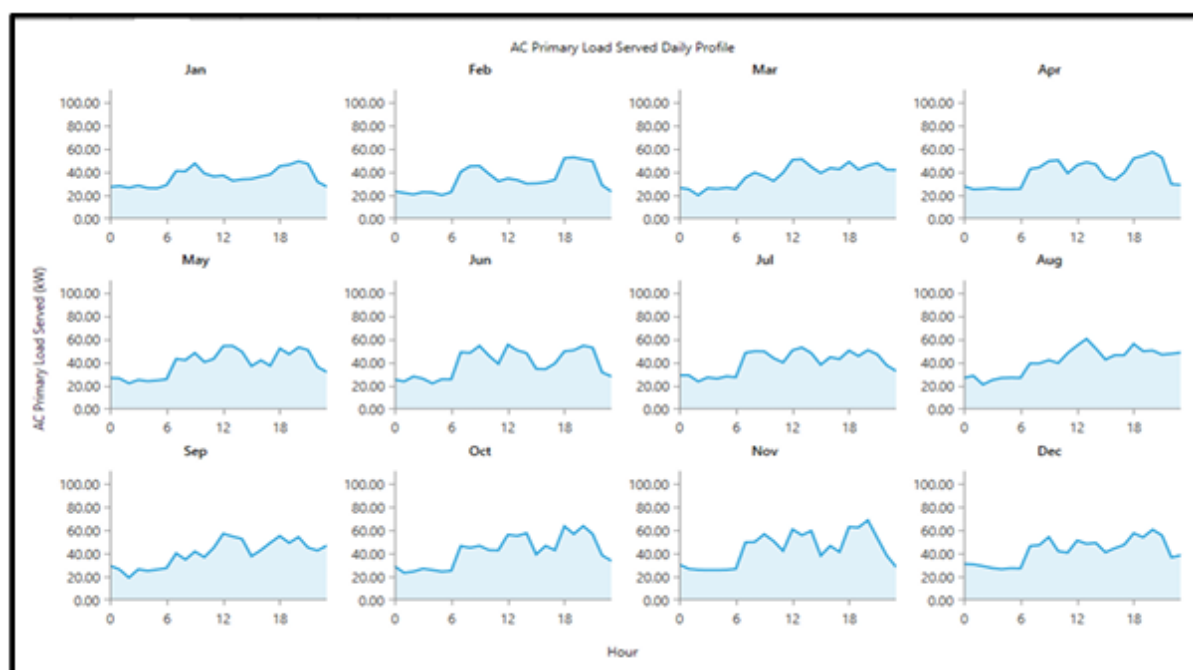


Figure 4.16: Daily Profile of AC Primary Load Served by Least Cost Microgrid

Table 4.11: Details of Grid Electricity Purchase, Sale and Charges

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge (£)	Demand Charge (£)
Jan	25,782	0	25,782	77	3,991.14	30.92
Feb	21,450	0	21,450	95	3,278.61	37.87
Mar	25,261	6	25,256	67	4,060.47	26.84
Apr	23,434	8	23,426	89	3,575.89	35.47
May	24,109	14	24,095	83	3,733.86	33.08
Jun	23,324	30	23,294	80	3,665.74	32.18
Jul	24,856	27	24,829	79	3,789.05	31.54
Aug	26,036	6	26,029	83	4,153.27	33.36
Sep	25,327	23	25,304	80	4,103.38	32.17
Oct	29,572	0	29,572	111	4,730.67	44.27
Nov	30,543	0	30,543	99	5,031.39	39.80
Dec	30,735	0	30,735	90	4,966.97	35.81
Annual	310,429	114	310,315	111	49,080.44	413.31

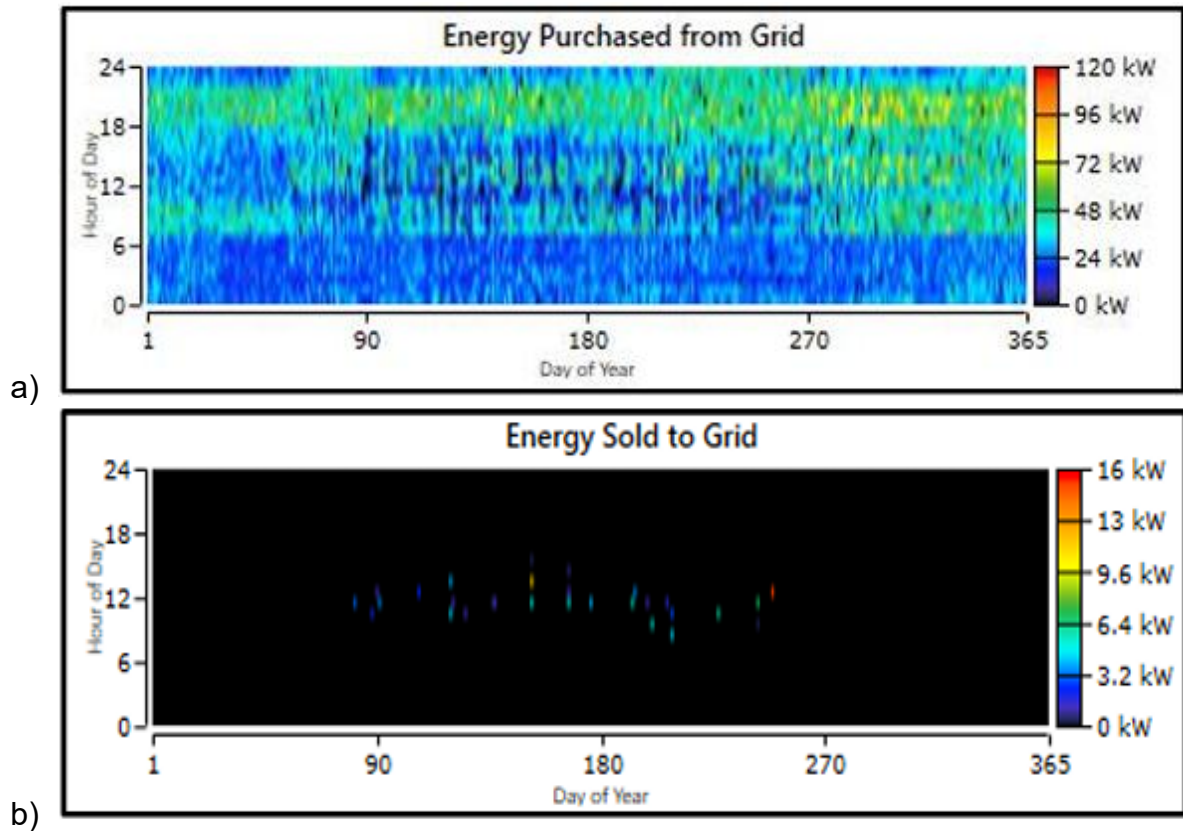


Figure 4.17: Heat Map of Grid Electricity Purchases and Sale

Boiler

Table 4.12: Microgrid Thermal Generator Output

Quantity	Value
Hours of operation (h/yr)	8,760
Total production (kWh/yr)	884,165
Mean Output (kWh/d)	101
Minimum Output (kW)	13.6
Maximum Output (kW)	414
Fuel consumption (m ³ /yr)	105,230
Specific fuel consumption (m ³ /kWh)	0.119
Fuel energy input (kWh/yr)	930,700
Mean efficiency (%)	95

The thermal consumption of the least cost microgrid is presented in Table 4.12.

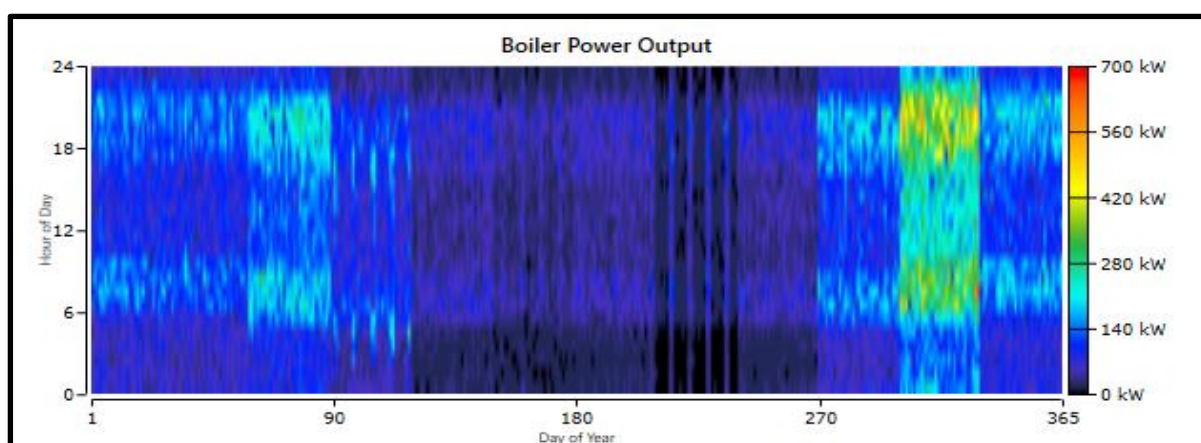


Figure 4.18: Heat Map of Microgrid Boiler Output

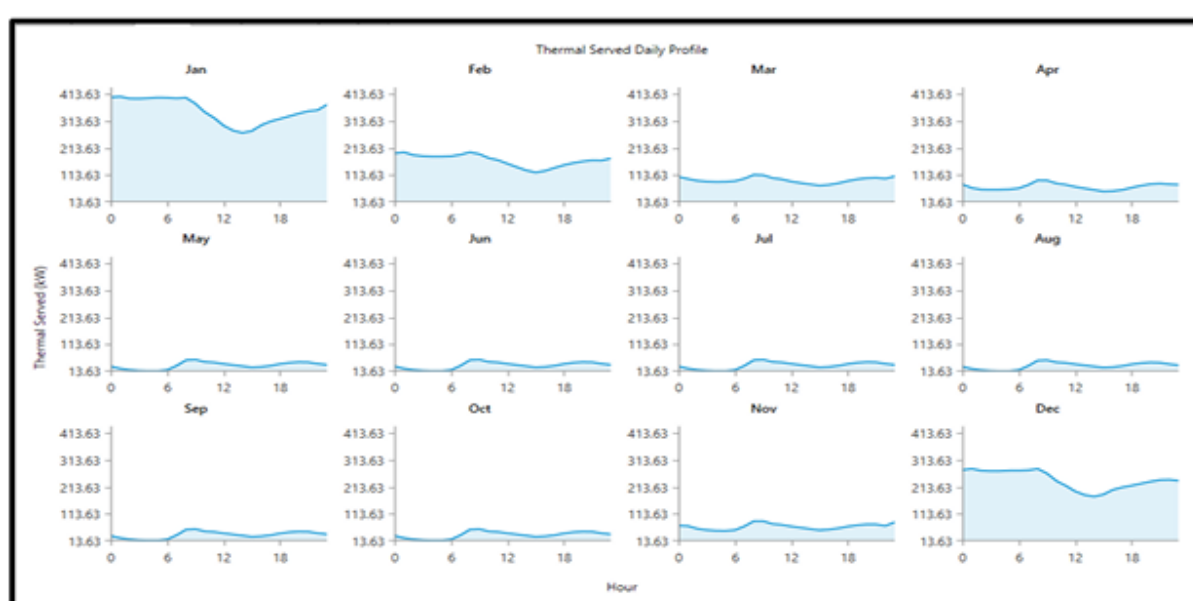


Figure 4.19: Daily Profile of Thermal Load Served by Microgrid

The heat map of boiler output (Figure 4.18) and the daily profile of thermal load in the microgrid (Figure 4.19) shows that thermal power demand lies between 280 – 560 kW between 6am – 12 noon, and 6pm – midnight in Days 270 – 365, while it remains does not exceed 140 kW all day, in the summer period between Day 90 – 270.

Emissions

The ratio of the CO₂ emissions to the GIA of the hotel is the limit of Carbon Emissions Intensity (CEI), with which hotels transforming to operational net zero could benchmark emissions performance.

Table 4.13: Breakdown of Emissions generated by Least Cost System

Quantity	Value
Carbondioxide (kg/yr)	266,553

Quantity	Value
Carbon Monoxide (kg/yr)	95.2
Unburned Hydrocarbons (kg/yr)	0.0210
Particulate Matter (kg/yr)	0.0210
Sulphur Dioxide (kg/yr)	9,260
Nitrogen Oxides (kg/yr)	484

The emissions generated by the winning system is presented in Table 4.13. The ratio of the CO₂ emissions to the GIA of the hotel is the limit of CEI, with which hotels transforming to operational net zero could benchmark emissions performance.

4.8 CALCULATION OF CARBON AND COST METRICS

The microgrid model was simulated using a multi-dimensional sensitivity analysis of the variables; (a) power price (£/kWh), (b) grid CO₂ (g/kWh), (c) expected inflation rate (%), (d) renewable fraction (%), and € natural gas fuel price (£/m³). These parameters affect the electricity and thermal usage, CO₂ emissions and the O&M cost (£) and were obtained at the lowest Total Net Present Cost (TNPC) to calculate the indicative benchmark targets and limits of the operational net zero metrics; CEI and ECI. The optimal base case system had a TNPC of £3,073,016, LCOE of £0.1585 and operating cost of £85,541.87. Hence,

Electricity Energy Use Intensity (EUI_{el}):

$$EUI_{el} = \frac{\text{Total Annual Electricity Consumption (kWh)}}{\text{GIA (m}^2\text{)}}$$

Considering grid sales of 114 kWh,

$$EUI_{el} = \frac{\text{Total Annual Electricity Consumption (kWh) - Grid Sales (kWh)}}{\text{GIA (m}^2\text{)}}$$

$$EUI_{el} = \frac{\text{Total Annual Electricity Consumption (kWh) - Grid Sales (kWh)}}{\text{GIA (m}^2\text{)}} = \frac{310,429 - 114}{2964} = 105 \text{ kWh/m}^2$$

Thermal Energy Use Intensity (EUI_{th}):

The EUI_{th} metric is computed as the ratio of thermal demand of the least TNPC system (kWh) to the GIA (m²) of the building (equation 3.60):

$$EUI_{th} = \frac{\text{Total Annual Thermal Consumption (kWh)}}{\text{GIA (m}^2\text{)}} = \frac{884,165}{2964} = 298 \text{ kWh/m}^2$$

Hence, overall EUI (kWh/m²), is computed using equation 3.61, as:

$$\text{Total site- EUI} = \frac{(EUI_{el} + EUI_{th}) \text{ kWh}}{\text{GIA (m}^2\text{)}} = \frac{310,429 + 884,165}{2964} = 406 \text{ kWh/m}^2$$

Carbon Emissions Intensity:

The benchmark of operational net zero carbon metric, is calculated as the ratio of CO₂ emissions of the lowest TNPC (£) system to the GIA (m²) of the building:

$$CEI = \frac{\text{Total CO}_2 \text{ Emissions (kg.CO}_2\text{)}}{\text{GIA (m}^2\text{)}} = \frac{266,553}{2964} = 89.93 \text{ kg.CO}_2\text{/m}^2$$

Energy Cost Intensity:

The indicative limit of cost on operation and maintenance of the energy system to achieve operational net zero is calculated as the ratio of O&M cost of the lowest TNPC system to the GIA (m²) of the building:

$$ECI = \frac{\text{Microgrid O\&M Cost (£)}}{\text{GIA (m}^2\text{)}} = \frac{85,541.47}{2964} = \text{£}35.75\text{/m}^2$$

The benchmark values of EUI, CEI and ECI calculated under the assumptions and context of this study, are sensitive to changes in weather, electricity tariffs, and grid carbon intensity, but are indicative limits that hotels with service-level, construction, operational and meteorological characteristics similar to the case study should meet to achieve operational net zero in 2050. A recent systematic review of 28 international hotel studies confirms that outdoor temperature—remains one of the strongest predictors of hotel EUI, with hotels in colder regions exhibiting substantially higher energy consumption due to elevated space-heating and hot-water loads (Arenhart et al., 2024). Colder weather exerts a consistently inflationary effect on EUI, with empirical evidence demonstrating that heating demand is the dominant climatic driver of operational energy use in the global hotel sector. This relationship is reinforced by research finding that heating energy demand scales almost linearly with HDD, with correlation coefficients frequently exceeding $R^2 > 0.9$ (D’Amico et al., 2019), indicating that reductions in outdoor temperature translate directly into increased delivered energy. As heating in the case study is supplied by fossil-fuel boilers, higher winter energy use also produces proportionally higher CEI, consistent with broader findings that heating is the principal source of building-related CO₂ emissions in cold climates (Li et al., 2021). Few studies quantify ECI directly, the literature establishes that energy consumption is the primary cost driver in hotel operations (Arenhart et al., 2024), and given the strong HDD–energy relationship, it follows that colder weather would increase operating costs through higher fuel consumption. Hence, colder weather would systematically elevate EUI, CEI, and ECI of the hotel.

There is no published evidence that electricity tariffs influences the EUI, but higher tariffs can induce demand-side reductions, load-shifting, or investment in efficiency measures. Higher electricity tariffs influence hotel EUI, CEI and ECI primarily through cost-driven behavioural and operational responses rather than through direct changes in physical energy demand. Higher tariffs may encourage reduced electricity consumption or fuel-switching, but the carbon intensity of delivered electricity is determined by grid generation mix rather than tariff structure. The strongest and most direct effect of increased electricity tariffs would be a rise in the ECI of the hotel, as ECI is a cost-based metric. Therefore, higher electricity tariffs in the hotel will not directly increase EUI or CEI but would substantially increase ECI and may indirectly reduce EUI and CEI through behavioural or investment responses to reduce the higher operating costs.

Grid carbon intensity has no direct effect on the hotel's EUI, because EUI is a physical measure of delivered energy per unit floor area and is determined by building demand, not by the carbon characteristics of the electricity supply. However, lower-carbon grids substantially reduce operational CEI, since CEI is the product of energy consumption and the carbon factor of electricity. In addition, reduction in the calculated CEI due to onsite solar-PV generation would be more significant when combined with a decarbonised grid mix. As grid carbon intensity falls, CEI would decrease proportionally even when EUI remains unchanged. The effect on ECI is indirect because lower-carbon grids do not inherently reduce electricity prices, as observed in the EU report on energy prices in Europe (European Commission, 2025) notes that retail electricity prices remain elevated due to market and policy factors even as decarbonisation progresses, implying that lower grid carbon intensity does not necessarily translate into lower ECI unless accompanied by long-term reform of cost structures. Therefore, based on published evidence, lower grid carbon intensity will not change the hotel EUI but would reduce the CEI. ECI would be indirectly impacted in the long-term exclusion of the Climate Change Levy, which currently constitutes, on average, between 2.5 – 4% of the hotel's monthly electricity bill (Appendix -2D: BREAKDOWN OF TYPICAL ELECTRICITY RATES AND COST).

Contextually, the calculated EUI, CEI and ECI benchmarks are compared to benchmarks of energy, carbon and cost metrics. The benchmarks available in literature for hotels are predominantly national and international benchmark datasets,

notably the CHSBI, produced through a partnership with Cornell University Center for Hospitality Research, Greenview®, and major international hotel brands for benchmarking energy, carbon, water and waste performance.

Table 4.14: CHSBI-2024 Metrics for 3-star Non-resort Hotels in London, UK (Ricaurte and Jagarajan, 2024)

Metrics/ Measures	Low	LQ	Mean	Median	UQ	High	SD
M4 (kgCO ₂ /m ²)	9.4	26.9	45	38.6	61.6	144.6	23.6
M6 (kWh/m ²)	50.5	142.2	240.2	205.4	332.9	787.1	127.9
M13 (% of Total Energy)	1.0	16.4	22.6	23.5	27.8	41.2	8.6
M13 ^a (RE/kWh of Total Energy)	0.01	16.4	22.6	23.5	27.8	41.2	8.6

In this study, the baseline results were benchmarked against the median CHSBI benchmark energy and carbon metrics or measures as obtained from 51 (M4 and M6), and 54 (M13), shown in Table 4.14 and published in CHSBI-2024, (Ricaurte and Jagarajan, 2024) for 3-star, non-resort hotels in London, UK. The metrics are described as follows:

- a) Carbon Metric (Measure-4; M4): Total carbon footprint of the property for a calendar year divided by the total floor area (m²).
- b) Energy Metric (Measure-6; M6): Total energy usage of the property for a calendar year divided by the floor area (m²).
- c) Energy Metric (Measure-13; M13): Percentage of property's total energy that is generated from renewable sources, excluding renewable mix of electric power grid.

Using the CHBSI benchmarks for midscale (3-star), non-resort hotels in the temperate European climate zone (EUI ≈150 kWh/m²; CEI ≈25 kgCO₂e/m²·yr), the case-study hotel's performance is significantly above expected levels. Its EUI of 406 kWh/m² is approximately 2.7 times the CHBSI median, while its CEI of 89.93 kgCO₂e/m² is 3.6 times higher. Even when accounting for UK tariff structures, the hotel's ECI of 35.75 GBP/m² remains more than double the implied CHBSI cost benchmark. This confirms that the building is a clear outlier relative to its typology and region.

^a This is a modification of the metric to benchmark absolute values of M13.

The hotel's heating demand is disproportionately high relative to its typology, suggesting that fabric heat losses and uncontrolled air infiltration are major contributors. Thermal bridging at façade interfaces, poorly sealed doors and service penetrations, limited insulation in walls and roof. These characteristics increase space-heating loads and extend boiler runtimes, directly elevating EUI and CEI. In addition, the hotel has a North-South orientation with a high glazing ratio and solar gains through the east/west façades. This results in simultaneous heating and cooling and increases both gas and electricity consumption. Another possible reason for the difference between CHSBI and calculated values is attributable to the absence of a HVAC system necessitating very high heating demand in the winter months and increased plug loads for fans in the summer. In addition, the on-site laundry serves a neighbouring students residential building, placing a disproportionate demand on heating and electricity for domestic hot water and powering of the laundry equipment, respectively, leading to the high CEI.

5.0 OVERALL DISCUSSION, LIMITATIONS, RECOMMENDATIONS AND CONCLUSION

This chapter summarises the key findings and analysis presented in chapter 4.0 in relation to the aim, research questions, and research objectives. In addition, the specific contribution of the study to the body of knowledge in research on net zero buildings, particularly hotel typologies are outlined. Furthermore, reflection on the limitations of the study is done, on the basis of which opportunities for future research are proposed. In addition, specific recommendations to enable implementation of the findings of the study in planning decarbonisation projects for energy profiles of any building typology and proofing operational NZ claims in UK hotels are presented.

5.1 OVERALL DISCUSSION

The study aimed to investigate the feasibility of operational Net Zero in an existing UK hotel building typology, develop energy, carbon and cost metrics, and compute indicative benchmark targets and limits of energy efficiency, carbon emissions, and LCOE for proofing net zero claims in UK hotel typologies. The baseline model developed from empirical construction and operational characteristics of the CS was simulated using the 2022 weather file. The verification of the results of dynamic thermal simulation of the CS against the baseline time series electricity consumption, was done according to ASHRAE-14 protocol for hourly calibration. RMSE and C_vRMSE were found to be 4.75% and 12.6%, respectively, compared to the corresponding benchmarks of $\pm 10\%$ and 30%. On the basis of a GIA of 2964 m², a baseline EUI (EUI-1.0) of 122 kWh/m², was calculated, which is within the range (120 – 250 kWh/m²) for UK hotels.

The climate resilience and energy efficiency models of the CS were developed by applying successive EEMs and future weather files. The cumulative effect of stepped application of the EEMs and weather files in 7 models, (a) Model-1.0 (“as is” condition of CS, the 2006 UK Building Regulations-Part L, and 2022 weather file), (b) Model-2.1 (insulation uplift), (c) Model-2.2 (LED Retrofit to reduce lighting power consumption and gain) (d) Model-2.3 (daylighting), (e) Model-2.4 (adaptive ventilation), and (f) Model-2.5 (2050 weather file), showed that energy consumption and carbon emissions reduced from 769-566MWh (26%) and 73,589–583kgCO₂ (62%), respectively.

The requirement for Net Zero is that following application of EEMs, RE should be integrated, first on-site, and if insufficient, verified offsets should be procured. In the UKNZCBS, increase in onsite-RES to complete decarbonisation of the grid is required for NZBs. The simulation of rooftop solar-PV generation at the CS, showed that in 4576 sunshine hours, the system could generate 43.8MWh (14.8 kWh/m²), at a performance ratio of 75.5%, specific yield of 906.1 kWh/kW_p, and grid capacity of 40.1kW. Compared to the electricity requirement at the CS (884MWh), the solar-PV yield is about 4.5% of requirement. This value is below the 40% renewable share envisaged in the PPM framework. In addition, the RE intensity of 14.8 kWh/m² is below the target of 40 kWh/m² in the UKNZCBS. The implication of these findings is that the renewable energy target requirement for Net Zero can be met only when certified offsets are procured. The microgrid simulation and optimisation proposed a lease cost system with the following component sizing, economics, energy balance, environmental impact and sensitivities.

5.2 LIMITATIONS OF THE STUDY

The study provides methodological insight to the application of energy efficiency and renewable energy retrofit to develop operational net zero metrics and computation of the benchmark values for a representative hotel load profile in the UK. The methodology is transferable, but the generalisability of the benchmark values, and their validity to similar typologies in different situational, meteorological and operational contexts is limited by the use of purposive sampling and deterministic uncertainty methods. It is pertinent to identify and discuss these limitations to enable a more detailed understanding of the transferable methodology, and applicability of the non-transferable, case-specific, numerical benchmark values obtained from the modelling assumptions of this study. The discussion of the limitations would provide direction for future research on the application of dynamic thermal modelling, energy efficiency measures, renewable energy sizing, and microgrid optimisation for net zero. The following paragraphs outline and elaborate on these limitations, and their effects on the study:

Sampling and Data Limitations

The consideration that the results obtained from the study would be a significant contribution to the 2040 target of the university because the case study is part of the

institution's portfolio of buildings informed the selection of the case study by a convenience non-probabilistic method, hence the existence of sampling bias. The construction, operational, energy consumption, and meteorological data for the case study were readily-available for modelling and simulation of the energy, carbon and cost performance of the microgrid. While the methodology for development of energy, carbon and cost metrics, and computation of corresponding benchmarks is transferrable, the use of data for a single hotel at a specific location, climatic, energy and emissions context limit the generalisability of the calculated benchmark values for making design and policy decisions on net zero hotels.

Methodological Limitations

The study adopted the fundamental decarbonisation approach that is common to all net zero frameworks; “energy efficiency first” before renewables integration and the “fabric first” retrofit/ renovation strategy was also used. Regardless, the study would have benefited from a detailed energy audit but was constrained by time and access restrictions to the facility. In addition, the baseline electricity consumption of the case study was referenced to a year's consumption. The average historical consumption over several years, such as was done in the case of the occupancy rate, would have been more representative. This could not be achieved because the BMS did not have the functionality to retrieve historical data on power consumption. To ensure generalisability of the results, the average of occupancy of the hotel for the 3 years preceding the baseline (excluding 2020, the COVID-19 year) was used to create a representative occupancy profile for dynamic thermal modelling. In addition, and consequent on the inaccessibility to neither the dedicated gas consumption gas invoices for the case study, the gas consumption was not calibrated

Methodical Limitations

The use of specific modelling tools, for dynamic thermal simulation, solar-PV retrofit and microgrid modelling created a methodical limitation that is worthy of future investigation. Regardless that these tools are commercially-tested and represent the best-practice, it would be an interesting axis of inquiry to investigate net zero using other tools such as DesignBuilder™ (dynamic thermal modelling), RETSCREEN™ and PVSyst™ (solar-PV modelling) and HOMER Grid™ for microgrid modelling. In addition, the use of TMY (typically based on 10 or more years of historical data and

does not capture extreme events or inter-annual variabilities) and not AWY, also limited the accuracy of energy consumption and solar-PV generation obtained from IESVE™ dynamic simulation and HelioScope™, respectively.

The calculated benchmark values of EUI, CEI, and ECI are inherently constrained by methodological, data-quality, and contextual limitations, each of which reduces the confidence with which they can be applied or interpreted. First, data heterogeneity—differences in building typology, climate, occupancy, metering resolution, and operational practices—introduces structural variability that cannot be fully normalised. This limits the comparability of benchmarks across hotels and reduces confidence in interpreting deviations as true performance gaps rather than artefacts of underlying differences. Second, residual errors associated with calibration and measurement uncertainty affects the reliability of the EUI and CEI values. Hence the resulting benchmarks are indicative values with uncertainty bands, even as the models meet ASHRAE Guideline-14 Calibration threshold. Third, weather-related limitations related to the use of TMY files affect the stability of benchmarks across climates. This constrains the interpretation of EUI and CEI differences between colder and warmer regions, as part of the variation reflects climatic exposure rather than intrinsic performance.

In addition, grid-carbon variability introduces temporal instability into CEI benchmarks: as grid carbon intensity changes hourly and seasonally, CEI benchmarks based on annual averages may misrepresent the emissions profile of buildings with highly variable load shapes. This reduces confidence in CEI comparisons unless temporal alignment is explicitly controlled. Fifth, economic and tariff-related limitations affect ECI benchmarks because ECI is sensitive to market conditions, policy charges, and tariff structures, benchmarks derived in one pricing regime may not be transferable to another. This limits interpretability across regions and reduces confidence in using ECI as a stable performance indicator. Finally, sample-size and representativeness limitations—common in hotel benchmarking due to proprietary data—mean that published benchmarks may reflect the characteristics of a narrow subset of buildings rather than the sector as a whole. This constrains generalisability and reduces confidence in applying benchmarks to atypical hotels. Collectively, these limitations mean that EUI, CEI, and ECI benchmarks should be interpreted as indicative ranges with uncertainty, not deterministic performance thresholds. Confidence is highest

when benchmarks are used for relative comparisons within homogeneous groups, and lowest when applied across climates, tariff regimes, or operational contexts without adjustment.

5.3 CONTRIBUTIONS

The study was necessitated by several observed shortcomings of energy certificates that rendered them unsuitable for monitoring net zero in buildings. Energy certificates do not accurately reflect the energy consumption of the building because they rely on visual inspections rather than energy performance measurements, hence the performance gap problem. In addition, they are susceptible to standardisation and measurement errors from the use of pre-defined models in SAP (or RdSAP) and SBEM for dwellings and non-residential typologies, respectively. Hence, the contributions of this work are as follows:

- ❑ **Engineering Contribution:** the empirical approach of this work through the use of actual construction, operational, occupancy and electricity consumption data of the building markedly differs from the methodologies of SAP and SBEM, and the qualitative designs of most studies on energy efficiency, decarbonisation and net zero, as presented in the summary of literature review. The methodology of this work integrates existing net zero strategies, theories, and frameworks such as CIBSE Carbon Hierarchy, Fabric First Principle, deep and stepped retrofit, and renewable energy integration, with a possibility for integrating verified offsets. In this sense, the methodology is applicable on any building typology, in any jurisdiction provided the collection of requisite architectural, construction, operational and meteorological data aligns with the UKNZCBS requirements for reporting and assessment, (Anderson *et al.*, 2024), and the operational reporting period (Appendix -5A). Furthermore, the indicative computed values of EUI, CEI and ECI could serve as an informed basis for comparison of energy intensity in UK hotels of similar construction and, star-rating as the case study.
- ❑ **Economic Contribution:** the benchmark value EUI metric computed in this work is indicative of the energy efficiency of hotels of similar star-rating, constructional and operational features, and situation. Hence, implementation of EEMs to reduce energy intensity and keep EUI below the benchmark would translate to reduction of energy loads and bills and increase Gross Operating Profit (GOP). Hotels

increasingly face carbon taxes, emissions reporting requirements and Scope 1 & 2 compliance obligations. As these are direct operating costs related and proportionate to energy use, the computation of CEI outlined in this study would inform better control on the profitability of hotels. In addition, the growing interest of individuals and corporate organisations in sustainable hospitality implies that hotels with low CEI gain higher occupancy and strong brand reputation, both of which contribute to profitability of hotels. An additional economic contribution of the computation of CEI is that it enables access to tax incentives and lower interest rates on sustainability-linked loans which main core assessment metric is CEI. Furthermore, tracking the CEI metric protects long-term asset value by mitigating future regulatory risk associated with higher emissions compliance costs and retrofit penalties. The ECI metric was computed by integrating tariffs, energy mix, demand charges and an operational scenario to give the indicative benchmark ECI for net zero. Tracking the metric to keep ECI below the indicative benchmark ensures lower utility bills and higher net operating income for hotels. In addition, the ECI benchmark is crucial to CAPEX planning for net zero retrofit projects because it varies directly with ROI and Payback. Furthermore, the ECI metric enhances competitiveness of hotels because the lower ECI hotels can maintain lower room rates and improve the Revenue Per Available Room (RevPAR). A higher RevPAR implies higher room revenues, net operating income and asset value of the hotel.

- ❑ **Policy Contribution:** in the UK, EUI, CEI and ECI metrics are relevant to regulation of energy and carbon intensity of hotels to determine compliance, access to incentives, exposure to penalties and alignment with national climate goals. The value of EUI enables benchmarking and comparison of compliance of hotels of similar construction, star-rating and situation, with UK Building Regulations (Part L2). The data requirement for assessment and reporting of the operational energy and emissions, electricity demand, heating and cooling delivered to buildings, retrofit and reportable works is consistent with the UKNZCBS. Hence, the EUI, CEI, ECI and renewable energy share calculated from this study contribute to the body of evidence on target values/ limits for proofing net zero in hotels under the UK Climate Change Policy. On its part, the CEI is related to carbon pricing and mandatory/voluntary reporting framework for hotel

Scope 1 & 2 emissions. Monitoring the CEI metric to keep the value below the benchmark ensures compliance with the emissions reporting obligations and reduces reputational risks. In addition, keeping the CEI below the benchmark reduces the Climate Change Levy (CCL) while an increase in renewable energy share reduces the electricity carbon price due to lowered grid consumption.

5.4 FUTURE RESEARCH CONSIDERING THE LIMITATIONS AND RESULTS OF THIS STUDY

Under the assumptions of this study, a typology-transferable methodology was developed for computing benchmark values of operational net zero metrics. In the context of the discussed limitations, the following recommendations are proposed for implementation in future studies to enhance the validity and transferability of the results for decision- and policy-making:

- ❑ **Sample Selection:** The use of systematic, data-driven sampling frameworks such as probabilistic sampling should be adopted for the selection of representative case study hotels within particular typologies, to eliminate sampling bias and achieve archetype-based modelling. Future studies could categorise the hotel stock by age, climate zone, service and star level. In this sense, a stratified sampling strategy could be applied to select representative buildings with the desired characteristics for the study.
- ❑ **Multi-year Weather Analysis:** The use of AMY climate data would give more accurate values of future energy consumption as the impact of extreme climate conditions would be included in the simulation. Furthermore, future studies for hotel typologies should be performed for different climatic zones, categories, and use functions to enable like-for-like comparison of metrics. In addition, multi-parameter calibration of energy models should be used in future studies, as against single-parameter calibration that was used in this study. The calibration of BEMs with other parameters such as gas bills, gas consumption, water usage, and wastewater discharge would enhance the validity of the BEM.
- ❑ **Tariff and Carbon Trajectory Sensitivity:** tariff sensitivity measures the response of the operational cost of a building to fluctuations in energy prices, while carbon trajectory sensitivity measures the extent to which a building is low-carbon as the carbon intensity of the national grid changes. It is recommended that future studies should interrogate the impact of diverse tariff structures and scenarios of grid

carbon intensity on the viability of net zero. This study considered the sensitivity of carbon intensity in the HOMER-Pro™ microgrid model using the UK projected grid emission factors to 2100 (Appendix-1R), the factors are susceptible to change in response to changes in the energy mix. This necessitates periodic studies to update the benchmark values of net zero metrics.

- ❑ **Multi-building Validation:** closing the “Performance Gap”- the difference between predicted and actual energy use due to unregulated loads, limited knowledge about occupancy, operations, and design details of the building envelope occupancy. As net zero is ramped-up towards 2050, innovative research approaches such as multi-building validation are required to further reduce the gap, compared to single-building validation method used in this work. Hence future studies could consider a multi-building validation process that entails collection of historical energy demand and utility bills data over an operational period, typically 12 months, baseline modelling of representative geometry and assignment of thermal properties, parameter tuning to calibrate the building to specified thresholds and comparison against benchmark EUI to verify fit.
- ❑ **Formal Uncertainty Propagation:** TMY weather files were used in modelling and simulation, with the potential to reduce the accuracy of predicted energy use, peak demand and net zero compliance. It is recommended that future research should develop multi-year ensemble-based weather forecasts that capture extreme conditions, and inter-annual variability of parameters such as temperature, irradiance and humidity.
- ❑ **Expanded DER Integration:** Consequent on the limitations imposed by planning requirements of the Greater London Authority and the context of urban location of the case study, the renewable energy option was limited to rooftop solar-PV system, despite the possibility of other sources such as wind, geothermal, bioenergy, heat pumps, and multi-fuel Solid Oxide Fuel Cells. Hence, conducting future studies in contexts that allow the expanded integration of Distributed Energy Resources (DER) that transform the hotel into an Active Building that manages power supply and demand in real-time could enhance the renewable energy intensity beyond the value of 14.8 kWh/m² to, or above, 40 kWh/m² envisaged in the UKNZCBS. The studies could include consideration of a BESS for load shifting, peak shaving and back-up power, implementing smart building and Demand Response management systems for HVAC optimisation, occupancy-sensing

lighting and HVAC controls, and flexible water heating. Furthermore, expansion of solar footprint through BIPV solutions such as replacement of windows or façade panels with solar-generating glass could be investigated in future studies to ascertain potential for increasing the renewable share.

5.5 CONCLUSION

This work aimed to investigate the feasibility of operational net zero in an existing UK hotel building typology, develop energy, carbon and cost metrics, and compute benchmark targets and limits of energy efficiency, carbon emissions, and LCOE for proofing net zero claims in UK hotel typologies. This context underscore the recommendation by the UK Climate Change Committee that the EPC system should be reformed arguing that the current system does not reflect real-world energy performance, undervalues low-carbon heating, and is misaligned with Net Zero objectives. The reforms entail the update of EPCs with current carbon factors, integration into a national retrofit strategy, and to support the rapid deployment of heat pumps and building-fabric upgrades. In addition, the methodological limitations of EPC ratings; derivation from SAP and the use of estimated models of theoretical energy demand did not reflect actual operational energy use, carbon emissions, and by implication, cost of energy. The problem with EPCs as an indicator of energy efficiency and net zero progress is also highlighted by the UKNZCBS which stated that EPCs are misaligned with the direction of the UK Building Policy on energy efficiency, decarbonisation and net zero. While there are several published literature on NZBs and metrics, evidential and empirical gaps exist due to the dominance of qualitative research designs and sparsity of case studies that are based on actual construction, operational and meteorological data of buildings.

In addition, most studies recommend solar-PV applications to increase the renewable energy share in dwellings and commercial buildings without clarity on the net zero framework for verifying the adequacy of the generated solar-PV energy for net zero. In using HelioScope™ tool for modelling solar-PV generation, the methodological and practical knowledge gaps inherent in the reported sources was addressed because the Perez transposition and MRM decomposition models, which are suitable for commercial loads and London sky conditions, respectively were applied. The literature also showed the prevalence of Building Energy Simulation Tools running on the EnergyPlus™ simulation engine for energy optimisation and CO₂ emissions studies,

in residential and commercial (mostly office and educational) building typologies, but there were no reported studies for hotels.

The foregoing context highlights methodological and empirical gaps in the measurement of energy efficiency, decarbonisation and energy cost for proofing net zero. Using a case study commercial building (hotel typology), this work developed a transferable methodology for quantifying energy (EUI), carbon (CEI) and cost (ECI) metrics for proofing net zero. Actual construction, occupancy, operational, macroeconomic and meteorological data, and real energy tariffs were used to develop simulate and optimise dynamic models to compute indicative benchmarks of the metrics, under the modelling assumptions of the study. Thus, the thesis answered the three (3) research questions as follows:

- ❑ Operational net zero is not feasible in a typical mid-range UK hotel under the UKGBC-PPM and UKNZCBS frameworks. None of the investigated energy efficiency and decarbonisation pathways met the operational net zero requirement of 60% EUI reduction under the PPM framework, nor reduction of EUI to 120 kWh/m² required under the UKNZCBS framework. In addition, the renewable energy generated from solar-PV annually (43.8 MWh), representing a renewable energy intensity of 14.8 kWh/m², is about 4.5% of the annual electricity requirement of 884MWh. These values are below the targets of 40% renewable share and 40 kWh/m² renewable energy intensity, targets stipulated in the PPM and UKNZCBS operational net zero frameworks, respectively.
- ❑ Evaluation of energy and carbon performance between the baseline year and 2050 under SSP2-4.5 scenario showed that climate change resulted in 15% and 230% reduction in EUI and emissions, respectively. The highest reduction in EUI (40%) over the corresponding period occurred from reduction of envelope U-values to conform with the “2025 UK Future Buildings Standard” (UKFBS), lighting retrofit from fluorescent to LED, and application of Adaptive Ventilation (AV) strategy, translated to 236% emissions reduction.
- ❑ The benchmark targets/ limits of operational net zero energy, carbon and cost intensities from simulation and optimisation of the microgrid model are del was simulated and optimised to get a least cost system from which the computed EUI of 256 kWh/m² ($EUI_{el} = 105 \text{ kWh/m}^2$, $EUI_{th} = 406 \text{ kWh/ m}^2$), CEI (87 CO₂/m²), and ECI (29.48 £/m²)

This thesis implemented ten (10) objectives within a quantitative case study design framed around four main methodical pillars; data collection, IESVE™ dynamic thermal modelling and simulation, HelioScope™ solar-PV modelling, and HOMER-Pro™ microgrid modelling while ensuring energy balance and consistency in the transfer of data across the three (3) modelling platforms. Using a calibrated baseline dynamic thermal model, 30 additional climate-resiliency and energy efficiency models were adapted and simulated to ascertain the energy intensity reduction pathway feasible for operational net zero under the UKNZCBS or UKGBC PPM framework. Furthermore, the electrical and thermal loads from IESVE™ dynamic thermal simulation and solar-PV output from the HelioScope™ model were coupled to HOMER-Pro™ and the resulting microgrid model simulated and optimised for the least cost system.

The methodology for operational net zero demonstrated in this study and tested with the PPM and UKNZCBS frameworks, and the corresponding benchmark values computed informs three (3) novel contributions. In an engineering sense, the integration of existing net zero strategies, theories, and frameworks with renewable energy integration, and the potential for integration of verified offsets makes the methodology applicable on any building typology, in any jurisdiction provided the requisite architectural, construction, operational and meteorological data is collected. Furthermore, the values of EUI, CEI and ECI, though indicative as they are computed from a single scenario, could serve as an informed basis for comparison of energy intensity in UK hotels of similar construction and, star-rating as the case study. In terms of economic contribution of the work, the computed benchmark value of EUI metric is indicative of the energy efficiency of hotels of similar star-rating, constructional and operational features, and situation. Hence, implementation of EEMs to reduce energy intensity and keeping EUI below the benchmark would translate to reduction of energy loads and bills and increase Gross Operating Profit (GOP and reduction in direct operating costs related and proportionate to energy use. Furthermore, tracking the CEI metric protects long-term asset value by mitigating future regulatory risk associated with higher emissions compliance costs and retrofit penalties. In addition, the ECI benchmark is crucial to CAPEX planning for net zero retrofit projects because it varies directly with ROI and Payback. Furthermore, the ECI metric enhances competitiveness of hotels because the lower ECI hotels can maintain lower room rates

and improve the Revenue Per Available Room (RevPAR). A higher RevPAR implies higher room revenues, net operating income and asset value of the hotel.

In summary, the methodology of this thesis demonstrated a transferable workflow for proofing operational net zero in and was tested in a commercial building. Regardless that Net Zero was not achieved in the case study under the UKNZCBS or PPM frameworks, the work contributes to UK policy on regulation of energy and carbon intensity of hotels. In addition, the results enable determination of compliance, access to incentives, exposure to penalties and alignment with national climate goals. The value of EUI enables benchmarking and comparison of compliance of hotels of similar construction, star-rating and situation, with UK Building Regulations (Part L2). The calculated EUI, CEI, ECI and renewable energy share obtained from this study contribute to the body of evidence on target values/ limits for proofing net zero in hotels under the UK Climate Change Policy. Furthermore, monitoring the CEI metric to keep the value below the benchmark ensures compliance with the emissions reporting obligations and reduces reputational risks in addition to reducing the Climate Change Levy (CCL). Hence, performance-aligned, net-zero compatible metrics were developed, with assessment frameworks similar to those of the UKGBC-PPM, and the UKNZCBS.

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APPENDICES

Appendix-1A: TIME SERIES ELECTRICITY CONSUMPTION DATA

		January																														
Date:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
Day	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	
00:30	18	26	20	22	18	20	20	22	18	28	26	26	28	36	36	36	34	36	36	22	32	30	22	22	24	24	32	28	28	22	22	
01:30	18	22	18	28	18	32	26	24	20	22	22	22	26	34	28	36	34	34	34	36	24	30	32	26	22	28	22	26	22	22	22	
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03:30	24	18	24	18	24	36	20	22	26	20	22	22	32	34	34	34	36	34	36	34	24	24	22	28	30	32	30	22	28	22	26	
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06:30	26	18	26	20	18	30	18	20	18	34	30	38	42	44	36	36	50	56	58	50	42	20	26	34	24	26	30	30	22	26	50	
07:30	24	24	24	24	20	28	24	40	28	46	36	42	42	54	56	48	48	52	50	52	56	30	40	58	48	46	42	46	42	34	44	
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11:30	18	24	24	32	28	36	32	28	26	40	36	36	46	48	34	40	46	44	56	46	30	36	32	28	48	50	42	28	26	36	46	
12:30	18	24	20	38	26	28	30	22	26	40	36	34	40	46	42	36	44	46	54	44	28	32	28	30	38	42	48	38	28	32	32	
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23:30	20	28	18	26	18	18	18	28	30	32	34	28	36	34	36	36	34	36	36	22	30	26	24	24	28	24	30	32	22	30	30	

Month	February																											
Date/Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Day	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon
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09:30	44	50	48	44	50	60	44	44	44	44	42	38	52	38	44	42	42	40	46	48	44	40	40	48	36	44	46	46
10:30	36	34	38	34	36	44	54	32	32	32	28	40	34	32	32	32	34	50	36	44	34	30	38	34	32	28	36	34
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13:30	30	32	34	30	30	30	30	30	30	30	26	30	30	28	28	28	32	30	30	28	28	26	28	30	30	30	30	32
15:30	40	34	30	30	36	28	30	30	28	32	30	28	30	28	30	30	30	30	30	32	30	32	30	32	32	34	28	30
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Month	March																															
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Month	May																																
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Month	June																													
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Month		September																														
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Month		October																														
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Month	Jan																														
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Time/Day	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon
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Month	Feb																											
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Month	Mar																														
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Month	May																														
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Month	Jun																														
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Month	Sep																																
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19:00	52	62	54	44	62	64	56	56	58	54	56	66	60	60	72	68	64	66	60	64	70	52	56	54	54	50	70	72	64	68			
20:00	58	58	54	56	60	62	60	60	54	48	60	76	62	74	68	68	58	66	62	72	74	62	58	58	68	70	72	84	66	74			
21:00	52	60	46	46	62	60	62	58	56	48	58	60	62	60	58	58	56	50	58	58	58	58	54	52	52	48	58	68	68	60			
22:00	44	26	26	34	36	44	38	32	36	48	34	38	32	34	30	32	38	48	42	34	30	32	34	32	34	32	38	30	42	36			
23:00	26	30	24	24	34	30	28	32	34	26	28	34	30	28	34	26	32	26	32	30	30	24	26	26	28	36	26	30	32	26			

Month	Oct																																
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31		
Time/Day	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon		
00:00	26	34	28	24	26	32	26	30	24	26	26	26	24	30	22	24	26	30	28	24	24	32	22	22	24	30	26	28	24	32	24		
01:00	30	24	22	22	24	32	26	30	24	28	22	24	22	30	26	22	22	26	24	22	24	18	28	26	24	32	24	24	24	24	30		
02:00	24	24	24	36	32	22	24	24	24	22	30	34	28	20	20	26	28	22	22	20	30	22	20	30	34	22	22	26	30	32	24		
03:00	24	32	30	36	24	32	22	30	22	30	28	34	24	28	22	20	22	28	22	36	20	32	20	30	36	28	22	26	24	24	22		
04:00	28	24	28	36	24	24	28	28	22	22	24	34	22	22	28	20	22	22	30	34	20	22	18	22	24	22	24	24	24	24	28		
05:00	24	22	22	24	30	22	24	24	30	24	22	22	22	20	26	30	30	22	22	28	26	22	18	22	20	22	22	28	28	30	22		
06:00	22	30	22	28	26	28	26	24	28	28	26	32	28	22	24	30	30	24	28	28	24	18	28	26	30	24	28	22	24	24	28		
07:00	52	62	54	52	66	62	64	54	44	58	54	60	56	68	34	52	48	58	52	28	48	56	28	36	48	54	64	46	48	60			
08:00	50	52	52	62	52	58	64	46	48	46	54	68	44	46	66	52	44	56	52	38	44	42	32	40	44	48	58	62	64	66	62		
09:00	60	60	64	54	52	50	48	60	54	56	48	60	50	48	50	58	50	54	42	52	64	56	36	46	52	50	54	66	54	60	64		
10:00	54	60	48	48	38	42	42	50	60	44	46	48	48	46	42	46	44	54	38	48	50	50	32	40	40	50	40	58	52	54	54		
11:00	36	42	40	44	38	38	56	42	46	46	42	38	42	46	36	34	34	42	44	48	42	40	34	42	40	42	50	44	38	38	34		
12:00	32	34	66	62	66	64	62	40	44	68	54	64	60	62	34	34	62	60	64	64	66	32	40	46	60	52	56	60	40	36	66		
13:00	38	38	60	66	48	60	54	34	42	56	62	60	60	60	42	34	58	66	56	58	58	50	46	42	64	60	62	60	48	42	68		
14:00	38	34	52	50	52	60	62	48	34	54	70	56	52	70	40	32	62	58	62	68	58	44	48	40	66	60	62	66	40	46	68		
15:00	40	34	38	42	42	34	40	34	32	44	46	42	36	38	32	36	36	42	38	34	34	38	34	34	44	36	56	42	38	40	40		
16:00	42	44	46	34	44	46	44	38	36	46	48	42	46	40	34	42	46	40	38	32	48	42	40	50	48	38	72	40	42	34	38		
17:00	44	36	42	32	46	48	44	34	44	34	40	38	42	42	36	34	42	36	34	40	34	38	36	48	34	50	60	38	36	34	36		
18:00	56	66	64	68	66	62	70	58	56	54	68	62	66																				

Appendix-1B: EXTRACT OF CIBSE TM46 ENERGY BENCHMARKS

[A]	[B]	[C]	[K]	[L]	[M]	[N]	[O]
Name and description			Energy benchmarks		Illustrative CO ₂ benchmarks calculated from the energy benchmarks (see Table 3)		
Category	Name	Brief description	Electricity typical benchmark (kW-h/m ²)	Fossil-thermal typical benchmark (kW-h/m ²)	Illustrative electricity typical benchmark (kgCO ₂ /m ²)	Illustrative fossil-thermal typical benchmark (kgCO ₂ /m ²)	Illustrative total typical benchmark (kgCO ₂ /m ²)
1	General office	General office and commercial working areas	95	120	52.3	22.8	75.1
2	High street agency	High street agency	140	0	77.0	0.0	77.0
3	General retail	General street retail and services	165	0	90.8	0.0	90.8
4	Large non-food shop	Retail warehouse or other large non-food store	70	170	38.5	32.3	70.8
5	Small food store	Small food store	310	0	170.5	0.0	170.5
6	Large food store	Supermarket or other large food store	400	105	220.0	20.0	240.0
7	Restaurant	Restaurant	90	370	49.5	70.3	119.8
8	Bar, pub or licensed club	Bar, pub or club	130	350	71.5	66.5	138.0
9	Hotel	Hotel or boarding house	105	330	57.8	62.7	120.5
10	Cultural activities	Museum, art gallery or other public building with normal occupancy	70	200	38.5	38.0	76.5
11	Entertainment halls	Entertainment halls	150	420	82.5	79.8	162.3
12	Swimming pool centre	Swimming pool hall, changing and ancillaries	245	1130	134.8	214.7	349.5
13	Fitness and health centre	Fitness centre	160	440	88.0	83.6	171.6
14	Dry sports and leisure facility	Dry sports and leisure facility	95	330	52.3	62.7	115.0
15	Covered car park	Car park with roof and side walls	20	0	11.0	0.0	11.0

16	Public buildings with light usage	Light use public and institutional buildings	20	105	11.0	20.0	31.0
17	Schools and seasonal public buildings	Public buildings nominally used for part of the year	40	150	22.0	28.5	50.5
18	University campus	University campus	80	240	44.0	45.6	89.6
19	Clinic	Health centres, clinics and surgeries	70	200	38.5	38.0	76.5
20	Hospital (clinical and research)	Clinical and research hospital	90	420	49.5	79.8	129.3
21	Long term residential	Long term residential accommodation	65	420	35.8	79.8	115.6
22	General accommodation	General accommodation	60	300	33.0	57.0	90.0
23	Emergency services	Emergency services	70	390	38.5	74.1	112.6
24	Laboratory or operating theatre	Laboratory or operating theatre	160	160	88.0	30.4	118.4
25	Public waiting or circulation	Bus or train station, shopping centre mall	30	120	16.5	22.8	39.3
26	Terminal	Regional transport terminal with concourse	75	200	41.3	38.0	79.3
27	Workshop	Workshop or open working area (not office)	35	180	19.3	34.2	53.5
28	Storage facility	Storage warehouse or depot	35	160	19.3	30.4	49.7
29	Cold storage	Refrigerated warehouse	145	80	79.8	15.2	95.0

Appendix-1C: UKNZCBS EUI LIMITS IN ONE-GO RETROFIT

EUI Limits for Existing Buildings with One-Go Retrofit (2025 – 2050)

Table OE-2: Energy use intensity limits, Existing Building with One-Go Retrofit

← Date of commencement on site	Commercial Residential		Culture & Entertainment	Data Centres		Healthcare	Higher Ed.	Homes	Hotels	Offices (either /GIA or /NIA metrics may be used)	Retail	Schools	Science & Tech.	Sport & Leisure	Storage & Distribution																							
	Student resi.	Care homes		Performance	Collection											Archives	Low utilisation	High utilisation	Acute Trust	Care Trust	Community Trust	Mental health & Learning Trust	Ambulance Trust	-	Single family homes	Flats	General	Call Centres	Trading Floors	Supermarket	High street retail, Department store	F&B without catering ^a	F&B with catering ^b	Landlord areas ^c	Retail warehouse	Early years	Primary	Secondary incl. SEN
2025	110	220	130	100	10	1.4	1.2	258	140	162	166	182	130	75	65	180	100	125	191	239	220	275	230	90	250	450	80	100	90	85	95	360	210	500	280	35	100	230
2026	108	216	128	98	10	1.4	1.2	259	140	163	167	182	127	74	65	176	97	122	187	234	216	270	224	87	243	438	79	97	89	84	94	351	206	490	275	34	97	221
2027	106	211	125	96	10	1.39	1.19	259	140	163	167	182	123	73	64	172	94	118	183	229	211	264	217	84	236	425	77	94	88	83	92	341	202	480	270	33	94	211
2028	103	206	122	93	10	1.38	1.18	259	140	163	167	182	119	72	64	168	91	114	179	224	206	258	210	81	228	412	75	90	86	81	90	331	198	470	264	32	90	201
2029	101	202	120	91	10	1.38	1.18	259	140	163	167	182	116	71	63	164	88	110	174	218	201	252	204	78	221	400	74	87	85	80	89	322	194	460	259	31	87	192
2030	99	197	117	89	9	1.37	1.17	259	140	163	167	182	112	70	63	160	85	107	170	213	196	245	197	75	214	387	72	84	84	79	87	312	190	450	254	30	84	182
2031	96	192	114	86	9	1.36	1.16	259	140	163	167	182	108	69	62	156	82	103	166	208	191	239	190	72	206	374	70	80	82	77	85	302	186	440	248	29	80	172
2032	94	188	112	84	9	1.36	1.16	259	140	163	167	182	105	68	62	152	79	99	162	203	186	233	184	69	199	362	69	77	81	76	84	293	182	430	243	28	77	163

^a i.e. only cold/hot drinks or cold food, no on-site kitchen

^b e.g., restaurant, pub, fast food with on-site food preparation / catering

^c in this Pilot version, this is only for use in Commercial Centres, to create area-weighted whole building limits, using the landlord areas and retail mix

For details of commencement dates, see section 4.2.6

EUI Limits for Existing Buildings with One-Go Retrofit (2025 – 2050)

← Date of commencement on site	Commercial Residential		Culture & Entertainment		Data Centres		Healthcare				Higher Ed.	Homes	Hotels	Offices (either /GIA or /NIA metrics may be used)				Retail				Schools				Science & Tech.	Sport & Leisure		Storage & Distribution																																							
	kWh/m²GIA/yr	Student resi.	kWh/m²GIA/yr	Care homes	kWh/m²GIA/yr	Performance	kWh/m²GIA/yr	Collection	kWh/m²GIA/yr	Archives	PUE	Low utilisation	PUE	High utilisation	kWh/m²GIA/yr	Acute Trust	kWh/m²GIA/yr	Care Trust	kWh/m²GIA/yr	Community Trust	kWh/m²GIA/yr	Mental health & Learning Trust	kWh/m²GIA/yr	Ambulance Trust	kWh/m²GIA/yr	-	kWh/m²GIA/yr	Single family homes	Flats	kWh/m²GIA/yr	General	kWh/m²GIA/yr	kWh/m²NIA/yr	kWh/m²GIA/yr	Call Centres	kWh/m²NIA/yr	kWh/m²GIA/yr	Trading Floors	kWh/m²NIA/yr	Supermarket	kWh/m²GIA/yr	High street retail, Department store	kWh/m²GIA/yr	F&B without catering ^a	kWh/m²GIA/yr	F&B with catering ^b	kWh/m²CPA/yr	Landlord areas ^c	kWh/m²GIA/yr	Retail warehouse	kWh/m²GIA/yr	Early years	kWh/m²GIA/yr	Primary	kWh/m²GIA/yr	Secondary incl. SEN	kWh/m²GIA/yr	-	kWh/m²GIA/yr	Dry	kWh/m²GIA/yr	Wet	Fitness	kWh/m²GIA/yr	Unconditioned storage	kWh/m²GIA/yr	Conditioned storage	kWh/m²GIA/yr
2033	92	183	109	82	9	1.35	1.15	259	140	163	167	182	101	66	61	148	76	95	157	197	182	228	177	66	192	349	67	74	80	75	82	283	178	420	238	27	74	153																														
2034	89	178	106	79	9	1.34	1.14	259	140	163	167	182	97	65	61	144	73	92	153	192	177	222	170	63	184	336	65	70	78	73	80	273	174	410	232	26	70	143																														
2035	87	174	104	77	8	1.34	1.14	259	140	163	167	182	94	64	60	140	70	88	149	187	172	215	164	60	177	324	64	67	77	72	79	264	170	400	227	25	67	134																														
2036	85	169	101	75	8	1.33	1.13	259	140	163	167	182	90	63	60	136	67	84	145	182	167	209	157	57	170	311	62	64	76	71	77	254	166	390	222	24	64	124																														
2037	82	164	98	72	8	1.32	1.12	259	140	163	167	182	86	62	59	132	64	80	140	175	162	203	150	54	162	298	60	60	74	69	75	244	162	380	216	23	60	114																														
2038	80	160	96	70	8	1.32	1.12	259	140	163	167	182	83	61	59	128	61	77	136	170	157	197	144	51	155	286	59	57	73	68	74	235	158	370	211	22	57	105																														
2039	78	155	93	68	8	1.31	1.11	259	140	163	167	182	79	60	58	124	58	73	132	165	152	190	137	48	148	273	57	54	72	67	72	225	154	360	206	21	54	95																														
2040	75	150	90	65	7	1.3	1.1	258	140	162	166	182	75	58	57	120	55	69	127	159	147	184	130	45	140	260	55	50	70	65	70	215	150	350	200	20	50	85																														
2050	75	150	90	65	7	1.3	1.1	258	140	162	166	182	75	58	57	120	55	69	127	159	147	184	130	45	140	260	55	50	70	65	70	215	150	350	200	20	50	85																														

^a i.e. only cold/hot drinks or cold food, no on-site kitchen

^b e.g., restaurant, pub, fast food with on-site food preparation / catering

^c in this Pilot version, this is only for use in Commercial Centres, to create area-weighted whole building limits, using the landlord areas and retail mix
For details of commencement dates, see section 4.2.6

Appendix-1D:UKNZCBS EUI LIMITS IN STEPPED RETROFIT



Table OE-3: Energy use intensity limits, Existing Building with Stepped Retrofits

← Date of commencement on site	Commercial		Residential		Culture & Entertainment		Data Centres		Healthcare		Higher Ed.		Homes		Hotels		Offices (either G/A or N/A metrics may be used)		Retail		Schools		Science & Tech.		Sport & Leisure		Storage & Distribution											
	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr	W/Whm	G/A yr										
2025	135	290	165	125	20	1.4	1.2	293	159	185	189	206	160	95	85	220	120	150	207	259	238	298	430	120	310	510	100	155	120	110	110	360	300	650	400	70	155	300
2026	131	281	160	121	20	1.4	1.2	291	158	184	188	205	155	93	84	214	116	145	202	253	233	293	390	115	299	494	97	148	117	107	108	537	290	630	367	67	148	286
2027	127	272	156	117	19	1.39	1.19	289	157	182	186	204	149	91	82	207	112	140	197	247	227	284	373	110	288	477	94	141	114	104	105	514	280	610	374	64	141	272
2028	123	262	150	113	18	1.38	1.18	287	156	181	185	202	143	88	80	200	107	134	191	239	220	275	354	108	278	460	91	134	110	101	102	491	270	590	360	60	134	257
2029	119	253	145	109	17	1.38	1.18	284	154	179	183	200	138	86	78	194	103	129	186	233	214	268	336	100	265	444	88	127	107	98	100	468	260	570	347	57	127	243
2030	115	244	140	105	16	1.37	1.17	282	153	178	182	199	132	83	76	187	99	124	181	227	208	260	317	95	264	427	85	120	104	95	97	445	250	550	334	54	120	239
2031	111	234	135	101	15	1.36	1.16	280	152	176	180	197	126	81	74	180	94	118	175	219	202	253	298	90	242	410	82	113	100	92	94	422	240	530	320	50	113	214
2032	107	225	130	97	14	1.36	1.16	277	151	172	179	195	121	78	72	174	90	113	170	213	198	245	280	85	231	394	79	106	97	89	92	399	230	510	307	47	106	200

* i.e. only cold/soft drinks or cold food, no on-site kitchen

† e.g. restaurant, pub, fast food with on-site food preparation / catering

‡ in this Pilot version, this is only for use in Commercial Centres, to create area-weighted whole building limits, using the landlord areas and retail mix

For details of commencement dates, see section 4.2.6

Appendix A

Appendix-1E: CHSBI 2024 FOR 3-STAR NON-RESORT, UK HOTEL

		CORNELL HOTEL SUSTAINABILITY BENCHMARKING INDEX 2024 CARBON, ENERGY & WATER		 Nolan Cornell SC Johnson College of Business CENTER FOR HOSPITALITY RESEARCH	
Select Geography Type :	Country	Select Segment Type :	Stars		
Select Country :	United Kingdom	Select Stars :	3 Stars NonResort		
Select Region/Metro Area [Optional]* :	London, UK				

2022 CALENDAR YEAR BENCHMARKS								
MEASURE	Count	Low	Lower Quartile	Mean	Median	Upper Quartile	High	SD
MEASURE 1: HCMI Rooms Footprint Per Occupied Room (kgCO2e)	27	3.04	6.70	8.42	8.57	9.47	14.02	2.57
MEASURE 2: Hotel Carbon Footprint Per Room (kgCO2e)	51	643.05	1,293	1,782	1,734	2,039	5,203	758
MEASURE 3: Hotel Carbon Footprint Per Occupied Room (kgCO2e)	52	2.22	5.04	6.69	6.25	7.58	22.01	3.17
MEASURE 4: Hotel Carbon Footprint Per Square Meter (kgCO2e)	51	9.41	26.90	45.03	38.55	61.62	144.58	23.57
MEASURE 4a: Hotel Carbon Footprint Per Square Foot (kgCO2e)	51	0.87	2.50	4.18	3.58	5.72	13.43	2.19
MEASURE 5: Hotel Energy Usage Per Occupied Room (kWh)	52	11.72	26.71	35.67	33.54	40.13	119.84	17.24
MEASURE 6: Hotel Energy Usage Per Square Meter (kWh)	51	50.53	142.24	240.18	205.42	332.91	787.12	127.88
MEASURE 6a: Hotel Energy Usage Per Square Foot (kWh)	51	4.69	13.21	22.31	19.08	30.93	73.13	11.88
MEASURE 7: HCMI Meetings Footprint Per SQM-HR (kgCO2e)	21	0.0076	0.0124	0.0197	0.0188	0.0250	0.0375	0.0082
MEASURE 8: Hotel Water Usage Per Occupied Room (L)	34	82.22	229.26	268.73	263.34	312.37	616.81	94.10
MEASURE 9: Hotel Water Usage Per Square Meter (L)	31	326.37	1,348.07	1,801.36	1,702.44	2,097.43	4,498.22	849.27
MEASURE 9a: Hotel Water Usage Per Square Foot (L)	31	30.32	125.24	167.35	158.16	194.86	417.90	78.90
MEASURE 10: HWMi Rooms Footprint Per Occupied Room (L)	20	138.86	265.19	339.77	334.99	391.44	717.77	133.62
MEASURE 11: HWMi Meetings Footprint Per SQM-HR (L)	14	0.2098	0.7192	0.9026	0.8707	1.0220	1.7691	0.3561
MEASURE 12: Hotel Energy from Renewables, Exc. Renewable Mix of Electric Power Grid (%)	54	0.00%	0.00%	0.08%	0.00%	0.00%	0.50%	0.19%
MEASURE 13: Hotel Energy from Renewables, Inc. Renewable Mix of Electric Power Grid (%)	54	0.96%	16.45%	22.60%	23.55%	27.84%	41.20%	8.62%

Appendix-1F: UK RETAIL ELECTRICITY PRICE PROJECTIONS TILL 2100

Table 4 - Retail Electricity Prices (real 2021 p/kWh)									
Year	Low			Central			High		
	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial
2010	15.25	10.08	8.42	15.25	10.08	8.42	15.25	10.08	8.42
2011	16.26	10.52	8.73	16.26	10.52	8.73	16.26	10.52	8.73
2012	16.87	11.19	9.53	16.87	11.19	9.53	16.87	11.19	9.53
2013	17.62	11.70	10.43	17.62	11.70	10.43	17.62	11.70	10.43
2014	18.23	12.25	10.59	18.23	12.25	10.59	18.23	12.25	10.59
2015	17.92	12.68	10.70	17.92	12.68	10.70	17.92	12.68	10.70
2016	17.33	12.19	10.47	17.33	12.19	10.47	17.33	12.19	10.47
2017	18.19	12.45	10.90	18.19	12.45	10.90	18.19	12.45	10.90
2018	19.33	13.24	10.87	19.33	13.24	10.87	19.33	13.24	10.87
2019	20.68	13.52	11.63	20.68	13.52	11.63	20.68	13.52	11.63
2020	19.71	13.34	11.50	19.71	13.34	11.50	19.71	13.34	11.50
2021	21.32	14.38	13.10	21.32	14.38	13.10	21.32	14.38	13.10
2022	30.73	21.77	19.84	30.73	30.09	28.07	30.73	52.35	49.88
2023	26.82	15.12	13.14	41.70	28.98	26.83	41.70	69.87	67.19
2024	23.72	13.46	11.47	40.34	23.03	20.91	73.16	52.09	49.55
2025	23.49	12.41	10.46	34.83	13.80	11.87	69.15	16.85	14.91
2026	20.87	12.46	10.21	22.30	13.21	11.34	25.15	14.32	12.98
2027	20.04	12.35	10.08	21.31	13.00	11.20	22.59	14.02	12.82
2028	19.51	12.14	9.85	20.75	12.68	10.94	22.00	13.67	12.52
2029	19.49	12.26	9.99	20.72	12.79	11.10	21.97	13.79	12.70
2030	19.39	12.19	9.95	20.62	12.73	11.05	21.86	13.73	12.65
2031	18.57	12.16	10.05	19.75	12.70	11.17	20.94	13.69	12.78
2032	18.66	12.05	9.97	19.83	12.58	11.08	21.03	13.57	12.68
2033	18.88	12.09	10.06	20.08	12.62	11.18	21.29	13.60	12.79
2034	19.21	12.46	10.41	20.42	13.01	11.56	21.65	14.03	13.23
2035	19.03	12.52	10.52	20.23	13.07	11.69	21.45	14.10	13.38
2036	18.97	12.55	10.56	20.17	13.10	11.73	21.39	14.12	13.43
2037	18.48	12.38	10.53	19.64	12.93	11.70	20.83	13.94	13.39
2038	18.69	12.49	10.56	19.87	13.03	11.73	21.07	14.05	13.42
2039	18.54	12.46	10.54	19.71	13.00	11.71	20.89	14.02	13.40
2040	19.02	12.74	10.77	20.22	13.30	11.97	21.44	14.35	13.70
2041	18.74	12.53	10.61	19.92	13.08	11.79	21.12	14.11	13.50
2042	18.74	12.52	10.61	19.92	13.07	11.79	21.12	14.09	13.49
2043	18.70	12.62	10.81	19.88	13.18	12.01	21.08	14.21	13.74
2044	18.89	12.75	10.92	20.08	13.31	12.13	21.29	14.35	13.88
2045	18.48	12.71	10.90	19.65	13.27	12.11	20.83	14.31	13.86
2046	18.82	12.76	10.97	20.01	13.32	12.19	21.22	14.36	13.95
2047	18.52	12.69	10.97	19.69	13.25	12.19	20.88	14.28	13.95
2048	18.06	12.57	10.93	19.20	13.13	12.14	20.35	14.15	13.89
2049	18.38	12.47	10.86	19.54	13.02	12.07	20.71	14.04	13.81
2050	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2051	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2052	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2053	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2054	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2055	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2056	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2057	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2058	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2059	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2060	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2061	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87

Table 4 - Retail Electricity Prices (real 2021 p/kWh)									
Year	Low			Central			High		
	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial
2062	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2063	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2064	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2065	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2066	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2067	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2068	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2069	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2070	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2071	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2072	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2073	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2074	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2075	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2076	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2077	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2078	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2079	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2080	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2081	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2082	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2083	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2084	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2085	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2086	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2087	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2088	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2089	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2090	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2091	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2092	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2093	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2094	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2095	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2096	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2097	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2098	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2099	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87
2100	18.02	12.48	10.91	19.16	13.03	12.12	20.31	14.05	13.87

Appendix-1G: UK RETAIL NATURAL GAS PROJECTIONS TO 2100

Table 5 - Retail Gas Prices (real 2021 p/kWh)												
Year	A			B			C			D		
	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial
2010	4.53	2.68	2.01	4.53	2.68	2.01	4.53	2.68	2.01	4.53	2.68	2.01
2011	5.04	3.05	2.54	5.04	3.05	2.54	5.04	3.05	2.54	5.04	3.05	2.54
2012	5.41	3.52	2.63	5.41	3.52	2.63	5.41	3.52	2.63	5.41	3.52	2.63
2013	5.63	3.82	2.75	5.63	3.82	2.75	5.63	3.82	2.75	5.63	3.82	2.75
2014	5.89	3.72	2.45	5.89	3.72	2.45	5.89	3.72	2.45	5.89	3.72	2.45
2015	5.54	3.35	2.12	5.54	3.35	2.12	5.54	3.35	2.12	5.54	3.35	2.12
2016	4.95	2.90	1.66	4.95	2.90	1.66	4.95	2.90	1.66	4.95	2.90	1.66
2017	4.76	2.73	1.73	4.76	2.73	1.73	4.76	2.73	1.73	4.76	2.73	1.73
2018	4.75	3.00	2.08	4.75	3.00	2.08	4.75	3.00	2.08	4.75	3.00	2.08
2019	4.82	2.80	1.86	4.82	2.80	1.86	4.82	2.80	1.86	4.82	2.80	1.86
2020	4.18	2.53	1.61	4.18	2.53	1.61	4.18	2.53	1.61	4.18	2.53	1.61
2021	4.14	3.26	2.69	4.14	3.26	2.69	4.14	3.26	2.69	4.14	3.26	2.69
2022	7.36	6.07	5.37	7.36	8.85	8.20	7.36	16.16	15.65	7.36	16.16	15.65
2023	7.58	3.75	2.97	11.30	8.92	8.24	11.30	24.05	23.66	11.30	24.05	23.66
2024	5.60	3.02	2.20	11.25	6.40	5.64	19.90	16.31	15.74	19.90	16.31	15.74
2025	5.14	2.34	1.49	8.57	3.31	2.47	18.66	5.10	4.30	18.66	6.23	5.45
2026	4.24	2.38	1.54	5.22	3.02	2.19	7.04	3.96	3.15	8.19	6.23	5.45
2027	4.25	2.38	1.54	4.91	3.09	2.27	5.86	4.00	3.19	8.17	6.22	5.45
2028	4.19	2.41	1.58	4.92	3.12	2.31	5.84	4.03	3.23	8.10	6.21	5.45
2029	4.20	2.44	1.62	4.92	3.16	2.34	5.84	4.06	3.26	8.07	6.21	5.46
2030	4.20	2.47	1.65	4.93	3.19	2.38	5.85	4.09	3.30	8.04	6.20	5.45
2031	4.22	2.51	1.69	4.95	3.22	2.42	5.87	4.13	3.34	8.02	6.20	5.46
2032	4.24	2.51	1.69	4.97	3.26	2.46	5.89	4.17	3.38	8.00	6.20	5.46
2033	4.24	2.55	1.73	5.00	3.30	2.50	5.92	4.21	3.42	7.99	6.21	5.46
2034	4.26	2.59	1.77	5.03	3.34	2.54	5.95	4.24	3.46	7.98	6.21	5.46
2035	4.29	2.59	1.77	5.06	3.38	2.58	5.98	4.28	3.50	7.97	6.21	5.46
2036	4.29	2.59	1.77	5.09	3.38	2.58	6.01	4.28	3.50	7.97	6.21	5.46
2037	4.28	2.59	1.77	5.08	3.38	2.58	6.00	4.29	3.50	7.96	6.21	5.46
2038	4.27	2.60	1.77	5.07	3.39	2.58	5.99	4.29	3.50	7.95	6.21	5.46
2039	4.26	2.60	1.77	5.07	3.39	2.58	5.98	4.29	3.50	7.94	6.21	5.46
2040	4.25	2.60	1.77	5.06	3.39	2.58	5.98	4.29	3.50	7.94	6.22	5.46
2041	4.25	2.60	1.77	5.06	3.39	2.58	5.97	4.29	3.50	7.93	6.22	5.46
2042	4.25	2.60	1.77	5.05	3.39	2.58	5.97	4.29	3.50	7.93	6.22	5.46
2043	4.25	2.60	1.77	5.05	3.39	2.58	5.97	4.30	3.50	7.93	6.22	5.46
2044	4.24	2.61	1.77	5.05	3.40	2.58	5.97	4.30	3.50	7.93	6.22	5.46
2045	4.24	2.61	1.78	5.05	3.40	2.58	5.96	4.30	3.50	7.92	6.22	5.46
2046	4.24	2.61	1.78	5.04	3.40	2.58	5.96	4.30	3.50	7.92	6.23	5.46
2047	4.24	2.61	1.78	5.04	3.40	2.58	5.96	4.30	3.50	7.92	6.23	5.46
2048	4.23	2.61	1.78	5.04	3.40	2.58	5.96	4.31	3.50	7.91	6.23	5.46
2049	4.23	2.62	1.78	5.03	3.40	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2050	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2051	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2052	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2053	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2054	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2055	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2056	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2057	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2058	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2059	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2060	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46

Table 5 - Retail Gas Prices (real 2021 p/kWh)												
Year	A			B			C			D		
	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial	Domestic	Commercial/ Public sector	Industrial
2061	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2062	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2063	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2064	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2065	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2066	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2067	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2068	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2069	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2070	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2071	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2072	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2073	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2074	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2075	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2076	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2077	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2078	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2079	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2080	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2081	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2082	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2083	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2084	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2085	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2086	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2087	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2088	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2089	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2090	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2091	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2092	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2093	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2094	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2095	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2096	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2097	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2098	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2099	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46
2100	4.23	2.62	1.78	5.03	3.41	2.58	5.95	4.31	3.50	7.91	6.23	5.46

Appendix-1H: TYPICAL ELECTRICITY INVOICE AT CASE STUDY



Account enquiries? Call 0845 301 3500
Partnerships 1
Our business hours
Mon - Fri 09:00 - 17:00
edfenergy.com/largebusiness
For power cut or emergency
call 105
or visit www.powercut105.com

Account number / Invoice Number:
2321154277 / 000013124823

Invoice period: 01 Aug 22 - 31 Aug 22

Invoice issue date: 01 Sep 22

Your ref: 612016

Page 2 of 7

Electricity invoice detail: period 01 Aug 22 - 31 Aug 22 (31 days)

Supply Address

Main Campus, Kingston Lane, Uxbridge, UB8 3PH

Framework Information

Framework reference	5175436088
Framework start date	01 Apr 22
Framework end date	30 Sep 22
Contract type	Flex
Organisation VAT relief status	54 %

Contract Period Information

Contract period reference	Q_1236753
Contract period start date	01 Apr 22
Contract period end date	30 Sep 22
Price point	Grid Supply Point
Electricity source	Zero Carbon for Business 80%, Standard 20%
TNUoS charging method	Monthly TNUoS charging method - 1/12 of your forecasted triad demand for each site (2490.84 kW)
Effective from 01 Apr 2022	

Your contract term will automatically expire at the agreed Earliest Termination Date shown above. After this date Extended Supply Charges will apply until you agree another supply contract with EDF Energy or transfer to another supplier, which you will be free to do at any time (as long as you have no outstanding balance on your account). These Extended Supply Charges are variable and typically higher than our fixed contract charges.

Meter & network information

Voltage	Effective Date	Available capacity
L - Low Voltage	01 Apr 22	5,500.00

Supply charges

This section contains a breakdown of all charges associated with the physical supply of electricity provided by EDF Energy during this invoicing period.

Consumption charges

The following charges apply to invoice period: 01 Aug 22 - 31 Aug 22

MPAN	Rate Component	Charge Description	Average Loss Adjustment Factor	Units	Units of measure	Cost (£)
2000027284418	1	Energy Charge 1,487,686.98 kWh at £0.110108 per kWh (All Times)	1.072962	1,487,686.98	kWh	£163,806.24
	2	Demand Charge 2,279.20 at £0.00 per kW	-	2,279.20	kW	£0.00
Total charge for MPAN						£163,806.24

VAT registration number: 523 0412 02

Electricity invoice detail: period 01 Aug 22 - 31 Aug 22 (31 days)

Continues over



Account enquiries? Call 0845 301 3500
Partnerships 1
Our business hours
Mon - Fri 09:00 - 17:00
edfenergy.com/largebusiness
For power cut or emergency
call 105
or visit www.powercut105.com

Account number / Invoice Number:
2321154277 / 000013124823

Invoice period: 01 Aug 22 - 31 Aug 22
Invoice issue date: 01 Sep 22
Your ref: 612016

Page 4 of 7

Electricity invoice detail: period 01 Aug 22 - 31 Aug 22 (31 days)

> Supply Address

Main Campus, Kingston Lane, Uxbridge, UB8 3PH

> Transmission and agent charges

This section contains a breakdown of all related transmission and agent charges that are levied onto your electricity supply charges.

> Fixed charges

The following charges apply to invoice period: 01 Aug 22 - 31 Aug 22

MPAN	Description	Units	Cost (£)
2000027284418	Data Collection (DC/DA) Agent Charge at £1.3643836 per day	31.00	£42.30
	Settlement Agency Charge at £0.02302 per day	31.00	£0.71
Total charges for MPAN			£43.01
Total fixed charges			£43.01

> Transmission Network Use of System

The following charges apply to invoice period: 01 Aug 22 - 31 Aug 22

MPAN	Forecast TRIAD demand	MD%	Charge description	Charge for period
2000027284418	2,490.84	-	Monthly TNUs Charge 207.57 kW at £62.263662 per kW	£12,924.07
Total Transmission network use of system				£12,924.07

Total transmission and agent charges £12,967.08

> Power information summary

MPAN	Power factor	Meter reg.	Time of use	Usage start	Usage end	Units (kVA)	Units (kW)	Units (kVAh)	Units (kWh)
2000027284418	0.977205	HH	Rate - All Day Every Day	01 Aug 22	31 Aug 22	-	-	-	e1,386,524.00
		MD	Aug 22 12:30:00 19	-	-	e2,322.70	-	-	-
		MD	Aug 22 12:30:00	-	-	-	e2,279.20	-	-
		RE	-	01 Aug 22	31 Aug 22	-	-	-	-
		RI	-	01 Aug 22	31 Aug 22	-	-	e297,765.40	-
		REAP	-	01 Aug 22	31 Aug 22	-	-	-	-

VAT registration number: 523 0412 02

Electricity invoice detail: period 01 Aug 22 - 31 Aug 22 (31 days)
> Continues over



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For power cut or emergency
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or visit www.powercut105.com

Account number / Invoice Number:
2321154277 / 000013124823

Invoice period: 01 Aug 22 - 31 Aug 22
Invoice issue date: 01 Sep 22
Your ref: 612016

Page 5 of 7

Electricity invoice detail: period 01 Aug 22 - 31 Aug 22 (31 days)

> Supply Address

Main Campus, Kingston Lane, Uxbridge, UB8 3PH

> Power information summary

...continued

MPAN sub total					2,322.70	2,279.20	-	1,386,524.00
Total units					2,322.70	2,279.20	-	1,386,524.00

a = actual reading e = estimate reading c = customer reading REAP = reactive power MD = maximum demand

> Charges and adjustments

> CCL charges detail

Charge element	Charge excl. VAT
MPAN 2000027284418 - CCL on 637,801.04 kWh @ £0.00775 per kWh	£4,942.96
Total CCL	£4,942.96
Total charges and adjustments	£4,942.96

Distribution Network Operator details

Southern Electric Power Distribution, Walton Park, Walton Road, Cosham, Portsmouth, PO16 1UJ

EDF Energy reserves the right to use unclaimed credit balances within your account portfolio to clear unpaid overdue balances.

> COVID - 19 Support

Full details of the different support available can be found on the government's website :

The UK Government have made a full range of business support measures available to UK Businesses and employees.

www.businesssupport.gov.uk/coronavirus-business-support/

For any questions around the support available, please follow the link to the government website. Here at EDF, we're also on hand to support our customers and partners through the challenging period.

The quickest and easiest way to get the information you need is to self-serve by visiting edfenergy.com/mybusiness where you can also Live Chat with us via the green 'Chat' button.

> MPANS

S	00	845	H89
	20	0002	7284 418

VAT registration number: 523 0412 02

Electricity invoice detail: period 01 Aug 22 - 31 Aug 22 (31 days)
> Ends

Appendix-1I: TYPICAL NATURAL GAS INVOICE AT CASE STUDY

Your ref C206375931
Date: 16/09/2022



Brunel University London
Brunel University London
Kingston Lane
Uxbridge
Middlesex
UB8 3PH

Customer Ref 20425728
Our ref PO 612063
Billing period: Aug-22 to Sep-22
Invoice No.: 17148145
Gas Supplied To Ux 05 Kingston Lane
UB8 3PH

Page: 1 of 1

Meter Point Reference	Meter Serial Number	Previous Read Date	Previous Read	Present Read	Present Read Date	Metered Consumption	Correction Factor	Corrected Consumption	Read Factor	Calorific Value	Total kWh
9116436705	M1075D341103B7	01/08/2022	0074786	R 0087775	R 01/09/2022	12989	1.025937	13326	1.00	39.8	147.325

For accurate monthly billing, please visit our website, www.coronaenergy.co.uk/submit-meter-reading to submit your meter read.

	kWh	Rate p/kWh	Totals
Total Gas Usage	147.325	0.2191	£322.79
Climate Change Levy	0	Relief 0.00% 0.5680	£0.00
Daily Charge	31 Days at £120.48 per day		£3,734.88
AMR Charge			N/A
Charge for current period			£4,057.67
VAT @ 5.0%		£4,057.67	£202.88
@ 20.0%		£0.00	£0.00
Total Invoice Charge			£4,260.55

Pursuant to Schedule 5 Section 7 of The Gas Act 1986 this invoice constitutes a demand in writing for payment of charges due. Corona Energy is a trading name of Corona Energy Retail 4 Ltd.
Registered office: BUILDING 2, CROXLEY PARK, WATFORD WD18 9YA. Registered in England & Wales Number 2798334.
VAT Registration No.: 577 7948 00. CCL Accounting Document.

Please return this tear-off remittance advice with your payment

Remittance Advice

Invoice Date	Due Date	Customer Ref	Our Ref	Invoice No.	Total Due
16/09/2022	14/10/2022	20425728	PO 612063	17148145	£4,260.55

Cheques should be made payable to: Corona Energy Retail 4 Limited
For payment through the bank, please quote the following: Barclays Bank, Sort Code: 20-06-24 Account Number: 30877700

Please email remittance advices to remit@coronaenergy.co.uk or via post to Corona Energy, PO BOX 4934, Slough, SL1 0JQ

AP Anthony Prosser (Staff)
RE: Lancaster Occupancy Data
Brunel University London Research

Hi Benedict,

OCCUPANCY

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Full year total
2022/23	75.4%	80.9%	75.0%	75.0%	80.0%	80.0%	88.3%	75.0%	80.0%	80.0%	88.0%	88.0%	88.4%
2023/24	86.4%	78.3%	86.0%	80.0%	80.0%	80.0%	80.0%	80.0%	80.0%	80.0%	86.0%	80.0%	79.0%

Kind regards,
Tony

Tony Prosser
Head of Lancaster Hotel
Brunel University London | Uxbridge | UB8 3PH | UK
www.brunel.ac.uk

From: Benedict Shinku (Doctoral Researcher) <Benedict.Shinku@brunel.ac.uk>
Sent: 31 July 2024 18:40
To: Anthony Prosser (Staff) <Anthony.Prosser@brunel.ac.uk>
Subject: RE: Lancaster Occupancy Data

Dear Anthony,
I trust you are well.
Following from the preceding mail, kindly assist me with occupancy data for 2023 up to June 2024.

Kind regards

Benedict Tertsea Shinku B.Eng. (Mech.), M.Sc. (Mech; Building Services Eng.)
Doctoral Researcher
E: benedict.shinku@brunel.ac.uk
Brunel University London
Institute of Energy Futures
Department of Mechanical and Aerospace Engineering
Brunel University London, Uxbridge, UB8 3PH, United Kingdom
T +44(0)1895 274000
www.brunel.ac.uk

From: Anthony Prosser (Staff) <Anthony.Prosser@brunel.ac.uk>
Sent: 23 May 2023 11:28
To: Benedict Shinku (Doctoral Researcher) <Benedict.Shinku@brunel.ac.uk>
Subject: RE: Lancaster Energy Audit

Hi Benedict,

Good to meet you today to support your PhD.

Please see Hotel Occupancy numbers below as requested. NB: the Hotel was closed a lot during the 2020/21 pandemic.

Occupancy	August (Actual)	September (Actual)	October (Actual)	November	December	January	February	March	April	May	June	July	Feb / YTD
22/23 Actual	75.41%	82%	75%	87.58%	40.59%	83.12%	73%	82%	82%				82%
21/22 Actual	26.22%	62.58%	68.00%	88.62%	23.18%	23.32%	46.50%	63.91%	80.50%	86.45%	89.00%	86.50%	81%
17/18 Actual (past 'normal' year)	67.00%	72.00%	66.00%	57.00%	37.00%	48.00%	68.00%	48.00%	50.00%	85.00%	89.00%	66.00%	57%

As mentioned hot rooms in summer is our No.1 guest complaint. Bedrooms are not on movement sensors to control lighting. Solar panel energy production sounds interesting to reduce cost of energy we purchase from the grid.

I am currently working on Future BUL Hotel strategy... Much appreciated if you can share any PhD recommendations for the Hotel with me in the future, to help build into future energy related / 'green' investment recommendations.

Kind regards,
Tony

Tony Prosser
Head of Lancaster Hotel & Spa
Brunel University London | Uxbridge | UB8 3PH | UK
www.brunel.ac.uk
<http://www.brunel.ac.uk/business-commercial-services/hotel>

Appendix-1K: KITCHEN WATER CONSUMPTION FOR BASELINE YEAR

Month		January																														
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
Day	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	
Time	Hourly Kitchen Water Consumption (L)																															
00:30	0	0	0	0	0	0	0	150	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
01:30	0	0	0	0	0	0	0	140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	
02:30	0	0	0	0	0	0	0	150	0	0	0	0	0	0	0	10	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	
03:30	0	0	0	0	0	0	0	140	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
04:30	0	0	0	0	0	0	0	150	0	0	0	10	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
05:30	0	0	0	10	0	20	20	30	10	20	20	10	10	20	20	10	0	10	10	20	10	20	0	10	10	20	20	10	0	10	0	
06:30	0	0	0	0	20	0	0	0	0	0	0	30	10	0	0	0	20	10	60	20	10	0	0	10	0	0	0	0	0	10	40	
07:30	0	0	0	0	0	0	0	50	40	10	0	90	60	70	0	0	10	70	40	80	40	50	0	10	50	0	40	10	0	10	0	
08:30	0	0	0	20	10	0	0	50	10	0	10	50	50	10	10	0	30	40	110	20	40	0	0	20	80	30	20	10	0	0	30	
09:30	0	0	0	0	50	30	0	60	20	20	10	50	60	90	0	0	20	70	100	10	30	20	0	40	20	60	50	20	10	20	90	
10:30	0	0	0	20	20	40	10	50	30	10	0	90	50	40	10	10	20	70	140	0	50	0	10	10	120	80	70	10	0	10	40	
11:30	10	0	0	10	10	110	20	10	10	20	20	40	50	60	10	0	30	50	70	40	60	0	0	30	70	70	20	10	0	60	0	
12:30	0	0	0	20	10	20	10	0	0	30	20	20	30	20	0	10	90	0	60	70	100	0	0	50	100	70	30	40	0	0	30	
13:30	0	0	0	0	10	30	30	10	0	10	40	10	110	10	0	0	30	40	20	20	40	10	0	30	50	20	30	50	20	0	90	
14:30	0	0	0	10	20	10	30	0	10	20	10	10	10	10	0	0	10	10	50	10	40	10	0	20	20	30	60	10	0	10	70	
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18:30	0	0	0	0	0	70	10	10	10	20	10	10	20	30	20	40	0	20	10	10	10	70	50	0	70	10	0	30	30	10	10	
19:30	0	0	0	0	10	60	260	40	0	0	50	10	20	90	10	20	10	20	0	10	30	20	20	10	90	100	20	30	10	10	100	
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23:30	0	0	0	0	10	0	0	170	0	0	0	20	10	0	0	0	0	0	0	10	10	0	10	0	0	10	0	10	0	0	10	

Month	February																												
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	
Day	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	
Time	Hourly Kitchen Water Consumption (L)																												
00:30	0	0	0	0	0	0	0	0	0	0	10	10	0	0	0	0	0	0	0	0	10	0	10	0	10	0	0	0	
01:30	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
02:30	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
03:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
04:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
05:30	20	10	0	0	10	10	0	10	20	0	10	10	10	10	10	10	20	10	10	10	0	10	20	20	20	0	10	20	
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19:30	30	20	40	60	20	10	10	20	40	20	30	20	100	40	50	60	50	70	40	20	10	20	110	170	20	80	10	100	
20:30	40	50	40	10	50	50	20	150	10	30	30	20	30	10	20	0	30	50	10	10	50	60	90	20	10	0	80	80	
21:30	30	40	50	20	20	10	10	10	30	30	50	60	20	20	30	20	30	60	10	20	20	10	20	30	110	10	30	20	40
22:30	30	20	20	20	30	20	0	30	20	10	20	10	0	10	0	0	20	30	10	10	0	10	0	10	10	10	10	10	
23:30	0	0	0	0	10	20	0	0	0	0	0	20	10	10	10	0	0	0	10	0	10	10	10	10	10	0	0	0	

Date	March																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
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Day	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri

Month	May																														
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Day	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue
Time	Hourly Kitchen Water Consumption (L)																														
00:30	0	0	0	0	10	10	20	0	0	0	0	10	0	10	0	0	0	0	0	0	0	0	0	180	0	0	0	10	0	0	0
01:30	0	0	0	0	10	0	0	0	10	10	0	0	0	0	10	0	0	0	0	0	0	0	0	170	0	0	0	0	0	0	0
02:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	180	0	0	0	0	0	0	0
03:30	0	0	0	0	0	20	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	180	0	0	0	0	0	0	0	0
04:30	0	0	0	0	0	10	10	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	170	0	0	0	0	0	0	0	0
05:30	0	0	20	20	20	20	0	0	10	20	10	10	0	0	0	10	20	30	20	10	20	10	10	140	10	10	20	20	0	10	20
06:30	20	0	0	0	10	20	0	10	30	0	0	20	10	0	10	10	10	0	10	0	10	0	10	10	10	10	0	20	0	20	0
07:30	20	10	20	40	50	20	0	20	40	40	20	60	80	60	20	90	140	70	70	20	0	50	100	120	130	110	20	40	110	100	
08:30	20	20	90	40	110	50	20	20	40	30	100	60	70	40	60	40	50	50	40	50	70	20	80	40	30	70	40	30	70	100	
09:30	20	50	50	50	40	50	20	20	20	70	100	30	30	70	60	90	60	20	70	30	40	40	80	70	30	40	40	70	40	70	
10:30	70	60	60	50	40	20	20	30	60	20	30	60	20	30	60	30	10	70	60	40	70	60	40	70	90	60	140	90	50	50	
11:30	10	20	50	30	40	0	0	10	70	30	40	50	40	40	30	60	100	80	0	30	60	160	60	30	20	70	100	30	100	30	
12:30	20	0	90	130	120	60	0	0	160	70	70	80	70	70	40	100	140	60	60	70	0	20	80	70	130	40	130	50	60	120	70
13:30	30	50	90	80	70	90	30	10	100	190	140	100	100	80	20	80	110	120	120	190	30	20	140	140	150	100	120	70	70	90	240
14:30	0	90	60	150	30	50	50	20	30	40	70	40	150	40	20	40	100	50	80	80	30	10	150	110	80	130	80	80	50	70	50
15:30	10	30	30	20	30	10	40	30	30	20	40	10	80	30	20	20	80	20	20	100	50	10	40	10	30	50	20	40	40	40	90
16:30	10	10	20	30	10	50	0	30	50	10	80	50	40	10	90	40	80	140	60	140	20	10	40	30	20	40	10	20	30	30	
17:30	10	10	40	30	10	40	10	20	10	10	30	110	80	30	40	20	40	80	50	30	20	0	20	70	40	70	80	50	10	40	70
18:30	20	30	20	30	20	90	40	10	20	40	60	90	40	20	20	60	70	20	40	90	20	10	140	40	70	60	90	30	50	50	110
19:30	50	20	40	40	70	80	30	40	40	30	80	20	70	60	0	80	80	40	120	20	20	280	50	110	70	160	110	50	170	80	50
20:30	70	60	90	110	30	380	30	0	50	60	60	10	80	50	50	40	90	70	80	150	40	50	230	40	100	70	70	10	140	200	40
21:30	30	30	30	90	10	270	70	20	90	120	70	30	80	90	60	70	100	30	50	120	30	10	280	70	250	150	60	50	150	70	60
22:30	0	40	10	50	40	50	20	100	30	30	50	10	50	30	20	60	60	70	40	50	0	10	260	50	70	60	40	20	20	60	70
23:30	0	0	10	10	10	30	10	10	20	10	10	0	10	10	0	0	0	0	0	20	10	10	0	210	10	20	30	60	30	10	20

Month	June																													
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Day	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu
Time	Hourly Kitchen Water Consumption (L)																													
00:30	0	0	0	0	0	0	0	0	0	0	0	20	0	10	0	0	0	10	10	10	0	0	0	0	30	0	10	0	0	10
01:30	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	20	0	10	0	0	40	0	20	0	0	0
02:30	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
03:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04:30	0	0	10	0	0	0	0	0	0	10	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0
05:30	20	0	0	20	0	20	20	20	20	10	10	10	10	10	10	0	10	20	10	0	20	10	10	20	20	0	20	10	10	10
06:30	0	0	0	0	20	0	20	90	10	40	10	10	10	10	10	10	0	0	10	50	20	20	10	0	10	10	50	40	20	10
07:30	110	60	50	50	0	130	120	110	80	120	60	50	100	130	100	90	120	70	40	130	100	160	50	60	0	60	100	70	110	170
08:30	80	50	30	110	40	60	50	30	80	70	10	20	60	120	90	80	90	40	30	110	100	240	30	80	40	30	20	60	80	80
09:30	30	20	70	60	40	110	20	70	90	100	80	100	50	70	90	40	40	60	50	100	70	60	140	80	60	200	50	40	20	30
10:30	150	130	80	50	50	50	60	90	90	100	110	90	40	60	70	60	100	110	20	80	120	110	90	110	130	130	100	140	80	50
11:30	90	60	50	50	60	70	90	70	140	80	100	130	90	60	50	20	90	120	40	40	170	80	100	160	80	40	60	90	140	90
12:30	90	40	50	150	50	90	180	130	220	240	90	10	70	100	50	80	170	120	40	210	170	80	180	50	50	30	180	140	160	100
13:30	240	60	20	50	60	150	360	130	320	240	80	20	170	170	360	140	170	60	30	150	310	120	210	80	60	20	50	110	100	290
14:30	70	110	40	120	70	60	140	160	210	270	50	80	110	60	120	60	120	30	50	70	80	140	50	20	80	70	120	80	130	30
15:30	70	20	80	30	60	60	70	110	70	60	140	70	20	20	50	70	50	60	30	30	70	140	160	20	50	60	80	20	50	70
16:30	80	10	20	50	60	40	30	50	90	50	40	40	20	50	90	170	30	20	50	40	40	0	120	40	20	80	10	30	30	30
17:30	50	20	10	30	60	20	50	100	80	20	40	80	130	120	10	70	20	70	30	40	30	90	110	70	140	60	40	30	40	0
18:30	40	30	30	20	60	100	10	80	100	100	30	90	130	80	80	50	80	80	70	90	60	10	70	80	120	20	30	30	40	0
19:30	60	40	50	30	110	70	90	80	110	160	60	80	60	80	120	120	80	90	40	90	70	110	90	120	300	30	80	50	90	0
20:30	100	90	90	50	40	80	80	80	160	110	40	50	70	70	140	100	300	80	110	140	100	90	90	160	130	40	10	80	30	610
21:30	200	60	100	80	70	50	90	30	150	40	60	140	80	110	90	70	70	70	90	30	120	40	100	70	60	80	50	150	0	0
22:30	40	60	20	50	60	50	100	100	90	150	80	90	100	90	90	90	80	70	30	100	40	40	20	70	30	60	40	90	70	0
23:30	30	20	0	10	20	60	20	0	40	40	70	60	20	10	20	30	20	20	40	10	60	20	0	120	50	20	0	80	10	0

Month	September																														
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Day	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	
Time	Hourly Kitchen Water Consumption (L)																														
00:30	0	0	0	0	50	0	0	0	70	0	110	0	0	0	0	0	10	0	10	0	10	0	0	110	10	0	0	0	0	20	
01:30	0	0	0	0	60	0	0	0	70	10	100	0	0	0	0	0	0	0	10	0	0	0	110	0	0	0	0	0	0	10	
02:30	0	0	0	0	60	0	0	0	70	0	100	0	0	0	0	0	0	0	0	0	0	0	0	120	0	0	0	0	0	0	
03:30	0	0	0	0	60	0	0	0	80	0	110	0	0	0	0	0	0	0	0	0	0	0	0	120	0	0	0	0	0	0	
04:30	0	0	0	0	70	0	0	0	70	10	110	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	
05:30	0	0	0	10	50	10	20	20	50	0	80	10	20	10	10	20	20	0	0	10	20	20	20	80	0	20	10	10	20	10	
06:30	0	0	10	10	20	30	30	10	0	10	10	10	10	10	10	20	0	0	20	10	0	30	10	0	10	10	10	10	10	10	
07:30	80	100	50	50	60	140	100	30	80	10	30	100	50	40	50	100	10	60	90	40	30	10	0	30	20	50	30	50	10	40	
08:30	20	50	10	10	40	70	60	50	40	30	30	380	30	60	20	10	10	10	30	40	30	30	10	60	30	40	40	20	80	50	
09:30	40	60	30	40	50	40	90	40	40	100	50	60	60	30	50	50	80	30	30	20	40	20	30	40	10	60	10	80	60	60	
10:30	50	50	30	40	70	80	90	50	110	40	140	160	40	10	60	40	60	60	30	30	60	40	20	50	50	20	50	150	60	160	
11:30	20	60	50	10	90	50	70	90	100	20	60	30	60	40	240	20	10	10	190	100	80	100	20	40	20	90	60	50	160	160	
12:30	70	40	60	20	260	100	160	160	90	40	40	240	210	160	240	100	20	30	10	180	120	40	80	30	20	190	80	60	100	150	
13:30	30	40	10	10	130	300	150	190	170	40	90	80	40	220	50	100	30	10	40	140	70	70	110	10	10	160	50	20	110	140	
14:30	60	90	60	30	70	140	80	130	60	10	110	30	50	160	140	50	80	60	120	150	20	50	100	20	40	70	40	30	120	80	
15:30	20	20	0	30	50	100	20	150	50	50	130	130	160	40	70	0	10	50	40	30	30	20	20	20	50	10	90	20	120	30	
16:30	20	70	20	50	40	60	60	210	30	70	80	50	50	20	20	20	10	10	30	50	20	30	10	40	20	30	60	50	30	30	
17:30	0	90	60	30	70	30	90	40	70	50	20	50	60	150	70	20	10	10	40	10	80	30	40	30	20	20	50	30	20	10	
18:30	10	30	20	30	80	50	40	100	40	20	40	70	50	10	150	60	40	40	30	30	110	30	110	20	30	20	10	60	30	120	
19:30	10	90	90	110	50	160	30	40	80	30	40	200	90	50	110	30	60	50	10	60	140	10	40	50	50	40	50	20	90	120	
20:30	10	40	50	100	40	90	70	40	110	20	40	220	100	90	120	70	50	40	50	130	120	30	40	10	40	110	340	80	100	100	
21:30	60	90	50	120	80	160	80	150	40	60	60	180	60	90	40	20	30	30	60	100	80	40	90	60	60	70	60	120	70	190	
22:30	10	30	20	90	20	150	20	140	30	40	80	30	40	30	20	60	30	20	110	10	30	20	90	20	10	50	20	80	80	80	
23:30	40	20	10	80	10	0	0	80	30	90	20	0	30	10	10	0	0	0	10	10	10	10	0	100	0	0	20	10	0	50	20

Month	October																																
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31		
Time	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon		
Hourly Kitchen Water Consumption (L)																																	
00:30	0	0	10	0	0	0	10	10	10	0	0	0	0	0	0	0	0	80	0	0	0	0	0	0	0	0	0	20	10	0	10		
01:30	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	70	0	0	0	0	0	0	0	0	0	0	0	0	0		
02:30	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	70	10	0	0	0	0	0	0	0	0	0	0	0	0		
03:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0	0	0	0	0	0	0	0	0	0	0	0	0		
04:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0	0	10	0	0	0	0	0	0	0	10	0	0		
05:30	10	10	10	10	20	10	10	20	0	10	10	20	10	10	10	0	20	50	10	20	20	10	0	10	0	10	20	20	10	0	10		
06:30	0	0	10	10	0	10	0	0	10	10	0	10	10	0	10	0	30	0	10	0	10	10	0	0	10	20	10	0	0	10	10		
07:30	10	20	10	10	20	20	40	40	30	20	30	20	10	20	20	20	20	40	20	20	40	20	0	0	20	30	50	50	70	20	80		
08:30	30	40	40	60	20	40	10	20	0	20	10	10	20	10	20	10	10	20	20	20	10	0	0	20	30	10	60	20	80	70	70		
09:30	40	30	40	30	10	10	10	20	20	40	90	0	30	20	40	60	10	20	30	120	20	20	0	0	50	60	10	30	60	50	40		
10:30	50	80	60	30	40	60	20	10	0	30	50	10	10	70	50	20	90	40	130	100	40	10	0	60	40	20	50	60	40	30	30		
11:30	50	10	110	60	70	40	190	20	30	130	90	40	80	150	10	20	130	100	250	30	30	10	0	760	100	90	80	70	10	20	100		
12:30	20	0	180	200	70	40	130	40	40	100	10	30	110	150	20	10	50	70	50	0	40	20	0	110	60	100	50	50	10	30	180		
13:30	10	10	150	60	50	80	50	30	10	50	20	90	60	30	0	10	40	110	110	0	60	0	0	30	60	60	50	120	20	30	90		
14:30	430	40	40	40	20	10	50	30	0	40	40	180	60	60	0	20	30	30	70	0	40	0	0	30	40	50	60	80	40	40	110		
15:30	520	40	10	0	20	20	50	0	0	10	10	110	30	20	10	20	10	40	60	170	30	0	0	10	60	50	40	10	40	40	30		
16:30	550	0	20	10	50	30	30	0	20	20	30	20	50	10	0	10	10	0	30	60	10	0	0	10	10	50	100	70	10	30	10		
17:30	520	10	30	0	30	20	0	20	0	0	50	20	70	30	0	0	20	20	10	30	10	0	0	20	0	20	50	160	30	20	10		
18:30	180	30	10	0	120	30	40	10	20	20	10	30	30	40	20	10	30	30	40	230	20	0	0	10	20	90	40	70	50	20	60		
19:30	10	10	40	0	130	30	40	10	30	10	40	50	70	80	30	10	60	50	20	60	20	0	0	60	90	60	150	90	40	40	0		
20:30	10	0	20	70	30	20	50	20	50	20	80	70	60	70	30	40	150	30	30	30	10	0	0	50	50	50	70	80	50	30	10		
21:30	80	10	30	90	90	50	50	50	20	30	20	70	20	10	10	140	30	50	30	30	0	0	0	50	40	90	130	30	110	30	50		
22:30	20	0	10	0	10	20	40	10	10	10	10	50	10	20	40	20	160	60	20	30	20	0	0	20	40	80	110	40	20	30	20		
23:30	0	0	0	0	20	10	0	10	10	10	0	0	0	0	0	10	0	90	20	0	0	0	0	0	10	40	50	50	10	0	10		

Appendix-1L: BOOSTED WATER CONSUMPTION FOR BASELINE YEAR

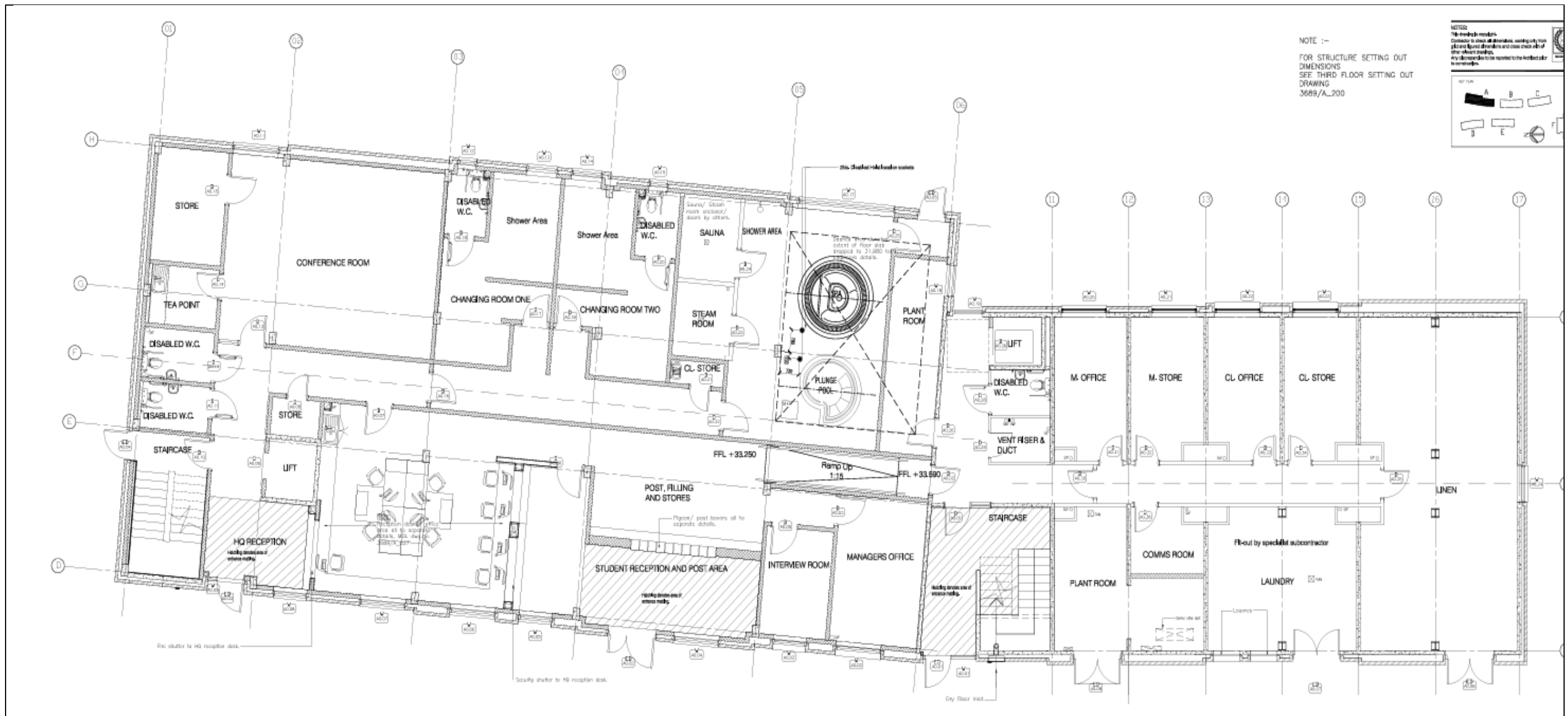
Date	Boosted Water Consumption (Litres)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	-	2,700	1,600	7,800	9,400	11,900	9,800	5,800	-	-	-	-
2	-	3,200	800	8,400	7,200	11,000	10,100	8,600	-	-	-	-
3	200	3,000	2,500	7,800	9,900	11,900	10,000	7,400	-	-	-	-
4	300	2,600	1,100	8,500	10,100	12,900	10,300	6,900	-	-	-	-
5	200	4,600	1,200	9,200	9,800	10,600	12,200	7,100	-	-	-	-
6	1,300	3,300	700	9,000	9,600	11,500	13,000	6,900	-	-	-	-
7	1,200	4,800	1,000	9,900	10,800	13,400	9,600	8,700	-	-	-	-
8	100	3,900	2,500	8,100	8,400	11,100	10,400	8,100	-	-	-	-
9	200	2,700	1,500	8,800	13,600	22,800	7,300	7,300	-	-	-	-
10	800	2,800	2,200	8,400	13,700	11,100	11,600	6,300	-	-	-	-
11	900	1,400	1,800	7,700	8,500	10,900	9,800	7,200	-	-	-	-
12	900	1,700	2,500	10,800	13,200	11,600	12,700	7,300	-	-	-	-
13	800	5,300	4,000	8,700	11,000	10,400	16,000	10,000	-	-	-	-
14	2,200	8,100	2,900	10,000	10,200	11,900	10,800	7,100	-	-	-	-
15	900	8,900	6,200	6,200	9,100	13,100	13,600	5,900	-	-	-	-
16	1,000	7,100	7,100	6,900	8,400	9,500	8,700	8,000	-	-	-	-
17	1,500	7,000	9,000	10,600	9,200	11,500	7,400	7,400	-	-	-	-
18	3,100	2,300	7,000	6,600	8,800	9,200	12,100	10,300	-	-	-	-
19	2,200	2,200	7,300	5,700	7,200	9,400	12,700	9,300	-	-	-	-
20	1,700	7,300	6,300	7,600	9,600	7,600	11,100	9,100	-	-	-	-
21	1,100	4,900	7,500	8,700	11,800	9,000	8,800	9,100	-	-	-	-
22	500	4,900	9,700	8,000	6,200	9,400	10,100	10,400	-	-	-	-
23	1,400	4,000	9,500	7,200	8,200	7,300	10,500	12,600	-	-	-	-
24	1,900	5,500	7,200	7,700	11,000	6,600	10,500	6,700	-	-	-	-
25	3,400	4,300	10,100	5,600	11,200	8,900	12,300	1,600	-	-	-	-
26	2,700	2,900	10,100	9,300	10,000	9,400	11,100	100	-	-	-	-
27	4,200	3,900	9,500	9,200	10,500	5,300	9,400	-	-	-	-	-
28	1,200	2,500	7,300	8,300	9,800	8,300	9,300	-	-	-	-	-
29	800		10,200	8,800	9,400	8,200	8,900	-	-	-	-	-
30	2,700		8,800	9,700	14,500	8,600	11,400	-	-	-	-	-
31	1,700		9,200		13,000		8,900	-		-		-
Total (Litres)	41,100	117,800	168,300	249,200	313,300	314,300	330,400	195,200	-	-	-	-

Appendix-1M: CELCIUS HEATING DEGREE DAY (HDD15.5)

2022 Month/ Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2.1	5.3	7.4	11	3.7	2.8	0.9	0	0	0.9	3.1	10.4
2	4.2	5.8	8.7	11.5	3	1.8	0.9	0	0	1.4	3.4	10
3	5.9	6.6	6.8	10.7	2.6	1	0.9	0	0	3.4	5	9.3
4	10.5	8.8	8.2	5.6	2.4	1.2	0.6	0	0	0.5	6.6	10.7
5	12.5	8.6	9.5	3.7	2.6	2.7	0.9	0.1	0	0.7	4.9	9.3
6	13	6.3	10.2	4.5	1.8	1.5	0.4	0.7	0.1	3	3.1	10.7
7	11.9	8.2	10.9	5.9	1.3	1.1	0	0.4	0.1	1.7	2.1	13
8	9.1	4.6	9.3	8.5	2.6	0.3	0.1	0	0.4	4	2.5	15.8
9	10.9	5.4	5.5	8.4	2.7	1	0	0	0.1	4.3	3.8	15.4
10	9.5	9.5	4.1	7.6	0.5	0	0	0	0.7	3.4	2.3	15.7
11	6.3	11.2	5.5	4.1	1.9	0.8	0	0	0.5	5.6	1.1	17.2
12	11	9.9	6	2.3	2.8	1	0	0	0	3.9	3.5	15.4
13	12.3	7.2	6.2	2.3	1.8	1.2	0	0	0	1.9	3.7	15.8
14	12.8	8.3	7.3	2.8	2.3	1.1	0	0	0.3	3	4.4	16.1
15	12.6	8.3	5.4	2.2	0.6	0.6	0.3	0	1	3.1	4.5	17.7
16	9.6	2.9	6.4	2.8	0.7	0.1	0.1	0	2.5	1.8	5.7	16.6
17	11.5	5.9	7.2	3.1	1	0	0	0	3.9	0.5	5.7	16
18	12.9	7.4	6.1	3	0.9	0.6	0	0	2.7	3.8	5.9	12.7
19	9.4	9.3	5.4	3.6	0.4	1.8	0	0	1.7	1.5	7.3	3.1
20	12.4	5.5	7.5	3.7	1.6	1	0	0.4	1.9	0.9	8	5.7
21	13.8	7.8	6.6	3.3	1.7	1	0	0.1	0.4	1.3	9	7.1
22	10.5	6.4	2.9	3.6	1.3	0.3	0	0.1	1.4	1	8.4	6.3
23	10	8.5	4	2.8	1.6	0.1	0	0	0.4	0.9	6.7	5.7
24	11.2	9.3	4.7	3.2	2.4	0.1	0	0	2.3	1.5	6.1	6.4
25	13.1	9.2	4.8	5.6	2.2	0.7	0	0	2.8	1.8	6.2	5.3
26	10.3	10.7	4.2	5.1	1.3	1	0	0.8	2.7	0.2	4.9	8.9
27	7.4	9.7	6.6	6.3	0.6	0.9	0.2	0	4.5	0.6	3.9	8.6
28	9.8	6.7	5.8	5.2	2.2	1	0	0.2	5.1	0.8	7.6	4.9
29	5.2	-	5.9	6.5	3.3	0.2	0.1	0	4.5	1.1	9.1	7.2
30	10	-	8	4.7	4.9	0.7	0	0.4	3.6	1.2	8.6	5.4
31	8.8	-	11.7	-	3.9	-	0	0.2	-	1.8	-	2.9
Total HDD	310.50	213.30	208.80	153.60	62.60	27.60	5.40	3.40	43.60	61.50	157.10	325.30

[illegible]

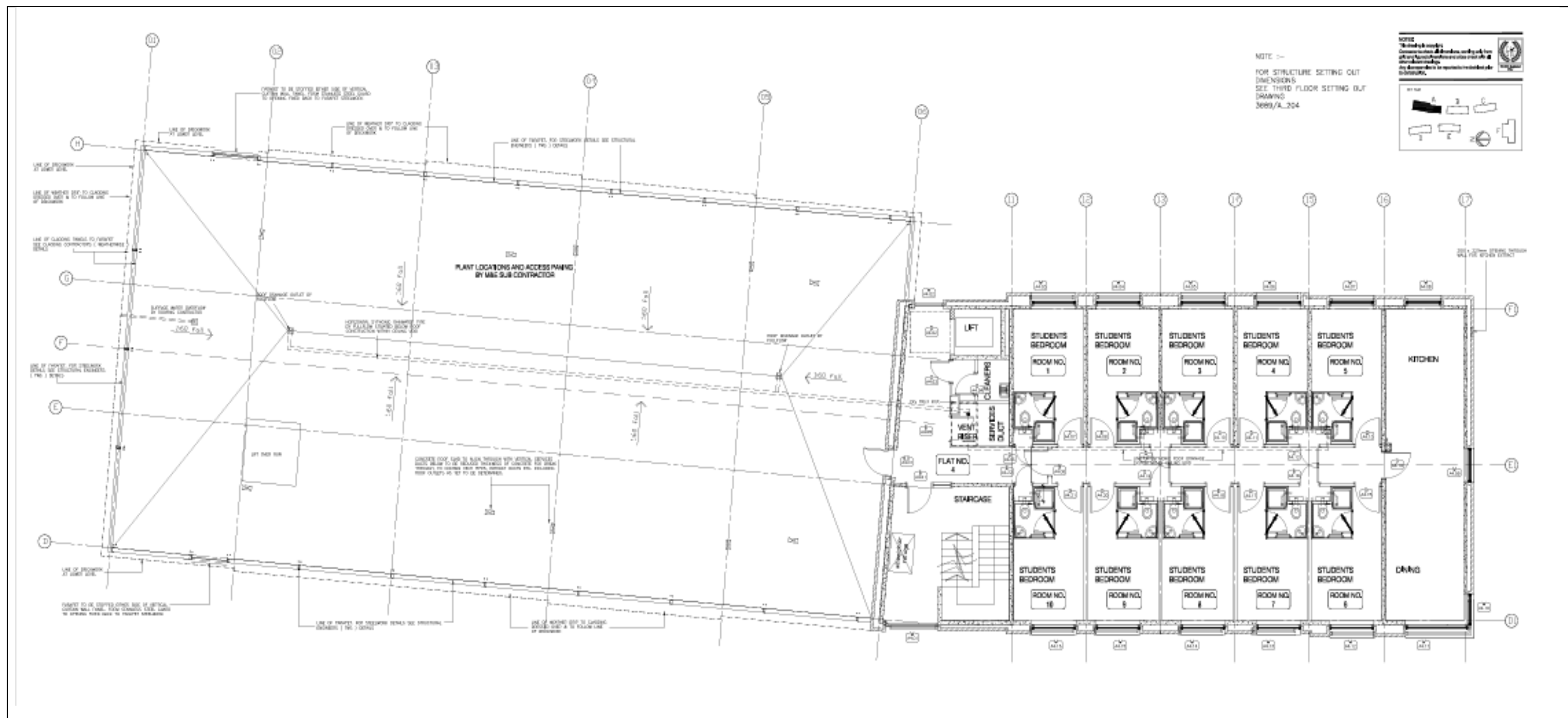
Appendix-10: ARCHITECTURAL DRAWINGS OF CASE STUDY

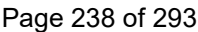


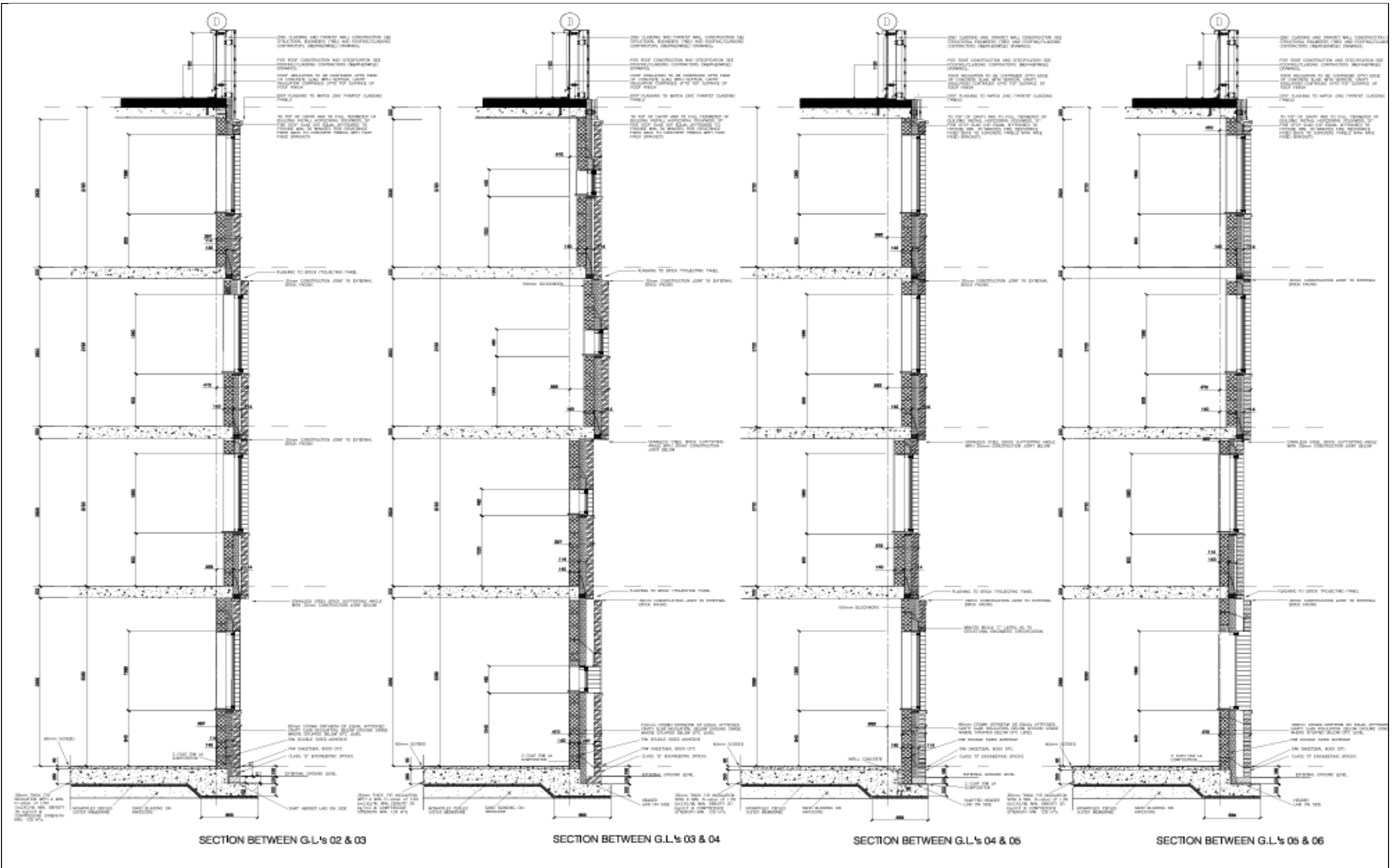




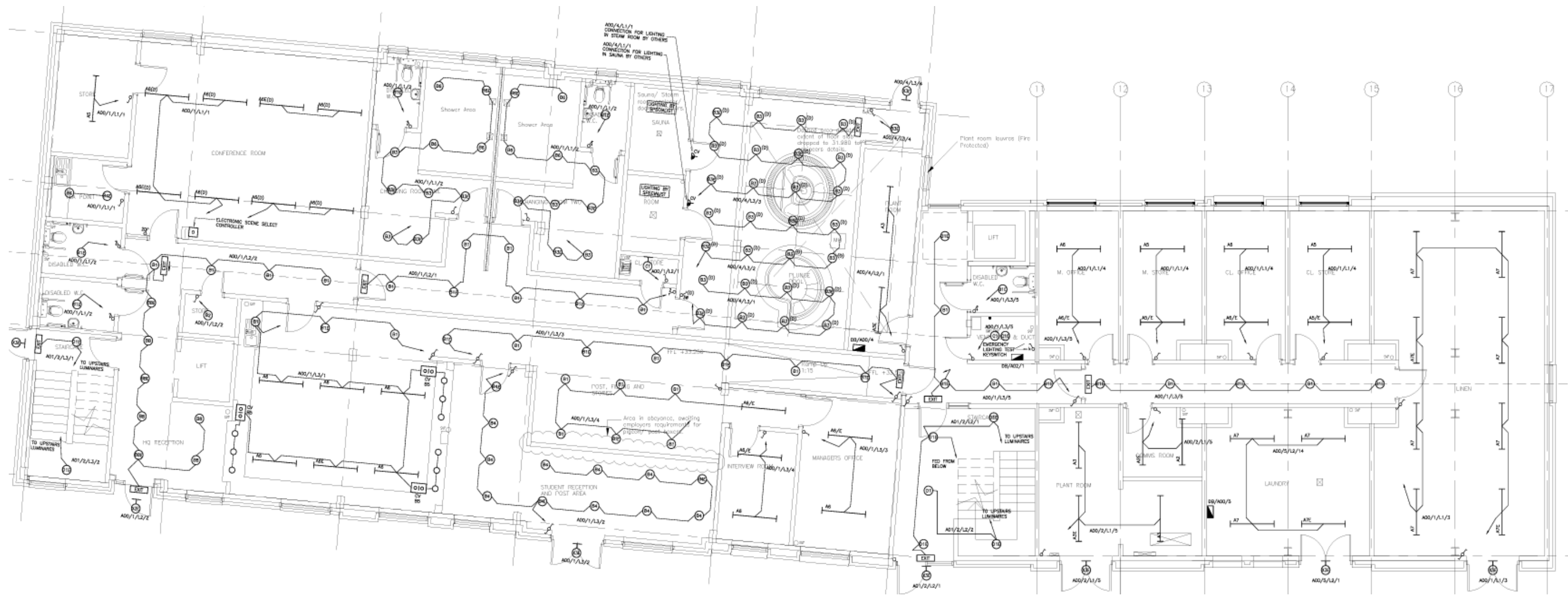








Appendix-1P: LIGHTING DRAWINGS OF THE CASE STUDY



NOTES.

1. POC UNIT PROVIDED WITH SWITCH BANK, STAND ALONE LIGHTING & JUNCTION BOX. INTERCONNECTION BETWEEN THESE & EXISTING POC UNIT SHOWN IN CONSTRUCTION. REFER TO DRAWING NO. 114228/101 FOR DETAILS & INTERCONNECTION SCHEDULE.
2. LUMINAIRE TO BE DIRECTLY CONNECTED TO SUPPLY INDEPENDENT FROM POC SWITCHING CIRCUIT.

LEGEND

- A1 2x20W 1000mm TB SURFACE MOUNTED FLUORESCENT MODULAR LUMINAIRE. PAPERLESS OPAL WHITE FINISHED REFLECTOR & ADDRESS UP LIGHTING VIA SECONDARY GUARDED (ANGLED) DIFFUSER WITH MATT WHITE POWDER COATED SURFACE (RHS-MIN).
- A2 1x20W 1000mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W OPTICAL SATIN LOW BRIGHTNESS REFLECTOR (SAT 2) (TUBERN - POPULAT).
- A3 1x20W 1000mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W POLYCARBONATE DIFFUSER (PDS-MIN).
- A4 1x20W 1000mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W SATIN COVER (SS) & SINGLE COULE (ST) (AS SPECIFICATION MTD).
- A5 1x20W 1000mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W PRISMATIC DIFFUSER.
- A6 1x20W 1000mm TB SUSPENDED DIRECT/INDIRECT LUMINAIRE (DIRECT LIGHT COMPONENT TO BE PROVIDED WITH LOW BRIGHTNESS SATIN DIFFUSER).
- A7 AS A2 BUT 2x20W.
- A8 2x20W 1000mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER.
- A9 2x20W 1000mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER.
- A10 2x20W TRACED MOUNTED MODULAR LUMINAIRE C/W LOW BRIGHTNESS DIFFUSE F.S.C.
- A11 2x20W SURFACE MOUNTED TB MODULAR LUMINAIRE C/W OPAL DIFFUSER.
- A12 TRACK SYSTEM (USING DECORATIVE MULTICOLOURED SPOTLIGHTS).
- B1 1x32W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B2 2x10W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B3 1x20W TC-TCL LUMINAIRE C/W 10W HALOGEN RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B4 2x10W TC-TCL LUMINAIRE C/W 10W HALOGEN RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.

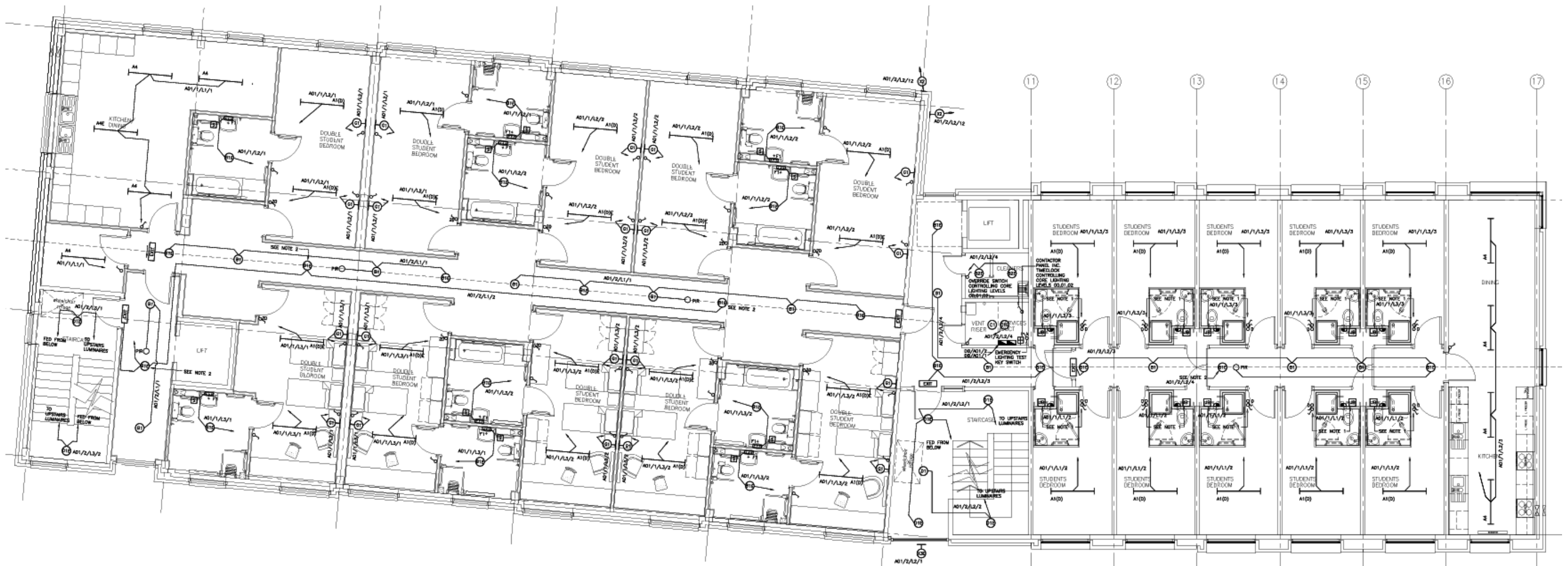
- B5 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B6 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B7 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
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- B20 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
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- B41 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B42 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.

- B43 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B44 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B45 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
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- B49 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B50 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B51 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B52 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B53 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.
- B54 2x20W TC-TCL 2000mm DEE LUMINEE RECESSED DOWNLIGHT C/W WHITE COOL & OPAL DIFFUSER, 10W HALOGEN.

Ground Floor Lighting Layout

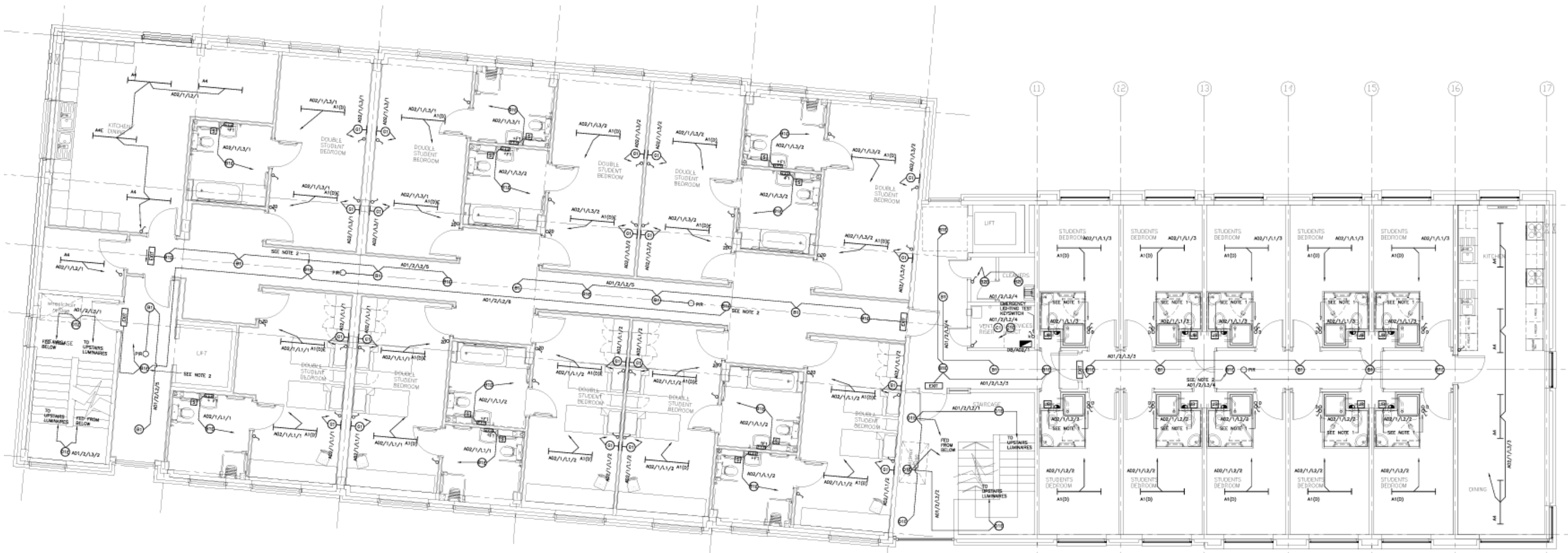


LEGEND

- A1 2x50W 1500mm T8 SURFACE MOUNTED FLUORESCENT MODULAR LUMINAIRE PROVIDING OPAL WHITE PERFORATED REFLECTOR & INDIRECT LIGHTING VIA SECONDARY V-SHAPED PARABOLIC DIFFUSER WITH MAT WHITE POWDER COATED SURFACE (R12-4000L)
- A2 1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL SATIN LOW BRIGHTNESS REFLECTOR (CAT 2) (THORN - POPULAR)
- A3 1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W POLYCARBONATE DIFFUSER (R12-4000L)
- A4 1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W SATIN COVER (SC) & SINGLE CABLE (ST) (AS ENCAPSULATED MTD)
- A5 1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W PRISMATIC DIFFUSER
- A6 1x50W 1500mm T8 SUSPENDED DIRECT/INDIRECT LUMINAIRE, DIRECT LIGHT COMPONENT TO BE PROVIDED WITH LOW BRIGHTNESS SATIN DIFFUSER
- A7 AS A3 BUT 2x50W
- A8 2x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER
- A9 2x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER
- A10(A) 2x50W TRACK MOUNTED MODULAR LUMINAIRE C/W LOW BRIGHTNESS DIFFUSE T.B.C.
- A11 1 X 50W SURFACE MOUNTED T8 MODULAR LUMINAIRE C/W OPAL DIFFUSER
- A1000 TRACK SYSTEM UTILISING DECORATIVE MULTI COLOURED SPOTLIGHTS
- A1 1x20W TO-TL 200mm DIA. SLIMLINE RECESSED DOWNLIGHT C/W WHITE REZEL & OPAL DIFFUSER, IP44 RATED
- A2 2x10W TO-TL IP44 RATED CIRCULAR SURFACE MOUNTED LUMINAIRE WITH POLYCARBONATE BODY & WHITE TRIM C/W POLYCARBONATE OPAL DIFFUSER
- A3 1x25W TO-TL LUMINAIRE C/W IP44 ETCHED GLASS ONLY
- A4 2x50W TC-D RECESSED CIRCULAR DOWNLIGHT C/W DECORATIVE FLOATING GLASS RING
- A5 2x25W TO-TL IP44 RATED RECESSED CIRCULAR DOWNLIGHT C/W ETCHED GLASS COVER
- A6 2x25W TO-TL RECESSED CIRCULAR FLUORESCENT DOWNLIGHT C/W FLOATING GLASS RING
- A7 2x25W TO-TL RECESSED CIRCULAR FLUORESCENT DOWNLIGHT C/W LOW BRIGHTNESS (CAT2) DIFFUSER
- A8 1x21W 3D SURFACE BULKHEAD LUMINAIRE C/W POLYCARBONATE BODY & POLYCARBONATE PRISMATIC DIFFUSER
- A9 2x18W TO-TL 335mm DIA. CEILING MOUNTED CIRCULAR DECORATIVE LUMINAIRE WHITE POLYCARBONATE BODY & POLYCARBONATE OPAL DIFFUSER
- A10 TO BE CONFIRMED
- A11 1x50W 1500mm 300mm T8 FLUORESCENT LUMINAIRE IP44 RATED MOUNTED ABOVE MIRROR
- A12 WALL MOUNTED LUMINAIRE 140WATT READING LIGHT (EXACT DETAILS TO BE CONFIRMED)
- A13 STANDARD CEILING ROSE PENDANT & DROP (DOMESTIC TYPE)
- A14 STANDARD CEILING MOUNTED BATTEN HOLDER (DOMESTIC TYPE)
- A15 DARKROOM LUMINAIRE TBC
- A16 1x30W 20 T8 BULKHEAD LUMINAIRE WALL MOUNTED C/W IP65 RATED POLYCARBONATE ENCLOSURE
- A17 500W TUNGSTEN HALOGEN FLOODLIGHT C/W INTEGRAL MOTION DETECTION & PHOTOCELL (P65 RATED)
- A18 1x20W 20 SURFACE MOUNTED DECORATIVE CIRCULAR LUMINAIRE WITH OPAL DIFFUSER & SILVER TRIM, IP65 RATED
- A19 AS A3 BUT C/W BLACK H200
- A20 'E' DENOTES C/W 3 HOUR EMERGENCY PACK
- A21 'V' DENOTES LUMINAIRE TO BE PROVIDED WITH DIMMABLE CONTROL GEAR

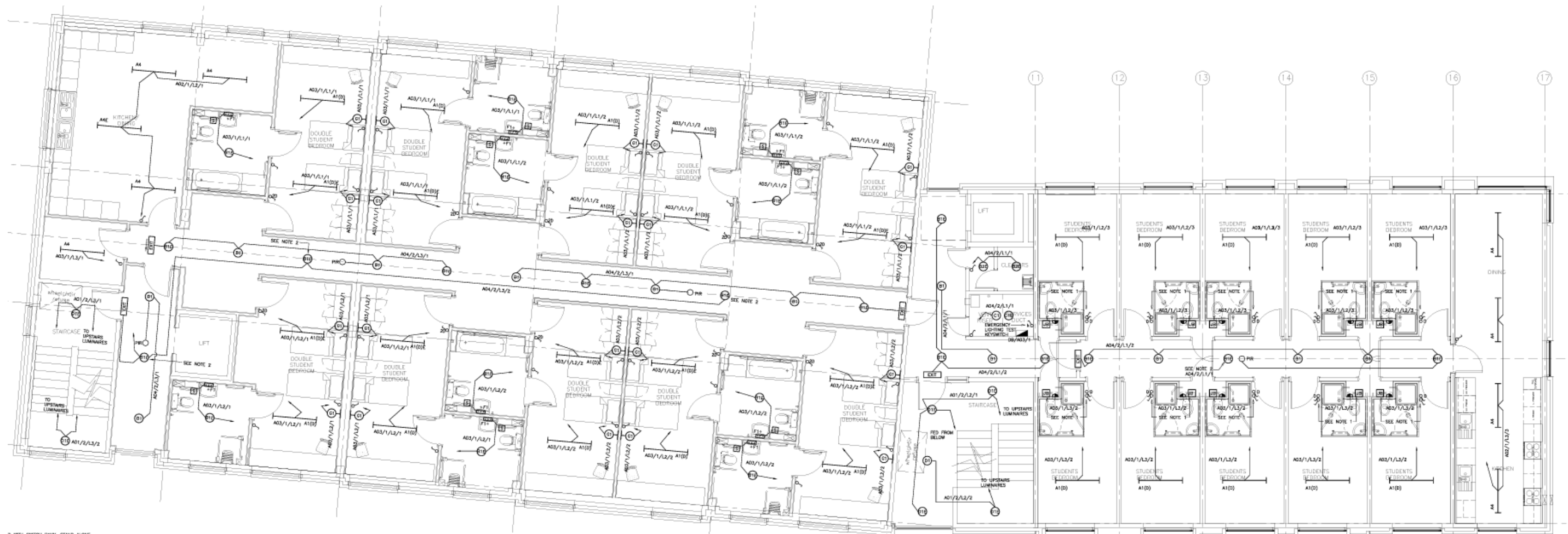
- 1 GANG 1 WAY SWITCH
- 1 GANG 2 WAY SWITCH
- 1 GANG DIMMER SWITCH
- IP65 RATED DIMMER SWITCH
- PASSIVE INFRARED PRESENCE DETECTOR
- PULL CORD 1 GANG 1 WAY SWITCH
- FUSED CONNECTION UNIT
- JOINT BOX FOR SWITCH INTERCONNECTION (PROVIDED BY PDD MANUFACTURER)
- SHOWER SOCKER C/W ISOLATING TRANSFORMER
- ILLUMINATED RUNNING MAN EXIT SIGN C/W INTEGRAL 3 HOUR BATTERY MAINTAINED TYPE
- DISTRIBUTION BOARD

First Floor Lighting Layout



- LEGEND**
- A1 2x58W 1500mm T8 SURFACE MOUNTED FLUORESCENT MODULAR LUMINAIRE PROVIDING OPAL WHITE PERFORATED REFLECTOR & INDIRECT UP LIGHTING VIA SECONDARY V-SHAPED PARABOLIC DIFFUSER WITH MATT WHITE POWDER COATED SURFACE (R10-HBM).
 - A2 1x58W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPTICAL SATIN LOW BRIGHTNESS REFLECTOR (CAT 2) (THORN - POPULAR).
 - A3 1x58W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W POLYCARBONATE DIFFUSER IP65 RATED.
 - A4 1x58W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W SATIN COVER (SC) & SINGLE CABLE (ST) (AS ENCAPSULATED M770).
 - A5 1x58W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W PRISMATIC DIFFUSER.
 - A6 1x58W 1500mm T8 SUSPENDED DIRECT/INDIRECT LUMINAIRE. DIRECT LIGHT COMPONENT TO BE PROVIDED WITH LOW BRIGHTNESS SATIN DIFFUSER.
 - A7 AS A3 BUT 2x58W
 - A8 2x58W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER.
 - A9 2x36W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER.
 - A10(A) 2x58W TRACE MOUNTED MODULAR LUMINAIRE C/W LOW BRIGHTNESS DIFFUSE T.B.C.
 - A11 1 X 58W SURFACE MOUNTED T8 MODULAR LUMINAIRE C/W OPAL DIFFUSER
 - △A10(B) TRACK SYSTEM UTILISING DECORATIVE MULTI COLOURED SPOTLIGHTS
 - B1 1x32W TC-TEL 200mm DIA SUMLINE RECESSED DOWNLIGHT C/W WHITE BEZEL & OPAL DIFFUSER. IP44 RATED.
 - B2 2x18W TCL IP44 RATED CIRCULAR SURFACE MOUNTED LUMINAIRE WITH POLYCARBONATE BODY & WHITE TRIM C/W POLYCARBONATE OPAL DIFFUSER.
 - B3 1x26W TC-TEL LUMINAIRE C/W IP44 ETCHED GLASS OVER
 - B4 2x26W TC-D RECESSED CIRCULAR DOWNLIGHT C/W DECORATIVE FLOATING GLASS RING.
 - B5 240 :12V TRANSFORMER AND 3 NO. 12V 50W HALOGEN BICHROMIC 100MM DIA CIRCULAR CHROME DOWNLIGHTS.
 - B6 2x26W TCL IP44 RATED RECESSED CIRCULAR DOWNLIGHT C/W FROSTED GLASS COVER
 - B7 2x26W TCL RECESSED CIRCULAR FLUORESCENT DOWNLIGHT C/W FLOATING GLASS RING
 - B8 2x26W TCL RECESSED CIRCULAR FLUORESCENT DOWNLIGHT C/W LOW BRIGHTNESS (CAT2) DIFFUSER
 - B9 1x21W 2D SURFACE BULKHEAD LUMINAIRE C/W POLYCARBONATE BODY & POLYCARBONATE PRISMATIC DIFFUSER.
 - B10 2x18W TC-L 335mm DIA CEILING MOUNTED CIRCULAR DECORATIVE LUMINAIRE WHITE POLYCARBONATE BODY & POLYCARBONATE OPAL DIFFUSER.
 - B11 TO BE CONFIRMED
 - B12 1x8W 1500mm 300mm T8 FLUORESCENT LUMINAIRE IP44 RATED MOUNTED ABOVE MIRROR
 - B13 WALL MOUNTED LUMINAIRE 1x8WATT READING LIGHT (EXACT DETAILS TO BE CONFIRMED)
 - B14 STANDARD CEILING ROSE PENDANT & DROP (DOMESTIC TYPE)
 - B15 STANDARD CEILING MOUNTED BATTEN HOLDER (DOMESTIC TYPE)
 - B16 DARKROOM LUMINAIRE TBC
 - B17 1x38W 2D T8 BULKHEAD LUMINAIRE WALL MOUNTED C/W IP65 RATED POLYCARBONATE ENCLOSURE
 - B18 500W TUNGSTEN HALOGEN FLOODLIGHT C/W INTEGRAL MOTION DETECTION & PHOTOCCELL IP65 RATED.
 - B19 1x28W 2D SURFACE MOUNTED DECORATIVE CIRCULAR LUMINAIRE WITH OPAL DIFFUSER & SILVER TRIM, IP65 RATED.
 - B20 AS X3 BUT C/W BLACK HOOD
 - B21 '1' DENOTES C/W 3 HOUR EMERGENCY PACK
 - B22 'D' DENOTES LUMINAIRE TO BE PROVIDED WITH DIMMABLE CONTROL GEAR.
 - C1 1 GANG 1 WAY SWITCH
 - C2 1 GANG 2 WAY SWITCH
 - C3 1 GANG DIMMER SWITCH
 - C4 IP65 RATED DIMMER SWITCH
 - C5 PASSIVE INFRA RED PRESENCE DETECTOR
 - C6 PULL CORD 1 GANG 1 WAY SWITCH
 - C7 FUSED CONNECTION UNIT
 - C8 JOINT BOX FOR SWITCH INTERCONNECTION (PROVIDED BY POO MANUFACTURER)
 - C9 SHOWER SOCKER C/W ISOLATING TRANSFORMER
 - C10 ILLUMINATED RUNNING MAN EXIT SIGN C/W INTEGRAL 3 HOUR BATTERY MAINTAINED TYPE
 - C11 DISTRIBUTION BOARD

Second Floor Lighting Layout



NOTES

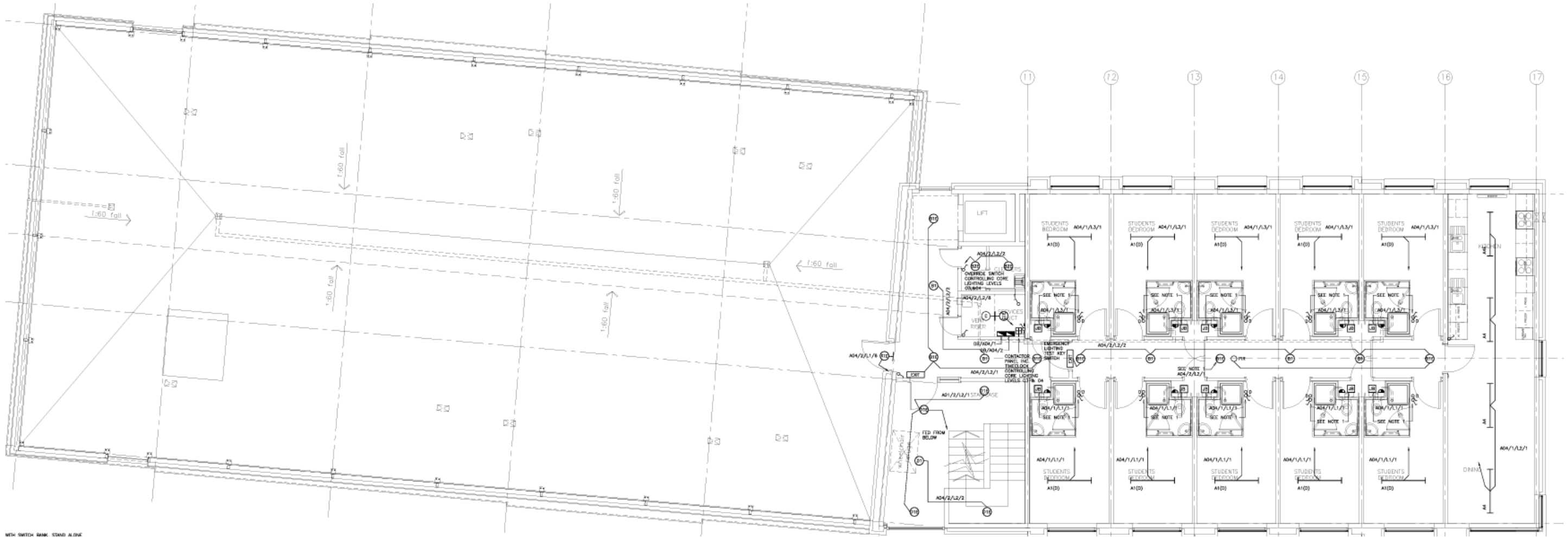
1. PDS UNIT PROVIDED WITH SWITCH BANK, STAND ALONE LIGHTING & JUNCTION BOX. INTERCONNECTION BETWEEN THESE & EXTRACT FAN DAMPER TO BE UNDERTAKEN BY CONTRACTOR. REFER TO DRAWING No. #1628/01 FOR DETAILS & INTERCONNECTION SCHEMATIC.
2. LUMINAIRE TO BE DIRECTLY CONNECTED TO SUPPLY INDEPENDENT FROM PIR SWITCHING CIRCUIT

LEGEND

A1	2x50W 1500mm T25 SURFACE MOUNTED FLOURESCENT MODULAR LUMINAIRE PROVIDING OPAL WHITE PERFORATED REFLECTION & INDIRECT LIGHTING VIA SECONDARY V-SHAPED PARABOLIC DIFFUSER WITH MATT WHITE POWDER COATED SURFACE (R90-NSM).
A2	1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPTICAL SATIN LOW BRIGHTNESS REFLECTOR (DAT 2) (THORN - POPULAR).
A3	1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W POLYCARBONATE DIFFUSER IP65 RATED.
A4	1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W SATIN COVER (DC) & SINGLE CABLE (ST) (AS ENCAPSULATED M720).
A5	1x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W PRISMATIC DIFFUSER.
A6	1x50W 1500mm T8 SUSPENDED DIRECT/INDIRECT LUMINAIRE, DIRECT LIGHT COMPONENT TO BE PROVIDED WITH LOW BRIGHTNESS SATIN DIFFUSER.
A7	AS A3 BUT 2x50W
A8	2x50W 1500mm T25 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER.
A9	2x50W 1500mm T8 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER.
A10(A)	2x50W TRACE MOUNTED MODULAR LUMINAIRE C/W LOW BRIGHTNESS DIFFUSE T-5 C.
A11	1 x 50W SURFACE MOUNTED T8 MODULAR LUMINAIRE C/W OPAL DIFFUSER
A12	TRACK SYSTEM UTILISING DECORATIVE MULTI COLOURED SPOTLIGHTS
B1	1x30W TC-TEL 300mm DIA SILKLINE RECESSED DOWNLIGHT C/W WHITE BEZEL & OPAL DIFFUSER, IP44 RATED.
B2	2x15W TC-TEL IP44 RATED CIRCULAR SURFACE MOUNTED LUMINAIRE WITH POLYCARBONATE BODY & WHITE TRIM C/W POLYCARBONATE OPAL DIFFUSER.
B3	1x50W TC-TEL LUMINAIRE C/W IP44 ETCHED GLASS OVER
B4	2x20W TC-D RECESSED CIRCULAR DOWNLIGHT C/W DECORATIVE FLOATING GLASS RING
B5	240 (15V) TRANSFORMER AND 3 NO. 15V 50W HALOGEN DISCHARGING 100MM DIA CIRCULAR CHROME DOWNLIGHTS.

B6	2x20W TC-TEL IP44 RATED RECESSED CIRCULAR DOWNLIGHT C/W TROTTED GLASS COVER
B7	2x20W TC-TEL RECESSED CIRCULAR FLUORESCANT DOWNLIGHT C/W FLOTTING GLASS RING
B8	2x20W TC-TEL RECESSED CIRCULAR FLUORESCANT DOWNLIGHT C/W LOW BRIGHTNESS (DAT2) DIFFUSER
C1	1x20W 20 SURFACE BULKHEAD LUMINAIRE C/W POLYCARBONATE BODY & POLYCARBONATE PRISMATIC DIFFUSER.
C2	2x15W TC-TEL 330mm DIA CEILING MOUNTED CIRCULAR DISCHARGING LUMINAIRE WHITE POLYCARBONATE BODY & POLYCARBONATE OPAL DIFFUSER.
C3	TO BE CONFIRMED
C4	1x50W 1500mm 300mm T8 FLUORESCENT LUMINAIRE IP44 RATED MOUNTED ABOVE MIRROR
C5	WALL MOUNTED LUMINAIRE 1x8WATT READING LIGHT (EXACT DETAILS TO BE CONFIRMED)
D1	STANDARD CEILING ROSE PENDANT & DROP (DOMESTIC TYPE)
D2	SARKOWSKI CEILING MOUNTED SATIN HOLDER (DOMESTIC TYPE)
D3	BATHROOM LUMINAIRE TRC
D4	1x50W 20 T8 BULKHEAD LUMINAIRE WALL MOUNTED C/W IP65 RATED POLYCARBONATE ENCLOSURE
D5	500W FLUORESCENT HALOGEN FLOODLIGHT C/W INTERNAL MOTION DETECTION & PHOTOCELL, IP65 RATED.
D6	1x20W 20 SURFACE MOUNTED DECORATIVE CIRCULAR LUMINAIRE WITH OPAL DIFFUSER & SILK TRIM, IP65 RATED.
D7	AS D6 BUT C/W BLACK HOOD
D8	T* DENOTES C/W 3 HOUR EMERGENCY PACK
D9	T* DENOTES LUMINAIRE TO BE PROVIDED WITH DIMMABLE CONTROL SEAR.

Third Floor Lighting Layout



WITH SWITCH BANK STAND ALONE

NOTES

1. FPD UNIT PROVIDED WITH SWITCH BANK, STAND ALONE LIGHTING & JUNCTION BOX, INTERCONNECTION BETWEEN THESE & EXTRACT FAN EXTRACT TO BE UNDERSTOOD BY CONTRACTOR, REFER TO DRAWING NO. J1622W/TD1 FOR DETAILS & INTERCONNECTION SCHEMATIC
2. LUMINAIRE TO BE DIRECTLY CONNECTED TO SUPPLY INDEPENDENT FROM PIR SWITCHING CIRCUIT

LEGEND

- A1** 2x50W 1500mm T25 SURFACE MOUNTED FLUORESCENT MODULAR LUMINAIRE PROVIDING C/W WHITE PREDIATED REFLECTOR & INDIRECT UPWARDING VIA SECONDARY Y-SHAPED PARABOLIC DIFFUSER WITH MAT WHITE POWDER COATED SURFACE (70%-ABLE)
- A2** 1x50W 1500mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W OPTICAL SATIN LOW BRIGHTNESS REFLECTOR (CAT 2) (70%-ABLE)
- A3** 1x50W 1500mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W POLYCARBONATE DIFFUSER (PIES SATD)
- A4** 1x50W 1500mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W SATIN COVER (SC) & SINGLE CABLE (ST) (AS DISCRETELY MTD)
- A5** 1x50W 1500mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W PRISMATIC DIFFUSER
- A6** 1x50W 1500mm TB SUSPENDED DIRECT/INDIRECT LUMINAIRE DIRECT LIGHT COMPONENT TO BE PROVIDED WITH LOW BRIGHTNESS SATIN DIFFUSER
- A7** AS A3 BUT 2x50W
- A8** 2x50W 1500mm T25 SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER
- A9** 2x50W 1500mm TB SURFACE MOUNTED MODULAR LUMINAIRE C/W OPAL DIFFUSER
- A10(A)** 2x50W TRACER MOUNTED MODULAR LUMINAIRE C/W LOW BRIGHTNESS DIFFUSE T/80
- A11** 1 x 50W SURFACE MOUNTED TB MODULAR LUMINAIRE C/W OPAL DIFFUSER
- A10(D)** TRACK SYSTEM UTILISING DECORATIVE MULTI COLOURED DIFFUSERS
- D1** 1x30W TO-TL 200mm DIA SLIMLINE RECESSED DOWNLIGHT C/W WHITE BEZEL & OPAL DIFFUSER, IP44 RATED
- D2** 2x10W TO-TL IP44 RATED CIRCULAR SURFACE MOUNTED LUMINAIRE WITH POLYCARBONATE BODY & WHITE TRIM C/W POLYCARBONATE OPAL DIFFUSER
- D3** 1x20W TO-TL LUMINAIRE C/W IP44 CLEAR GLASS OVER
- D4** 500W TO-D RECESSED CIRCULAR DOWNLIGHT C/W DECORATIVE FLOATING GLASS HING
- D5** 250 12V TRANSFORMER AND 3 NO. 12V 50W HALOGEN DICHROMIC 100MM DIA CIRCULAR CHROME DOWNLIGHTS

- D6** 2x20W TO-TL IP44 RATED RECESSED CIRCULAR DOWNLIGHT C/W FROSTED GLASS OVER
- D7** 2x20W TO-TL RECESSED CIRCULAR FLUORESCENT DOWNLIGHT C/W FLOATING GLASS HING
- D8** 2x20W TO-TL RECESSED CIRCULAR FLUORESCENT DOWNLIGHT C/W LOW BRIGHTNESS (CAT2) DIFFUSER
- D9** 1x21W 20 SURFACE BULKHEAD LUMINAIRE C/W 40 CARBONATE BODY & POLYCARBONATE PRISMATIC DIFFUSER
- D10** 2x15W TO-TL 335mm DIA CEILING MOUNTED CIRCULAR DECORATIVE LUMINAIRE WHITE POLYCARBONATE BODY & POLYCARBONATE OPAL DIFFUSER
- D11** TO BE CONFIRMED
- D12** 1x50W 1500mm 300mm TB FLUORESCENT LUMINAIRE IP44 RATED MOUNTED ABOVE M-RACK
- D13** WALL MOUNTED LUMINAIRE 1x1WATT BODILY LIGHT (EXACT DETAILS TO BE CONFIRMED)
- D14** STANDARD CEILING ROSE PENDANT & DROP (DOMESTIC TYPE)
- D15** STANDARD CEILING MOUNTED BATHING HOLDER (DOMESTIC TYPE)
- D16** DARKROOM LUMINAIRE TBC
- D17** 1x30W 20 TB BULKHEAD LUMINAIRE WALL MOUNTED C/W IP44 RATED POLYCARBONATE BODY
- D18** 500W TUNGSTEN HALOGEN FLOODLIGHT C/W INTERNAL MOTION DETECTION & PHOTOCCELL, PIR SWD.
- D19** 1x30W 20 SURFACE MOUNTED DECORATIVE CIRCULAR LUMINAIRE WITH OPAL DIFFUSER & SHAD FROM IP65 RATED
- D20** AS D3 BUT C/W BLACK HOOD
- D21** 'E' DENOTES C/W 3 HOUR EMERGENCY PACK
- D22** 'V' DENOTES LUMINAIRE TO BE PROVIDED WITH DIMMABLE CONTROL GEAR

Fourth Floor Lighting Layout

28# CONSTANT TEMP HTG RETURN IN CEILING VOID

28# CONSTANT TEMP HTG FLOW IN CEILING VOID

78# BOOSTED COLD WATER MAIN IN CEILING VOID

35# HOT WATER SERVICE RETURN IN CEILING VOID

67# HOT WATER SERVICE FLOW IN CEILING VOID

54# VARIABLE TEMP HTG FLOW IN CEILING VOID

54# VARIABLE TEMP HTG RETURN IN CEILING VOID

15# VARIABLE TEMP HTG FLOW IN CEILING VOID

15# VARIABLE TEMP HTG RETURN IN CEILING VOID

UPPM HEATING PRESSURISATION UNIT WITH EXPANSION VESSEL

15# BOOSTED COLD WATER TO UPPM PRESS UNIT WITH IV

450mm CABLE BASKET

STAIRS

MAIN ELECTRICAL PANEL

HEATING HEAT EXCHANGER

50# CONSTANT TEMP HTG F & R TO HEATING HEAT EXCHANGER WITH 2 PORT CONTROL VALVE, N/S, COMB VALVE & DRV

MECHANICAL CONTROL PANEL

COMMS. ROOM

50# VARIABLE TEMP HTG RETURN DROP TO RETURN HEADER WITH DRV

28# CONSTANT TEMP HTG RETURN DROP TO RETURN HEADER WITH DRV

25# PRESSURISATION UNIT SYSTEM MAKE UP CORN. DROP TO RETURN HEADER WITH IV

CONSTANT TEMP HTG TWIN PUMP SET WITH FLEX CORN. N/S

VARIABLE TEMP HTG TWIN PUMP SET WITH FLEX CORN. N/S

35# HOT WATER SERVICE RETURN WITH MAGNET TYPE WATER CONDITIONER & IV'S

35# HOT WATER SERVICE RETURN WITH CIRCULATING PUMP WITH IV'S

50# VARIABLE TEMP HTG PUMP SECTION WITH 3 WAY VALVE SET

67# BOOSTED COLD WATER TO HOT WATER GENERATOR WITH IV

67# HOT WATER SERVICE FLOW OFF HWS GENERATOR WITH IV

200 LITRE HOT WATER SERVICE EXPANSION VESSEL

1500 LITRE HOT WATER SERVICE GENERATOR

85# CONSTANT TEMP LOSS LOSS HEADER SERVING HWS GENERATOR

67# BOOSTED COLD WATER TO HOT WATER SERVICE GENERATOR WITH ELECTROMAGNETIC WATER CONDITIONER & IV'S

85# CONSTANT TEMP HTG FLOW TO LOW LOSS HEADER WITH 2 PORT CONTROL VALVE & IV & COMB VALVE

85# MOPPE BOOSTED COLD WATER RISE FROM BELOW GROUND & CHANGE TO 78# CU WITH IV DRIVE ASSEMBLY

78# BOOSTED COLD WATER TO STUDENT BEDROOMS

85# CONSTANT TEMP HTG F&R RISE FROM BELOW GROUND & CHANGE TO 85# STEEL WITH IV'S

85# BOOSTED COLD WATER BELOW GROUND

85# CONSTANT TEMP HTG F&R BELOW GROUND

LAUNDRY

28# CONSTANT TEMP HTG RETURN IN CEILING VOID

54# VARIABLE TEMP HTG RETURN FROM CEILING VOID

50# VARIABLE TEMP HTG FLOW

CONSTANT TEMP HTG TWIN PUMP SET WITH FLEX CORN. N/S

VARIABLE TEMP HTG TWIN PUMP SET WITH FLEX CORN. N/S

50# VARIABLE TEMP HTG PUMP SECTION WITH 3 WAY VALVE SET

50# VARIABLE TEMP HTG RETURN DROP TO RETURN HEADER WITH DRV

28# CONSTANT TEMP HTG RETURN DROP TO RETURN HEADER WITH DRV

50# VARIABLE TEMP HTG RETURN HEADER

50# VARIABLE TEMP HTG RETURN TO 3 WAY VALVE WITH DRV

VIEW ON PUMP SETS

78# BOOSTED COLD WATER MAIN IN CEILING VOID

67# HOT WATER SERVICE FLOW IN CEILING VOID

35# HOT WATER SERVICE RETURN IN CEILING VOID

54# VARIABLE TEMP HTG RETURN IN CEILING VOID

54# VARIABLE TEMP HTG FLOW IN CEILING VOID

150# LV BASKET

200# 4 COMPARTMENT TRUNKING L-R/DATA/TA/TV/SEC-BMS LIGHT FITTING

SECTION A-A

Appendix-1R: UK ELECTRICITY EMISSIONS FACTORS TO 2100

Year	Long-run Marginal (kgCO ₂ e/kWh)				Grid Average (kgCO ₂ e/kWh)			
	Consumption-based			Generation-based	Consumption-based			Generation-based
	Domestic	Commercial/ Public sector	Industrial		Domestic	Commercial/ Public sector	Industrial	
2010	0.389	0.382	0.375	0.357	0.499	0.490	0.480	0.457
2011	0.384	0.377	0.370	0.351	0.479	0.471	0.462	0.438
2012	0.377	0.370	0.363	0.344	0.530	0.520	0.510	0.483
2013	0.368	0.361	0.355	0.336	0.493	0.484	0.475	0.450
2014	0.361	0.355	0.348	0.329	0.443	0.434	0.426	0.403
2015	0.351	0.344	0.338	0.320	0.370	0.364	0.357	0.338
2016	0.340	0.334	0.328	0.311	0.296	0.291	0.285	0.271
2017	0.330	0.324	0.318	0.301	0.265	0.260	0.255	0.242
2018	0.319	0.313	0.307	0.291	0.246	0.241	0.237	0.224
2019	0.306	0.301	0.295	0.280	0.222	0.218	0.214	0.203
2020	0.293	0.288	0.283	0.268	0.197	0.194	0.190	0.180
2021	0.279	0.274	0.269	0.255	0.217	0.213	0.209	0.198
2022	0.264	0.260	0.255	0.241	0.158	0.155	0.152	0.144
2023	0.248	0.244	0.239	0.227	0.146	0.143	0.140	0.133
2024	0.231	0.227	0.223	0.211	0.151	0.149	0.146	0.138
2025	0.213	0.209	0.205	0.195	0.131	0.129	0.127	0.120
2026	0.193	0.190	0.186	0.177	0.098	0.096	0.095	0.090
2027	0.172	0.169	0.166	0.157	0.073	0.072	0.070	0.067
2028	0.150	0.147	0.144	0.137	0.063	0.062	0.061	0.058
2029	0.126	0.124	0.121	0.115	0.054	0.053	0.052	0.049
2030	0.100	0.098	0.096	0.091	0.049	0.049	0.048	0.045
2031	0.083	0.082	0.080	0.076	0.042	0.041	0.040	0.038
2032	0.069	0.068	0.067	0.063	0.033	0.032	0.032	0.030
2033	0.058	0.057	0.056	0.053	0.026	0.025	0.025	0.024
2034	0.048	0.047	0.046	0.044	0.021	0.020	0.020	0.019
2035	0.040	0.039	0.039	0.037	0.020	0.020	0.019	0.018
2036	0.033	0.033	0.032	0.030	0.020	0.019	0.019	0.018
2037	0.028	0.027	0.027	0.025	0.018	0.018	0.018	0.017
2038	0.023	0.023	0.022	0.021	0.018	0.018	0.017	0.016
2039	0.019	0.019	0.019	0.018	0.017	0.017	0.016	0.015
2040	0.016	0.016	0.015	0.015	0.016	0.016	0.015	0.015
2041	0.015	0.015	0.015	0.014	0.015	0.015	0.015	0.014
2042	0.015	0.014	0.014	0.013	0.015	0.014	0.014	0.013
2043	0.009	0.009	0.009	0.008	0.009	0.009	0.009	0.008
2044	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
2045	0.008	0.008	0.008	0.007	0.008	0.008	0.008	0.007
2046	0.008	0.008	0.007	0.007	0.008	0.008	0.007	0.007
2047	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
2048	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
2049	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
2050	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2051	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2052	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2053	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2054	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002

Year	Long-run Marginal (kgCO ₂ e/kWh)				Grid Average (kgCO ₂ e/kWh)			
	Consumption-based			Generation-based	Consumption-based			Generation-based
	Domestic	Commercial/ Public sector	Industrial		Domestic	Commercial/ Public sector	Industrial	
2055	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2056	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2057	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2058	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2059	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2060	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2061	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2062	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2063	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2064	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2065	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2066	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2067	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2068	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2069	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2070	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2071	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2072	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2073	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2074	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2075	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2076	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2077	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2078	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2079	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2080	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2081	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2082	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2083	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2084	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2085	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2086	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2087	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2088	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2089	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2090	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2091	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2092	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2093	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2094	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2095	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2096	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2097	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2098	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2099	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002
2100	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002

Appendix -2A: WGBC SUSTAINABLE BUILT ENVIRONMENT PRINCIPLES

PRINCIPLES	WHEN DEVELOPING POLICIES AND PROGRAMMES, NATIONAL AND LOCAL GOVERNMENTS MUST
 CARBON	Prioritise renovation of existing buildings and eliminate both operational and embodied carbon emissions across the lifecycle of all buildings.
 RESILIENCE	Enhance the ability of homes and communities to respond to external shocks and stressors by integrating climate resilience and promoting adaptation.
 CIRCULARITY	Drive waste out of the construction value chain and minimise the use of primary materials by optimising use of resources and materials.
 WATER	Conserve and protect water resources and guarantee equitable access to potable water and sanitation.
 BIODIVERSITY	Regenerate natural systems and restore biodiversity loss by avoiding development on land with high biodiversity, and by prioritising nature-based solutions that enhance, expand, and protect the natural environment.
 HEALTH	Develop healthy, equitable and resilient buildings and cities that deliver improvement in occupant, community and public health and wellbeing throughout the building and construction lifecycle.
 EQUITY AND ACCESS	Support equal access to safe, healthy, sustainable homes and communities for all citizens.

Appendix -2B: WEEKDAY HOURLY ELECTRICAL LOAD FOR THE BASE YEAR

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	27.43	23.00	25.48	26.10	27.82	28.00	29.33	25.48	27.36	26.38	27.27	28.82
01:00	27.62	23.20	23.22	25.33	25.64	26.09	28.29	27.83	26.45	24.67	26.64	29.27
02:00	27.24	22.60	19.18	25.52	24.64	25.55	26.95	20.11	21.11	26.38	24.91	27.36
03:00	26.48	21.50	24.78	25.33	26.91	25.55	27.90	25.04	26.18	27.62	26.55	27.64
04:00	27.05	21.80	25.51	24.38	25.18	23.82	26.95	26.84	26.91	25.81	24.00	25.64
05:00	25.81	21.70	24.84	24.95	23.73	25.91	28.95	25.38	25.05	24.10	24.09	25.55
06:00	27.62	22.90	25.02	25.81	26.82	28.00	30.10	27.56	27.00	27.24	25.82	26.55
07:00	42.57	42.50	36.71	43.90	48.64	53.91	55.43	41.02	38.95	53.62	51.73	45.00
08:00	41.52	43.10	37.24	48.57	47.00	50.00	53.81	39.20	37.41	51.14	53.64	44.55
09:00	44.29	44.40	36.98	49.52	49.55	54.09	54.57	39.38	43.00	53.33	59.27	50.36
10:00	39.14	36.40	31.64	43.71	45.55	44.73	44.00	35.42	38.27	46.00	46.27	44.18
11:00	38.95	33.60	39.20	40.10	42.73	40.18	39.52	44.98	47.09	43.43	41.55	42.91
12:00	40.29	33.90	49.24	52.95	59.55	58.00	58.67	52.98	55.64	60.67	65.18	56.36
13:00	35.71	32.00	50.44	52.67	59.82	60.55	58.38	57.82	56.41	58.48	62.45	52.82
14:00	34.10	30.80	46.89	51.14	55.45	56.45	54.76	52.53	54.14	59.43	63.64	55.09
15:00	33.33	30.50	38.13	36.48	37.27	35.36	40.38	40.40	41.32	39.90	39.73	42.55
16:00	35.81	32.10	39.69	38.19	38.73	37.45	42.29	45.96	47.05	44.00	44.82	46.09
17:00	39.33	33.90	40.13	40.38	36.91	39.55	44.57	43.47	47.23	40.48	42.45	51.27
18:00	50.10	50.90	46.40	54.19	54.36	53.82	53.05	54.22	55.59	60.86	64.55	58.00
19:00	50.38	52.90	44.00	55.90	55.45	55.00	53.24	46.27	49.82	61.05	64.00	58.45
20:00	50.86	52.20	44.71	60.38	58.55	56.18	55.52	49.33	54.00	64.86	66.82	59.82
21:00	47.81	49.70	44.84	53.33	53.73	53.55	51.62	46.76	49.09	57.81	59.45	54.09
22:00	30.48	28.20	42.49	30.29	33.64	34.09	35.52	44.18	47.64	33.43	35.00	36.00
23:00	28.86	24.80	40.22	28.76	28.09	28.91	29.33	44.00	44.55	27.90	29.18	36.45

Appendix -2C: WEEKEND HOURLY ELECTRICAL LOAD FOR THE BASE YEAR

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	24.80	24.50	25.50	28.44	28.00	27.25	28.40	27.50	27.50	27.00	30.00	30.00
01:00	25.60	24.25	25.00	25.56	27.78	26.75	28.20	26.75	27.50	25.60	29.00	31.33
02:00	25.20	23.25	20.25	25.33	20.50	28.75	20.95	22.25	20.13	20.05	29.75	28.22
03:00	25.80	23.00	23.00	26.89	26.44	26.00	25.40	28.75	27.25	25.00	31.25	25.33
04:00	25.20	21.00	25.13	26.22	27.22	24.50	26.00	26.13	25.75	25.90	31.50	25.11
05:00	25.00	21.00	24.63	24.89	25.44	27.50	26.10	28.25	25.38	25.80	27.75	27.78
06:00	27.20	22.25	25.00	24.67	24.78	25.50	25.80	26.50	28.25	24.00	29.50	25.78
07:00	32.20	41.50	32.50	38.00	32.78	44.75	38.50	39.75	42.50	37.60	52.50	44.89
08:00	34.80	42.50	34.88	45.56	36.11	50.75	42.10	39.75	37.25	36.60	52.25	47.11
09:00	40.00	44.50	35.00	50.44	39.67	57.00	41.00	40.38	41.75	38.90	60.50	49.78
10:00	35.00	43.00	32.88	49.78	39.11	52.75	40.40	42.00	42.13	38.10	54.50	45.56
11:00	28.80	32.00	40.50	39.11	45.89	38.00	47.60	48.38	47.88	46.10	38.75	35.11
12:00	31.60	31.25	41.63	34.67	44.00	36.75	45.80	45.13	44.63	45.40	42.25	39.78
13:00	30.20	30.00	41.25	33.78	45.11	35.00	43.10	48.00	45.63	50.50	42.00	34.67
14:00	31.60	29.50	37.88	37.33	40.89	35.00	40.50	47.88	43.75	43.60	42.50	35.33
15:00	30.20	30.25	36.63	34.44	39.00	35.25	35.00	39.38	40.50	38.20	38.00	41.56
16:00	32.20	30.75	45.63	34.89	48.11	36.75	46.10	50.75	51.25	52.90	47.00	43.33
17:00	32.00	30.50	43.50	35.56	49.78	37.50	46.40	48.50	48.88	49.60	45.00	41.11
18:00	41.80	45.75	48.38	54.00	52.89	50.50	52.90	56.63	55.63	62.20	59.50	51.11
19:00	41.60	46.50	40.63	53.11	41.56	49.00	43.60	47.50	48.25	49.20	56.00	56.44
20:00	43.80	46.00	43.75	52.22	44.67	55.50	45.20	50.13	51.63	51.60	67.75	53.56
21:00	42.20	43.50	44.13	48.89	44.67	53.50	42.70	49.88	44.63	48.80	53.75	53.11
22:00	30.40	27.25	41.88	32.67	42.44	33.25	44.10	46.38	47.25	49.10	35.50	33.78
23:00	25.60	23.75	39.13	29.33	42.33	28.25	41.00	47.13	44.63	45.70	29.25	34.44

Appendix -2D: BREAKDOWN OF TYPICAL ELECTRICITY RATES AND COST

Month	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23	May-23	Jun-23	Jul-23	Total
Variable	2022 Annual Costs and Rates												
Fixed Commodity	£118,677	£120,951	£208,939	£217,132	£218,815	£233,465	£216,308	£238,585	£259,377	£262,650	£282,968	£249,806	£2,627,673
CapRebate	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
Float Commodity	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
Margin + Fees	£1,692	£1,673	£1,808	£1,808	£1,847	£1,904	£1,741	£1,924	£1,609	£1,650	£1,668	£1,618	£20,943
Shape	£0	£0	£17,070	£17,739	£17,876	£19,073	£17,672	£19,492	£8,174	£8,277	£8,918	£7,873	£142,164
BSUOS	£13,570	£13,830	£34,943	£36,314	£36,595	£39,045	£36,176	£39,902	£35,134	£35,578	£38,330	£33,838	£393,254
Imbalance Swing	£3,316	£3,380	£3,995	£4,151	£4,184	£4,464	£4,136	£4,562	£1,502	£1,521	£1,639	£1,447	£38,296
Elexon	£644	£657	£780	£811	£817	£872	£808	£891	£740	£750	£808	£713	£9,288
RO	£43,291	£44,120	£46,348	£48,002	£48,407	£51,654	£47,897	£53,005	£51,041	£51,685	£55,684	£49,158	£590,292
FIT	£11,980	£12,209	£12,826	£13,283	£13,395	£14,294	£13,254	£14,668	£14,893	£15,081	£16,248	£14,344	£166,474
Capacity Mechanism	£0	£0	£9,041	£9,364	£9,443	£10,076	£9,343	£10,340	£9,260	£9,377	£10,102	£8,918	£95,265
FIT CFD	-£7,592	-£7,738	-£9,846	-£10,232	-£10,311	-£11,001	-£10,193	-£11,243	£13,488	£13,658	£14,715	£12,990	-£23,304
HydroLevy	£715	£729	£812	£844	£851	£908	£842	£929	£695	£703	£758	£669	£9,455
Rebate	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0
DUOSVAR	£16,221	£16,366	£18,289	£19,997	£19,313	£21,233	£19,711	£22,029	£16,076	£17,339	£18,793	£15,997	£221,364
DUOSCAP	£11,674	£11,298	£11,674	£11,298	£11,674	£11,674	£10,544	£11,674	£12,917	£13,348	£12,917	£13,348	£144,041
DUOSST	£3,129	£3,028	£3,129	£3,028	£3,129	£3,129	£2,827	£3,129	£1,956	£2,021	£1,956	£2,021	£32,485
TUOS	£21,057	£20,377	£21,057	£20,377	£21,057	£21,057	£19,019	£21,057	£1,736	£1,794	£1,736	£1,794	£172,118
TUOS_BND	£0	£0	£0	£0	£0	£0	£0	£0	£4,790	£4,949	£4,790	£4,949	£19,478
CCLeq	£6,803	£6,959	£7,807	£8,097	£8,066	£8,630	£8,030	£8,932	£7,327	£7,473	£7,912	£7,139	£93,176
VAT	£32,795	£33,180	£51,089	£52,827	£52,901	£56,244	£52,101	£57,732	£57,947	£59,143	£62,711	£56,593	£625,263
Total Cost	£277,972.50	£281,019.62	£439,762.17	£454,839.72	£458,059.15	£486,720.84	£450,215.17	£497,605.53	£498,664.12	£506,997.89	£542,653.29	£483,215.40	£5,377,725.40
Fixed Volume MWh	1,626	1,657	1,899	1,967	1,983	2,116	1,962	2,172	1,787	1,809	1,947	1,719	22,644
Floating Volume MWh	0	0	0	0	0	0	0	0	0	0	0	0	0
Cover Level %	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Volume MWh	1,626	1,657	1,899	1,967	1,983	2,116	1,962	2,172	1,787	1,809	1,947	1,719	22,644
Rate £/MWh	170.97	169.61	231.59	231.28	230.97	229.99	229.43	229.14	279.11	280.20	278.66	281.11	
Rate (£/kWh)	0.17	0.17	0.23	0.23	0.23	0.23	0.23	0.23	0.28	0.28	0.28	0.28	

Appendix -2E: AVERAGE DERIVED OCCUPANCY PROFILE FOR CASE STUDY

Time	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Actual Occupancy	42%	61%	58%	64%	73%	71%	76%	66%	75%	69%	61%	35%
	Average Derived Occupancy	Modulated Occupancy Profile											
00:00	0.313	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.3	0.3	0.2
07:00	0.313	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.3	0.3	0.2
07:00	0.600	0.4	0.6	0.6	0.6	0.7	0.7	0.7	0.6	0.7	0.7	0.6	0.3
08:00	0.600	0.4	0.6	0.6	0.6	0.7	0.7	0.7	0.6	0.7	0.7	0.6	0.3
08:00	0.369	0.2	0.4	0.3	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.2
09:00	0.369	0.2	0.4	0.3	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.2
09:00	0.313	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.3	0.3	0.2
10:00	0.313	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.3	0.3	0.2
10:00	0.181	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
15:00	0.181	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
15:00	0.175	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
19:00	0.175	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
19:00	0.206	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.1
21:00	0.206	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.1
21:00	0.256	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1
22:00	0.256	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1
22:00	0.407	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.4	0.4	0.2
23:00	0.407	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.4	0.4	0.2
23:00	0.357	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.2
00:00	0.357	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.2

Appendix -2F: INFLATION RATES: ELECTRICITY, GAS & OTHER FUELS

Year	Parts per 1000	Average Inflation (%)
1988	62.00	6.2
1989	62.00	6.2
1990	58.00	5.8
1991	54.00	5.4
1992	53.00	5.3
1993	52.00	5.2
1994	49.00	4.9
1995	49.00	4.9
1996	45.00	4.5
1997	44.00	4.4
1998	43.00	4.3
1999	40.00	4
2000	33.00	3.3
2001	29.00	2.9
2002	28.00	2.8
2003	28.00	2.8
2004	26.00	2.6
2005	28.00	2.8
2006	32.00	3.2
2007	39.00	3.9
2008	35.00	3.5
2009	46.00	4.6
2010	47.00	4.7
2011	44.00	4.4
2012	56.00	5.6
2013	48.00	4.8
2014	45.00	4.5
2015	42.00	4.2
2016	35.00	3.5
2017	34.00	3.4
2018	34.00	3.4
2019	31.00	3.1
2020	33.00	3.3
2021	33.00	3.3
2022	36.00	3.6
2023	49.00	4.9
2024	40.89	4.09
2025	33.66	3.37

Appendix -2G: BANK OF ENGLAND MONTHLY MPC RATES, 1997 – 2024

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Year	BOE Bank Rates (%) between 1997- 2024												
1997	-	-	-	-	6.25	6.50	6.75	7.00	7.00	7.00	7.25	7.25	6.88
1998	7.25	7.25	7.25	7.25	7.25	7.50	7.50	7.50	7.50	7.25	6.75	6.25	7.21
1999	6.00	5.50	5.50	5.25	5.25	5.00	5.00	5.00	5.25	5.25	5.50	5.50	5.33
2000	5.75	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	5.98
2001	6.00	5.75	5.75	5.50	5.25	5.25	5.25	5.00	4.88	4.75	4.50	4.00	5.16
2002	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
2003	4.00	3.75	3.75	3.75	3.75	3.75	3.50	3.50	3.50	3.50	3.75	3.75	3.69
2004	3.75	4.00	4.00	4.00	4.25	4.50	4.50	4.75	4.75	4.75	4.75	4.75	4.40
2005	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.50	4.50	4.50	4.50	4.50	4.65
2006	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.75	4.75	4.75	5.00	5.00	4.65
2007	5.25	5.25	5.25	5.25	5.50	5.50	5.75	5.75	5.75	5.75	5.75	5.50	5.52
2008	5.50	5.25	5.25	5.00	5.00	5.00	5.00	5.00	5.00	4.50	3.00	2.00	4.63
2009	1.50	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.63
2010	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2011	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2012	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2013	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2014	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2015	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
2016	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.40
2017	0.25	0.25	0.25	0.25	0.25	0.25	0.50	0.50	0.50	0.50	0.50	0.50	0.38
2018	0.50	0.50	0.50	0.50	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.67
2019	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	-	-	-	-	0.75
2020	0.75	0.25	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	-	-	0.18
2021	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.25	-	-	-	-	0.12
2022	0.50	0.75	1.00	1.25	1.75	2.25	3.00	3.50	-	-	-	-	1.75
2023	-	4.00	4.25	-	4.50	5.00	-	5.25	5.25	-	5.25	5.25	4.84
2024	-	5.25	5.25	-	5.25	5.25	-	5.00	5.00	-	-	-	5.17

Appendix -2H: IESVE®-APACHE™ SYSTEM INPUTS

System Variables/ Parameters	Annotations and References
A. Heating 1) Generator: ☐ Equipment: Boiler; Meter: Natural Gas (Meter-1) ☐ Seasonal Efficiency: 1.0890; Heating Delivery Efficiency (HDE): 0.8923 ☐ Seasonal Coefficient of Performance -SCoP (kW/kW): 0.96; ☐ Generator Size (kW): 245.71 2) Heat Recovery ☐ Ventilation Heat Recovery Effectiveness: 0.8000 ☐ Ventilation Heat Recovery Return Air Temp.: 21°C	☐ Seasonal Efficiency (Annual Efficiency = 108.9%) of boiler is obtained from the boiler datasheet in (Error! Reference source not found.). ☐ SCoP value is selected within the range of (0.9 – 1.2), the typical range for UK commercial condensing boilers. ☐ The Generator Size is autosized from IESVE®-Apache™ CIBSE Loads calculations. ☐ The measured value of Heat Recovery Effectiveness for industrial boilers in the UK (0.8) is assumed.
B. Cooling/ Ventilation Mechanism 1) Natural or Mechanical Ventilation 2) Applicable to systems that include Air-conditioning: a) Generator: ☐ Mechanism: Air-conditioning, Meter: Electricity (Meter-1) ☐ Nominal Energy Efficiency Ratio- EER (kW/kW): 3.51 ☐ Seasonal Energy Efficiency Ratio -SEER (kW/kW): 4.0 ☐ Cooling Delivery Efficiency (CDE): ☐ SSEER (kW/kW): 1.3 ☐ Generator Size (kW): 683.37 b) Heat Rejection (% of rejected heat): 10%	☐ Nominal EER is based on performance data of AERMEC LPG-500D unitary air conditioner in datasheet Error! Reference source not found. ☐ SEER value of (4.0) is selected based on the benchmark minimum EER of 3.37 in the “UK Government Buying Standards” for air-conditioning units. ☐ SSEER (Equation 3.31).
C. Hot Water 1) Generator: a) DHW Delivery Efficiency: 100% 2) Set Points: a) Mean Cold Water Inlet Temp. (°C):10, Hot Water Supply Temp. (°C): 60 3) Storage (Factory-insulated): a) Is this a storage system? YES, Storage Volume (l): 1500 b) Insulation Thickness (mm): 50 c) Secondary Circulation: YES, Loop Length (m) =100 d) Storage Losses (kWh/(l.day): 0.0152	☐ DHW Delivery Efficiency is set at 100% because secondary circulation is used in the model, implying that the pip heat losses are accounted in the cold water run-off. ☐ Hot water supply temperature is set at 60°C according to recommendation of CIBSE Guide A (Parand <i>et al.</i> , 2021) to prevent multiplication of legionella. ☐ The storage tank size and insulation thickness are 1500L and 50mm respectively, from the design drawings (Error! Reference source not found.). ☐ The value of storage losses is adapted from IESVE®-Apache™ documentation adapted from UK SAP 2005 “Hot Water Storage Loss Factors and Cylinder Loss Factors” below.

System Variables/ Parameters	Annotations and References																																
	<table><tr><th rowspan="2">Insulation thickness, mm</th><th colspan="2">Cylinder loss factor (L) kWh/litre/day</th></tr><tr><th>Factory insulated cylinder</th><th>Loose jacket</th></tr><tr><td>0</td><td>0.1425</td><td>0.1425</td></tr><tr><td>12</td><td>0.0394</td><td>0.0760</td></tr><tr><td>25</td><td>0.0240</td><td>0.0516</td></tr><tr><td>35</td><td>0.0191</td><td>0.0418</td></tr><tr><td>38</td><td>0.0181</td><td>0.0396</td></tr><tr><td>50</td><td>0.0152</td><td>0.0330</td></tr><tr><td>80</td><td>0.0115</td><td>0.0240</td></tr><tr><td>120</td><td>0.0094</td><td>0.0183</td></tr><tr><td>160</td><td>0.0084</td><td>0.0152</td></tr></table> <i>Note:</i> <i>Alternatively the heat loss factor, L, may be calculated for insulation thickness of t mm as follows:</i> 1) Cylinder, loose jacket $L = 0.005 + 1.76/(t + 12.8)$ 2) Cylinder, factory insulated $L = 0.005 + 0.55/(t + 4.0)$	Insulation thickness, mm	Cylinder loss factor (L) kWh/litre/day		Factory insulated cylinder	Loose jacket	0	0.1425	0.1425	12	0.0394	0.0760	25	0.0240	0.0516	35	0.0191	0.0418	38	0.0181	0.0396	50	0.0152	0.0330	80	0.0115	0.0240	120	0.0094	0.0183	160	0.0084	0.0152
Insulation thickness, mm	Cylinder loss factor (L) kWh/litre/day																																
	Factory insulated cylinder	Loose jacket																															
0	0.1425	0.1425																															
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35	0.0191	0.0418																															
38	0.0181	0.0396																															
50	0.0152	0.0330																															
80	0.0115	0.0240																															
120	0.0094	0.0183																															
160	0.0084	0.0152																															
D. Auxiliary Energy 1) Auxiliary Energy Method: Use AEV (and any zone-level SFP). a) AEV (W/m²): 8.287 b) Eq. to () 3255 hrs of operation: 26.974 c) Off-schedule Heating/ Cooling AEV (W/m²): 0.0 d) Auxiliary Energy Fan Fraction: 0.500 e) Meter: Electricity (Meter-1)																																	
E. Air Supply 1) Outside Air Supply: a) Supply Condition: External Air. b) Max. flow rate (l/s): . 2) Fans- Air Supply Mechanism: Local Ventilation 3) Cooling (Vent.) Air Supply Sizing: a) Air supply temp. diff. (K): 4 b) Max.flow rate (l/s): 63.90																																	

Appendix -2I: TECHNICAL DATA - REMEHA® GAS 610 ECO™ BOILER

Extract of Technical Data - Remeha® Gas 610 ECO™ Boiler

Remeha Gas 610 ECO

2 GENERAL DESCRIPTION OF BOILER

The Remeha Gas 610 ECO is a free standing, gas fired (Natural gas only), fully modulating high efficiency condensing boiler. The boiler consists of two modules with each a heat exchanger, fan and control. Each module is being delivered fully assembled, plastic wrapped and crated on a pallet. The sectional cast aluminium heat exchangers and other major components are contained within a rigid steel frame with removable casing parts for maintenance purposes. The frame of each module is fitted with a set of casters to enable the assembled unit to be easily manoeuvred into position within the plant room on site with the minimum of effort. All major electrical and electronic controls are contained within the instrument panel (of each boiler module) mounted on top of the boiler module at the opposite end to the connections facing to the front of each module (long side) but can be rotated 90° towards the short side to suit site location.

The boiler consists of two modules, a "left-hand" version and a "right-hand" version. The service side (with the inspection hatch of the heat exchanger) of each module is considered to be the front side of that module (see par. 4.4).

The flue gas outlet c/w the condensate connections will be at low level on the same side as the connections. Combustion air inlet (for room sealed operation) is located at the top of the boiler.

The boiler is suitable for room sealed or open flue applications and have been designed for central heating and indirect hot water production at working pressures not exceeding 6 bar. It must be installed on a fully pumped system and is designed for operating pressures between 0.8 and 6 bar.

The pre-mix gas burners (NG only) with its gas/ air ratio control system ensures clean, trouble free operation with higher than average efficiencies of up to 109% Hi (NCV) in the condensing mode combined with ultra low NOx and minimum CO emissions.

The standard control package allows for external On/ Off, High Low (volt free switch/s) or modulating control (0-10V input) of each module. The built in digital display of each module shows normal operating/ fault code indication and allows actual and set values to be read and adjusted.

The intelligent, advanced boiler control ('abc[®]') continuously monitors the boiler module operating conditions, varying the heat output to suit the system load. The control is able to react to external "negative" influences in the rest of the system (flow rates, air/ gas supply problems) maintaining boiler output for as long as possible without resorting to a lock out condition. At worst the boiler will reduce its output and/ or shut down (shut off mode) awaiting the "negative" conditions to return to normal before re-starting.

The 'abc[®]' control cannot override the standard flame safety controls.

All Gas 610 ECO boilers are live fired after assembly to ensure the boiler and controls comply with our strict quality policy.

The unit has been inspected for compliance with the essential requirements of the following directives:

- Gas Appliances Directive, no. 90/396/EEC
- Efficiency Directive, no. 92/42/EEC
- EMC Directive, no. 89/336/EEC
- Electrical Low Voltage Directive, no. 73/23/EEC
- Pressure Equipment Directive, no. 97/23/EEC, art. 3, item 3

CE identification number (PIN) : 0063BP3474

NO_x Class : 5

Type classification of
flue gas discharge : B23, C33, C43, C53,
C63, C83

Remeha Gas 610 ECO

4.2 Technical data

Boiler type		Unit	Remeha Gas 610 ECO			
			2 x 6 sections	2 x 7 sections	2 x 8 sections	2 x 9 sections
General						
Boiler control options		-	Modulating, 2-stage or 4-stage			
Nominal output P _n (80/ 60°C)	min	kW	87	123	122	148
	max	kW	654	790	924	1062
Nominal output P _n (50/ 30°C)	min	kW	94	131	130	156
	max	kW	706	854	998	1146
Nominal input Q _n (GCV/ Hs)	min	kW	101	142	141	170
	max	kW	744	896	1046	1196
Nominal input Q _n (NCV/ Hi)	min	kW	91	128	127	153
	max	kW	672	808	942	1078
Efficiency (Hi)						
Combustion (Hi) at 80/ 60°C		%	up to 99			
Heat to water (Hi) at 80/ 60°C		%	up to 98,5			
Standing losses (T _{average} = 45°C)		%	< 0.3			
Annual efficiency (Hi)		%	108,9			
Gas and flue gas side						
Gas category		-		Natural gas only		
Inlet pressure gas (boiler running)	min	mbar		17		
	max	mbar		100		
Gas consumption		m ₀ ³ / h	74	86	100	114
NO _x emission* (DIN 4702 p.8; annual emissions)		mg/ kWh	< 60			
NO _x emission* (DIN 4702 p.8; annual emissions, O ₂ = 0%, dry)		ppm	< 35			
Residual fan duty		Pa	130			
Flue gas mass	min	kg/ h	153	215	214	257
	max	kg/ h	1130	1360	1586	1814
Flue gas temperature at 80/ 60°C	min	°C	57			
	max	°C	65			
Type classification due to discharging flue gasses		-	B23, C33, C43, C53, C63, C83			
Water side						
Flow temperature	High Limit	°C	110			
	Operating	°C	20 - 90			
Operating pressure	min	bar	0.8			
	max PMS	bar	6			
Water contents		litres	120	142	164	186
Water resistance at 11°C ΔT		mbar (kPa)	364 (36.4)	397 (39.7)	364 (36.4)	413 (41.3)
Water resistance at 20°C ΔT		mbar (kPa)	110 (11)	120 (12)	110 (11)	125 (12.5)



5 EFFICIENCY INFORMATION

5.1 Annual efficiency (92/42EEC)

Up to 108.9% at Hi (up to 97% at Hs) at an average water temperature of 40°C (50/ 30°C).

5.2 Heat to water efficiency (92/42EEC)

- a. Up to 98.5% at Hi (88% at Hs) at an average water temperature of 70°C (80/ 60°C).
- b. Up to 106.4% at Hi (98% at Hs) at an average water temperature of 40°C (50/ 30°C).

5.3 Standing losses

Less than 0.3% at Hi (0.33% at Hs) at an average water temperature of 45°C

Note: NCV = Hi, GCV = Hs

6 APPLICATION DATA

The Gas 610 ECO can be used on all new and refurbishment projects in both single and multiple configurations. Conventional and room sealed flue system capability means that the boiler modules can be sited almost anywhere within a building.

The Remeha weather compensators (option) are able to communicate directly with the boiler's controls to make full use of their fully modulating features, ensuring that the boiler module closely matches the system demand at all times.

External control systems (BMS) can be interfaced with the boiler modules to provide 2-stage or 4-stage or modulating (0 -10V) control options.

Appendix -3A: CONTEMPORARY AND FUTURE WEATHER PARAMETERS

2020/22	Gh (kWh/m ²)	Dh (kWh/m ²)	Bn (kWh/m ²)	Ta (°C)	Td (°C)	FF (m/s)
Jan	35	20	51	0.4	-2.5	2.7
Feb	55	24	82	1.2	-2.6	2.8
Mar	101	46	116	5.3	0.1	3
Apr	137	61	137	9.4	3.6	2.9
May	164	80	137	13.4	7.6	2.8
Jun	185	76	173	17.6	11.6	2.8
Jul	188	76	179	19	12.7	2.7
Aug	160	65	158	18.4	12.9	2.5
Sep	116	51	125	14.3	10.1	2.5
Oct	73	32	96	10	6.9	2.4
Nov	38	20	58	4.7	2.1	2.4
Dec	28	16	44	1.1	-1.4	2.6
Year	1280	567	1356	9.6	5.1	2.7

2030	Gh (kWh/m ²)	Dh (kWh/m ²)	Bn (kWh/m ²)	Ta (°C)	Td (°C)	FF (m/s)
Jan	34	22	42	1.0	-1.9	2.7
Feb	54	29	71	2.0	-1.9	2.8
Mar	101	46	113	6.4	1.1	3.0
Apr	141	56	151	10.2	4.4	2.9
May	171	81	142	14.5	8.7	2.8
Jun	193	84	175	18.5	12.5	2.8
Jul	198	72	203	20.2	14.0	2.7
Aug	171	63	181	19.7	14.3	2.5
Sep	125	42	158	15.4	11.3	2.5
Oct	75	38	88	10.8	7.8	2.4
Nov	38	22	54	5.2	2.6	2.4
Dec	28	17	40	1.9	-0.6	2.6
Year	1329	572	1418	10.5	6	2.7

2050	Gh (kWh/m ²)	Dh (kWh/m ²)	Bn (kWh/m ²)	Ta (°C)	Td (°C)	FF (m/s)
Jan	33	21	43	1.9	-0.9	2.7
Feb	54	27	71	2.6	-1.3	2.8
Mar	100	42	122	6.6	1.4	3.0
Apr	141	70	129	10.8	4.9	2.9
May	174	78	158	15.2	9.4	2.8
Jun	198	79	191	19.4	13.4	2.8
Jul	202	79	201	21.1	14.8	2.7
Aug	177	60	195	20.9	15.4	2.5
Sep	126	50	144	16.1	11.8	2.5
Oct	76	40	87	11.4	8.3	2.4
Nov	38	21	52	5.8	3.1	2.4
Dec	28	17	43	2.3	-0.3	2.6
Year	1347	584	1436	11.2	6.7	2.7

Appendix -3B: U-VALUES IN UKFBS

	2013 U-values for new elements in existing non-domestic buildings (W/m ² .K)	Proposed U-values for new elements in existing non-domestic buildings(W/m ² .K)
Pitched roof – insulation at ceiling level	0.16	0.16
Pitched roof – insulation at rafter level	0.18	0.16
Flat roof or roof with integral insulation	0.18	0.18
Wall	0.28	0.26
Floors	0.22	0.18
Swimming pool basin	0.25	0.25
Windows in buildings similar to dwellings	1.6 or Window Energy Rating Band C	1.6 or Window Energy Rating Band B
Rooflight ⁱ	1.8 (vertical plane)	2.2 (horizontal plane)
All other windows, roof windows and curtain walling	1.8	1.6
Pedestrian doors (including glazed doors)	1.8	1.4
High usage entrance doors	3.5	3.0
Vehicle access or similar large doors	1.5	1.3
Roof ventilators (including smoke vents)	3.5	3.0

Notes:

- i. Section 3.9 of this consultation sets out our proposal to adopt the latest version of BR 443 for calculating U-values for rooflights. In current standards, the limiting U-value is based on a rooflight in a vertical position. The proposed standard is based on a rooflight in a horizontal position.

Appendix -3C: DESIGN WEATHER DATA FOR THE CASE STUDY LOCATION

a)

	Min Tdb (°C)	Max Tdb (°C)	Min Twb (°C)	Twb at Max Tdb (°C)	Linke Turbidity Factor
January	7.80	13.50	6.20	11.60	2.100
February	8.30	14.80	6.00	10.90	2.200
March	9.10	18.10	6.10	11.50	2.500
April	12.40	23.50	8.90	14.60	2.900
May	14.00	26.00	11.00	16.80	3.200
June	17.60	29.90	13.40	18.90	3.400
July	19.00	31.50	15.20	19.90	3.500
August	19.50	31.20	15.40	19.90	3.300
September	16.50	26.70	13.30	18.00	2.900
October	14.10	21.60	12.20	16.80	2.600
November	10.80	16.40	9.90	14.40	2.300
December	9.50	14.40	7.90	12.50	2.200

b)

	Min Tdb (°C)	Max Tdb (°C)	Min Twb (°C)	Twb at Max Tdb (°C)	Linke Turbidity Factor
January	8.60	14.30	6.20	12.80	2.100
February	9.10	15.60	6.00	12.10	2.200
March	9.90	18.90	6.10	12.70	2.500
April	13.20	24.30	8.90	15.80	2.900
May	14.80	26.80	11.00	18.00	3.200
June	18.40	30.70	13.40	20.10	3.400
July	19.80	32.30	15.20	21.10	3.500
August	20.30	32.00	15.40	21.10	3.300
September	17.30	27.50	13.30	19.20	2.900
October	14.90	22.40	12.20	18.00	2.600
November	11.60	17.20	9.90	15.60	2.300
December	10.30	15.20	7.90	13.70	2.200

c)

	Min Tdb (°C)	Max Tdb (°C)	Min Twb (°C)	Twb at Max Tdb (°C)	Linke Turbidity Factor
January	9.30	15.00	6.20	13.20	2.100
February	9.80	16.30	6.00	12.50	2.200
March	10.60	19.60	6.10	13.10	2.500
April	13.90	25.00	8.90	16.20	2.900
May	15.50	27.50	11.00	18.40	3.200
June	19.10	31.40	13.40	20.50	3.400
July	20.50	33.00	15.20	21.50	3.500
August	21.00	32.70	15.40	21.50	3.300
September	18.00	28.20	13.30	19.60	2.900
October	15.60	23.10	12.20	18.40	2.600
November	12.30	17.90	9.90	16.00	2.300
December	11.00	15.90	7.90	14.10	2.200

(a) 2022 (b) 2030 and (c) 2050

Appendix -3 D: UK PRIMARY AND FINAL ENERGY PROJECTIONS

UK Primary Energy Demand (TWh)							UK Final Energy Demand (TWh), excluding International Aviation	
Fuel	Electricity Net Imports	Natural Gas	Nuclear	Oil	Renewables & Waste	Solids	Electricity	Natural gas
2000	13	1126	228	1012	33	451	325	664
2001	9	1121	242	990	34	477	328	672
2002	7	1106	234	984	38	437	329	642
2003	-0.074	1109	233	987	41	472	332	659
2004	5	1133	211	1010	47	455	339	664
2005	8	1104	214	1039	56	463	349	644
2006	7	1047	199	1025	60	506	345	612
2007	6	1059	163	993	64	476	342	581
2008	11	1087	139	963	83	442	342	599
2009	3	1014	177	921	92	365	322	545
2010	3	1095	162	909	102	374	329	600
2011	6	910	182	884	113	377	318	499
2012	12	854	177	861	121	475	318	545
2013	16	848	180	845	141	457	316	552
2014	22	778	161	845	166	369	303	470
2015	20	800	180	870	199	291	303	487
2016	18	884	179	887	210	148	304	492
2017	14	865	176	902	232	120	300	487
2018	19	871	164	892	262	101	301	505
2019	21	859	141	874	280	72	298	492
2020	18	806	125	671	300	66	283	483
2021	24	848	115	697	296	67	287	513
2022	-5	781	120	766	310	61	274	443
2023	27	659	123	773	303	44	270	422
2024	22	664	123	791	318	36	268	438
2025	10	659	123	780	342	22	271	447
2026	6	644	101	768	366	22	275	446
2027	8	623	79	754	379	21	281	452
2028	9	619	66	736	389	21	289	457
2029	10	625	26	715	411	21	299	460
2030	2	595	45	692	435	21	310	462
2031	-10	578	101	668	445	21	319	464
2032	0	583	101	648	444	21	329	466
2033	9	591	101	629	442	21	339	470
2034	16	602	101	614	439	19	349	473
2035	29	611	97	598	432	18	358	478
2036	32	614	120	584	426	16	367	483
2037	37	619	147	572	419	14	376	489
2038	47	631	147	562	416	13	386	494
2039	51	641	147	553	415	11	395	498
2040	56	653	147	545	417	11	403	504
2041	63	665	147	538	416	12	412	510
2042	67	682	147	532	411	12	420	515
2043	72	696	147	526	412	12	427	520
2044	74	707	147	518	416	12	435	524
2045	75	715	147	512	421	12	441	529
2046	77	726	147	507	428	12	448	533

2047	78	738	147	501	432	12	454	538
2048	77	754	147	495	436	12	461	542
2049	76	770	147	488	444	12	466	545
2050	75	777	147	480	455	12	471	549

Appendix -4A: UK FUTURE HOMES AND BUILDINGS U-VALUES

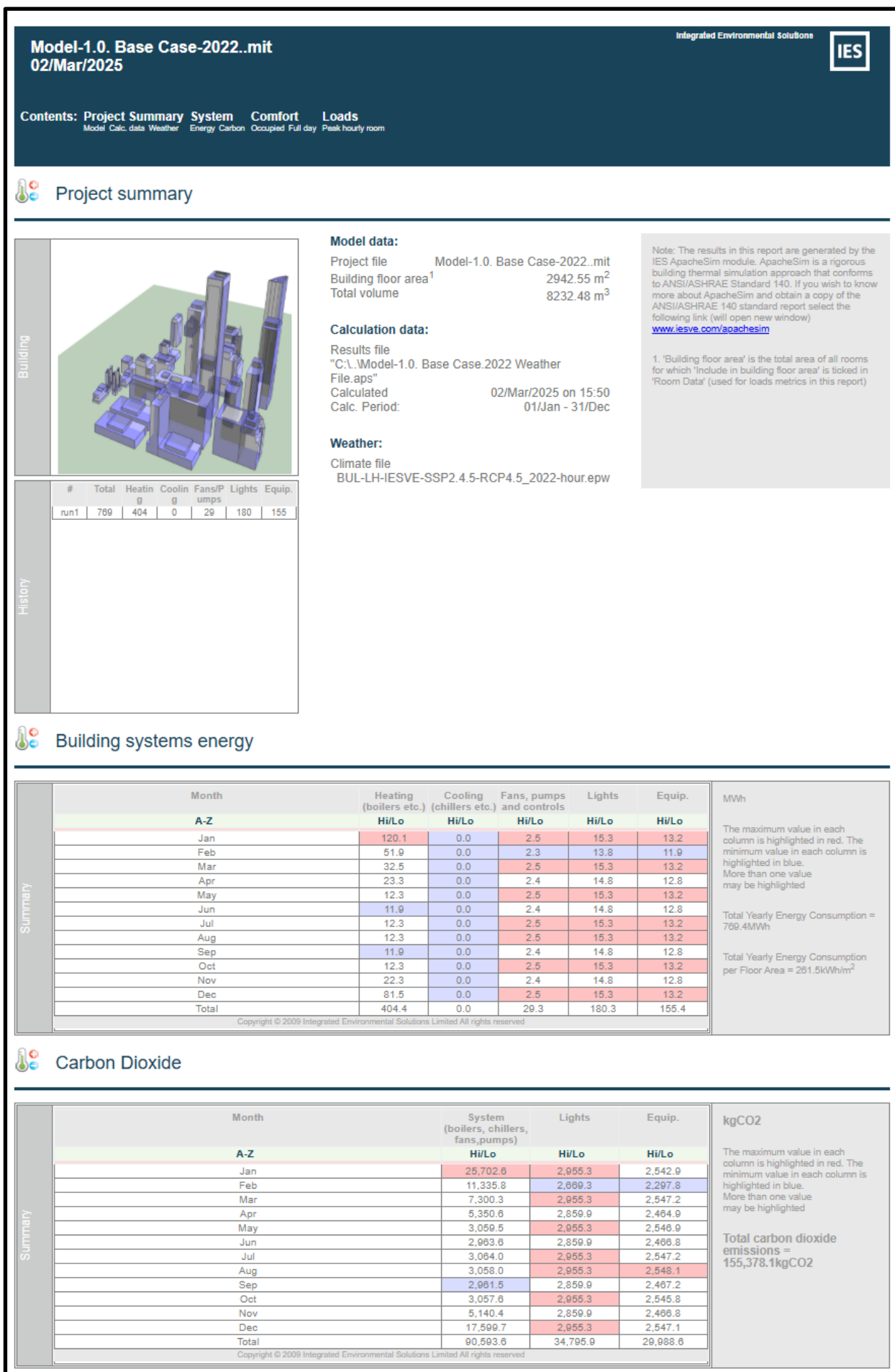
Table 4.1 Limiting U-values for new or replacement elements in new and existing buildings and air permeability in new buildings

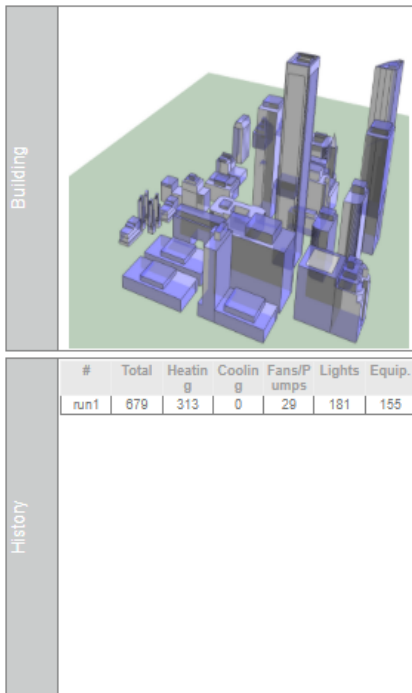
Element type	Maximum U-value ⁽¹⁾ W/(m ² ·K) or air permeability
Roof (flat roof) ⁽²⁾	0.18
Roof (pitched roof) ⁽²⁾	0.16
Wall ⁽²⁾⁽³⁾	0.26
Floor ⁽⁴⁾⁽⁵⁾	0.18
Swimming pool basin ⁽⁶⁾	0.25
Windows in buildings similar to dwellings ⁽⁷⁾⁽⁸⁾	1.6 or Window Energy Rating ⁽⁹⁾ Band B
All other windows, ⁽⁸⁾⁽¹⁰⁾⁽¹¹⁾ roof windows, curtain walling	1.6
Rooflights ⁽¹²⁾⁽¹³⁾	2.2
Pedestrian doors (including glazed doors) ⁽¹⁴⁾	1.6
Vehicle access and similar large doors	1.3
High-usage entrance doors	3.0
Roof ventilators (including smoke vents)	3.0
Air permeability (for new buildings)	8.0m ³ /(h·m ²) @ 50Pa

NOTES:

1. Area-weighted average values, except for new windows, rooflights and doors in existing buildings.
2. For dormer windows, 'roof' includes the roof parts of the windows and 'wall' includes the wall parts (cheeks).
3. If meeting such a standard in an existing building would reduce by more than 5% the internal floor area of the room bounded by the wall, a lesser provision may be appropriate.
4. The U-value of the floor of an extension may be calculated using the exposed perimeter and floor area of either the whole enlarged building or the extension alone.
5. If meeting such a standard in an existing building, would create significant problems in relation to adjoining floor levels, a lesser provision may be appropriate.
6. The U-value of a swimming pool basin (walls and floor) calculated according to **BS EN ISO 13370**.
7. For example, student accommodation, care homes and similar uses where the occupancy levels and internal heat gains are essentially domestic in character.
8. If other performance (e.g. wind load, safety, security or acoustic attenuation) requires thicker glass to be used, an equivalent window unit with standard thickness glazing should be shown to meet the required standard.
9. The methods for calculating Window Energy Rating are set out in the Glass and Glazing Federation's Glazing Manual Data Sheet 2.3, Guide to the Calculation of Energy Ratings for Windows, Roof Windows and Doors.
10. No maximum U-value is set for display windows and similar glazing. There are no limits on the design of display windows and similar glazing, but for new buildings their impact must be taken into account in the calculation of primary energy and CO₂ emissions.
11. In buildings with high internal heat gains, the average U-value for windows can be relaxed from the values given above if this can be shown to be an appropriate way of reducing overall CO₂ emissions and primary energy. However, values should be no higher than 2.7W/(m²·K).
12. U-values for rooflights or rooflight-and-kerb assemblies should be based on the developed surface area of the rooflight (U_d values), which is often greater than the area of the roof opening. Further guidance on U_d-values is given in the Building Research Establishment's BR 443 and the National Association of Rooflight Manufacturers' Technical Document NTD02.
13. The limiting value for rooflights also applies to kerbs that are supplied as part of a single rooflight-and-kerb assembly sourced from the same supplier and for which the supplier can provide a combined U_d-value for the assembly. An upstand built on site should have a maximum U-value of 0.35W/m²·K.
14. For external fire doorsets, as defined in Appendix A of Approved Document B, Volume 2, in new and existing non-domestic buildings, a maximum U-value of 1.8W/(m²·K) is permissible.

Appendix -4B: HEATING AND COOLING LOAD REPORTS OF MODELS



Contents: Project Summary System Comfort Loads
Model Calc. data Weather Energy Carbon Occupied Full day Peak hourly room Project summary**Model data:**

Project file
MODEL-2.0. DO NOTHING. 2030 Climate..mit
Building floor area¹ 2942.55 m²
Total volume 8232.48 m³

Calculation data:

Results file
"C:\MODEL-2.0. DO NOTHING.2030
Climatee.aps"
Calculated 15/Jun/2025 on 02:44
Calc. Period: 01/Jan - 31/Dec

Weather:

Climate file
BUL-LH-IESVE-SSP2.4.5-RCP4.5_2030-hour.epw

Note: The results in this report are generated by the IES ApacheSim module. ApacheSim is a rigorous building thermal simulation approach that conforms to ANSI/ASHRAE Standard 140. If you wish to know more about ApacheSim and obtain a copy of the ANSI/ASHRAE 140 standard report select the following link (will open new window)
www.iesve.com/apacheSim

1. 'Building floor area' is the total area of all rooms for which 'Include in building floor area' is ticked in 'Room Data' (used for loads metrics in this report)

 Building systems energy

Summary	Month		Heating (boilers etc.)	Cooling (chillers etc.)	Fans, pumps and controls	Lights	Equip.	MWh
	A-Z		Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan		82.3	0.0	2.5	15.4	13.2	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total Yearly Energy Consumption = 679.1MWh Total Yearly Energy Consumption per Floor Area = 230.8kWh/m²
	Feb		35.4	0.0	2.3	13.9	11.9	
	Mar		24.1	0.0	2.5	15.4	13.2	
	Apr		18.4	0.0	2.4	14.9	12.8	
	May		12.3	0.0	2.5	15.4	13.2	
	Jun		11.9	0.0	2.4	14.9	12.8	
	Jul		12.3	0.0	2.5	15.4	13.2	
	Aug		12.3	0.0	2.5	15.4	13.2	
	Sep		11.9	0.0	2.4	14.9	12.8	
	Oct		12.3	0.0	2.5	15.4	13.2	
	Nov		17.8	0.0	2.4	14.9	12.8	
	Dec		62.0	0.0	2.5	15.4	13.2	
	Total		313.1	0.0	29.3	181.3	155.4	

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 Carbon Dioxide

Summary	Month		System (boilers, chillers, fans, pumps)	Lights	Equip.	kgCO2
	A-Z		Hi/Lo	Hi/Lo	Hi/Lo	
	Jan		17,409.3	754.6	646.3	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total carbon dioxide emissions = 83,678.6kgCO2
	Feb		7,551.3	681.6	583.4	
	Mar		5,190.8	754.6	646.0	
	Apr		3,988.0	730.3	626.2	
	May		2,700.7	754.6	647.0	
	Jun		2,616.4	730.3	625.6	
	Jul		2,705.3	754.6	647.4	
	Aug		2,699.2	754.6	646.6	
	Sep		2,614.4	730.3	626.0	
	Oct		2,698.8	754.6	647.0	
	Nov		3,865.2	730.3	625.9	
	Dec		13,140.0	754.6	646.7	
	Total		67,179.4	8,885.1	7,614.0	

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Model-2.1. 2030 Case. Insulation Uplift.mit 15/Jun/2025

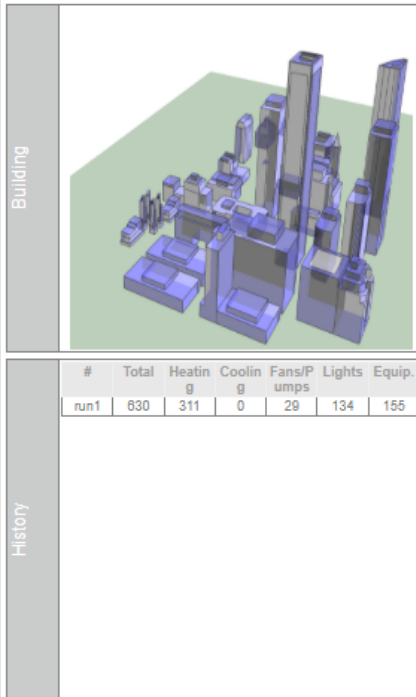
Integrated Environmental Solutions



Contents: Project Summary System Comfort Loads
Model Calc. data Weather Energy Carbon Occupied Full day Peak hourly room



Project summary



Model data:

Project file
Model-2.1. 2030 Case. Insulation Uplift.mit
Building floor area¹ 2942.55 m²
Total volume 8232.48 m³

Calculation data:

Results file
"C:\...\MODEL-2.1. 2030 Case. Insulation Uplift.aps"
Calculated 15/Jun/2025 on 12:12
Calc. Period: 01/Jan - 31/Dec

Weather:

Climate file
BUL-LH-IESVE-SSP2.4.5-RCP4.5_2030-hour.epw

Note: The results in this report are generated by the IES ApacheSim module. ApacheSim is a rigorous building thermal simulation approach that conforms to ANSI/ASHRAE Standard 140. If you wish to know more about ApacheSim and obtain a copy of the ANSI/ASHRAE 140 standard report select the following link (will open new window)
www.iesve.com/apachesim

¹ 'Building floor area' is the total area of all rooms for which 'Include in building floor area' is ticked in 'Room Data' (used for loads metrics in this report)



Building systems energy

Summary	Month	Heating (boilers etc.)	Cooling (chillers etc.)	Fans, pumps and controls	Lights	Equip.	MWh
	A-Z	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan	81.0	0.0	2.5	11.4	13.2	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total Yearly Energy Consumption = 629.5MWh Total Yearly Energy Consumption per Floor Area = 213.9kWh/m²
	Feb	35.3	0.0	2.3	10.3	11.9	
	Mar	24.2	0.0	2.5	11.4	13.2	
	Apr	18.5	0.0	2.4	11.0	12.8	
	May	12.3	0.0	2.5	11.4	13.2	
	Jun	11.9	0.0	2.4	11.0	12.8	
	Jul	12.3	0.0	2.5	11.4	13.2	
	Aug	12.3	0.0	2.5	11.4	13.2	
	Sep	11.9	0.0	2.4	11.0	12.8	
	Oct	12.3	0.0	2.5	11.4	13.2	
	Nov	18.0	0.0	2.4	11.0	12.8	
	Dec	61.2	0.0	2.5	11.4	13.2	
	Total	311.1	0.0	29.3	133.8	155.4	

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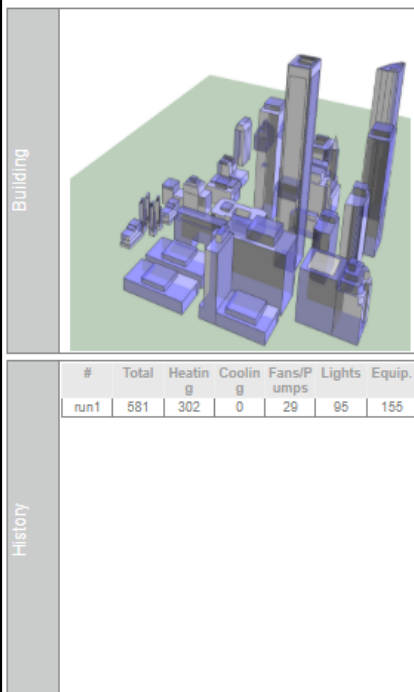
Carbon Dioxide

Summary	Month	System (boilers, chillers, fans, pumps)	Lights	Equip.	kgCO ₂
	A-Z	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan	17,249.7	1,113.4	1,292.6	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total carbon dioxide emissions = 96,533.4kgCO₂
	Feb	7,631.4	1,005.7	1,166.8	
	Mar	5,332.1	1,113.4	1,292.0	
	Apr	4,116.4	1,077.5	1,252.3	
	May	2,822.8	1,113.4	1,294.0	
	Jun	2,734.6	1,077.5	1,251.1	
	Jul	2,827.3	1,113.4	1,294.8	
	Aug	2,821.3	1,113.4	1,293.1	
	Sep	2,732.5	1,077.5	1,252.1	
	Oct	2,820.9	1,113.4	1,294.1	
	Nov	4,008.4	1,077.5	1,251.9	
	Dec	13,098.2	1,113.4	1,293.3	
	Total	68,195.5	13,109.8	15,228.1	

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Contents: Project Summary System Comfort Loads
Model Calc. data Weather Energy Carbon Occupied Full day Peak hourly room

Project summary



Model data:

Project file
MODEL-2.2. 2030 Case. Light Gain Red. 0.7DF.mit
Building floor area¹ 2942.55 m²
Total volume 8232.48 m³

Calculation data:

Results file
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07DF.aps"
Calculated 15/Jun/2025 on 13:56
Calc. Period: 01/Jan - 31/Dec

Weather:

Climate file
BUL-LH-IESVE-SSP2.4.5-RCP4.5_2030-hour.epw

Note: The results in this report are generated by the IES ApacheSim module. ApacheSim is a rigorous building thermal simulation approach that conforms to ANSI/ASHRAE Standard 140. If you wish to know more about ApacheSim and obtain a copy of the ANSI/ASHRAE 140 standard report select the following link (will open new window)
www.iesve.com/apachesim

1. 'Building floor area' is the total area of all rooms for which 'Include in building floor area' is ticked in 'Room Data' (used for loads metrics in this report)

Building systems energy

Summary	Month		Heating (boilers etc.)	Cooling (chillers etc.)	Fans, pumps and controls	Lights	Equip.	MWh
	A-Z		Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan		83.8	0.0	2.5	8.0	13.2	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total Yearly Energy Consumption = 598.6MWh Total Yearly Energy Consumption per Floor Area = 203.4kWh/m²
	Feb		36.6	0.0	2.3	7.3	11.9	
	Mar		25.0	0.0	2.5	8.0	13.2	
	Apr		18.9	0.0	2.4	7.8	12.8	
	May		12.3	0.0	2.5	8.0	13.2	
	Jun		11.9	0.0	2.4	7.8	12.8	
	Jul		12.3	0.0	2.5	8.0	13.2	
	Aug		12.3	0.0	2.5	8.0	13.2	
	Sep		11.9	0.0	2.4	7.8	12.8	
	Oct		12.3	0.0	2.5	8.0	13.2	
	Nov		18.5	0.0	2.4	7.8	12.8	
	Dec		63.4	0.0	2.5	8.0	13.2	
	Total		319.1	0.0	29.3	94.8	155.4	

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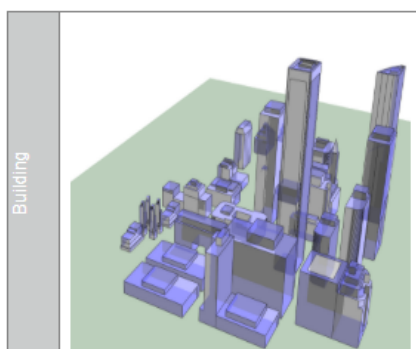
Carbon Dioxide

Summary	Month		System (boilers, chillers, fans, pumps)	Lights	Equip.	kgCO2
	A-Z		Hi/Lo	Hi/Lo	Hi/Lo	
	Jan		17,846.0	788.7	1,292.6	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total carbon dioxide emissions = 94,401.4kgCO2
	Feb		7,903.0	712.4	1,166.8	
	Mar		5,503.5	788.7	1,292.0	
	Apr		4,195.9	763.2	1,252.3	
	May		2,822.8	788.7	1,294.0	
	Jun		2,734.6	763.2	1,251.1	
	Jul		2,827.3	788.7	1,294.8	
	Aug		2,821.3	788.7	1,293.1	
	Sep		2,732.5	763.2	1,252.1	
	Oct		2,820.9	788.7	1,294.1	
	Nov		4,116.3	763.2	1,251.9	
	Dec		13,563.1	788.7	1,293.3	
	Total		69,887.1	9,286.2	15,228.1	

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Contents: Project Summary System Comfort Loads
Model Calc. data Weather Energy Carbon Occupied Full day Peak hourly room

Project summary



Model data:

Project file
MODEL-2.3. 2030 Case. Daylighting
Sensors.07DF.mit
Building floor area¹ 2942.55 m²
Total volume 8232.48 m³

Calculation data:

Results file
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Sensors.0.7DF.aps"
Calculated 13/Jun/2025 on 18:30
Calc. Period: 01/Jan - 31/Dec

Weather:

Climate file
BUL-LH-IESVE-SSP2.4.5-RCP4.5_2030-hour.epw

Note: The results in this report are generated by the IES ApacheSim module. ApacheSim is a rigorous building thermal simulation approach that conforms to ANSI/ASHRAE Standard 140. If you wish to know more about ApacheSim and obtain a copy of the ANSI/ASHRAE 140 standard report select the following link (will open new window)
www.iesve.com/apachesim

1. 'Building floor area' is the total area of all rooms for which 'Include in building floor area' is ticked in 'Room Data' (used for loads metrics in this report)

#	Total	Heatin g	Coolin g	Fans/P umps	Lights	Equip.
run1	567	306	0	29	76	155

Building systems energy

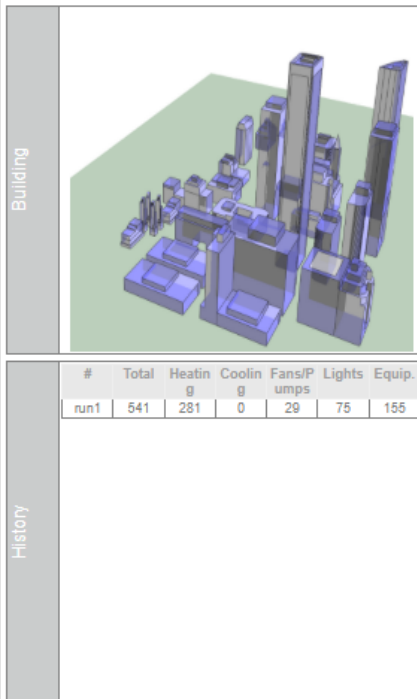
Summary	Month	Heating (boilers etc.)	Cooling (chillers etc.)	Fans, pumps and controls	Lights	Equip.	MWh
	A-Z	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan	79.3	0.0	2.5	6.2	13.2	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total Yearly Energy Consumption = 566.7MWh Total Yearly Energy Consumption per Floor Area = 192.6kWh/m²
	Feb	34.8	0.0	2.3	5.7	11.9	
	Mar	23.9	0.0	2.5	6.4	13.2	
	Apr	18.2	0.0	2.4	6.3	12.8	
	May	12.3	0.0	2.5	6.6	13.2	
	Jun	11.9	0.0	2.4	6.4	12.8	
	Jul	12.3	0.0	2.5	6.6	13.2	
	Aug	12.3	0.0	2.5	6.6	13.2	
	Sep	11.9	0.0	2.4	6.3	12.8	
	Oct	12.3	0.0	2.5	6.3	13.2	
	Nov	17.9	0.0	2.4	6.0	12.8	
	Dec	59.4	0.0	2.5	6.2	13.2	
	Total	306.5	0.0	29.3	75.5	155.4	

Carbon Dioxide

Summary	Month	System (boilers, chillers, fans,pumps)	Lights	Equip.	kgCO2
	A-Z	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan	16,900.4	605.3	1,292.6	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total carbon dioxide emissions = 89,863.5kgCO2
	Feb	7,538.8	555.6	1,168.8	
	Mar	5,264.5	625.7	1,292.0	
	Apr	4,061.2	618.9	1,252.3	
	May	2,822.8	646.6	1,294.0	
	Jun	2,734.6	626.6	1,251.1	
	Jul	2,827.3	645.5	1,294.8	
	Aug	2,821.3	645.1	1,293.1	
	Sep	2,732.5	614.3	1,252.1	
	Oct	2,820.9	621.0	1,294.1	
	Nov	3,999.7	591.0	1,251.9	
	Dec	12,709.8	605.9	1,293.3	
	Total	67,233.8	7,401.6	15,228.1	

Contents: Project Summary System Comfort Loads
Model Calc. data Weather Energy Carbon Occupied Full day Peak hourly room

Project summary



Model data:

Project file
MODEL-2.4. 2030 Case. Adaptive Ventilation...mit
Building floor area¹ 2942.55 m²
Total volume 8232.48 m³

Calculation data:

Results file
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Calculated 13/Jun/2025 on 19:25
Calc. Period: 01/Jan - 31/Dec

Weather:

Climate file
BUL-LH-IESVE-SSP2.4.5-RCP4.5_2030-hour.epw

Note: The results in this report are generated by the IES ApacheSim module. ApacheSim is a rigorous building thermal simulation approach that conforms to ANSI/ASHRAE Standard 140. If you wish to know more about ApacheSim and obtain a copy of the ANSI/ASHRAE 140 standard report select the following link (will open new window)
www.iesve.com/apachesim

¹ 'Building floor area' is the total area of all rooms for which 'Include in building floor area' is ticked in 'Room Data' (used for loads metrics in this report)

Building systems energy

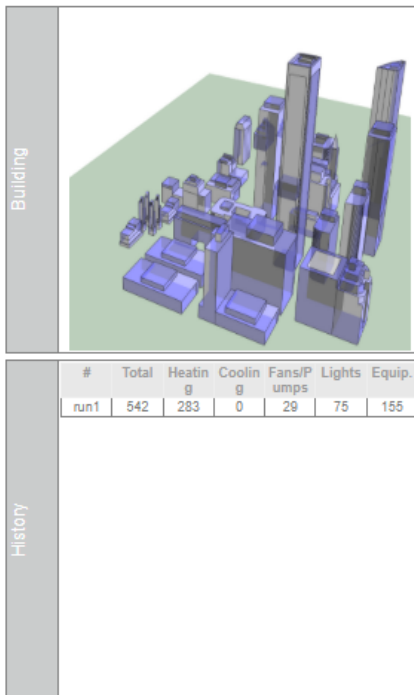
Summary	Month		Heating (boilers etc.)	Cooling (chillers etc.)	Fans, pumps and controls	Lights	Equip.	MWh
	A-Z		Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan		88.9	0.0	2.5	6.1	13.2	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total Yearly Energy Consumption = 540.6MWh Total Yearly Energy Consumption per Floor Area = 183.7kWh/m²
	Feb		31.2	0.0	2.3	5.6	11.9	
	Mar		22.0	0.0	2.5	6.3	13.2	
	Apr		16.9	0.0	2.4	6.2	12.8	
	May		12.3	0.0	2.5	6.5	13.2	
	Jun		11.9	0.0	2.4	6.3	12.8	
	Jul		12.3	0.0	2.5	6.5	13.2	
	Aug		12.3	0.0	2.5	6.5	13.2	
	Sep		11.9	0.0	2.4	6.2	12.8	
	Oct		12.3	0.0	2.5	6.3	13.2	
	Nov		16.9	0.0	2.4	6.0	12.8	
	Dec		52.3	0.0	2.5	6.1	13.2	
	Total		281.2	0.0	29.3	74.6	155.4	

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Carbon Dioxide

Summary	Month		System (boilers, chillers, fans,pumps)	Lights	Equip.	kgCO2
	A-Z		Hi/Lo	Hi/Lo	Hi/Lo	
	Jan		14,723.1	598.5	1,292.6	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total carbon dioxide emissions = 84,467.0kgCO2
	Feb		6,771.4	549.3	1,166.8	
	Mar		4,868.1	618.4	1,292.0	
	Apr		3,788.0	611.5	1,252.3	
	May		2,822.8	638.7	1,294.0	
	Jun		2,734.6	618.9	1,251.1	
	Jul		2,827.3	637.6	1,294.8	
	Aug		2,821.3	637.3	1,293.1	
	Sep		2,732.5	607.1	1,252.1	
	Oct		2,820.9	613.8	1,294.1	
	Nov		3,795.2	584.3	1,251.9	
	Dec		11,219.2	599.1	1,293.3	
	Total		61,924.3	7,314.6	15,228.1	

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Contents: Project Summary System Comfort Loads
Model Calc. data Weather Energy Carbon Occupied Full day Peak hourly room Project summary**Model data:**

Project file MODEL-3.0. 2050 Case..mit
Building floor area¹ 2942.55 m²
Total volume 8232.48 m³

Calculation data:

Results file "C:\.MODEL-3.0. 2050 Case..aps"
Calculated 13/Jun/2025 on 20:18
Calc. Period: 01/Jan - 31/Dec

Weather:

Climate file
BUL-LH-IESVE-SSP2.4.5-RCP4.5-2050-hour.epw

Note: The results in this report are generated by the IES ApacheSim module. ApacheSim is a rigorous building thermal simulation approach that conforms to ANSI/ASHRAE Standard 140. If you wish to know more about ApacheSim and obtain a copy of the ANSI/ASHRAE 140 standard report select the following link (will open new window)
www.iesve.com/apachesim

1. 'Building floor area' is the total area of all rooms for which 'Include in building floor area' is ticked in 'Room Data' (used for loads metrics in this report)

 Building systems energy

Summary	Month	Heating (boilers etc.)	Cooling (chillers etc.)	Fans, pumps and controls	Lights	Equip.	MWh
	A-Z	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan	66.2	0.0	2.5	6.1	13.2	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total Yearly Energy Consumption = 542.2MWh Total Yearly Energy Consumption per Floor Area = 184.3kWh/m²
	Feb	31.8	0.0	2.3	5.6	11.9	
	Mar	23.4	0.0	2.5	6.3	13.2	
	Apr	17.0	0.0	2.4	6.2	12.8	
	May	12.3	0.0	2.5	6.5	13.2	
	Jun	11.9	0.0	2.4	6.3	12.8	
	Jul	12.3	0.0	2.5	6.5	13.2	
	Aug	12.3	0.0	2.5	6.5	13.2	
	Sep	11.9	0.0	2.4	6.2	12.8	
	Oct	12.3	0.0	2.5	6.3	13.2	
	Nov	16.7	0.0	2.4	6.0	12.8	
	Dec	54.8	0.0	2.5	6.1	13.2	
	Total	282.8	0.0	29.3	74.7	155.4	

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 Carbon Dioxide

Summary	Month	System (boilers, chillers, fans, pumps)	Lights	Equip.	kgCO2
	A-Z	Hi/Lo	Hi/Lo	Hi/Lo	
	Jan	14,144.4	599.9	1,291.2	The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted Total carbon dioxide emissions = 84,804.0kgCO2
	Feb	6,893.8	550.1	1,166.8	
	Mar	5,153.6	619.0	1,293.4	
	Apr	3,812.9	611.7	1,251.6	
	May	2,822.8	638.5	1,293.3	
	Jun	2,734.6	619.5	1,252.6	
	Jul	2,827.3	638.7	1,293.4	
	Aug	2,821.3	637.8	1,293.9	
	Sep	2,732.5	606.0	1,252.8	
	Oct	2,820.9	615.0	1,292.7	
	Nov	3,740.4	584.5	1,252.6	
	Dec	11,753.7	598.0	1,293.3	
	Total	62,258.0	7,318.6	15,227.4	

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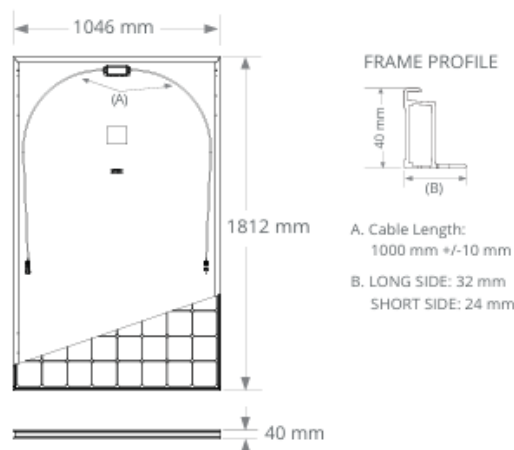
Appendix -4C: DATASHEET OF MAXEON 420W BLK SOLAR PANEL

MAXEON 3 POWER: 410–420 W | EFFICIENCY: Up to 22.2%

Electrical Data			
	SPR-MAX3-420- BLK	SPR-MAX3-415- BLK	SPR-MAX3-410- BLK
Nominal Power (P _{nom}) ²	420 W	415 W	410 W
Power Tolerance	+5/0%	+5/0%	+5/0%
Panel Efficiency	22.2%	21.9%	21.6%
Rated Voltage (V _{mpp})	71.3 V	70.8 V	70.4 V
Rated Current (I _{mpp})	5.89 A	5.86 A	5.82 A
Open-Circuit Voltage (V _{oc})	81.5 V	81.4 V	81.4 V
Short-Circuit Current (I _{sc})	6.33 A	6.32 A	6.31 A
Max. System Voltage	1000 V IEC		
Maximum Series Fuse	20 A		
Power Temp Coef.	-0.27% / °C		
Voltage Temp Coef.	-0.236% / °C		
Current Temp Coef.	0.058% / °C		

Warranties, Certifications and Compliance	
Standard Tests ³	IEC 61215, IEC 61730
Quality Management Certs	ISO 9001:2015, ISO 14001:2015
Ammonia Test	IEC 62716
Desert Test	IEC 60068-2-68, MIL-STD-810G
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	1000 V: IEC 62804
Available Listings	TUV
IFLI Declare Label	First solar panel labeled for ingredient transparency and LBC-compliance. ⁴
Cradle to Cradle Certified™ Bronze	First solar panel line certified for material health, water stewardship, material reutilization, renewable energy & carbon management, and social fairness. ⁵
Green Building Certification Contribution	Panels can contribute additional points toward LEED and BREEAM certifications.
EHS Compliance	RoHS, OHSAS 18001:2007, Recycle Scheme, REACH SVHC-163

Operating Condition And Mechanical Data	
Temperature	-40°C to +85°C
Impact Resistance	25 mm diameter hail at 23 m/s
Solar Cells	112 Monocrystalline Maxeon Gen 3
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-68, Stäubli (MC4), 3 bypass diodes
Weight	21,2 kg
Max. Load ⁶	Wind: 2400 Pa, 244 kg/m ² front & back Snow: 5400 Pa, 550 kg/m ² front
Frame	Class 1 black anodized (highest AAMA rating)



Declare.



Please read the safety and installation instructions.
Visit www.sunpower.maxeon.com/int/PVInstallGuideIEC.
Paper version can be requested through techsupport.ROW@maxeon.com.

1 40-year warranty is not available in all countries or all installations and requires registration, otherwise our 25-year warranty applies. Service availability varies by country and installation provider.

2 Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25° C). NREL calibration Standard: SONS current, LACCS FF and Voltage.

3 Class C fire rating per IEC 61730.

4 Maxeon DC panels first received the International Living Future Institute Declare Label in 2016.

5 Maxeon DC panels are Cradle to Cradle Certified™ Bronze -

www.c2ccertified.org/products/scorecard/e-series_xseries_solar_panels_-sunpower_corporation.

Cradle to Cradle Certified™ is a certification mark licensed by the Cradle to Cradle Products Innovation Institute.

6 Safety factor 1.5 included.

Made in Philippines (Cells)

Assembled in Malaysia (Module)

Specifications included in this datasheet are subject to change without notice.

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View warranty, patent and trademark information at maxeon.com/legal.

SUNPOWER
FROM MAXEON SOLAR TECHNOLOGIES

544456 REV A / A4_EN
Publication Date: June 2022

Appendix -4D: DATASHEET OF ENPHASE IQ8P MICROINVERTER

IQ8P Microinverter

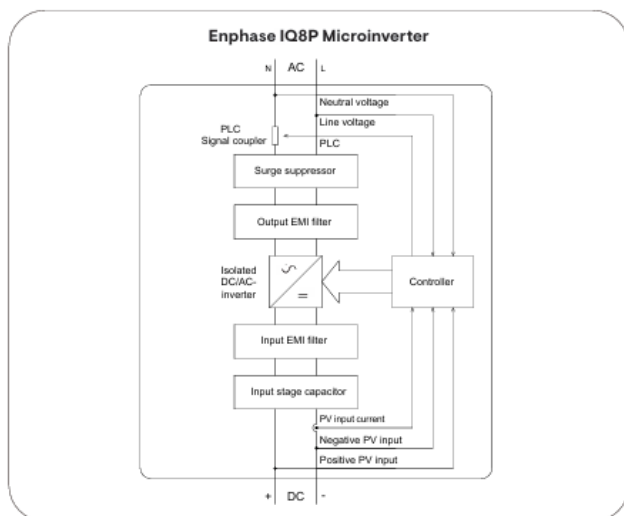
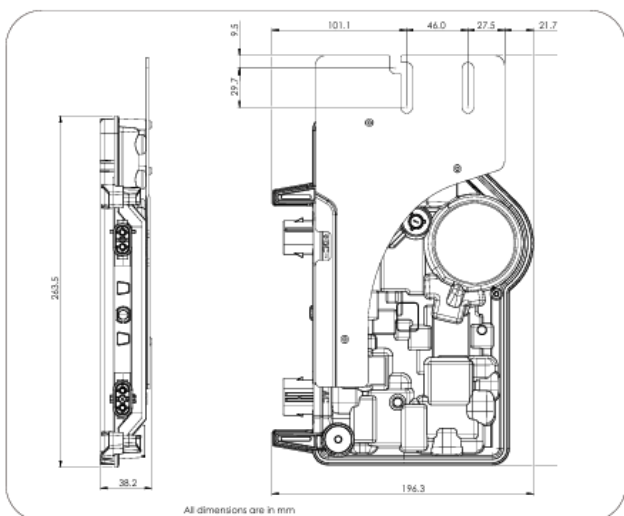
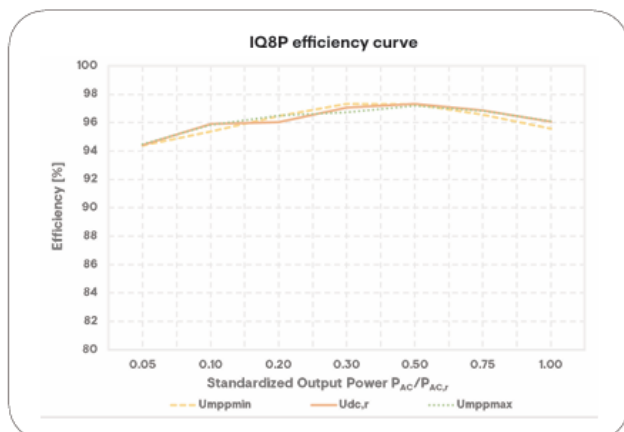
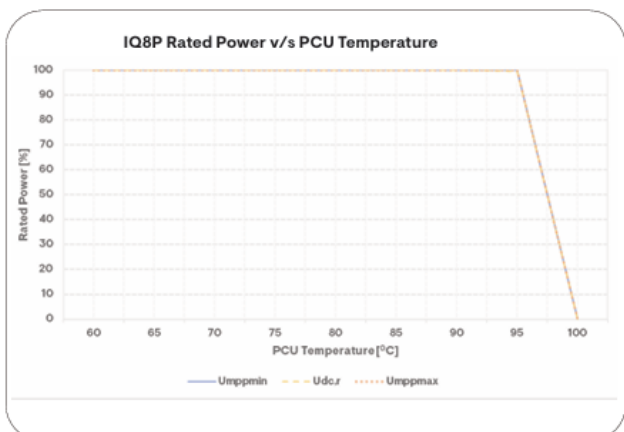
INPUT DATA (DC)		UNITS	IQ8P-72-2-INT
Typical module compatibility			60-cell/120-half-cell, 66-cell/132-half-cell, 72-cell/144-half-cell, 78-cell/156-half-cell No enforced DC/AC ratio and maximum input power. Modules can be paired as long as the maximum input voltage is not exceeded and the maximum input current of the inverter at the lowest and highest temperatures is respected. See the compatibility calculator at https://enphase.com/en-za/installers/microinverters/calculator .
Minimum/Maximum input voltage	U_{dcmin}/U_{dcmax}	V	16/65
Start-up input voltage	U_{dstart}	V	22
Rated input voltage	$U_{dc,r}$	V	45.5
Minimum/Maximum MPP voltage	U_{mppmin}/U_{mppmax}	V	36/55
Minimum/Maximum operating voltage	U_{opmin}/U_{opmax}	V	16/65
Maximum input current	I_{dcmax}	A	14
Maximum short-circuit DC input current	I_{scmax}	A	25
Maximum input power ⁽¹⁾	P_{dcmax}	W	670
OUTPUT DATA (AC)		UNITS	IQ8P-72-2-INT
Maximum apparent power	$S_{ac,max}$	VA	480
Rated power	$P_{ac,r}$	W	475
Nominal grid voltage	$U_{ac,nom}$	V	230
Minimum/Maximum grid voltage	U_{acmin}/U_{acmax}	V	184/276
Maximum output current	$I_{ac,max}$	A	2.07
Nominal frequency	f_{nom}	Hz	50
Minimum/Maximum frequency	f_{min}/f_{max}	Hz	47/55
Maximum units per single/ multi-phase 20 A circuit	16 A/ $I_{ac,max}$		7 (L+N)/21 (3L+N) For IQ Cable with 2.5 mm ² stranded conductors and using a 1.25 safety factor, 16 A per phase is calculated as the maximum current according to IEC 60364. The safety factor applied may vary based on the local regulations or best practices, as well as upon the characteristics the OCPD selected.
Maximum units per single/ multi-phase IQ Cable section			7 (L+N)/11 (3L+N) Centre feeding is the best practice. These design limits should ensure voltage rise and line conductor resistance on the IQ Cable are maintained within acceptable limits. In locations with a risk of high grid voltage at the point of connection, it may be necessary to decrease the maximum number of microinverters on the IQ Cable section by as much as 50%.
Protective class (all ports)			II
Total harmonic distortion		%	<5
Power factor setting			1.0
Power factor range	cos phi		0.80 leading...0.80 lagging
Inverter maximum efficiency	η_{max}	%	97.34
European weighted efficiency	η_{EU}	%	97.00
Inverter topology			Isolated (HF Transformer)
Nighttime power loss		mW	100
MECHANICAL DATA			IQ8P-72-2-INT
Ambient air temperature range			-40°C to 65°C (-40°F to 149°F)
Relative humidity range			4 % to 100 % (condensing)
Overvoltage class AC port			III
Number of input DC connectors (pairs) per single MPP-tracker			1

(1) Pairing PV modules with wattage above the limit may result in additional clipping losses. See the compatibility calculator at <https://enphase.com/en-za/installers/microinverters/calculator>.

MECHANICAL DATA		IQ8P-72-2-INT
AC connector type	IQ Cabling (refer to the individual datasheet for cable and accessories)	
DC connector type	Supplied with Stäubli MC4 adapter	
Dimensions (H x W x D)	265 mm (10.4") x 200 mm (7.9") x 35 mm (1.4") (without mounting brackets)	
Weight (with mounting plate)	1.6 kg (3.5 lbs)	
Cooling	Natural convection – no fans	
Enclosure	Class II double-insulated, corrosion-resistant polymeric enclosure	
IP rating	Outdoor - IPX6/IP67	
Altitude	< 2600 m	
Calorific value	59.25 MJ/unit	
STANDARDS		IQ8P-72-2-INT
Grid compliance (with IQ Relay)	NRS 097-2-1:2017	
Safety	EN IEC 62109-1, EN IEC 62109-2	
EMC	EN IEC 61000-3-2, 61000-3-3, 61000-6-2, 61000-6-3, EN IEC 50065-1, 50065-2-1, EN55011 ²	
Product labelling	CE	
Advanced grid functions ³	Power export limiting (PEL), Phase imbalance management (PIM), Loss of phase detection (LOP), Power factor control Q (U), cos (phi) (P)	
Microinverter communication	Power line communication (PLC) 110 – 120 kHz (Class B), narrowband 200 Hz	

(2) At STC within MPP range.

(3) Some of these functions require IQ Gateway Metered with current transformers and/or IQ Relay installed.



Assembled in China, India, and Mexico.

Enphase Energy, Inc. 47281 Bayside Pkwy. Fremont, CA 94538, The United States of America

IQ8P-DSH-00136-2.0-EN-ZAF-2023-09-14

Appendix -4E: 2022 HELIOSCOPE SOLAR-PV PRODUCTION REPORT

Annual Production Report produced by BENEDICT TERTSEA SHINKU

Case Study. Single Segment. Base Case Lancaster Hotel and Spa.

Project Details

Address	Lancaster Hotel and Spa.
Customer Name	Brunel University of London,UK.
Owner	BENEDICT TERTSEA SHINKU
Last Modified	BENEDICT TERTSEA SHINKU 2 hours ago
Location	(51.5342614, -0.4714351) (GMT 0)
AC Interconnect	230V-3Phase
Profile	Default Commercial (International)

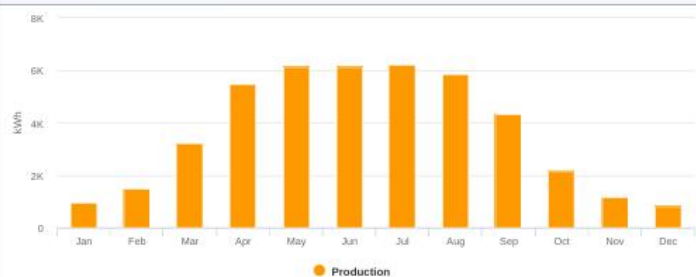
System Metrics

Design	Case Study. Single Segment.
Module DC Nameplate	48.3 kW
Inverter AC Nameplate	40.1 kW Load Ratio: 1.20
Annual Production	43.8 MWh
Performance Ratio	75.5%
kWh/kWp	906.1
Weather Dataset	TMY, BRS- HOMER_Helioscope, MN8 (custom)
Simulator Version	55152aaae8-5a57783db9-b50766d345-32844f1255

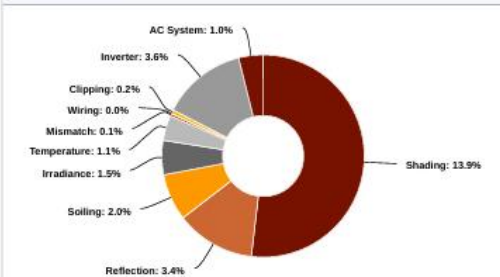
Project Location



Production



System Loss



Annual Production

	Description	Output	% Delta
Irradiance (kWh/m ²)	Annual Global Horizontal Irradiance	1,046.2	-
	POA Irradiance	1,200.7	14.8%
	Shaded Irradiance	1,034.2	-13.9%
	Irradiance After Reflection	999.2	-3.4%
	Irradiance After Soiling	979.2	-2.0%
	Total Collector Irradiance	978.2	-0.1%
Energy (kWh)	Nameplate	47,204.6	-
	Output at Irradiance Levels	46,514.2	-1.5%
	Output at Cell Temperature Derate	46,015.5	-1.1%
	Output After Mismatch	45,965.6	-0.1%
	Optimal DC Output	45,965.6	0.0%
	Constrained DC Output	45,889.6	-0.2%
	Inverter Output	44,226.2	-3.6%
	Energy to Grid	43,765.8	-1.0%
Temperature Metrics			
	Avg. Operating Ambient Temp		14.1°C
	Avg. Operating Cell Temp		19.2°C
Simulation Metrics			
	Operating Hours		4,576
	Solved Hours		4,576
	Pending Hours		-
	Error Hours		-

Condition Set

Description	2020-2022 Weather File											
Weather Dataset	TMY, BRS- HOMER_Helioscope, MN8(custom)											
Solar Angle Location	Meteo Lat/Lng											
Transposition Model	Perez Model											
Temperature Model	Diffusion Model											
Temperature Model Parameters	Rack Type	U _{const}				U _{wind}						
	Fixed Tilt	29.00				0.00						
	Flush Mount	15.00				0.00						
	East-West	29.00				0.00						
	Carport	29.00				0.00						
Soiling (%)	J	F	M	A	M	J	J	A	S	O	N	D
	2	2	2	2	2	2	2	2	2	2	2	2
Irradiation Variance	5.0%											
Cell Temperature Spread	4.0°C											
Module Binning Range	-2.5% to 2.5%											
AC System Derate	0.50%											
Component Characterizations	Type	Component				Characterization						
	Module	SPR-MAX3-420- BLK-R (Maxeon)				Spec Sheet Characterization, PAN						
	Inverter	IQ7A-72-2-INT (Enphase)				Spec Sheet						

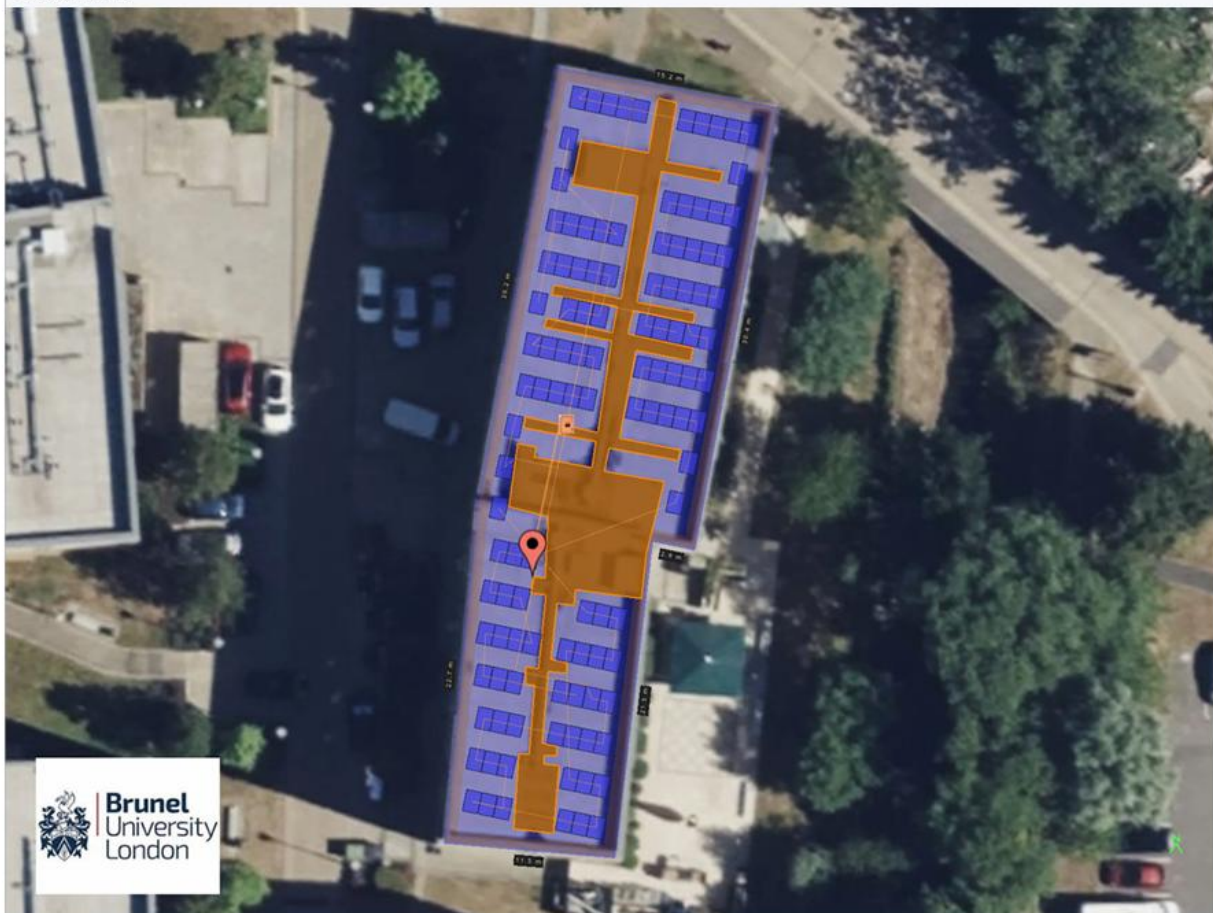
Design BOM

Component	Type	Quantity
25 mm2 (Copper)	AC Branches	4
35 mm2 (Copper)	AC Home Runs	1
4 input AC Panels	AC Panels	1
IQ7A-72-2-INT	Inverters	115
SPR-MAX3-420- BLK-R	Modules	115

Monthly Shading

Month	GHI (kWh/m ²)	POA (kWh/m ²)	Shaded (kWh/m ²)	Nameplate (kWh)	Grid (kWh)
January	21.9	36.8	22.1	1,002.1	938.1
February	37.6	56.8	34.7	1,569.3	1,488.2
March	74.4	94.5	73.5	3,350.9	3,168.1
April	116.0	132.0	126.1	5,781.4	5,438.0
May	149.4	150.9	144.5	6,604.6	6,125.9
June	158.4	152.4	145.7	6,649.0	6,136.8
July	157.8	155.5	149.1	6,806.5	6,206.5
August	134.6	144.6	139.2	6,370.5	5,825.4
September	94.1	117.3	101.8	4,658.5	4,312.5
October	56.1	78.7	50.6	2,290.8	2,142.5
November	28.0	47.5	27.8	1,258.1	1,178.2
December	17.9	33.5	19.1	863.0	805.6

Design Render



Project Location



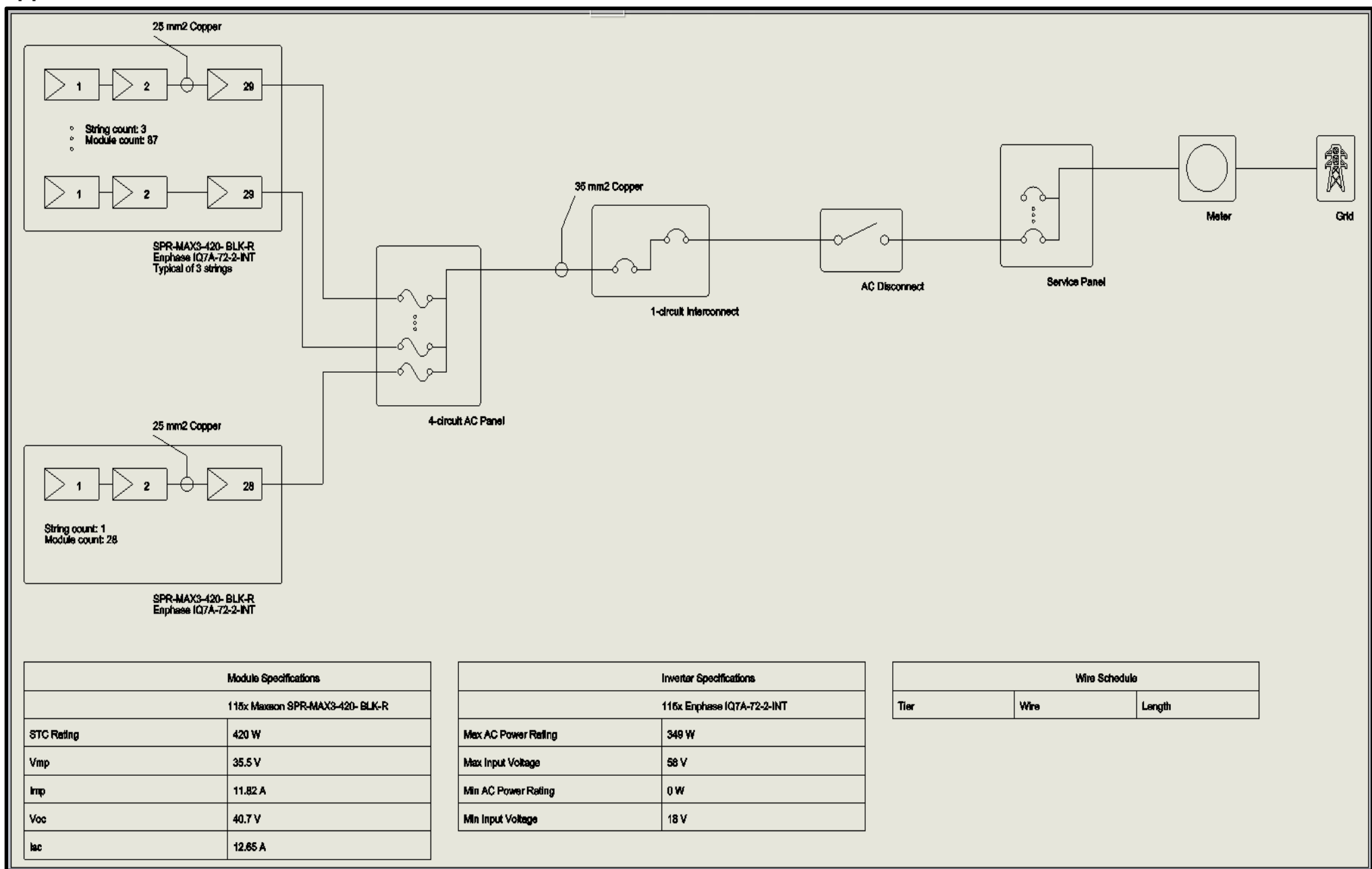
Design Wiring Zone

Description	Combiner Poles	String Size	Stringing Strategy
LS- Lancaster South	-	1 - 1	Along Racking

Field Segments

Description	Racking	Orientation	Tilt	Azimuth	Intrarow Spacing	Frame Size	Frames	Modules	Power
Lancaster Rooftop	Fixed Tilt	Portrait (Vertical)	Module: 36°	Module: 191.821°	1.4 m	1x1	115	115	48.30 kW

Appendix -4F: SOLAR-PV GENERATION SINGLE LINE DIAGRAM

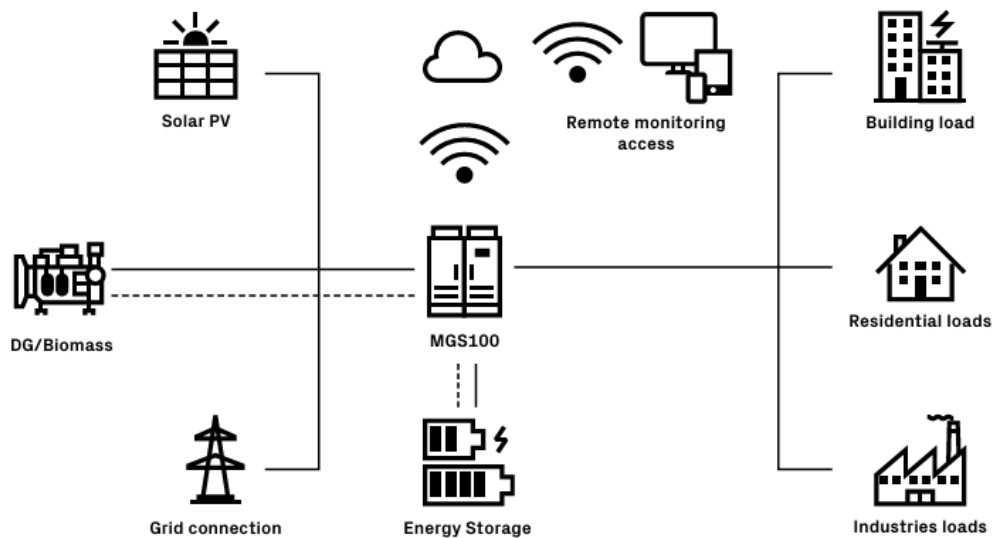


Appendix -4G: ABB MGS 100 CONVERTER DATASHEET

Microgrid solutions - MGS100

The system is formed from an integrated solar PV and battery energy storage converter with an additional AC input. This can incorporate either biofuel or diesel generation, or even an existing grid connection, into the microgrid's energy mix.

MGS100 product diagram



Technical data and types

Model/Rating	MGS100-20/20	MGS100-40/27.6	MGS100-80/50
General Data			
Nominal load power@u.p.f	20 kW	40 kW	80 kW
Max. recommended PV input power	24 kWp	32 kWp	60 kWp
Max. rated PV output power	20 kW	27.6 kW	50 kW
Max. battery charging power	12 kW	24 kW	48 kW
Max. input battery capacity @ C10 charging	138 kWh	276 kWh	552 kWh
PV input			
MPPT operating range	440 – 800 V	500 – 800 V	480 – 800 V
Max. PV input DC voltage		1000 V	
No. of independent MPPT	2	2	3
No. of DC input pairs/MPPT	4	5	5
PV input current protection for each input		Yes, DC Fuses, 15 A	
PV input over voltage protection		Yes, Type II	
AC input			
Nominal input voltage		3 × 380/220 V + N 3 × 400/230 V + N 3 × 415/240 V + N	
Voltage tolerance		±15%	
Input frequency		50 / 60 Hz	
Frequency tolerance (Generator operation)		-30% / +40%	
Frequency tolerance (Grid export)		±5%	
Maximum input current	36 A	71 A	142 A
AC input current protection		Yes, MCCB	
Rated short-time withstand current (I _{cw})		10 kA for 1.5 seconds	

Technical data and types

Model/Rating	MGS100-20/20	MGS100-40/27.6	MGS100-80/50
Output			
Nominal rated output voltage		3 × 380/220 V + N 3 × 400/230 V + N 3 × 415/240 V + N	
Output frequency		50 / 60 Hz	
Output rated current (In)	29 A	58 A	116 A
Output short capability on generator (RMS) for 100ms		2.7 x In A	
Output short term overload capability on grid (RMS) for 20ms		10 x In A	
Permissible unbalanced load (□-□)		100%	
Output protection		Yes, MCCB	
Transfer time from Generator←→Battery←→Grid		<5 ms	
Battery			
Nominal battery voltage range		504 to 576 V DC	
Operating battery voltage range		440 to 660 V DC	
Battery type		VRLA, Ni-Cd, Li-ion	
Maximum charging current	24 A	48 A	96 A
Battery protection		Yes, MCB	
Efficiency			
Max. PV to load		>98%	
Max. grid to load		>99%	
Max. generator to load		>95%	
Max. PV to battery		>94%	
Max. grid to battery		>95%	
Environmental			
Humidity (Non-condensing)		<95%	
Ambient temperature		-5 to 45 °C without derating	
Max. Ambient temperature		50 °C	
Temperature derating	-5%/°C after 45 °C	-5%/°C after 45 °C	-5%/°C after 45 °C
Altitude		1000 m	
Altitude derating		-5%/1000 m	
Audible noise at 1 m from front, 100% load		< 70 dB	
Electrical/Mechanical			
Degree of protection		IP31	
Cable entry		Bottom	
Color		RAL 7035	
User interface & remote monitoring			
Graphical touchscreen HMI	Graphical touchscreen display for control & monitoring (Optional)		
Remote monitoring hardware with Web based Remote monitoring solution	Yes (Optional) with GSM/Ethernet adapter		
Communication Protocol for external SCADA integration	MODBUS (Others on request)		
Weight, dimensions			
Weight – Unpacked	620 kg	640 kg	745 kg
Cabinet Dimensions W x H x D (mm)	1500 x 1800 x 800	1500 x 1800 x 800	1200 x 1800 x 800
Separate solar section dimensions W x H x D (mm)	N.A.	N.A.	1100 x 750 x 261.5

Technical data and types

Model/Rating	MGS100-120/150	MGS100-160/200	MGS100-240/200	MGS100-240/250
General Data				
Nominal load power@u.p.f	120 kW	160 kW	240 kW	240 kW
Max. recommended PV input power	180 kWp	240 kWp	240 kWp	300 kWp
Max. battery charging power	72 kW	96 kW	144 kW	144 kW
PV Input				
MPPT operating range	480 - 800 V			
Max. PV input DC voltage	1000 V			
No. of independent MPPT	6	6	6	6
No. of DC input pairs/MPPT	4	4	4	4
PV input current protection for each input	Yes, DC Fuses			
PV input over voltage protection	Yes			
AC Input				
Nominal input voltage	3 × 400/230 V + N			
Voltage tolerance	±15%			
Input frequency	50 / 60 Hz			
Frequency tolerance (Generator operation)	-30% / +40%			
Frequency tolerance (Grid export)	±5%			
Maximum input current	213 A	284 A	426 A	426 A
AC input current protection	Yes, MCCB			
Output				
Nominal output voltage	3 × 400/230 V			
Output rated current (In)	174 A	232 A	348 A	348 A
Output frequency	50 / 60 Hz			
Overload capability	150% load for 60 sec.			
Short term overload (RMS)	2.7xIn for 100ms			
Permissible unbalanced load	100%			
Output protection	Yes, MCCB			
No. of output breakers	1			
Battery				
Nominal battery voltage	504 to 576 V DC			
Operating battery voltage range	440 to 660 V DC			
Battery type	VRLA, Ni-Cd, Li-ion			
Maximum charging current	144 A	192 A	288 A	288 A
Environmental				
Humidity	<95% (Non-condensing)			
Ambient temperature (Without derating)	-5 to 45 °C			
Temperature derating	-5%/°C after 45 °C			
Max. Ambient temperature	50 °C			
Altitude	1000 m			
Altitude derating	-5%/1000 m			
Electrical/Mechanical				
Degree of protection	IP31			
Cable entry	Bottom			
User Interface & remote monitoring				
HMI	Graphical display for control & monitoring (optional)			
Local & remote monitoring	Yes (Optional)			
Communication Protocol	MODBUS			
Weight, dimensions				
Weight – Unpacked	1050 kg	<1200 kg	<1500 kg	<1500 kg



Li.ON ESS 51.2V

TECHNICAL DATASHEET



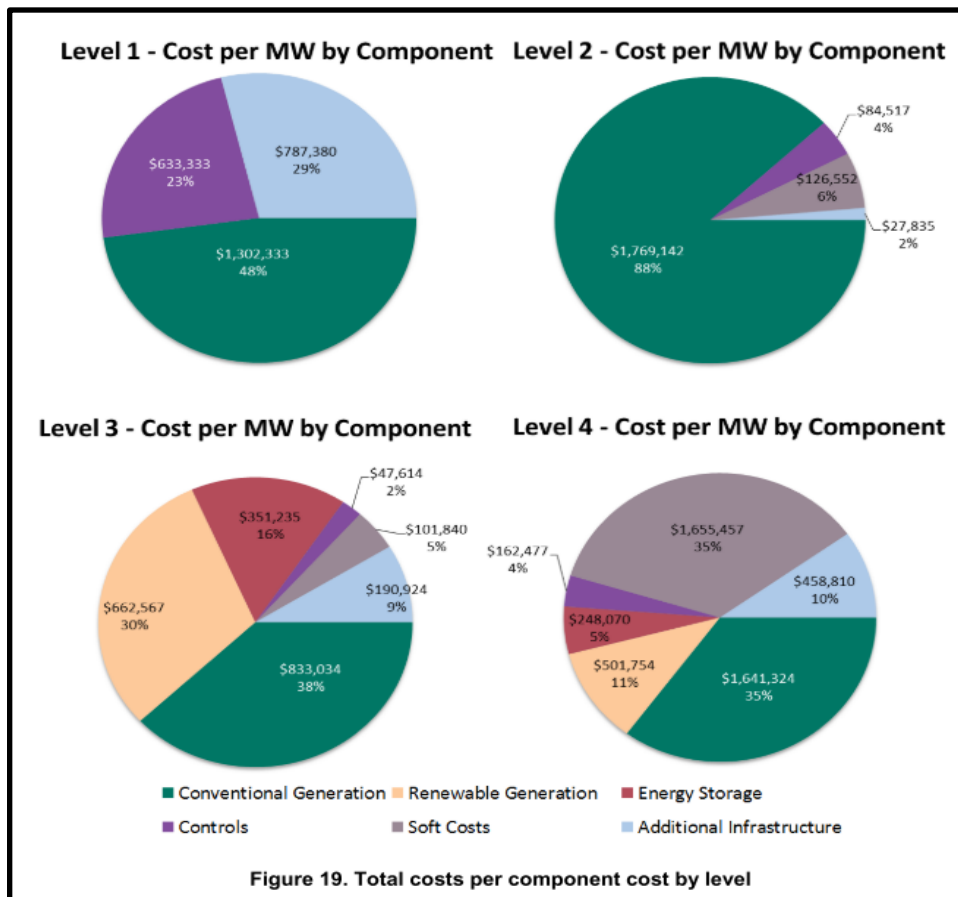
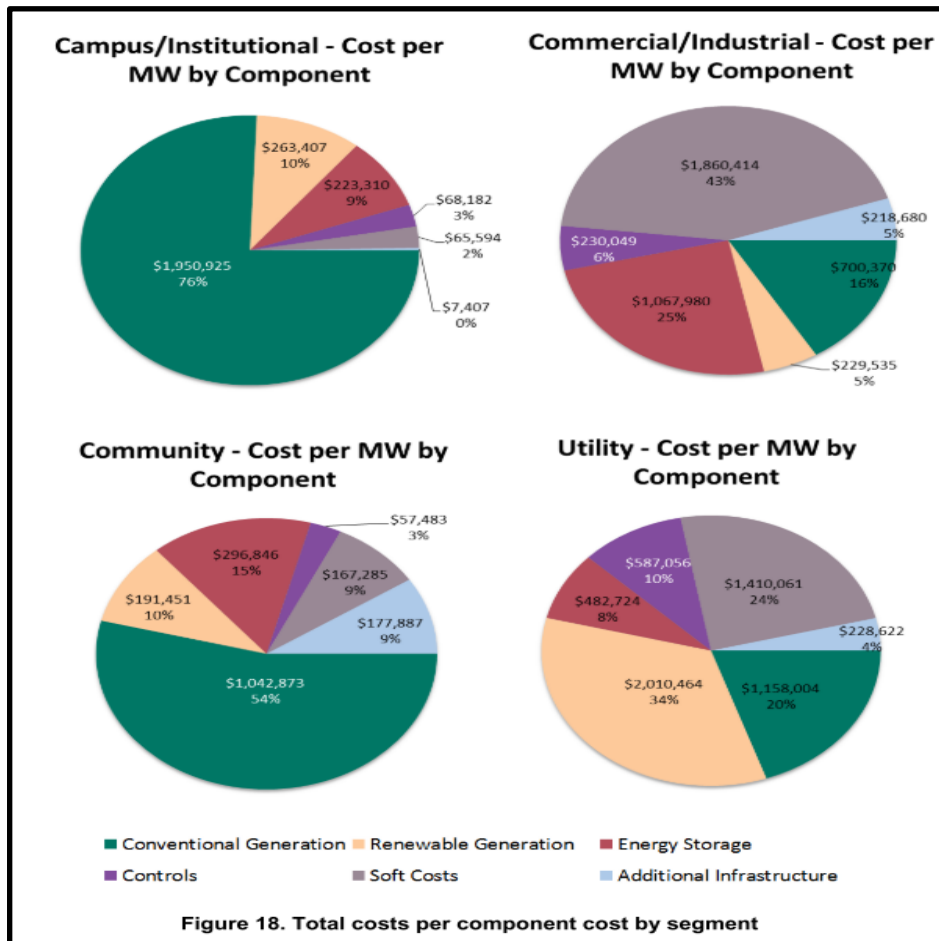
Technical specifications		
Module type	Standard	Heavy duty
Battery chemistry	LiFePO ₄ (LFP)	LiFePO ₄ (LFP)
Module electrical characteristics		
Rated energy	5.12kWh	7.68kWh
Nominal voltage	51.2V	51.2V
Minimum voltage	50.9V	50.9V
Maximum voltage	55.1V	55.1V
Nominal capacity	100Ah	150Ah
Maximum current	75A	100A
Recommended Charging Current	50A (0.5C)	75A (0.5C)
Charge/Discharge cycles SoH> 80%	>4500 @ 80%DoD	>4500 @ 80%DoD
Operating temperature	Charging: 0°C - 55°C Discharging: -20°C - 55°C	Charging: 0°C - 55°C Discharging: -20°C - 55°C
Efficiency	>98%	>98%
Physical characteristics		
Module dimensions (LxWxH)/ Weight (kg)	465mm x 653mm x 228mm / 77kg	583mm x 725mm x 228mm / 110Kg
Terminal connection	Rebling M8 screw	Rebling M8 screw
Casing	Steel	Steel
Available Cabinet Options	16U, 22U, 32U, 42U, 47U	16U, 22U, 32U, 42U
Battery Capacity Range at Cabinet Level	5.12kWh up to 35.84kWh (with 47U cabinet)	7.68kWh hasta 46.08kWh (con 42U cabinet)
Cabinet Size (LxW)	600mm x 800mm / 19-inch	800mm x 800mm / 23-inch
Protection Class	IP 20 (up to IP55 upon request)	IP 20 (up to IP55 upon request)
Battery management system and communication		
Battery Management System (BMS)	Active Balancing BMS	Active Balancing BMS
Monitoring & serviceability	Bi-directional communication: Remote monitoring and remote maintenance, diagnosis & debugging over GLocal	Bi-directional communication: Remote monitoring and remote maintenance, diagnosis & debugging over GLocal
Communication protocol	CAN BUS over RJ45	CAN BUS over RJ45
Inverter communication	Compatible with all major inverters	Compatible with all major inverters
Inverter/charger settings without CANBUS communication		
Float voltage	54.5V	54.5V
Absorption voltage	55V	55V
Low cut off voltage	51V	51V

Parallelization of modules

Standard BMS							
Nominal voltage (V)	51.2						
Nominal energy (kWh)	5	10	15	20	25	30	35 up to 200
Rated power (kW)	3.8	7.7	11.5	15.4	19.2	20.48	20.48
Nominal current (A)	75	150	225	300	375	400	400

High power BMS					
Nominal voltage (V)	51.2				
Nominal energy (kWh)	35	40	50	60	70 up to 200
Rated power (kW)	26,9	30.7	38.4	46.1	48.6
Nominal current (A)	525	600	750	900	950

Appendix -4I: NREL MICROGRID COST BENCHMARKS



Appendix -4J: EXTRACT OF AERMEC AIR CONDITIONER DATASHEET

INDOOR UNIT PERFORMANCE DATA

LPG_D

Indoor unit		LPG350D	LPG500D	LPG700D	LPG850D	LPG1000D	LPG1000D	LPG1200D	LPG1200D	LPG1400D	LPG1400D	LPG1600D
Outdoor unit		LPG350	LPG500	LCG700	LPG850	LPG1000	LPG1000T	LPG1200	LPG1200T	LPG1400	LPG1400T	LPG1600T
Nominal cooling performances												
Cooling capacity (1)	kW	3,50	5,30	7,10	8,50	10,50	10,50	12,10	12,10	13,40	13,40	16,00
Cooling input power (1)	kW	1,03	1,51	1,92	2,50	3,00	3,00	3,58	3,58	4,50	4,50	5,40
EER (2)	W/W	3,40	3,51	3,70	3,40	3,50	3,50	3,38	3,38	2,98	2,98	2,96
Moisture removed	l/h	1,0	1,7	2,4	2,8	3,3	3,3	3,7	3,7	3,9	3,9	4,6
Minimum cooling performances												
Cooling capacity	kW	0,90	1,60	2,40	2,90	3,20	3,20	3,60	3,60	4,00	4,00	4,80
Cooling input power	kW	0,20	0,30	0,50	0,75	0,90	0,90	1,10	1,10	1,35	1,35	1,50
Maximum cooling performances												
Cooling capacity	kW	4,00	5,80	7,60	9,00	11,00	11,00	13,10	13,10	14,20	14,20	17,00
Cooling input power	kW	1,30	1,80	2,60	3,30	4,00	4,00	5,30	5,30	5,60	5,60	6,80
Seasonal efficiency												
SEER	W/W	6,50	6,30	6,60	6,40	6,40	6,40	6,10	6,10	6,10	6,10	6,10
Efficiency energy class (3)		A++	A++	A++	A++	A++	A++	-	-	-	-	-
Pdesignc	kW	3,5	5,3	7,1	8,5	10,5	10,5	-	-	-	-	-
Annual power consumption	kWh/annum	189	294	377	465	574	574	-	-	-	-	-
Nominal heating performances												
Heating capacity (4)	kW	4,00	5,60	8,00	8,80	11,50	11,50	13,50	13,50	15,50	15,50	17,00
Heating input power (4)	kW	1,00	1,42	2,00	2,25	2,80	2,80	3,70	3,70	4,50	4,50	4,70
COP (2)	W/W	4,00	3,94	4,00	3,91	4,11	4,11	3,65	3,65	3,44	3,44	3,62
Minimum heating performances												
Heating capacity	kW	0,90	1,60	2,20	2,50	3,00	3,00	3,60	3,60	3,90	3,90	4,50
Heating input power	kW	0,20	0,30	0,50	0,75	0,90	0,90	1,10	1,10	1,35	1,35	1,50
Maximum heating performances												
Heating capacity	kW	4,50	6,10	8,60	9,50	12,50	12,50	14,50	14,50	16,00	16,00	18,00
Heating input power	kW	1,30	1,80	2,60	3,30	4,00	4,00	5,30	5,30	5,60	5,60	6,80
Seasonal efficiency (temperate climate)												
SCOP	W/W	4,00	4,00	4,10	4,10	4,20	4,20	4,10	4,10	4,00	4,00	4,00
Efficiency energy class (3)		A+	A+	A+	A+	A+	A+	-	-	-	-	-
Pdesignh	kW	3,00	3,90	4,70	6,00	7,00	7,00	-	-	-	-	-
Annual power consumption	kWh/annum	1050	1365	1605	2049	2333	2333	-	-	-	-	-
Electric data												
Rated power input (5)	kW	1,30	1,90	2,80	3,30	4,70	4,40	5,30	5,30	5,60	5,60	6,80
Rated current input (5)	A	6,0	9,5	14,0	15,0	21,0	7,0	23,0	9,0	25,0	11,0	12,0
Refrigeration pipework												
Diameter of liquid refrigerant connections	mm (inch)	6.35 (1/4")	6.35 (1/4")	15.9 (5/8")	15.9 (5/8")	15.9 (5/8")	15.9 (5/8")	15.9 (5/8")	15.9 (5/8")	15.9 (5/8")	15.9 (5/8")	15.9 (5/8")
Diameter of refrigerant gas connections	mm (inch)	9.52 (3/8")	12.7 (1/2")	9.52 (3/8")	9.52 (3/8")	9.52 (3/8")	9.52 (3/8")	9.52 (3/8")	9.52 (3/8")	9.52 (3/8")	9.52 (3/8")	9.52 (3/8")
Nominal length of refrigerant lines	m	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	7,5	7,5	7,5
Power supply												
Power supply		220-240V ~ 50Hz	220-240V ~ 50Hz	220-240V ~ 50Hz	220-240V ~ 50Hz	220-240V ~ 50Hz	380-415V 3N~50/60Hz	220-240V ~ 50Hz	380-415V 3N~50/60Hz	220-240V ~ 50Hz	380-415V 3N~50/60Hz	380-415V 3N~50/60Hz

(1) Cooling (EN 14511 and EN 14825) ambient air temperature 27 °C d.b. / 19 °C w.b.; outside air temperature 35 °C; turbo speed; length of refrigerant lines 5 m.

(2) EER/COP in accordance with the Standard (EN 14511), only declared for the purposes of the tax deductions in force at the time of this publication.

(3) Data in accordance with Delegated Regulation (EU) No. 626/2011.

(4) Heating (EN 14511 and EN 14825) ambient air temperature 20 °C d.b.; outside air temperature 7 °C d.b. / 6 °C w.b.; turbo speed; length of refrigerant lines 5 m.

(5) The rated power input (rated current input) is the maximum input electrical power (maximum current input) from the system, in accordance with the Standards EN 60335-1 and EN 60335-2-40.

		LPG350D	LPG500D	LPG700D	LPG850D	LPG1000D	LPG1200D	LPG1400D	LPG1600D
Indoor unit									
Type of fan	Type	Inverter centrifugal	Inverter centrifugal	Inverter centrifugal	Inverter centrifugal	Inverter centrifugal	Inverter centrifugal	Inverter centrifugal	Inverter centrifugal
Air flow rate									
Turbo	m³/h	600	900	1100	1400	1700	2000	2300	2600
Maximum	m³/h	550	800	1000	1300	1600	1800	2100	2300
Average	m³/h	500	700	900	1100	1400	1600	1800	2000
Minimum	m³/h	400	600	800	1000	1200	1400	1500	1700
High static pressure									
Nominal	Pa	25	25	25	37	50	50	50	50
Maximum	Pa	80	80	160	160	155	155	200	200
Sound pressure									
Turbo	dB(A)	35,0	36,0	37,0	43,0	39,0	43,0	43,0	46,0
Maximum	dB(A)	33,0	35,0	35,0	41,0	38,0	42,0	42,0	44,0
Average	dB(A)	32,0	33,0	33,0	39,0	37,0	41,0	40,0	42,0
Minimum	dB(A)	30,0	31,0	31,0	37,0	36,0	40,0	38,0	40,0
Indoor unit									
Condensate discharge diameter	mm	26,0	26,0	26,0	26,0	26,0	26,0	26,0	26,0

Sound pressure measured in semi anechoic chamber at a distance of 1 m from the source (1,5m for type Duct and Cassette)

Appendix -4K: DATASHEET OF DRITHERM® CAVITY SLAB INSULATION



knaufinsulation.co.uk

DRITHERM® CAVITY SLABS 32, 34 AND 37

December 2022



APPLICATION



DESCRIPTION

Dritherm® Cavity Slabs are water-repellent Glass Mineral Wool slabs, designed for use in external full-fill masonry cavity walls, offering a range of thermal performance to suit construction requirements. They are non-combustible with the best possible Euroclass A1 reaction to fire classification, and are manufactured using Knauf Insulation's unique bio-based binder, ECOSE® Technology.

BENEFITS

- ✓ Water repellent and BBA certified for use in all exposure zones, including those in very severe areas.
- ✓ Slabs are sized to fit between wall ties without the need for retaining discs.

PERFORMANCE

Thermal

Thermal conductivity: From 0.032 to 0.037 W/mK

Fire

Classification: Euroclass A1 to BS EN 13501-1

Vapour resistivity

Water vapour resistivity: 5.00 MNs/g.m

ADDITIONAL INFORMATION

Durability

Dritherm® Cavity Slabs are odourless, rot proof, non-hygroscopic, do not sustain vermin and will not encourage the growth of fungi, mould or bacteria.

Application

Dritherm® Cavity Slabs are for the thermal insulation of masonry cavity external walls and are installed to fully fill the cavity. They are approved for use in buildings up to 12m high in any exposure zone (subject to the requirements of the BBA certification being met) and for use in multi-storey applications up to 25m in height.

Standards and certification

Dritherm® Cavity Slabs are manufactured in accordance with BS EN 13162, ISO 50001 Energy Management Systems, ISO 14001 Environmental Management Systems, and ISO 9001 Quality Management systems, as certified by TÜV Nord. All our Glass Mineral Wool products have been awarded the DECLARE 'Red List Free' label. This allows product transparency disclosure that identifies where a product comes from, what it's made of, and where it goes at the end of its life. Having the 'Red List Free' label means that there are no ingredients in the product that are on the red list - including formaldehyde or phenol.

Environmental

Dritherm® Cavity Slabs contain no ozone-depleting substances or greenhouse gases. For further environmental information consult the relevant Environmental Product Declaration, available on our website.

Moisture resistance

Tests by the British Board of Agrément confirm that Dritherm® Cavity Slabs will not transmit water to the inner leaf. Nor will they transmit moisture by capillary action across the cavity or from below damp proof course level.

CERTIFICATIONS, CLASSIFICATIONS AND INDUSTRY STANDARDS



Generic BRE Green Guide Rating A+

EPD



Declare

Red List Free



DRITHERM® CAVITY SLABS 32, 34 AND 37

December 2022

ADDITIONAL INFORMATION

Real Performance

Glass and Rock Mineral Wool are easier to install correctly than other insulants such as rigid boards because they adapt to any slight imperfections in the substrate and knit together, eliminating any air gaps. Evidence shows the absence of air gaps is crucial to achieving real performance in the relevant application.

Handling and storage

DriTherm® Cavity Slabs are easy to handle and install, being lightweight and easily cut to size, where necessary. They are supplied in polythene packs (4LDPE) which are designed for short term protection only. For longer term protection on site, the product should either be stored indoors, or under cover and off the ground. DriTherm® Cavity Slabs should not be left permanently exposed to the elements.

SPECIFICATIONS

Thickness (mm)	Thermal conductivity (W/mK)	Thermal resistance (m ² K/W)	Length (mm)	Width (mm)	Slabs per pack	Area per pack (m ²)	Packs per pallet	Product code
DriTherm® Cavity Slab 37								
150	0.037	4.05	1200	455	8	4.37	25	715835
125	0.037	3.35	1200	455	6	3.28	40	316660
100	0.037	2.70	1200	455	12	6.55	25	715831
85	0.037	2.25	1200	455	8	4.37	45	316656
75	0.037	2.00	1200	455	8	4.37	50	316654
65	0.037	1.75	1200	455	10	5.46	40	316652
50	0.037	1.35	1200	455	12	6.55	30	316650
DriTherm® Cavity Slab 34								
150	0.034	4.40	1200	455	5	2.73	30	715834
125	0.034	3.65	1200	455	6	3.28	30	715836
100	0.034	2.90	1200	455	8	4.37	30	715832
75	0.034	2.20	1200	455	10	5.46	30	715833
DriTherm® Cavity Slab 32								
150	0.032	4.65	1200	455	4	2.18	30	580216
125	0.032	3.90	1200	455	4	2.18	40	715828
100	0.032	3.10	1200	455	6	3.28	30	715829
85	0.032	2.65	1200	455	5	2.73	45	715830
75	0.032	2.30	1200	455	6	3.28	45	715827



ECOSE® Technology is our unique bio-based binder, that is used in the manufacture of all of our Glass Mineral Wool products and the majority of our Rock Mineral Wool products, to bind insulation strands together. ECOSE® Technology contains no added formaldehyde or phenol. It is made from natural raw materials that are rapidly renewable and is 70% less energy-intensive to manufacture than traditional binders, so it is more environmentally-friendly. Products made with ECOSE® Technology are soft to touch and easy to handle. They generate low levels of dust and VOCs and have been awarded the Eurofins Gold Certificate for Indoor Air Comfort.

Knauf Insulation Ltd

PO Box 10, Stafford Road, St.Helens,
Merseyside, WA10 3NS. UK

Customer Service: 01744 766 766 Technical Support Team: 01744 766 666

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KINE1514DAT-V1222



Appendix -4L: TYPICAL GROUND FLOOR CONSTRUCTION & U-VALUES

Typical Constructions and U-values

Solid Concrete Ground Based Floors

Insulation Below the Floor Slab

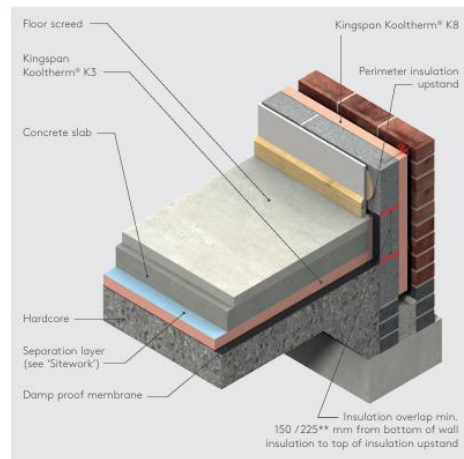


Figure 3

U-values (W/m ² K) for various thicknesses of Kingspan Kooltherm® K3 floor perimeter / area ratios			
Insulant thickness (mm)	Perimeter / Area (m ²)		
	0.4	0.5	0.6
25	X	X	X
30	0.34	X	X
40	0.29	0.31	0.32
50	0.25	0.26	0.27
60	0.22	0.23	0.24
70	0.20	0.21	0.22
80	0.18	0.19	0.20
90	0.17	0.18	0.18
100	0.16	0.16	0.17
110	0.15	0.15	0.15
120	0.14	0.14	0.14
130	0.13	0.13	0.13
140	0.12	0.12	0.13
150	0.11	0.12	0.12

* Where multiple layers of insulation of different thicknesses are used, the thickest layer should be installed as the outermost layer in the construction.

** 225 mm to the Republic of Ireland and 150 mm applies to the NI.

NB Refer to local distributor or Kingspan Insulation for current stock and non-stock sizes.

Insulation Below the Floor Screed

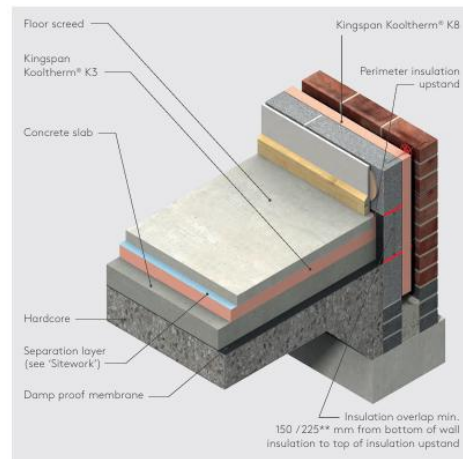


Figure 4

U-values (W/m ² K) for various thicknesses of Kingspan Kooltherm® K3 floor perimeter / area ratios			
Insulant thickness (mm)	Perimeter / Area (m ²)		
	0.4	0.5	0.6
25	X	X	X
30	0.34	X	X
40	0.29	0.31	0.32
50	0.25	0.26	0.27
60	0.22	0.23	0.24
70	0.20	0.21	0.22
80	0.18	0.19	0.20
90	0.17	0.18	0.18
100	0.16	0.16	0.17
110	0.15	0.15	0.15
120	0.14	0.14	0.14
130	0.13	0.13	0.13
140	0.12	0.12	0.13
150	0.11	0.12	0.12

* Where multiple layers of insulation of different thicknesses are used, the thickest layer should be installed as the outermost layer in the construction.

** 225 mm to the Republic of Ireland and 150 mm applies to the NI.

NB Refer to local distributor or Kingspan Insulation for current stock and non-stock sizes.

Appendix -4M: CONSTRUCTION PROPERTIES OF ENVELOPE ELEMENTS

IES

BC-External Wall

Reference ID: STD WA10

Construction is a External Wall from the project database

Layer Description	Thickness	Conductivity	Density	Capacity	Resistance	Vapour res.	Category
BRICKWORK (OUTER LEAF)	0.1030	0.840	1700.0	800.0	0.1226	200.00f	Brick & Blockwork
Crown Bricks-thin-22 Cavity Slab Insulation	0.1000	0.032	18.0	1030.0	3.1250	5.00f	Insulating Materials
BRICKWORK (INNER LEAF)	0.1400	0.620	1700.0	800.0	0.2258	35.00f	Brick & Blockwork
Plasterboard (Wallboard) [BR 443]	0.0150	0.075	900.0	1000.0	0.2000	-1.00f	Plaster
Inside Surface					0.130		
Outside Surface					0.040		
Total Resistance					3.843		
CIBSE Net U-Value W/m²·K	0.2602						
EN-ISO U-Value W/m²·K	0.2602						
ASHRAE 90.1 U-Value W/m²·K	0.2602						
Outside surface absorptance	0.6300						
Inside surface absorptance	0.9400						
Inside Emissivity	0.9100						
Outside Emissivity	0.9000						
BC-External Wall							
Normal wind exposure							
U-value	0.2602 W/m²·K						
Outside surface resistance	0.0400 m²K/W						
Inside surface resistance	0.1300 m²K/W						
Outside convective heat transfer coefficient	19.8700 W/m²·K						
Inside convective heat transfer coefficient	2.0903 W/m²·K						
Outside radiative heat transfer coefficient	5.1300 W/m²·K						
Inside radiative heat transfer coefficient	5.6020 W/m²·K						
Cm (SBE Thermal capacity)	129.10 kJ/(m²·K)						
Admittance	2.5826 W/m²·K						
Admittance time lead	1.07 Hrs						
Internal admittance	0.0000 W/m²·K						
Decrement factor	0.140 m²K/W						
Decrement factor time lag	11.000 Hrs						
Surface factor	0.68						
Internal surface factor	0.000						

IES

BC-Internal Partition.

Reference ID: WSCM

Construction is a Internal Partition from the project database

Layer Description	Thickness m	Conductivity W/(m·K)	Density kg/m³	Capacity J/(kg·K)	Resistance m²K/W	Vapour res. GH·s/(kg·m)	Category
Plasterboard	0.0050	0.210	700.0	1000.0	0.0238	0.00f	Plaster
BRICKWORK (INNER LEAF)	0.1340	0.620	1700.0	800.0	0.2161	35.00f	Brick & Blockwork
DENSE EPS SLAB INSULATION - LIKE STYROFOAM	0.0830	0.025	30.0	1400.0	3.3200	830.00f	Insulating Materials
Plasterboard	0.0050	0.210	700.0	1000.0	0.0238	0.00f	Plaster
Inside Surface					0.130		
Outside Surface					0.130		
Total Resistance					3.844		
CIBSE Net U-Value W/m²·K	0.2602						
EN-ISO U-Value W/m²·K	0.2602						
ASHRAE 90.1 U-Value W/m²·K	0.2602						
Outside surface absorptance	0.5500						
Inside surface absorptance	0.5500						
Inside Emissivity	0.9000						
Outside Emissivity	0.9000						

BC-Internal Partition.

Normal wind exposure

U-value	0.2602 W/m²·K
Outside surface resistance	0.1300 m²K/W
Inside surface resistance	0.1300 m²K/W
Outside convective heat transfer coefficient	2.1519 W/m²·K
Inside convective heat transfer coefficient	2.1519 W/m²·K
Outside radiative heat transfer coefficient	5.5404 W/m²·K
Inside radiative heat transfer coefficient	5.5404 W/m²·K
Cm (SBE Thermal capacity)	3.50 kJ/(m²·K)
Admittance	0.4402 W/m²·K
Admittance time lead	3.11 Hrs
Internal admittance	0.5149 W/m²·K
Decrement factor	0.318 m²K/W
Decrement factor time lag	7.000 Hrs
Surface factor	0.962
Internal surface factor	0.289

IES							
BC- Ground/Exposed Floor Reference ID: STD FLO3 Construction is a Ground/Exposed Floor from the project database							
Layer Description	Thickness m	Conductivity W/(m·K)	Density kg/m³	Capacity J/(kg·K)	Resistance m²K/W	Vapour res. GH s/(kg m)	Category
STONE CHIPPINGS	3.2550	0.960	1800.0	1000.0	3.3906	-1.00f	Sands, Stones and Soils
BRICKWORK (OUTER LEAF)	0.1030	0.840	1700.0	800.0	0.1226	58.00f	Brick & Blockwork
Cast concrete- 100 mm [AD-L2 (2002)]	0.2500	1.350	2000.0	1000.0	0.1892	-1.00f	Concretes
K3 Kooltherm-Rigid Thermoset Phenolic Insul	0.0350	0.023	35.0	1400.0	1.5217	300.00f	Insulating Materials
SCREEN	0.0600	0.410	1200.0	840.0	0.1463	50.00f	Screeds & Renders
Inside Surface					0.117		
Outside Surface					0.070		
Total Resistance					5.554		
CIBSE Net U-Value W/m²·K	0.1801						
EN-ISO U-Value W/m²·K	0.1793						
ASHRAE 90.1 U-Value W/m²·K	0.1799						
Outside surface absorptance		0.7000					
Inside surface absorptance		0.5500					
Inside Emissivity		0.9000					
Outside Emissivity		0.9000					
BC- Ground/Exposed Floor Normal wind exposure							
U-value	0.1801 W/m²·K						
Outside surface resistance	0.0700 m²K/W						
Inside surface resistance	0.1171 m²K/W						
Outside convective heat transfer coefficient	9.1600 W/m²·K						
Inside convective heat transfer coefficient	3.0000 W/m²·K						
Outside radiative heat transfer coefficient	5.1300 W/m²·K						
Inside radiative heat transfer coefficient	5.5404 W/m²·K						
Cm (SBE Thermal capacity)	60.48 kJ/(m²·K)						
Admittance	-nan(ind) W/m²·K						
Admittance time lead	-nan(ind) Hrs						
Internal admittance	-nan(ind) W/m²·K						
Decrement factor	0.000 m²K/W						
Decrement factor time lag	0.000 Hrs						
Surface factor	-nan(ind)						
Internal surface factor	-nan(ind)						

IES

BC-North and South End Flat Roof.
Reference ID: FROOF2
Construction is a Roof from the project database

Layer Description	Thickness m	Conductivity W/(m·K)	Density kg/m³	Capacity J/(kg·K)	Resistance m²K/W	Vapour res. GH s/(kg m)	Category
STONE - ST01	0.0100	1.802	2243.0	837.0	0.0055	242.00f	Sands, Stones and Soils
FELT/BITUMEN LAYERS	0.0050	0.500	1700.0	1000.0	0.0100	-1.00f	Asphalts & Other Roofing
CAST CONCRETE	0.2000	1.130	2000.0	1000.0	0.1770	-1.00f	Concretes
Expanded polystyrene (CIBSE)	0.1700	0.035	25.0	1400.0	4.8571	200.00f	Insulating Materials
Cavity	0.1000				0.1880		
Ceiling tile	0.0120	0.090	250.0	1000.0	0.1333	-1.00f	Tiles
Inside Surface					0.117		
Outside Surface					0.070		
Total Resistance					5.550		
CIBSE Net U-Value W/m²·K	0.1802						
EN-ISO U-Value W/m²·K	0.1817						
ASHRAE 90.1 U-Value W/m²·K	0.1818						
Outside surface absorptance	0.5000						
Inside surface absorptance	0.5500						
Inside Emissivity	0.9000						
Outside Emissivity	0.9000						

BC-North and South End Flat Roof. Normal wind exposure							
U-value	0.1802 W/m²·K						
Outside surface resistance	0.0700 m²K/W						
Inside surface resistance	0.1171 m²K/W						
Outside convective heat transfer coefficient	9.1600 W/m²·K						
Inside convective heat transfer coefficient	3.0000 W/m²·K						
Outside radiative heat transfer coefficient	5.1300 W/m²·K						
Inside radiative heat transfer coefficient	5.5404 W/m²·K						
Cm (SBE Thermal capacity)	3.00 kJ/(m²·K)						
Admittance	0.3924 W/m²·K						
Admittance time lead	3.63 Hrs						
Internal admittance	0.0000 W/m²·K						
Decrement factor	0.200 m²K/W						
Decrement factor time lag	10.000 Hrs						
Surface factor	0.974						
Internal surface factor	0.000						

IES

BC-Internal Ceiling/ Floor

Reference ID: CCR200

Construction is a Internal Ceiling/Floor from the project database

Layer Description	Thickness m	Conductivity W/(m·K)	Density kg/m³	Capacity J/(kg·K)	Resistance m²K/W	Vapour res. GN·s/(kg·m)	Category
LW CONCRETE 40 LBS - HF-C14	0.2000	0.038	641.0	837.0	5.3050	24.00f	Concretes
Inside Surface					0.117		
Outside Surface					0.117		
Total Resistance					5.539		
CIBSE Net U-Value W/m²·K	0.1805						
EN-ISO U-Value W/m²·K	0.1817						
ASHRAE 90.1 U-Value W/m²·K	0.1812						
Outside surface absorptance	0.5500						
Inside surface absorptance	0.5500						
Inside Emissivity	0.9000						
Outside Emissivity	0.9000						
BC-Internal Ceiling/ Floor							
Normal wind exposure							
U-value	0.1805 W/m²·K						
Outside surface resistance	0.1171 m²K/W						
Inside surface resistance	0.1171 m²K/W						
Outside convective heat transfer coefficient	3.0000 W/m²·K						
Inside convective heat transfer coefficient	3.0000 W/m²·K						
Outside radiative heat transfer coefficient	5.5404 W/m²·K						
Inside radiative heat transfer coefficient	5.5404 W/m²·K						
Cm (SBBM Thermal capacity)	2.60 kJ/(m²·K)						
Admittance	1.0974 W/m²·K						
Admittance time lead	2.65 Hrs						
Internal admittance	1.0991 W/m²·K						
Decrement factor	0.116 m²K/W						
Decrement factor time lag	3.000 Hrs						
Surface factor	0.905						
Internal surface factor	0.903						

IES

BC-High Usage Door

Reference ID: MDOOR

Construction is a Door from the project database

Layer Description	Thickness m	Conductivity W/(m·K)	Density kg/m³	Capacity J/(kg·K)	Resistance m²K/W	Vapour res. GN·s/(kg·m)	Category
STEEL	0.0050	50.000	7800.0	480.0	0.0001	3000000.00f	Metals
GLASS-FIBRE QUILT	0.0050	0.040	12.0	840.0	0.1250	6.00f	Insulating Materials
STEEL	0.0050	50.000	7800.0	480.0	0.0001	3000000.00f	Metals
Inside Surface					0.117		
Outside Surface					0.080		
Total Resistance					0.322		
CIBSE Net U-Value W/m²·K	3.1028						
EN-ISO U-Value W/m²·K	3.3875						
ASHRAE 90.1 U-Value W/m²·K	3.6378						
Outside surface absorptance	0.7000						
Inside surface absorptance	0.5500						
Inside Emissivity	0.9000						
Outside Emissivity	0.9000						
BC-High Usage Door							
Normal wind exposure							
U-value	3.1028 W/m²·K						
Outside surface resistance	0.0800 m²K/W						
Inside surface resistance	0.1171 m²K/W						
Outside convective heat transfer coefficient	7.3700 W/m²·K						
Inside convective heat transfer coefficient	3.0000 W/m²·K						
Outside radiative heat transfer coefficient	5.5404 W/m²·K						
Inside radiative heat transfer coefficient	5.5404 W/m²·K						
Cm (SBBM Thermal capacity)	18.72 kJ/(m²·K)						
Admittance	3.2426 W/m²·K						
Admittance time lead	0.74 Hrs						
Internal admittance	1.1956 W/m²·K						
Decrement factor	0.990 m²K/W						
Decrement factor time lag	1.000 Hrs						
Surface factor	0.632						
Internal surface factor	0.994						

IES

BC-Internal Doors

Reference ID: MFLD0009

Construction is a Door from the project database

Layer Description	Thickness m	Conductivity W/(m·K)	Density kg/m³	Capacity J/(kg·K)	Resistance m²K/W	Vapour res. GN·s/(kg·m)	Category
Hardwood (NCH Modelling Guide)	0.0050	0.180	2100.0	1000.0	0.0278	-1.00f	Timber
GLASS-FIBRE QUILT	0.0150	0.040	12.0	840.0	0.3750	6.00f	Insulating Materials
Hardwood (NCH Modelling Guide)	0.0050	0.180	2100.0	1000.0	0.0278	-1.00f	Timber
Inside Surface					0.117		
Outside Surface					0.080		
Total Resistance					0.628		
CIBSE Net U-Value W/m²·K	1.5933						
EN-ISO U-Value W/m²·K	1.6651						
ASHRAE 90.1 U-Value W/m²·K	1.7234						
Outside surface absorptance	0.7000						
Inside surface absorptance	0.5500						
Inside Emissivity	0.9000						
Outside Emissivity	0.9000						
BC-Internal Doors							
Normal wind exposure							
U-value	1.5933 W/m²·K						
Outside surface resistance	0.0800 m²K/W						
Inside surface resistance	0.1171 m²K/W						
Outside convective heat transfer coefficient	7.3700 W/m²·K						
Inside convective heat transfer coefficient	3.0000 W/m²·K						
Outside radiative heat transfer coefficient	5.5404 W/m²·K						
Inside radiative heat transfer coefficient	5.5404 W/m²·K						
Cm (SBBM Thermal capacity)	10.50 kJ/(m²·K)						
Admittance	1.7066 W/m²·K						
Admittance time lead	1.12 Hrs						
Internal admittance	0.7209 W/m²·K						
Decrement factor	0.995 m²K/W						
Decrement factor time lag	1.000 Hrs						
Surface factor	0.811						
Internal surface factor	0.996						

IES

BC-Double Glazed External Window

Reference ID: LWB0000

Construction is a External Window from the project database

Layer Description	Thick.	Cond.	Gas	Conv. Coeff.	Res.	Solar Trans.	Out.Solar Refl.	Ins.Solar Refl.	Visible Trans.	Out.Visible	Ins.Visible	Ref. Index
Outer Pane	0.0060	1.0600			0.5800	0.1860		0.2270	0.7800	0.0700	0.0700	1.5260
Cavity	0.0130		ARGON	1.2954	0.4296							
Inner Pane	0.0060	1.0600			0.0057	0.7830	0.0720	0.0720	0.7800	0.0700	0.0700	1.5260
Shading Device information												
Local Device:none												
External Device:none												
Internal Device:none												
Frame occupies 15.00% of area												
BC-Double Glazed External Window												
Normal wind exposure												
U-value (glass only):		1.5481 W/m²·K										
Net U-value (including frame):		1.6005 W/m²·K										
Outside surface resistance		0.0804 m²K/W										
Inside surface resistance		0.1227 m²K/W										
Outside convective heat transfer coefficient:		3.7000 W/m²·K										
Inside convective heat transfer coefficient:		3.0000 W/m²·K										
Outside radiative heat transfer coefficient:		4.7709 W/m²·K										
Inside radiative heat transfer coefficient:		5.1526 W/m²·K										
g-value (ISO EN 410):		0.5477										
g-value (BS6032):		0.4190										
THETA	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°		
T(D)	0.462	0.460	0.456	0.447	0.434	0.410	0.367	0.280	0.124	0.000		
T(R)	0.101	0.101	0.103	0.105	0.107	0.109	0.109	0.102	0.079	0.000		
Short-wave shading coefficient:		0.5307										
Long-wave shading coefficient:		0.1159										
Total shading coefficient:		0.6466										

Appendix -5A: UKNZCBS REPORTING TIMELINES (Anderson et al., 2024)

