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Retrofitting a Grade II Listed Building for Operational Carbon Reduction and Climate Resilience: The Inland Revenue Centre Case Study, Nottingham, UK

Ingrid Farfan * and Renata Tubelo

Department of Architecture and Built Environment, University of Nottingham, Nottingham NG7 2RD, UK; renata.tubelo@nottingham.ac.uk

* Correspondence: id.farfanmartinez@gmail.com

Abstract

Heritage buildings constitute a significant element of the United Kingdom's (UK) built environment, with 460,000 listed buildings across England, Scotland, Wales and Northern Ireland. These assets present substantial challenges for national decarbonisation due to statutory constraints on fabric alteration and the need to consider whole-life carbon impacts. This study evaluates the impact of conservation-compatible retrofit strategies on the operational energy and carbon performance of Fitzroy House, a Grade II listed late-modern office building in Nottingham. Dynamic building simulation (IES Virtual Environment) was used to assess baseline performance and to develop two retrofit scenarios incorporating improvements to glazing, airtightness, roof insulation, and the introduction of mechanical ventilation with heat recovery (MVHR). Climate resilience was evaluated using future weather files for the 2080s. Results are derived from comparative scenario-based modelling rather than calibrated predictions of absolute performance. Within this framework, the proposed measures can reduce annual heating demand by up to 68%, cooling demand by 60%, and operational carbon emissions by approximately 41% (district heating) to 64% (natural gas), relative to the as-built baseline under the most advanced retrofit scenario. Performance remains broadly robust under future climate scenarios, although cooling loads increase modestly. The findings demonstrate that, while meaningful reductions in operational carbon are achievable, retrofit outcomes are fundamentally shaped by conservation constraints, which act as an interpretive framework defining the limits and possibilities of intervention. However, results should be interpreted as indicative of relative performance improvements rather than fully generalizable or predictive outcomes, and embodied carbon impacts are not included within the scope of this study. The research provides an evidence-based pathway for improving similar late-modern listed office buildings while highlighting the limits imposed by conservation requirements and existing building fabric.

Keywords: non-domestic heritage retrofit; conservation-compatible retrofit; building performance simulation; operational carbon; climate resilience

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1. Introduction

The urgent need to decarbonise the built environment in order to meet the United Kingdom's (UK) net-zero target by 2050 has intensified focus on the retrofit of existing buildings. Approximately 80% of the UK's current building stock is expected to remain in use by 2050, making retrofit essential to achieving meaningful emissions reductions [1].

Beyond emissions reductions, retrofit also supports the retention of embodied carbon in existing structures while enhancing occupant comfort and wellbeing [1].

Despite increasing adoption of low-carbon design strategies in new construction, the majority of UK buildings were constructed before modern energy efficiency standards. As a result, they present substantial challenges for decarbonisation. Within this context, heritage and listed buildings are particularly complex due to statutory protections that limit the extent and type of permissible interventions. The UK contains approximately 460,000 listed buildings, including 374,000 in England alone [2], with Grade II buildings accounting 92% of listings. These assets span residential, industrial, and commercial typologies and represent a significant proportion of the national building stock. While their conservation safeguards cultural and architectural value, it also constrains retrofit pathways and limits conventional energy efficiency upgrades.

Although heritage retrofit research has expanded in recent years, it remains uneven across building typologies. Residential heritage buildings have received considerable attention due to their prevalence, technical simplicity, reduced scale of refurbishments and incentives, whereas the non-domestic sector remains comparatively underexplored [3]. As part of the non-domestic buildings, offices and other commercial buildings often have high energy demands and were not designed with energy performance in mind. Retrofit efforts in non-domestic buildings are fragmented and lack clear policy, resulting in inefficient approaches and limited research focus on heritage non-domestic assets [3]. This gap is particularly evident in Grade II listed non-domestic buildings, where intervention strategies must balance conservation requirements with operational carbon reduction targets.

Pre-2000 commercial buildings offer the greatest potential for cost-effective energy savings, despite facing institutional and logistical barriers such as split incentives, heritage constraints, and limited tailored guidance [4]. Commercial energy demand in England and Wales is approximately 90,000 gigawatt-hours (GWh) per year, with peak intensities exceeding 180 Kilowatt-hours per square metre per year (kWh/m^2·yr) in some public buildings, much of it concentrated in older stock, highlighting the scale of achievable reductions within this segment [4]. This highlights the opportunities for targeted retrofit strategies in this segment of the building stock.

However, existing research remains fragmented across three key domains: heritage retrofit practice, operational carbon assessment, and climate resilience analysis. While each domain is well developed in isolation, limited work integrates them into a coherent framework applicable to listed non-domestic buildings [5–9]. This fragmentation limits the ability to evaluate retrofit strategies as whole-building systems under both conservation and decarbonisation constraints.

This study addresses this gap through a single-case study of the Inland Revenue Centre (IRC), Nottingham, a Grade II listed late-modern office building designed by Michael Hopkins and Partners in the early 1990s [10–12], selected to enable an in-depth examination of retrofit strategies within a complex heritage context. The building has recently been repurposed as part of the University of Nottingham's Castle Meadow Campus. It is characterised by a modular structural system, lightweight façade technology, and a design strategy that prioritises daylighting and natural ventilation.

The study combines heritage conservation principles, operational carbon assessment, dynamic thermal simulation, and climate resilience analysis to evaluate retrofit interventions under both current and future climate scenarios. This integrated approach enables a holistic assessment of performance improvements while respecting the constraints imposed by listed status.

1.1. Research Questions, Aims and Objectives

This study is guided by the following research questions (RQ):

- RQ1: Which retrofit strategies can be feasibly implemented in a Grade II listed non-domestic building (the Inland Revenue Centre, Nottingham) without compromising its heritage value?
- RQ2: To what extent can these retrofit strategies reduce operational carbon and energy demand under current and future climate conditions?
- RQ3: How resilient is the proposed retrofit pathway when assessed against projected climate change scenarios, particularly in relation to overheating risk and energy performance stability?

This study is structured around three interrelated aims that operationalise the research questions. First, it examines the constraints and opportunities associated with retrofitting Grade II listed non-domestic buildings, with particular attention to heritage-compatible intervention strategies informed by precedent studies and retrofit standards. Second, it evaluates the impact of selected retrofit measures on operational carbon and energy demand through dynamic simulation of the case study building under current and future climate conditions. Third, it assesses the resilience of the proposed retrofit pathway in relation to overheating risk and long-term performance stability under projected climate scenarios.

1.2. Contribution of the Study

The contribution of this research is threefold. First, it provides a typological extension of retrofit research by focusing on a Grade II listed late-modern office building, a building type that remains largely underrepresented in the literature. Second, it develops an integrated assessment framework combining heritage conservation constraints, operational carbon modelling, dynamic building simulation, and climate resilience evaluation. Third, it assesses the transferability of conservation-compatible retrofit strategies to other similar Grade II listed non-domestic buildings, thereby contributing to both methodological development and practical retrofit guidance.

2. Background Research

The following literature review situates this study within three interrelated domains: heritage retrofit practice, operational carbon assessment methodologies, and climate resilience frameworks. It identifies a gap in integrated approaches applied to listed non-domestic buildings, which forms the basis for the present investigation.

2.1. Retrofit of Listed Buildings

In the UK, statutory listing protects buildings of architectural and historic significance, requiring proportionate and reversible interventions that minimise impact on heritage fabric. Historic England's Advice Note 18 (HEAN18) [6] frames retrofit as a whole-building process and recommends low-risk measures as a first step. In practice, this typically prioritises internal, reversible interventions, such as draught-proofing, secondary glazing, vapour-permeable insulation, and discreet renewable installations, designed to improve performance while preserving character-defining features and historic materials.

Precedent studies (Table 1) illustrate a series of strategies applicable to heritage-sensitive retrofit. Haddington Way, Newport–Somerton, and Stanmore schemes demonstrate thin-profile insulation, high-performance glazing, and hybrid ventilation systems while preserving existing fabric [7]. Cirencester Barrel Store and Bloomsbury House schemes show that internal insulation, triple-glazed windows, and ventilation can achieve Passive House retrofit standard (EnerPHit) aligned performance without compromising

character-defining features [9,13]. These cases provide lessons for material selection, spatial conservation, and system integration relevant to the case study considered.

Table 1. Selected precedent studies and their main characteristics (data from [7,9,13]).

Haddington Way **Mid 1990s** **Not Grade Listed** **Fabric-First Approach**	**Newport Sommerton** **1989** **Not Grade Listed** **Fabric-First Approach**	**Stanmore** **1960s** **Not Grade Listed** **Fabric-First Approach**	**Cirencester Barrel Store** **19th Century** **Grade II Listed** **Certified EnerPHit**	**Bloomsbury House** **18th Century** **Grade II Listed** **Achieved EnerPHit**
Existing construction type				
Masonry cavity walls Pitched roof on timber structure Suspended concrete ground floor Timber single-glazed windows	Masonry cavity walls Seam metal roof Ground floor concrete slab Timber double-glazed windows	Masonry cavity walls Tiled pitched roof Ground floor concrete slab Timber single-glazed windows	500 mm solid stone walls Pitched roof with 50 mm Styrofoam Ground floor concrete slab Timber single-glazed windows	Brick plastered walls Slate tiles on roofing felt Ground floor concrete slab Timber single-glazed windows
Improvements				
Walls				
40 mm Aerogel sheet	Internal dry-line foam	Knauf Techniterm for cavity and Aerogel (25 mm) for internal wall insulation	Wood-fibre insulation	Vapour closed spray-foam
Roof				
150 mm of Celotex	Warmcell insulation	Warmcell between joists, topped up with Thermafleece wool insulation	Polyisocyanurate (PIR) insulation added internally	300 mm cellulose with Oriented Strand Board (OSB)
Ground floor				
Rigid phenolic insulation (75 mm)	Perimeter insulation	Kingspan Kooltherm K3 insulation boards	350 mm Hexatherm Extruded Polystyrene (XPS) insulation above	Over 125 mm XPS insulation on existing concrete slab
Windows				
Argon-filled low-e double glazing	Triple glazing	Triple-glazed aluminium-clad timber units	Triple glazing	Additional secondary double-glazing system
Building services				
MVHR, solar photovoltaic (PV) and Exhaust Air Heat Pump (EAHP)	Ground Source Heat Pump (GSHP) + MVHR, solar PV	High efficiency boiler, solar PV	MVHR	MVHR, Air Source Heat Pump (ASHP) and solar PV
Achieved				
U-values ((Watts per square metre Kelvin (W/m^2K)				
Walls: 0.23 Roof: 0.15 Ground floor: 0.17 Windows: 1.10–1.24	Walls: 0.19 Roof: 0.16 Ground floor: 0.35 Windows: 0.9	Walls: 0.28 Roof: 0.12 Ground floor: 0.37 Windows: 0.88	Walls: 0.19 Roof: 0.104 Ground floor: 0.094 Windows: 1.1	Walls: 0.27 Roof: 0.12 Ground floor: 0.23 Windows: not specified
Airtightness (m^3/m^2h @50Pa)				
Before: 13 After: 5	Before: 9.68 After: 7.73	Before: 7.84 After: 5	Before: unknown After: 0.58	Before: >25 After: 2.8
Energy ($kWh/m^2 \cdot yr$)				
Before: 430 After: 174	Before: 620 After: 160	Before: 350 After: 160	Before: not modelled After: 122	Before: not modelled After: 114

Retrofit standards (Table 2) such as EnerPHit and Association for Environment Conscious Building (AECB) CarbonLite offer structured frameworks for measurable performance improvements, balancing technical feasibility with heritage constraints. London Energy Transformation Initiative (LETI) benchmarks and statutory Part L requirements contextualise these interventions within broader decarbonisation objectives and consider retrofit limitations linked to preservation of a building's character and appearance. A

combined EnerPHit and AECB approach allows phased, evidence-led retrofit without breaching conservation restrictions.

Table 2. Comparative summary of standards and their key metrics (data from [4,6,14–18]).

Metric	Part L	LETI (New-Build)	AECB CarbonLite	EnerPHit (Temperate Climate)
Total energy consumption	<190 kWh/m^2·yr	<55 kWh/m^2/yr	<120 kWh/m^2·yr	<120 kWh/m^2·yr
Delivered space energy for heating	<54 kWh/m^2·yr	-	<50 kWh/m^2·yr	-
Heating demand	-	<15 kWh/m^2/yr	-	<25 kWh/m^2·yr
Delivered space energy for cooling	<54 kWh/m^2·yr	-	<15 kWh/m^2·yr	-
Cooling demand	-	-	-	<15 kWh/m^2·yr
Frequency of overheating (>25 °C)%	-	-	<10%	<10%
Heat recovery efficiency	-	≥90%	≥75%	≥75%
Airtightness (n50 1/h)	5.0	1.0	1.5	1.0
U-values (W/m^{2}K)	Walls: 0.18 Roof: 0.13 Windows: ≤1.4 Ground floor: 0.13	Walls: 0.12–0.15 Roof: 0.10–0.12 Windows: ≤1.0 Ground floor: 0.10–0.12	Walls: ≤0.25 Roof: ≤0.15 Windows: ≤1.5 Roof lights: ≤1.8 Ground floor: ≤0.2	Walls (EWI): ≤0.15 Walls (IWI): ≤0.35 Roof: ≤0.35 Windows: ≤0.85 Roof lights: ≤1.10

2.2. Retrofitting for Climate Resilience and Operational Carbon

Climate resilience is increasingly integrated into retrofit design. Hulathdoowage et al. [8] highlight passive measures (insulation, secondary glazing), active low-carbon systems (MVHR, high-efficiency heating), and renewable energy integration as key to robustness, resistance, and recovery.

Operational carbon refers to the emissions produced from building use, excluding embodied emissions associated with materials, construction, and end-of-life processes. In the UK, this can be calculated using HEMFHS fuel factors [19] and Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum 46 (TM46) sector-specific benchmarks [20], allowing energy demand to be translated into carbon emissions for baseline and retrofit scenarios.

Although the UK electricity grid is decarbonising, operational carbon remains a policy-aligned and practical metric for retrofit assessment. In listed buildings, deep fabric replacement is often restricted, and much of the embodied carbon in the existing structure is already locked in. While retrofit measures may introduce additional embodied emissions, demolition and replacement would compromise both cultural value and retained carbon benefits.

This study therefore prioritises operational carbon as the most measurable pathway for performance improvement within conservation constraints. Embodied carbon is not explicitly quantified, representing a limitation, but focusing on operational performance reflects current regulatory practice and the realistic scope of heritage retrofit interventions.

3. Materials and Methods

3.1. Research Design

This research adopts a mixed-methods approach to evaluate operational carbon reduction and climate resilience in a Grade II listed non-domestic building. The methodology comprised three sequential stages:

(1) policy review to establish the retrofit and heritage context, discussed in Section 2;

(2) qualitative case study analysis through archival, documentary, and photographic sources; and
(3) quantitative simulation-based energy and carbon assessment using Integrated Environmental Solutions Virtual Environment (IES VE) in current and future climate scenarios.

The overall methodological workflow, including the sequence and integration of these stages, is illustrated in Figure 1. This sequence enabled the research to link conservation constraints with data-driven evaluation of retrofit measures and climate adaptation potential.

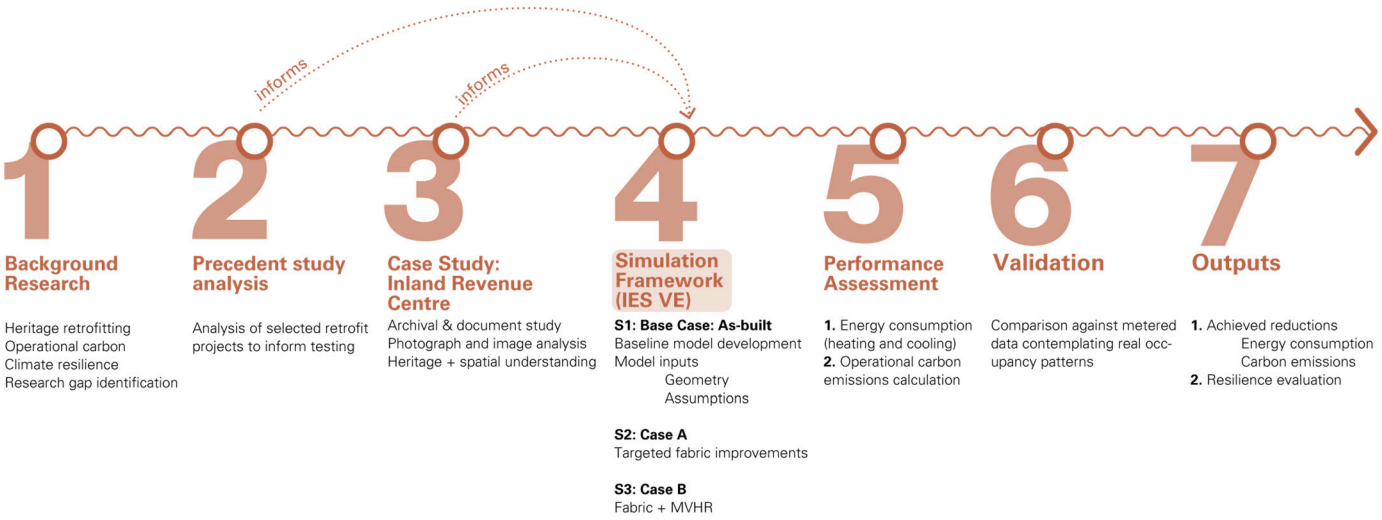


Figure 1. Methodological workflow of the study (authors' graphic).

3.2. Case Study Description and Climate

The Inland Revenue Centre (IRC) in Nottingham (Figure 2) was designed by Michael Hopkins and Partners and completed in 1995 as a purpose-built office complex. The development consists of a total of seven blocks of three and four storeys, a centrally located amenity building, all configured in modular block formations that emphasise modularity and coherence [11].

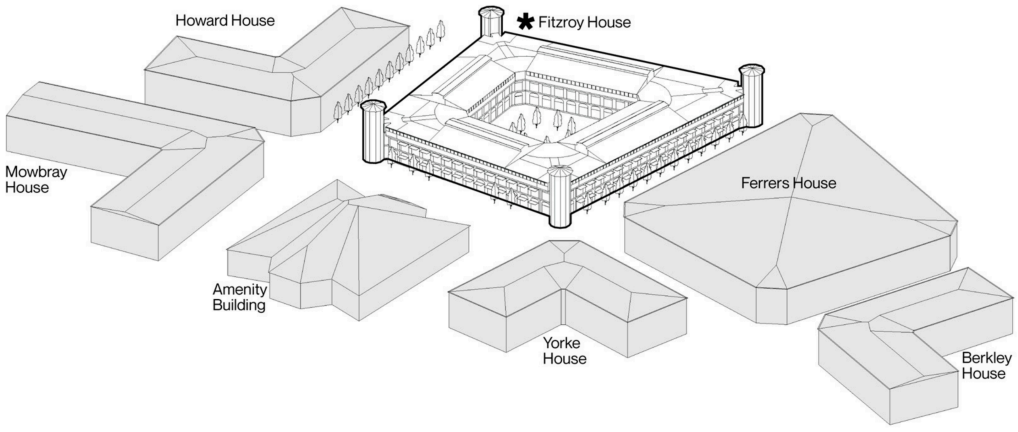


Figure 2. Castle Meadow Campus IES VE model, with the selected building for analysis (Fitzroy House) indicated by an asterisk. (authors' graphic).

Fitzroy House was selected for detailed analysis, comprising approximately 3500 m^2 of open-plan office accommodation across three storeys. The building has a rectangular footprint aligned along a north–south axis. Its structural system consists of a steel frame supporting precast concrete vaulted ceiling panels, enabling large, uninterrupted floorplates.

Vertical circulation is accommodated within glazed cylindrical stair towers positioned at each corner of the building, which also contribute to the natural ventilation strategy.

Beyond its material specification, the architectural significance of Fitzroy House lies in the deliberate tectonic articulation of its constituent elements and the spatial qualities that emerge from them. As recognised by Historic England [21], the building demonstrates a "tempered modernism" characteristic of early 1990s architecture, combining industrial materials with a refined compositional language. The palette of brick, concrete, steel, and glass is not only contextually responsive to the site's industrial character but is deployed in a manner that makes construction legible. The prefabricated brick piers (Figures 3 and 4), for instance, establish a regular structural rhythm across the elevations, their proportioning and detailing reinforcing both load-bearing function and visual order. This rhythmic articulation contributes to the building's formal clarity while anchoring it within a tradition of industrial masonry.



Figure 3. Facade of load-bearing brick piers alternating with full-height glazing, punctuated by a cylindrical glass stair tower (photograph by the authors, 2025).



Figure 4. Close-up of the second-floor facade at the IRC (photograph by the authors, 2025).

Internally, the precast concrete vaults (Figure 5) introduce a distinct spatial and atmospheric condition. Their undulating geometry softens the otherwise robust material

language, modulating light and producing a diffuse illumination that enhances the perceptual depth of the interior. This interplay between mass and light elevates what might otherwise be a utilitarian structural system into a defining architectural feature. Similarly, the roof assembly (Figure 6), combining a lightweight steel structure with a perimeter skylight, generates a contrasting spatial experience at second-floor level, where the originally functional storage areas acquire an unexpected sense of openness and luminosity.



Figure 5. Interior of the first floor at Fitzroy House (photograph by the authors, 2025).



Figure 6. Interior of the second floor at Fitzroy House (photograph by the authors, 2025).

As discussed by Davey and Gardner [22], prefabrication, while often associated with efficiency, is here employed with a notable degree of design intentionality. The coordination of prefabricated roof panels, vaults, and wall elements reflects a synthesis of industrialised building methods with careful material expression and detailing. This approach not only reduced construction time and improved quality control but also contributed to a coherent architectural language in which repetition, precision, and modularity become aesthetic drivers.

It is this integration of constructional clarity, spatial richness, and early prefabrication strategies that underpins the building's architectural value [22]. Fitzroy House can therefore be understood as a significant example of late twentieth-century industrial architecture, in which standardised components are deployed with a level of compositional and experiential sophistication that justifies its listed status.

The building services strategy [12] combines passive and mechanical systems. Heating is supplied via a district energy network through plate heat exchangers and trench radiators located beneath a raised access floor. Domestic hot water is provided by local electric heaters.

Ventilation is primarily natural, supplemented by underfloor mechanical fans. Lighting is fluorescent-based and controlled through an existing building management system.

The building's form factor (Figure 7) (ratio of exposed surface area to conditioned volume), which is an indicator of the heat loss area, is unusually low due to its geometry. In theory, this reduces heat loss, yet the benefits are undermined by an ageing envelope with limited thermal resistance.

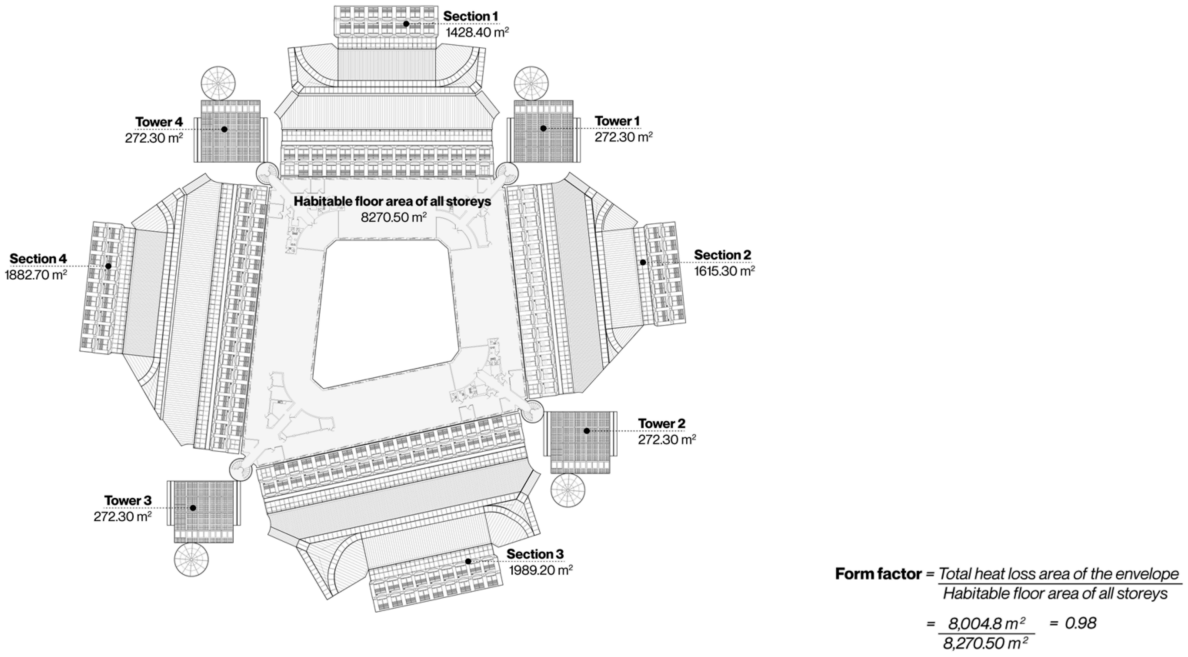


Figure 7. Form factor calculation diagram (authors' graphic).

Nottingham's temperate climate creates a dual environmental challenge for the Inland Revenue Centre. Cold, humid winters with frequent westerly and north-easterly winds drive significant heat-loss pressures, while mild but increasingly warming summers heighten the relevance of ventilation and overheating resilience. Psychrometric analyses using current Nottingham CIBSE Design Summer Year (DSY) weather file [23] and future Creation of Localized Weather for the Built Environment (COLBE) probabilistic datasets [24] climate files indicate that fewer than 45% of annual hours fall within comfort. Heating continues to dominate under both present and projected conditions. Future scenarios increasingly require cooling strategies, including shading and enhanced ventilation to mitigate overheating risk. For the IRC, already disadvantaged by poor insulation, ageing glazing, and limited thermal mass, this analysis underscores the need to reduce winter heating demand while preparing the building for higher summer temperatures and more frequent overheating episodes.

Overshadowing analysis indicates restricted passive solar opportunities from the impact of neighbouring buildings and courtyard geometry. The east and west façades receive limited winter and equinox radiation, the north façade remains consistently shaded, and the south façade, although the most favourable, is partially overshadowed in summer by the adjacent glass tower. Within the courtyard, low annual radiation values (281–630 kWh/m^2) reflect persistent shading, limiting its contribution to solar gain. By contrast, the roof exhibits the highest exposure (865 kWh/m^2), which heightens the risk of summer overheating beneath roof lights on the second floor and winter heat loss through under-insulated assemblies. Overall, solar availability is uneven and modest, reinforcing the need for improved envelope performance and cooling measures.

Optivent modelling [25] of the IRC's stack ventilation system shows that while buoyancy-driven airflow reliably meets fresh-air requirements 8–18 air changes per hour (ach) at inlets and >40 ach at outlets, it underperforms for cooling. Required summer ventilation rates of 35–40 ach are only partially achieved (8–18 ach), revealing a 77–55% shortfall and demonstrating that buoyancy alone cannot provide adequate thermal relief during peak periods, and that complementary mechanical ventilation may be required. Upper floors perform worst due to smaller operable areas and reduced stack effect; wind assistance produces negligible improvement, confirming the system's dependence on temperature differentials.

3.3. Simulation Framework

Dynamic whole-building simulations were conducted using IESVE [26] to evaluate the performance of the Inland Revenue Centre under its existing configuration and under targeted heritage-compatible retrofit interventions. The modelling framework integrates energy performance assessment, operational carbon calculation and future climate testing within a staged analytical structure.

Three analytical stages were undertaken:

(1) energy performance assessment of the as-built and retrofit configurations;
(2) operational carbon calculation using UK Government emission factors [19]; and
(3) future climate resilience testing using probabilistic weather files [24].

All key model inputs, assumptions, and boundary conditions are defined in Sections 3.3.1–3.3.4, including construction assemblies, internal gains, occupancy schedules, HVAC operation, and ventilation control strategies. Simulations were conducted using IES VE (version 2024). While certain source materials, including detailed architectural documentation and institutional datasets, are subject to data governance restrictions and cannot be publicly shared, sufficient methodological detail is provided to enable replication of the modelling approach and equivalent scenario-based analysis under the stated assumptions.

3.3.1. Stage 1: Energy Performance Assessment

Stage 1 evaluates the thermal and energy performance of three building configurations under current climatic conditions in order to establish baseline behaviour and quantify the impact of incremental fabric and ventilation interventions (Table 3). The assessment focuses on delivered space energy and plant sensible loads, enabling comparison between the as-built condition and the two retrofit configurations.

Table 3. Energy performance scenarios modelled.

Scenario	Description
Base Case: As-built	Existing envelope, glazing, ventilation and services configuration
Retrofit Case A	Fabric upgrades
Retrofit Case B	Fabric upgrades + MVHR

Base Case: As-built

The base-case model represents the existing envelope, services, and operational conditions of the building. Four orientation-based thermal zones (north, east, south and west) were defined to capture variations in solar exposure, ventilation performance and thermal behaviour. Surrounding buildings and vegetation were included to account for shading and wind-flow effects.

Energy performance was assessed using delivered space energy and plant sensible loads, compared with AECB CarbonLite Retrofit and EnerPHit benchmarks. This model serves as the reference case for subsequent retrofit and climate analyses.

Retrofit Case A: Fabric Improvements

Case A introduces medium-depth envelope upgrades compatible with heritage constraints, informed by the precedent retrofit case studies discussed in Table 1. Measures include internal insulation at panel walls and roof, mineral wool floor insulation, high-performance triple glazing, and increased second-floor window operability (from 18% to 50%). Airtightness improves from 11.7 cubic metres per square metre per hour at 50 Pascals (m^3/m^2h @ 50 Pa) (assumed, based on [27]) to 5–7 m^3/m^2h @ 50 Pa, consistent with reported UK medium-depth retrofit practice [18]. Façade geometry and architectural character remain unchanged.

Retrofit Case B: Fabric + MVHR

Case B builds on Case A by introducing mechanical ventilation with heat recovery (80% efficiency, automatic summer bypass), while retaining the existing underfloor mechanical fans. This configuration enables comparison between enhanced passive ventilation and hybrid ventilation strategies.

Stage 1 Modelling Assumptions

The modelling assumptions adopted for Stage 1 are summarised in Table 4. These include construction properties, internal gains, equipment loads, lighting profiles, ventilation settings and control schedules. Thermal properties for the retrofit cases reflect the upgraded specifications described above. Internal conditions and occupancy schedules were held constant across all three configurations to ensure comparability.

Table 4. Assumptions adopted in the simulation model. Modified parameters are indicated using bold text and marked with an asterisk.

Parameter	Base Case: As-Built		Retrofit Case A		Retrofit Case B
Climate	Nottingham CIBSE-DSY (typical weather year)		Same as As-built		Same as As-built
Location	Nottingham Watnall (ASHRAE Climate Zone: 5A) Latitude (°): 53.01 N Longitude (°): 1.25 W Elevation (m): 117.0 Holiday template: England & Wales		Same as As-built		Same as As-built
Fabric U-values (W/m^2K)	Brick cavity wall (Ground and first floor)	1.54	Same as As-built		Same as Retrofit Case A
	Alu-framed panel wall (Second floor)	**0.20**	**+50 mm phenolic insulation ***	**0.13 ***	
	Glass block wall (Vent. towers)	3.12	Same as As-built		
	Lead sheet roof	**0.19**	**+50 mm phenolic insulation ***	**0.12 ***	
	Polytetrafluoroethylene tower canopy roof	6.14	Same as As-built		
	Precast concrete floor	**4.67**	**+50 mm mineral wool insulation ***	**0.45 ***	
	Triple-glazed with micro-blinds	**1.34**	**Triple low-e argon glazing, micro-blinds (replacement) ***	**0.68 ***	
	Rooflight with rolling-blind	**2.01**	**Roof light with rolling-blind, triple glazing (replacement) ***	**0.95 ***	
Internal gains [28]					
Occupancy	Occupancy density of 4 m^2/person 07–09 partial, 09–12 full, 12–14 lunch, 14–17 full, 17–19 exit		Same as As-built		Same as As-built
Lighting	1300 light fittings—old fluorescent lamps Maximum power consumption: 9.53 W/m^2 Full on from 07:00 a.m. to 19:00 p.m.		Same as As-built		Same as As-built
Equipment	Maximum power consumption: 12 W/m^2 Full on from 07:00 a.m. to 19:00 p.m.		Same as As-built		Same as As-built

Table 4. *Cont.*

Parameter	Base Case: As-Built	Retrofit Case A	Retrofit Case B
Ventilation system Cooling season	Natural ventilation stack effect + mechanical ventilation Summer season (May–September) Chimney ventilation strategy *gt (ta,24,4) & (to < ta) & (to < 26)*	Same as As-built	Same as As-built
Natural ventilation Operation profile	Controller is on if Room air temp. (°C) > 24 AND Outside air temp. (°C) < Room air temp. (°C) AND Outside air temperature (°C) < 26 °C	Same as As-built	Same as As-built
Opening criteria	Sliding (Ground and first floor)—50% effective opening 1:1 exposed wall for exterior facades 1:1 semi-exposed wall for interior courtyard facades	Same as As-built	Same as As-built
	Bottom hung (Second floor)—18% effective opening 1:1 exposed wall for exterior facades 1:1 semi-exposed wall for interior courtyard facades Chimney outlet (Vent. towers)—100% effective opening 1:1 exposed wall	**Changed to 50% effective opening ***	Same as Retrofit Case A
Mechanical ventilation	**Underfloor fans, no heat recovery**	Same as As-built	**+MVHR (80% efficiency) ***
Operation profile	Matches occupancy schedule (09:00–17:00)		
Set point	24 °C		
Airtightness	Post-1995 dwellings—11.7 air changes per hour (ach) @ 50 Pa [27]	**6 ach @ Pa ***	Same as Retrofit Case A
Heating system Heating season Operation profile	District heating via plate heat exchangers 1 October–30 April Matches occupancy schedule (09:00–17:00) Heating setpoint ≤ 21 °C to avoid conflict with natural ventilation (per TM59) Heating setback: 16 °C	Same as As-built	Same as As-built

3.3.2. Model Validation and Limitations

The simulation model was developed to enable comparative assessment of retrofit scenarios rather than precise prediction of absolute energy consumption. Model inputs were defined based on available documentation, site observations, and standard reference values where direct measurements were not available. In particular, parameters such as airtightness were estimated using representative literature-based benchmarks for buildings of similar age and construction [27].

A comparison with energy consumption data provided by the University of Nottingham Estates Department indicates a discrepancy between simulated and reported values. To improve comparability, an additional simulation was undertaken for the ground floor only, reflecting site observations that indicated partial occupancy largely concentrated at this level. Despite this adjustment, a significant difference remains between simulated and reported energy use.

This discrepancy is primarily attributable to differences in operational conditions, as the simulation assumes fully conditioned spaces operating under standardised schedules, whereas the building is currently only partially occupied and likely operates with reduced heating and intermittent use of zones. In addition, uncertainties regarding the scope and definition of the reported energy data (e.g., system boundaries and included end uses)

further limit direct comparability. As a result, direct calibration of the model to measured data was not undertaken.

The model should therefore be interpreted as providing scenario-based comparative estimates of performance between baseline and retrofit configurations, rather than fully validated predictions of absolute energy use.

While this limits the reliability of absolute energy predictions, the percentage reductions between scenarios are considered more robust, as all simulations were conducted under consistent modelling assumptions and boundary conditions. As such, the results provide a credible indication of the relative effectiveness of the proposed retrofit strategies, rather than precise estimates of real-world performance.

3.3.3. Stage 2: Operational Carbon Assessment

Stage 2 calculates operational carbon emissions using annual energy outputs from Stage 1 simulations. The study focuses on operational carbon performance and does not include a detailed assessment of embodied carbon associated with retrofit interventions. While embodied carbon is a critical component of whole-life carbon analysis, its evaluation in retrofit contexts presents methodological challenges, including the definition of system boundaries and the distinction between maintenance-related replacement and energy-driven interventions that are beyond the scope of this investigation. Future work should incorporate whole-life carbon assessment, including embodied impacts of materials and systems, to provide a more comprehensive evaluation of retrofit strategies.

Electricity use, including lighting, equipment, fans, pumps, and cooling, was assessed using a factor of 0.086 kg of carbon dioxide equivalent ($kgCO_2e/kWh$) ([19], p. 18). Heating demand and service water heating, supplied by district heating in practice, were assessed using the FHS non-domestic "waste heat" factor of 0.009 $kgCO_2e/kWh$ ([19], p. 19) derived from the Department for Energy Security & Net Zero fuel factors [21].

A counterfactual scenario using natural gas (0.210 $kgCO_2e/kWh$) ([19], p. 18) was also modelled to enable comparison of fuel choice on emissions. Results are expressed as annual emissions per gross internal area ($kgCO_2e/m^2 \cdot yr$) and benchmarked against CIBSE TM46 sector intensities [20]: office (52.3 electricity; 22.8 fossil-thermal $kgCO_2/m^2 \cdot yr$ [20], p. 7) and higher education (44.0 electricity; 45.6 fossil-thermal $kgCO_2/m^2 \cdot yr$ [20], p. 6), reflecting the building's transition from office to university use.

3.3.4. Stage 3: Climate Resilience Assessment

Stage 3 applies probabilistic future weather files to the best-performing retrofit configuration (Retrofit Case B). The pTRY-90 and pDSY-50 datasets derived from the University of Bath's COLBE project [24] were used to evaluate performance under warmer and more extreme summer conditions.

All Stage 1 physical and operational assumptions were retained; only the weather file was modified. This ensures that changes in heating and cooling demand and associated operational carbon emissions arise solely from projected climatic variation.

4. Results and Discussion

4.1. Stage 1: Energy Performance Assessment

Base Case: As-Built

The as-built simulation establishes the baseline energy performance of the Inland Revenue Centre (IRC). Annual delivered heating energy reaches 6319.96 MWh (764.16 $kWh/m^2 \cdot yr$), indicating poor thermal performance relative to the AECB Carbon-Lite Retrofit benchmark (50 $kWh/m^2 \cdot yr$) [6]. This gap highlights the combined impact of envelope inefficiencies, limited thermal resistance, and ventilation-related heat losses.

Spatial analysis shows that the west and south orientations exhibit the highest heating loads, while the second floor consistently records the greatest demand, likely reflecting its exposed configuration and limited thermal buffering. These patterns may suggest that heat loss mechanisms outweigh potential passive solar gains, with factors such as envelope performance, courtyard exposure, and building geometry appearing to have a stronger influence on heating demand than orientation alone.

Cooling demand in the baseline case is comparatively low at 3.45 kWh/m^2·yr and remains within benchmark limits. However, it is seasonally concentrated, indicating short periods of overheating driven by internal gains and solar exposure rather than continuous cooling requirements.

A comparison with energy consumption data provided by the University of Nottingham Estates Department (460,897 kWh/year) indicates a substantial discrepancy relative to simulated results. To improve comparability, an additional simulation was undertaken for the ground floor only, reflecting site observations that indicated partial occupancy largely concentrated at this level. This scenario yielded an annual energy demand of approximately 3685,360 kWh/year. Despite this adjustment, a significant gap remains between simulated and reported values.

This discrepancy is primarily attributable to differences in operational conditions. The simulation assumes fully conditioned spaces operating under standardised schedules, whereas the building is currently only partially occupied (approximately 25–50%) and likely operates with reduced heating and intermittent use of zones. Furthermore, uncertainties regarding the scope and definition of the reported energy data (e.g., system boundaries, included end uses, and reporting basis) limit direct comparability. As a result, the model is not calibrated against measured data and should be interpreted as providing comparative scenario-based insights into relative performance between cases, rather than absolute predictions of energy consumption.

Retrofit Performance: Case A and Case B

Two retrofit strategies were evaluated, illustrating the relative effectiveness of retrofit strategies under consistent modelling assumptions. As such, reported percentage reductions should be interpreted as indicative of relative performance improvements rather than exact real-world savings. Case A (fabric upgrades) reduces heating demand to 3437.87 MWh (412.88 kWh/m^2·yr), while Case B (fabric + MVHR) further reduces it to 2001.80 MWh (239.24 kWh/m^2·yr), corresponding to reductions of approximately 46% and 68% relative to the baseline (Figure 8). All percentage reductions are calculated relative to the as-built baseline scenario and are based on consistent modelling assumptions, including occupancy, system operation, and fuel factors.

Despite these improvements, both scenarios remain above retrofit benchmarks, indicating that fabric constraints inherent to the existing building limit deeper reductions. Spatial heating patterns remain consistent with the baseline, with the second floor continuing to dominate demand.

Cooling demand decreases to 2.47 kWh/m^2·yr (Case A) and 1.39 kWh/m^2·yr (Case B), confirming that overheating risk remains secondary to heating demand. All retrofit cases remain comfortably below cooling benchmarks.

These findings demonstrate that targeted fabric measures, particularly roof insulation, secondary or replacement glazing, and carefully applied internal wall insulation, offer effective reductions in heating demand with minimal heritage impact. In terms of building services, while the hybrid ventilation system provided adequate fresh air, simulations revealed that it was insufficient to manage summer overheating. The integration of mechanical ventilation with heat recovery (MVHR) emerged as a viable improvement, though

its implementation would require heritage negotiation and considerable improvement in airtightness levels to ensure its efficiency.

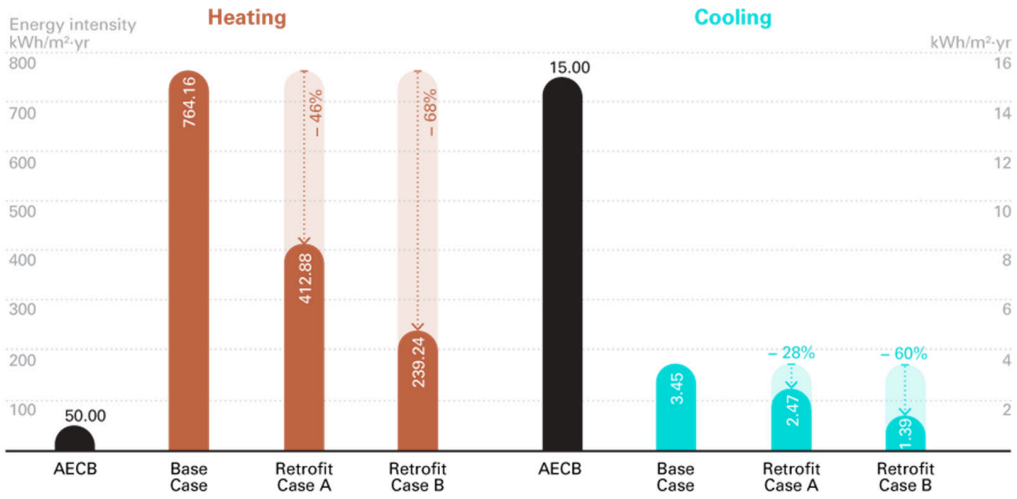


Figure 8. Delivered space heating (red, left) and cooling (blue, right) energy intensity for baseline, Case A, and Case B compared with the AECB CarbonLite Retrofit benchmark (black) (authors' graphic; benchmark values from [6]).

The IRC illustrates the retrofit challenges of large and complex heritage buildings. Conservation constraints limit invasive measures such as external wall insulation, while the building's scale means residual energy demand remains high compared with smaller precedents. Comparison with projects such as Haddington Way; Newport-Somerton; Stanmore; Cirencester Barrel Store; and Bloomsbury House shows that while percentage reductions (60–90%) are comparable, the IRC's absolute demand (247 kWh/m^2·yr) remains substantially higher. This highlights the difficulty of achieving deep retrofit targets such as EnerPHit within the constraints of this case (Figure 9).

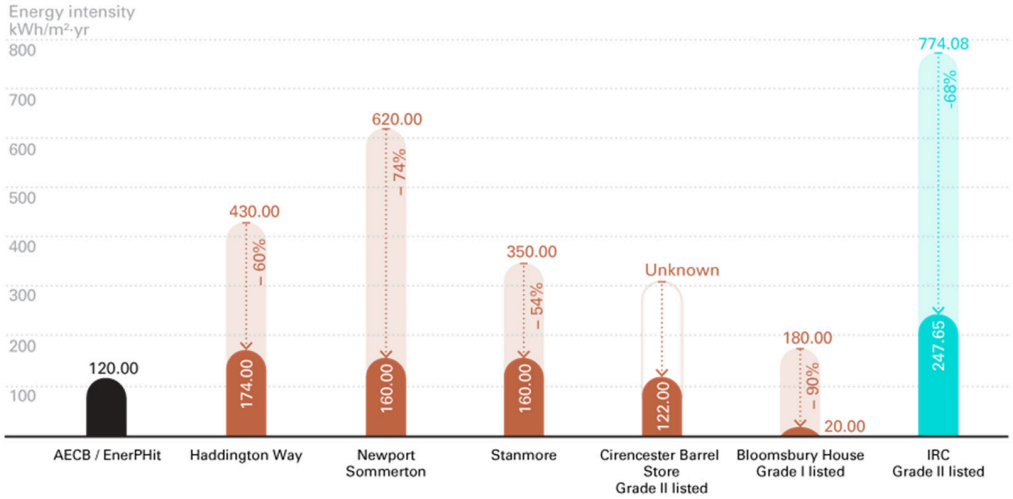


Figure 9. Annual energy consumption comparison from previous studies (red) to Inland Revenue Centre (blue) and Retrofit Standards (black) (authors' graphic; benchmark and precedent values from [4,6,7,9,13]).

These results nuance the assumption that deep retrofit standards such as EnerPHit can be broadly applied across heritage building types. While previous case studies, such as the Cirencester Barrel Store and Bloomsbury House [9,13], demonstrate that very substantial reductions in heating demand (up to 90%) are achievable, these outcomes are closely

linked to the degree of permissible intervention. In these cases, strategies such as extensive internal insulation or "building-within-a-building" approaches enabled near-complete thermal separation of the original fabric.

In contrast, the Inland Revenue Centre highlights that for large, non-residential, late-modern listed buildings, such interventions are often constrained by scale, construction systems, and stricter conservation requirements. This indicates that achieving deep retrofit targets is not inherently precluded in heritage contexts, but is highly contingent on the extent to which interventions can engage with and transform the existing fabric. As a result, a fundamental tension emerges between deep retrofit ambitions and conservation-compatible action, where the most effective energy measures may not always be feasible within heritage frameworks.

4.2. Stages 2 and 3: Operational Carbon and Climate Resilience Assessments

Operational carbon results mirror energy performance trends, with heating as the dominant contributor across all scenarios. In the baseline case, heating emissions under district heating are 6.97 $kgCO_2e/m^2$, substantially lower than CIBSE TM46 benchmarks (45.6 $kgCO_2e/m^2$ for universities, 22.8 $kgCO_2e/m^2$ for offices) [20] due to the very low-carbon intensity of the supply system (0.009 $kgCO_2e/kWh$). However, a natural gas counterfactual increases emissions to 162.56 $kgCO_2e/m^2$, revealing that low-carbon supply masks significant underlying fabric inefficiency (Figure 10).

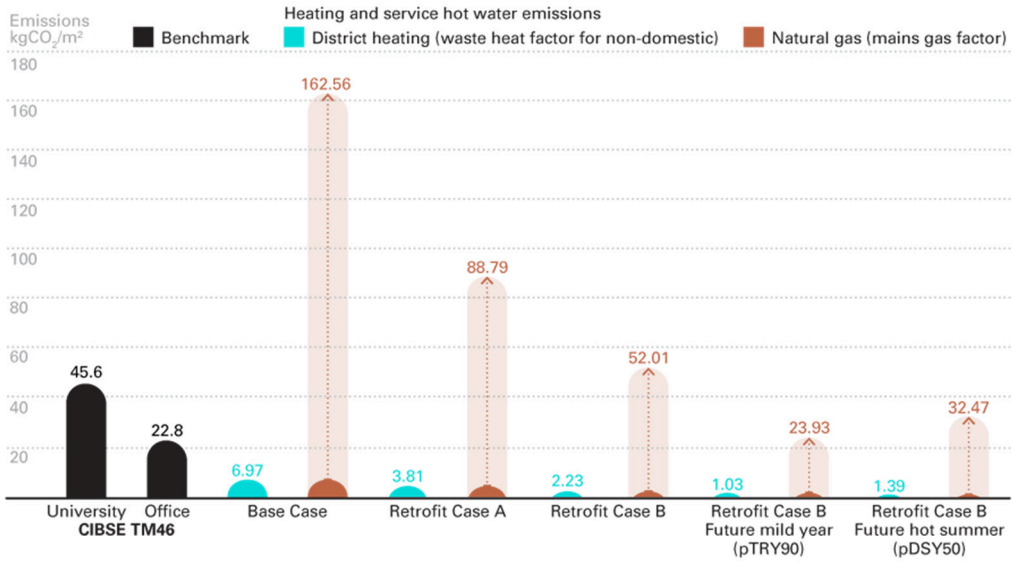


Figure 10. Heating and service hot water carbon emissions graph for district heating (blue) and natural gas (red) scenarios compared with the CIBSE TM46 benchmarks (black) for current and future climate scenarios (authors' graphic; benchmark values from [20]).

Retrofit Case A reduces heating-related emissions by approximately 45%, while Case B achieves a further reduction of around 40%, resulting in emissions of 2.23–3.81 $kgCO_2e/m^2$ under district heating. Even under gas, emissions are significantly reduced, though still above best-practice thresholds, confirming the importance of demand reduction prior to fuel decarbonisation.

Electricity-related emissions remain comparatively stable (12–17 $kgCO_2e/m^2$), as they are driven primarily by lighting, equipment, and ventilation systems rather than envelope performance (Figure 11). Cooling contributes marginally in all cases.

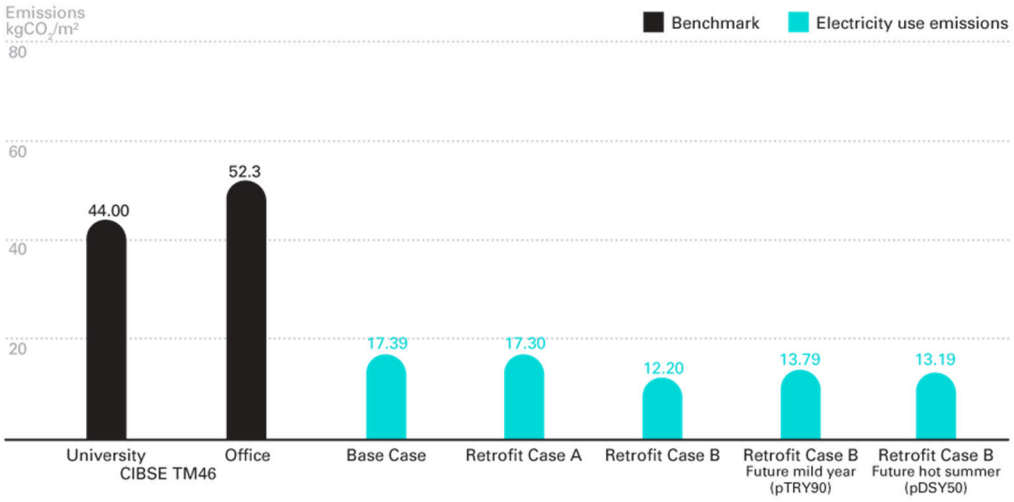


Figure 11. Electricity use emissions graphs (blue) compared with the CIBSE TM46 benchmarks (black) for current and future climate scenarios (authors' graphic; benchmark values from [20]).

Across all scenarios, total operational carbon is strongly heating-dominated (Figure 12):

- Baseline: 24.35 $kgCO_2e/m^2$ (district heating) vs. 179.94 $kgCO_2e/m^2$ (gas)
- Retrofit: 14.43–21.11 $kgCO_2e/m^2$ (district heating) vs. 64.20–106.09 $kgCO_2e/m^2$ (gas)
- Climate resilience: 14.59–14.81 $kgCO_2e/m^2$ (district heating) vs. 37.72–45.67 $kgCO_2e/m^2$ (gas)

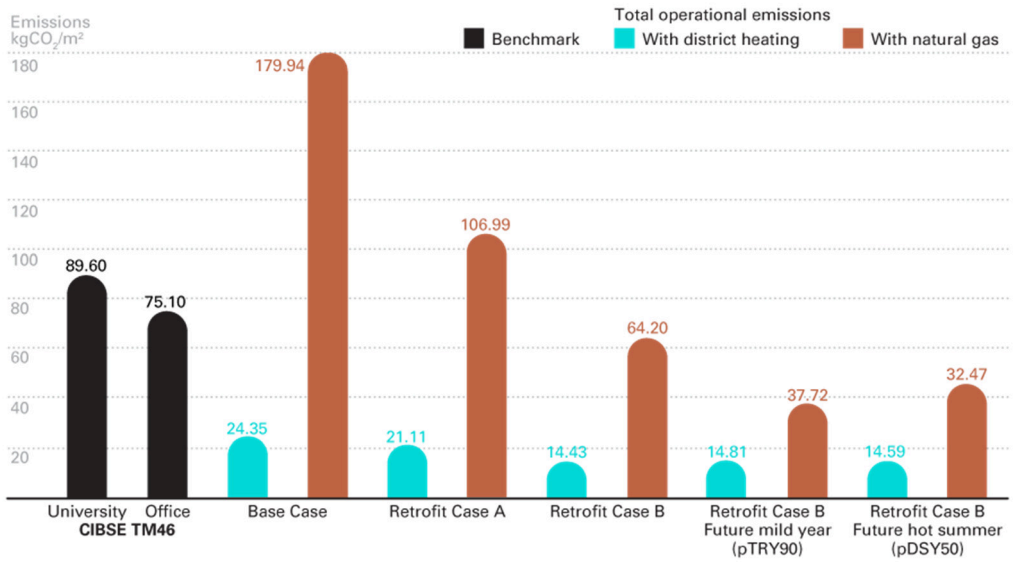


Figure 12. Total operational carbon emissions graph compared with the CIBSE TM46 benchmarks (black) for current and future climate scenarios under district heating (blue) and natural gas (red) (authors' graphic; benchmark values from [20]).

This corresponds to an overall reduction of approximately 41% under district heating and up to 64% under a natural gas counterfactual, relative to the baseline scenario.

Future climate scenarios (pTRY90) slightly increase cooling demand, but do not offset reductions achieved through heating demand reduction, and overall emissions continue to decline.

While operational carbon reductions are substantial, the exclusion of embodied carbon introduces an important limitation. In heritage retrofit contexts, where much of the existing structure is retained, embodied impacts are typically lower than in new construction or in

deep retrofit examples. However, the carbon cost of added materials (e.g., insulation, glazing, MVHR systems) may influence the overall carbon payback of the proposed interventions.

5. Conclusions

This study investigated conservation-compatible retrofit strategies for the Inland Revenue Centre (IRC), a Grade II listed late-modern office building, using dynamic simulation to assess operational energy, carbon performance, and climate resilience under current and future conditions. Across all scenarios (Figures 8–12), results are derived from scenario-based modelling and should be interpreted as comparative estimates of relative performance rather than calibrated predictions of absolute energy use.

5.1. Research Question 1: Feasible Retrofit Strategies

Drawing on the policy review and precedent analysis (Section 2), and supported by the quantitative simulation results (Section 4), the findings indicate that heritage-compatible, medium-depth interventions, including internal insulation, roof upgrades, improved glazing, enhanced airtightness assumptions, and mechanical ventilation with heat recovery (MVHR), are feasible within the constraints of a listed late-modern office building. These measures are largely reversible, align with conservation requirements, and are associated with substantial reductions in operational energy demand (Figure 12).

However, feasibility is shaped not only by policy constraints, but also by the building's inherent architectural and constructional characteristics. The IRC's prefabricated structural system and strongly articulated façade introduce multiple junctions that increase air leakage and thermal bridging. Although airtightness could not be empirically measured, modelled assumptions suggest that these characteristics contribute to persistent heat loss and limit retrofit effectiveness. Furthermore, the façade's high glazing ratio, central to its architectural identity, restricts envelope interventions, while strategies such as external wall insulation or façade reconfiguration are effectively precluded. As a result, retrofit interventions are constrained to optimisation within the existing envelope rather than comprehensive fabric transformation.

5.2. Research Question 2: Extent of Energy and Carbon Reduction

Within a scenario-based comparative framework, the proposed retrofit interventions result in substantial but bounded reductions in energy demand and operational carbon. Fabric upgrades combined with MVHR indicate potential heating demand reductions of up to 68% relative to the baseline (Figure 8), although absolute energy use remains above established retrofit benchmarks. This reflects the limited scope for further fabric improvement, as key elements, such as the exposed brick piers, cannot be insulated without compromising architectural character.

Operational carbon results follow a similar pattern (Figures 10–12). Under low-carbon district heating, emissions fall below CIBSE TM46 benchmarks, whereas gas-based scenarios remain significantly higher. This supports that energy supply plays a critical role alongside demand reduction in achieving low operational carbon outcomes.

5.3. Research Question 3: Climate Resilience and Future Performance

Under future climate scenarios (pTRY90), the retrofit pathway remains broadly robust, with overall operational carbon continuing to decline despite increases in cooling demand. Heating demand decreases slightly, while cooling demand becomes more pronounced, particularly in upper floors and roof-exposed zones (Figures 10–12).

It should be noted that climate resilience was assessed for the best-performing retrofit scenario (Case B) only, representing an upper-bound performance condition. This limits the generalisability of resilience outcomes across alternative retrofit configurations.

The findings indicate that while existing ventilation strategies and increased operability provide partial adaptive capacity, they are insufficient to fully mitigate overheating risk under projected conditions. MVHR improves environmental control but does not eliminate peak summer overheating, suggesting that additional adaptive measures such as shading, hybrid ventilation, and operational strategies may be required. Overall, resilience is improved, but full mitigation remains constrained by the building's architectural and environmental characteristics.

5.4. Interpretive Framework and Knowledge Contribution

Beyond its technical findings, this case demonstrates that conservation should be understood not merely as a constraint, but as an interpretive framework that actively shapes retrofit intervention strategies. Character-defining features, including façade articulation, material expression, and prefabricated construction systems, establish boundary conditions for energy performance.

This reframes retrofit in late-modern listed office buildings as a process of constrained optimisation, where architectural value and environmental performance are interdependent. The study contributes a typological insight: in large listed late-modern office buildings, deep retrofit pathways are structurally limited, and performance gains are primarily achieved through incremental, system-compatible interventions rather than transformative envelope modifications.

5.5. Implications and Transferability for Research, Policy, and Practice

The findings of this study broadly corroborate existing research on non-residential heritage retrofit, which emphasises fabric-first strategies, airtightness improvements, and integration of MVHR under conservation constraints. Consistent with prior case studies (e.g., Bloomsbury House and the Barrel Store [9,13]), substantial reductions in heating demand are achievable where more comprehensive internal interventions are feasible.

However, this study demonstrates that for more constrained or complex building typologies, tailored retrofit strategies may be more appropriate, even if they result in comparatively lower energy performance. This highlights the importance of context-specific solutions and advances current knowledge by explicitly illustrating the trade-offs between heritage compatibility and energy optimisation.

Although based on a single case study, the findings can be interpreted as an analytical generalisation to comparable non-residential heritage buildings operating under similar constraints. Rather than supporting universal application of deep retrofit models, this research suggests that transferable insights lie in adopting tailored, context-sensitive strategies that balance energy performance with the preservation of heritage value.

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Abbreviations

The following abbreviations are used in this manuscript:

ach	Air Changes per Hour
AECB	Association for Environment Conscious Building
ASHP	Air Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers
CO_2e	Carbon Dioxide Equivalent
COLBE	Creation of Localized Current and Future Weather for the Built Environment
DSY	Design Summer Year
EAHP	Exhaust Air Heat Pump
EnerPHit	Passive House retrofit standard
EWI	External Wall Insulation
GSHP	Ground Source Heat Pump
GWh	Gigawatt-hours
HEAN18	Historic England Advice Note 18
HEMS/HEMFHS	Home Energy Model/Future Homes Standard (fuel factors methodology)
IES VE	Integrated Environmental Solutions Virtual Environment (simulation software)
IRC	Inland Revenue Centre
IWI	Internal Wall Insulation
$kgCO_2e$	Kilograms of carbon dioxide equivalent
$KgCO_2e/m^2$	Kilograms of Carbon Dioxide Equivalent per square metre
$kgCO_2e/m^2{\cdot}yr$	Kilograms of Carbon Dioxide Equivalent per square metre per year
$KgCO_2e/kWh$	Carbon intensity factor
kWh	Kilowatt-hours
$kWh/m^2{\cdot}yr$	Kilowatt-hours per square metre per year
LETI	London Energy Transformation Initiative
$m^3/m^2{\cdot}h$ @50Pa	Cubic metres per square metre per hour at 50 Pascals (airtightness)
MWh	Megawatt-hour
MVHR	Mechanical Ventilation with Heat Recovery
OSB	Oriented Strand Board
pDSY-50	Probabilistic Design Summer Year (50th percentile)
PHPP	Passive House Planning Package
PIR	Polyisocyanurate (insulation)
pTRY-90	Probabilistic Test Reference Year (90th percentile)
PV	Photovoltaic
RQ	Research Question
TM46	Technical Memorandum 46 (CIBSE operational energy benchmarks)
TRY	Test Reference Year
UFH	Underfloor Heating
UK	United Kingdom
UKGBC	UK Green Building Council
W/m^2K	Watts per square metre Kelvin (thermal transmittance/U-value)
XPS	Extruded Polystyrene

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