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From Building Services to Process Loads: Whole-Building Utility-Calibrated Simulation of Sustainable Operational Decarbonisation Limits in a UK SME Restaurant Retrofit

Harshul Singhal [1,2] and Ali Badiei [2,*]

[1] Department of Engineering, University of Lancashire, Preston PR1 2HE, UK; hssinghal@lancashire.ac.uk or harshul.singhal@brunel.ac.uk
[2] Department of Engineering, Brunel University of London, Uxbridge UB8 3PH, UK
* Correspondence: ali.badiei@brunel.ac.uk

Abstract

Restaurants combine long opening hours, catering demand, kitchen ventilation, DHW, and mixed-fuel cooking loads, making their decarbonisation different from generic commercial retrofit. For small- and medium-sized enterprise (SME) hospitality premises, this makes the transition to net-zero operation a distinct sustainability challenge because a large, process-driven share of demand lies outside conventional building-fabric and building-services retrofit. This single-case study develops a whole-building utility-calibrated OpenStudio/EnergyPlus model for Beit El Zaytoun, a 655.82 m^2 restaurant in Park Royal, London. Monthly electricity and gas data for June 2024–May 2025 were used to calibrate the baseline at whole-building level. Standalone and cumulative scenarios tested insulation, low-emissivity double glazing, LED lighting and controls, ASHP service scenarios, and an 11 kWp PV array. Baseline demand was 413,895 kWh/yr, equivalent to 631.1 kWh/m^2·yr and 75,020 kgCO$_2$e/yr. The lowest-net-energy analytical package reduced net imported energy to 314,734 kWh/yr and operational carbon to 56,700 kgCO$_2$e/yr, a retained 24.0% reduction on the source reporting basis; this package is treated as an analytical bound rather than as a final design recommendation because it excludes cooling. The model-derived residual process load, kitchen and catering gas plus kitchen, and back-of-house electricity remained 233,920 kWh/yr across building-focused scenarios. The Residual-Load Index (RLI) rose from 0.57 to 0.74; with ±15% process-load allocation uncertainty, the optimised RLI range was 0.63–0.85, so the post-retrofit balance remained process-load dominated. The case demonstrates a practical decarbonisation ceiling likely to recur in similar high-process-load hospitality premises: fabric, lighting, heat electrification, and PV are necessary but insufficient without catering-equipment, cooking-fuel, kitchen-ventilation, refrigeration-control, sub-metering, and demand-response strategies. The paper contributes whole-building utility-calibrated quantitative evidence and a transferable RLI metric for sub-sector-specific sustainable retrofit policy, and the net-zero transition of SME food-service premises.

Keywords: sustainable restaurant retrofit; SME hospitality decarbonisation; operational carbon; process loads; EnergyPlus; OpenStudio; food-service energy use; residual-load index; heat-pump electrification; photovoltaic self-consumption

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1. Introduction

Within the UK non-domestic stock, food-service premises are an energy-intensive but poorly resolved sub-sector. Restaurant and commercial-kitchen energy use is often aggregated within broader commercial, retail, or hospitality categories, which is itself a policy and benchmarking problem because it obscures the process-driven loads that dominate kitchen-led premises [1–3]. Where the stock is resolved, the restaurant and hospitality energy problem is large enough to matter. DESNZ reports that Hospitality consumed 13,026 GWh of delivered electricity and gas in England and Wales in 2019, around 11% of all non-domestic CaRB3 energy [3–5]. Restaurant activities accounted for 1961 GWh, or 15% of Hospitality energy; the broader Cafes/restaurants & Takeaways group represented 3130 GWh [4]. The same source reports Restaurant activities at approximately 6.9 million m^2, about 12% of the 59.0 million m^2 England-and-Wales hospitality floorspace [4]. The consequence is practical. Where the split between building-services demand and catering process demand is uncertain, heat-pump and electrical-capacity sizing carry greater risk, predicted savings and payback estimates lose confidence, fabric, and catering interventions can be mis-prioritised, and measurement-and-verification disputes between landlords, tenants, and funders become more likely [6–9]. For SME food-service businesses, process-load uncertainty is therefore not a modelling detail; it affects capital planning, affordability, operational resilience, and the credibility of sustainable retrofit programmes, and it directly conditions whether a credible net-zero pathway can be designed for the premises.

Operational energy in existing buildings remains central to the United Kingdom's net-zero pathway [10,11]. In non-domestic buildings, operational carbon is governed not only by envelope heat transfer and HVAC efficiency, but also by operating hours, internal gains, process loads, ventilation rates, equipment control, tenancy arrangements, and maintenance practice [6,12,13]. These drivers are particularly important in food-service premises. Restaurants combine cooking equipment, refrigeration, kitchen extract, make-up air, domestic hot water, decorative lighting, variable occupancy, and extended daily service periods [5,14–16]. Their annual energy use intensity (EUI) can therefore exceed that of many conventional commercial premises even when the envelope is not the dominant load [1,5,14].

This paper examines Beit El Zaytoun, a Lebanese restaurant in Park Royal, London. The case is used as an analytical mechanism case rather than as a generic consultancy retrofit report. Its value lies in testing what happens when a conventional building-focused decarbonisation package is applied to a high-process-load hospitality building. Park Royal is one of the largest food-production and distribution clusters in Europe and the focus of the UKRI Place-Based Impact Acceleration Account programme on Net Zero Food Supply Chains [17–20]. Many SME hospitality premises in such clusters are leased, operationally constrained, and weakly sub-metered. These conditions are not incidental: they define the feasible retrofit boundary and the confidence with which savings can be verified.

The research problem is that conventional retrofit logic often assumes a progressive pathway from fabric improvement to efficient lighting, heat-pump electrification, and roof-mounted PV. That sequence is coherent for buildings where space conditioning and regulated electrical loads dominate [21,22], but it is incomplete where catering and other process loads remain large. In restaurants, cooking gas, kitchen electrical equipment, refrigeration, extract ventilation, and make-up air can still dominate after space-heating and lighting measures have been implemented [5,14,15]. Total percentage savings alone are therefore not enough, because the composition of residual demand changes after retrofit. The analysis separates demand reduction, fuel switching, HVAC service-coverage change, PV import offset, and remaining process demand.

The study uses OpenStudio/EnergyPlus because dynamic simulation is required to represent interactions between envelope heat transfer, internal gains, HVAC service coverage, electrification, and PV offset [23–25]. The model was calibrated against whole-building electricity and gas consumption for June 2024–May 2025. Monthly utility data were used where available for model calibration; however, the manuscript does not claim IPMVP-grade validation or sub-metered end-use calibration because appliance-level metering, measured kitchen ventilation rates, and full post-retrofit M&V data were not available [7,25–27]. The term whole-building utility-calibrated is used throughout in this restricted sense, and the model is suitable for comparative scenario appraisal and mechanism analysis rather than for verified savings claims [28,29].

This paper quantifies how far a conventional building-focused retrofit package can reduce energy use and operational carbon in a high-process-load UK restaurant and identifies the residual loads that constrain further decarbonisation. The analysis tests standalone and cumulative fabric, glazing, lighting, ASHP, and PV scenarios using the utility-calibrated OpenStudio/EnergyPlus model. It then applies a Residual-Load Index (RLI) to show how unchanged catering and process loads reshape the post-retrofit energy balance.

The paper makes three contributions. First, it provides a utility-calibrated OpenStudio/EnergyPlus retrofit analysis for an under-represented UK restaurant typology. Second, it separates demand reduction, fuel switching, service expansion, and PV import offset, avoiding a single undifferentiated retrofit-saving claim. Third, it proposes RLI as a transferable indicator for identifying when catering and process loads become the dominant constraint on operational decarbonisation in food-service buildings.

Figure 1 should be read from left to right as an input–model–scenario–output chain. The inputs (left) are the data that define the case: building geometry and floor area, whole-building electricity and gas bills, the operating schedule, envelope and glazing assumptions, lighting inputs, the HVAC and DHW systems, the kitchen and process assumptions, the PVGIS photovoltaic yield, and the DESNZ carbon factors (Appendix A). These feed the model (centre-left): an OpenStudio/EnergyPlus whole-building simulation, calibrated so that annual electricity and gas match the utility totals, against which scenarios are tested. The scenario families (centre) are envelope insulation, glazing, LED and controls, ASHP heating-and-cooling with DHW electrification, ASHP heating-only with DHW electrification, and PV import offset. The outputs (right) are annual energy, EUI, operational carbon, fuel split, unmet hours, the Residual-Load Index (RLI), and uncertainty screening. The boundary applied throughout the figure is explicit: process load is defined as kitchen and catering gas plus kitchen and back-of-house electrical equipment, while non-process load is space conditioning, DHW, lighting, general building services, and the modelled residual, with the exact composition depending on the scenario. The figure therefore makes clear that building-focused scenarios act mainly on the non-process load, leaving the process load largely unchanged, which is why the post-retrofit balance becomes process-dominated.

The remainder of the paper is structured as follows. Section 2 summarises the relevant evidence on restaurant energy use, simulation calibration, and residual process loads. Section 3 describes the case-study building. Section 4 sets out the modelling boundary, data provenance, scenario design, and uncertainty method. Section 5 presents the baseline, retrofit, and residual-load results. Sections 6 and 7 provide the discussion and practical and policy implications. Section 8 sets out the limitations and Section 9 concludes.

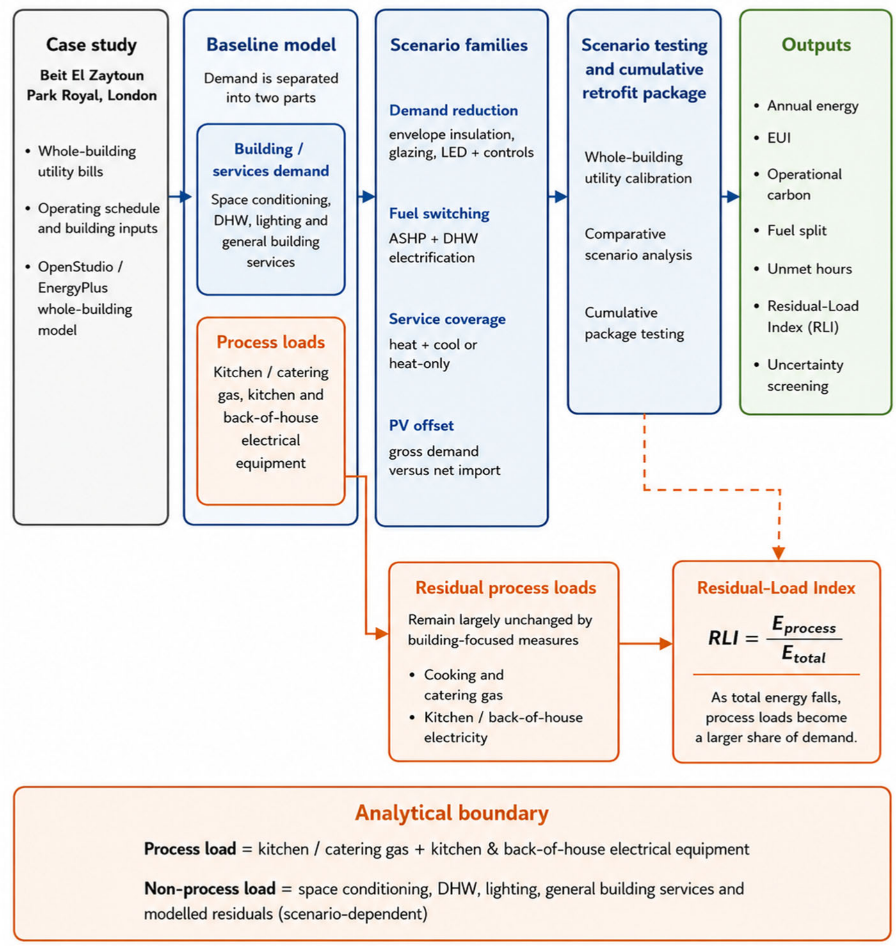

Figure 1. Analytical structure and boundary of the study. The diagram links case-study inputs, whole-building utility-calibrated OpenStudio/EnergyPlus modelling, scenario testing, outputs, and the Residual-Load Index (RLI); process and non-process loads are defined within the analytical boundary.

2. Background and Research Gap

Restaurant decarbonisation cannot be treated as a simple extension of generic commercial-building retrofitting. The relevant evidence base sits across non-domestic operational energy, commercial-kitchen and restaurant loads, simulation calibration, heat-pump service boundaries, PV import offset, and process-load reporting. The purpose of this section is therefore to define the specific gap addressed by the case study rather than to provide a broad review of commercial retrofit.

2.1. Operational Energy and Carbon in Existing Commercial Buildings

Operational carbon from non-domestic buildings remains a leading contributor to UK greenhouse-gas emissions despite progressive grid decarbonisation [1,2,10]. Reviews of building energy consumption and benchmarking also show that non-domestic energy demand varies strongly by building function [3,30]. Most commercial-building decarbonisation research has focused on offices, where archetype-led parametric studies dominate [26,27], or on supermarkets and large retail formats where refrigeration loads are an established research focus. Methodologically, the field has converged on a layered approach: an as-built baseline model, calibrated against whole-building or sub-metered data, against which energy efficiency measures are tested in isolation and in combination. Carbon impact is then derived using time-varying or static emission factors, with UK practice predominantly using the annually updated DESNZ GHG Conversion Factors [31], applied consistently across the baseline and all scenarios to enable like-for-like comparison [6]. The robustness of conclusions depends on three fragilities: the quality of the calibration step, the transparency of the EEM specification, and the appropriate treatment of process loads, all of which are tested in the present study. Recent literature on the building-energy performance gap further reinforces that aggregate utility agreement does not imply correct end-use disaggregation, and that operational verification is conditioned on data resolution [12,13].

2.2. Restaurant and Commercial-Kitchen Energy Use

Restaurants exhibit a markedly different end-use signature from general commercial premises. CIBSE TM46 [1] places restaurants in their own benchmark category with typical-practice values of approximately 800 kWh/m^2·yr (combined fossil and electrical) and best-practice values of approximately 460 kWh/m^2·yr; both figures are several times higher than typical office benchmarks. The drivers are well documented in the commercial-kitchen literature. Mudie et al. document UK commercial-kitchen electricity profiles that establish catering as the dominant electrical end use in food-service settings [14], with refrigeration, cooking, and dishwashing loads operating outside customer-facing hours. Mudie provides benchmarking evidence and highlights the difficulty of deriving stable floor-area metrics where production intensity and operating hours differ between premises [5]. Kolokotroni et al. show that ventilation and refrigeration are central to energy use in food retail and food-related premises [32]. Recent work by Zhang et al. on commercial-kitchen ventilation and air-conditioning systems demonstrates that demand-controlled ventilation and airflow optimisation, including cooking-oil control strategies [15], can deliver substantial energy savings while maintaining oil-fume control and thermal comfort. Restaurant-specific analysis of solar PV integration by Gunasegaran et al. indicates that roof-mounted PV usually offsets only a fraction of total demand in high-load dining and kitchen premises [16], even when annual PV yield matches well to occupied hours. UK-specific peer-reviewed evidence on operational restaurant performance is comparatively scarce; this sparsity is one motivation for the present contribution. Restaurant-sector data are also often hidden inside broad "commercial" benchmark classes, weakening retrofit targeting at the sub-sector scale.

2.3. Simulation, Utility Calibration, and Model Credibility

EnergyPlus and OpenStudio are established platforms for dynamic building-energy simulation and can represent heat-balance, HVAC, internal-gain, and control interactions relevant to retrofit scenarios [23,24]. The calibration literature distinguishes between model adjustment against measured data and formal compliance with statistical criteria such as NMBE and CV(RMSE) [25–29]. ASHRAE Guideline 14 and IPMVP are useful references for M&V [7,8], but they require data resolution and boundary definition stronger than whole-building utility comparison alone. Heo et al. develop Bayesian calibration approaches that quantify uncertainty under data sparsity [25], an approach particularly relevant when end-use sub-metering is absent. CIBSE TM54 sets out a structured approach to evaluating operational energy at the design stage [6]. The present study positions itself within this calibration spectrum: it is whole-building utility-calibrated for feasibility-stage option appraisal, but it is not represented as IPMVP-Option-D-grade validation because sub-metered and post-retrofit M&V data were not available.

2.4. Fabric, Glazing, and Lighting Measures

Fabric, glazing, and lighting upgrades are common first-stage retrofit measures. CIBSE Guide A provides reference constructions and environmental-design data used to judge envelope and thermal assumptions [33]. CIBSE Guide F and SLL guidance provide lighting-efficiency and lighting-quality reference points [34,35]. However, the whole-building effect of these measures depends on their baseline load share. In process-load-heavy premises, even high percentage savings in heating or lighting can translate into modest whole-building savings. This paper therefore reports both measure-level effects and residual-load composition in order to make the constraint visible.

2.5. Heat-Pump Electrification and Service Coverage

Heat-pump electrification is central to building decarbonisation, but its retrofit interpretation depends on the service boundary [9,21,22]. Replacing gas heating with an ASHP is not the same as adding cooling to previously uncooled zones, nor is it the same as electrifying DHW. These mechanisms have different energy, carbon, and comfort implications. Critically, air-to-air ASHP systems do not provide DHW, so any scenario that displaces gas DHW in a building modelled with an air-to-air proxy must represent DHW provision through a separate electrified load (a heat-pump water heater or direct electric resistance) or specify an air-to-water variant or hybrid configuration. The academic literature has not always made this distinction explicit, nor has it consistently distinguished between heat-pump scenarios that maintain existing service coverage and those that expand it. For these reasons, the ASHP scenarios in the present study are treated as service scenarios rather than simple equipment substitutions, and space-heating electrification, DHW fuel-switching assumptions, cooling operation, and served-zone changes are reported separately (see Section 4.8). Installation in the UK is governed by the MCS framework and supported [36], for eligible non-domestic premises, by the Boiler Upgrade Scheme [37].

These service-boundary distinctions have direct consequences for small businesses. Because an air-to-air ASHP cannot provide hot water, a real installation must add a dedicated heat-pump water heater, an air-to-water system with a hot-water cylinder, a hybrid arrangement, or direct electric resistance heating, each of which carries its own plant-space, electrical-capacity, and capital-cost implications. These investment and spatial realities, rather than the in-model energy result alone, often determine whether the modelled electrification is deliverable in a leased restaurant; they are examined further in Section 7.

2.6. PV and Behind-the-Meter Generation

Behind-the-meter PV can reduce grid-electricity import but does not reduce underlying building demand [38,39]. Its impact depends on roof area, orientation, shading, inverter sizing, self-consumption, export, and the temporal overlap between generation and demand [38,39]. In high-load restaurants, annual electricity demand may exceed PV generation, but this does not by itself prove full self-consumption at hourly resolution. The present study therefore reports PV as annual import-offset potential, distinguishing gross demand before PV from net imported energy after PV, and explicitly states the full annual self-consumption assumption used in the central carbon result. Installation in the UK is governed by the MCS PV standard [40].

2.7. Research Gap

Three gaps motivate the paper. First, peer-reviewed, modelled UK restaurant retrofit evidence remains thinner than evidence for offices, schools, dwellings, or generic retail premises [5,14,16]. Second, scenario studies often report total savings without identifying how residual load composition changes after retrofit. Third, ASHP and PV measures are frequently interpreted as simple technology swaps even when they alter DHW provision, cooling service, or electricity-import boundaries. This paper addresses these gaps through a single mechanism case with explicit data-provenance labels, scenario-boundary rules, RLI reporting, gross-versus-net energy reporting in PV cases, and analytical post-processing uncertainty screening on the dominant assumptions.

3. Case-Study Building

This section describes the case-study building as a physical asset, independent of the modelling treatment applied to it in Section 4. The aim is to establish the geometry, envelope, operating profile, existing systems, and lighting and process loads that the model must represent before any modelling, screening, or scenario assumption is introduced.

3.1. Location, Tenure, and Use

Beit El Zaytoun operates from 15–17 Barrett's Green Road, Park Royal, London. The use is a Lebanese sit-down restaurant with dining, kitchen, and back-of-house areas. The premises are within a leased single-storey shell, likely dating from the 1970s–1980s. The building illustrates a common converted-shell hospitality condition rather than claiming representativeness of a population. Tenancy matters because fabric alteration, external plant, and rooftop PV require landlord consent, structural checks, and statutory approvals; these are treated as research-relevant boundary conditions rather than incidental project-management details.

3.2. Geometry and Envelope

The floor area is 655.82 m^2 and the perimeter is approximately 108 m. The building is oriented approximately 13° east of due south, with an estimated window-to-wall ratio of 50%. The existing wall U-value is 1.19 W/m^2K, roof U-value is 3.84 W/m^2K, glazing U-value is 4.80 W/m^2K, and glazing g-value is 0.78 [33]. These are visual-survey and reference-construction values, not intrusive-survey measurements. Thermal bridging, moisture condition, and airtightness were not directly measured and are not claimed in this study.

3.3. Operating Profile

The reported operating hours are 11:00–23:30 Monday to Thursday, 11:00–00:00 on Friday, and 09:30–00:00 at weekends. The venue can accommodate high-peak dining occupancy (licensed maximum 250 covers), but typical service-period loads are lower than maximum capacity. The model therefore uses service-period diversity rather than constant maximum occupancy (Section 4.5). The interior design emphasises ambience through artificial planting and decorative lighting, which informs the lighting strategy and constrains the form, though not the substance, of any LED replacement programme.

3.4. Existing Systems (Heating, Cooling, and DHW)

Baseline heating is mixed. The dining and perimeter zones are served by a gas boiler and radiators, supplemented by gas patio heaters in one seating zone and electric suspended panels in peripheral seating areas. A Carrier 42QHC024DS split unit (6.4 kW cooling, 7.0 kW heating) provides heating and cooling in part of the central seating zone. The kitchen, utility, store, and loft areas are treated as unconditioned or partially untreated in the baseline model. DHW is provided by a packaged water-heating system. The reported 600 kBtu/h (~176 kW) input is retained as equipment context but not treated as a validated annual DHW load without sub-metering.

3.5. Lighting and Process Loads

Dining lighting combines decorative and functional luminaires, represented at 9.579 W/m^2. Kitchen lighting is represented at 18 W/m^2 [34]. The process-load definition used in the paper is deliberately narrow: kitchen and catering gas plus kitchen and back-of-house electrical equipment. Kitchen ventilation and make-up air affect HVAC load but are not directly metered as separate energy end uses. This boundary keeps the RLI transparent but conservative: some ventilation-related energy may also be process-driven, which would raise the effective RLI above the value reported here.

3.6. Implementation Context

The premises are leased, so any retrofit must be agreed with the landlord and the tenant; the tenant may not control fabric, roof, external plant, or electrical infrastructure. External ASHP condensers may trigger acoustic and planning assessments, and rooftop PV may require structural assessment, roof access, and grid and export arrangements. These constraints are not invalidating, but they bound which measures are technically and contractually deliverable; they are revisited in Section 8 (Limitations).

4. Materials and Methods

This section defines the operational boundary, data provenance, model setup, scenario design, and uncertainty-screening approach used to test retrofit measures against the case-study building described in Section 3. A distinction is maintained between measured utility totals, reported survey inputs, model-derived end-use allocations, and derived indicators so that the feasibility-stage results are not overstated as sub-metered validation. As-built geometry, envelope, operating hours, existing systems, and lighting and process loads are taken from Section 3 and not restated here.

4.1. Case Selection and Analytical Boundary

A single-case methodology was used because the purpose is mechanism testing rather than statistical generalisation [21]. Beit El Zaytoun was selected because it represents a high-load restaurant use, has full-year electricity and gas totals, sits within the Park Royal food-system decarbonisation context [17–19], and contains the practical constraints typical of leased SME hospitality premises. The findings should be transferred analytically to similar high-process-load premises rather than statistically to the restaurant stock as a whole.

The operational boundary includes purchased electricity, natural gas, building services, lighting, space conditioning, DHW, and catering or process loads. Embodied carbon, refrigerant leakage, construction-stage emissions, and whole-life carbon are outside the boundary. This exclusion is deliberate: the paper addresses operational-energy retrofit, not product-level, or whole-life assessment. Refrigerant leakage is noted as relevant to a whole-life or full operational-carbon assessment of heat-pump systems, but it is not included in the delivered-energy and location-based operational-carbon boundary used here.

4.2. Data Provenance Taxonomy

The model uses five data classes, applied consistently throughout the paper to make the numerical claims traceable. Measured data are the annual whole-building electricity and gas totals for June 2024–May 2025. Reported survey data include floor area, approximate WWR, orientation, existing U-values, lighting power densities, and visible HVAC equipment (Section 3). Modelled data include end-use allocation, HVAC loads, unmet hours, and scenario outputs. Derived data include EUI, operational carbon, PV offset fractions, and RLI. Screening assumptions are used where the source dataset does not contain detailed schedules, ventilation rates, infiltration, exact zone areas, or hourly profiles. A value is described as measured only where it comes from annual utility records; reported where it comes from site observations, drawings, nameplate information, or the source feasibility dataset; model-derived where it comes from end-use allocation or scenario simulation; and derived where it is calculated from other reported or model-derived values. This terminology prevents the residual-load result being misread as sub-metered evidence.

4.3. Whole-Building Utility-Calibrated Baseline

The baseline is constrained by whole-building utility data, summarised in the calibration evidence table in Section 5.1. The source dataset includes electricity and gas consumption for June 2024–May 2025 and supports whole-building feasibility calibration. The manuscript does not claim sub-metered or IPMVP-grade calibration because end-use metering, measured kitchen extract rates, and post-retrofit monitoring were not available. The model was calibrated to a total of 413,895 kWh/yr, consisting of 117,008 kWh/yr electricity and 296,886 kWh/yr natural gas, yielding an EUI of 631.1 kWh/m^2·yr over a floor area of 655.82 m^2 (Section 3.2). Annual operational carbon is reported on the source-reporting basis of 75,020 kgCO_2e/yr. Because the displayed conversion factors are rounded in the source feasibility dataset, all scenario carbon values in this manuscript retain the source-reporting basis rather than recalculating each row independently from rounded factors.

The term whole-building utility-calibrated is used throughout this paper in a single, restricted sense: annual electricity and gas totals were matched at whole-building level to provide a consistent baseline for feasibility-stage scenario comparison. It does not imply sub-metered end-use calibration, hourly validation, or IPMVP-grade measurement and verification. The calibrated model is therefore suitable for comparative scenario appraisal and mechanism analysis rather than for verified savings claims, and all end-use, process, and residual-load allocations reported below are model-derived within this whole-building constraint.

4.4. Simulation and Reproducibility Specification

A whole-building OpenStudio/EnergyPlus model was used to represent the restaurant geometry, envelope, internal gains, lighting, HVAC service coverage, and annual energy balance [23,24]. The modelling approach is documented against EnergyPlus v25.1 and OpenStudio 3.6 documentation. The executable model file is not released with this manuscript because the study is based on a commercially sensitive premises dataset. Instead, the manuscript reports the inputs, assumptions, and scenario boundaries needed to understand and scrutinise the feasibility-stage results.

The model was constructed and run as a feasibility-stage workflow rather than as a detailed design model. The steps were: (1) source geometry and floor area were taken from the feasibility dataset and site and survey information; (2) the building was reconstructed in OpenStudio as a simplified multi-zone geometry; (3) zones were aggregated into front-of-house dining, kitchen, back-of-house and storage and utility, and circulation and vestibule (Table 1); (4) envelope constructions, glazing, lighting power densities, schedules, and HVAC and DHW assumptions were assigned from Sections 3 and 4; (5) EnergyPlus simulated the annual energy balance; (6) annual electricity and gas totals were matched to the full-year utility totals at whole-building level; (7) retrofit scenarios were applied first individually and then cumulatively; and (8) operational carbon, EUI, PV offset, and the Residual-Load Index were derived in post-processing. Importantly, the drawing information was not imported as a fully detailed BIM or CAD model; instead, the restaurant was reconstructed as a simplified OpenStudio geometry using the reported floor area, approximate perimeter, orientation, window-to-wall ratio, and zone-area allocation. This level of abstraction is appropriate for feasibility-stage comparative analysis but not for final design. For reproducibility, the workflow is documented against EnergyPlus v25.1 and OpenStudio 3.6, a weather file representative of the London location, the zone aggregation in Table 1, the schedules in Table 2, EnergyPlus unmet-setpoint hours as the comfort output, and whole-building annual utility totals as the calibration basis; the executable model file and the underlying premises dataset are not released because they are commercially sensitive.

Table 1. Zone-area aggregation used to make the whole-building model reproducible.

Reporting Zone	Area Allocation	Basis	Main Energy Role
Front-of-house dining/perimeter/core	430.00 m^2	Screening allocation	Occupancy, lighting, space conditioning
Kitchen	145.00 m^2	Screening allocation	Cooking, kitchen electricity, extract interaction
Back-of-house/ store/utility	55.00 m^2	Screening allocation	Equipment, storage, partial or untreated service
Vestibule/circulation	25.82 m^2	Screening allocation	Entry losses and circulation lighting
Total	655.82 m^2	Survey/source dataset total	EUI denominator

Table 2. Screening operating schedule used for reproducibility. Fractions are profile multipliers, not measured occupancy or metered equipment load.

Period	Occupancy Fraction	Lighting Fraction	Catering/Process Fraction	Notes
Closed overnight	0.00	0.05	0.05	Security/standby only
Prep/cleaning	0.05	0.50	0.35	Before/after service
Lunch service	0.45	0.90	0.75	Typical weekday active period
Afternoon shoulder	0.20	0.70	0.55	Lower occupancy/service
Dinner service	0.70	1.00	1.00	Peak cooking and dining
Weekend service	0.60–0.80	1.00	0.90–1.00	Longer operating period

The model uses a London-region typical meteorological-year weather basis. Because the source manuscript package did not include the exact archived weather-file identifier, London Gatwick IWEC/TMY is identified here only as a reproducibility assumption for an equivalent screening model, not as a confirmed original file. This limitation mainly affects load distribution and scenario deltas rather than the annual baseline total, which is constrained by utility data. Any design-stage or post-retrofit M&V study should archive the exact weather file, OpenStudio model, EnergyPlus IDF, and output files alongside anonymised utility and sub-metering data [7,8,23,24].

The model uses a four-zone reporting aggregation: front-of-house dining and perimeter areas, kitchen, back-of-house and storage and utility areas, and circulation and vestibule. The aggregated area schedule used for reproducibility is shown in Table 1. These areas are screening allocations consistent with the total floor area; they are not derived from a measured zone survey and may differ from the actual fitout. They are reported only to enable reproduction of an equivalent screening model.

4.5. Operating Schedules, Setpoints, and Internal Gains

The case-study operating hours (Section 3.3) are represented in the model through fractional service-period profiles rather than constant maximum occupancy because hourly cover counts were not available. Table 2 reports the schedule specification as a screening assumption rather than as metered occupancy. Heating setpoints are represented as 20–21 °C for occupied dining zones and 18 °C for back-of-house zones where heating service is provided, and cooling setpoints in cooling-enabled zones are represented as 24–26 °C. These setpoints are screening assumptions consistent with CIBSE Guide A occupant comfort criteria for hospitality and back-of-house spaces [33]; they are not derived from a building management system log. The heating-only ASHP scenario does not by itself demonstrate summer comfort; that question is treated as a limitation in Section 8 with reference to CIBSE TM52 [41]. People, lighting, and equipment gains are represented through the schedules and the as-built lighting power densities reported in Section 3.5. Catering process electricity and gas are constrained by the model-derived annual process allocation, not by appliance-level metering.

4.6. Ventilation, Extract, and Infiltration Assumptions

Kitchen ventilation is a critical uncertainty in restaurant energy modelling [15]. The source dataset did not include measured extract rates, hood operation, or make-up air temperatures. To avoid leaving this hidden, the reproducibility model uses explicit screening assumptions consistent with practice reported by Zhang et al. [15]. Kitchen extract is represented as 20 air changes per hour during active cooking, 10 air changes per hour during prep and cleaning, and 2 air changes per hour during closed and standby periods. Make-up air is assumed to follow extract operation, with 80–90% supplied through transfer or make-up pathways and the remaining imbalance affecting infiltration. No ventilation heat recovery is assumed in the baseline, reflecting the typical converted-shell condition. Dining outdoor air is represented as occupancy-linked ventilation during service periods, aligned with the operating profile. Infiltration is represented as an equivalent 0.5 ACH during closed periods and 1.0 ACH during active service for front-of-house zones, with higher effective exchange possible near entrances and kitchen pressure paths. These values are screening assumptions because no blower-door test, pressure measurement, or extract commissioning data were available. The uncertainty screening therefore includes a $\pm$20% ventilation and extract band (Section 4.10).

Kitchen ventilation matters disproportionately in restaurant energy modelling because the extract–make-up air loop drives a large fraction of the heating load through cold-air introduction during winter operation. Even modest reductions in extract rate during prep and standby periods, or the introduction of partial heat recovery where hygiene and grease-management constraints permit, can deliver disproportionate heating-energy savings relative to the absolute volumetric flow change. This is why kitchen ventilation is an explicit candidate for second-stage process-side intervention, as revisited in the practical implications and limitations sections, and why the present uncertainty screening band is set at $\pm$20% rather than a narrower envelope-grade band.

4.7. Modelled Envelope, Lighting, and HVAC Parameters

The as-built fabric, lighting, and HVAC parameters for the case-study building are given in Section 3 (geometry and envelope in Section 3.2; existing systems in Section 3.4; lighting and process loads in Section 3.5). For the modelled retrofit scenarios, the envelope scenario reduces wall and roof thermal transmittance to a post-upgrade screening range consistent with cavity and roof insulation, and the glazing scenario uses U = 1.6 W/m^2K and g = 0.50 representative of low-emissivity double glazing [33]. The LED and controls scenario reduces dining and kitchen lighting power densities from the as-built values of 9.579 W/m^2 and 18 W/m^2 to 6 W/m^2 and 12 W/m^2, respectively, with occupancy, scene, daylight, and time-schedule control assumptions consistent with CIBSE Guide F and SLL lighting guidance [34,35]. Boiler efficiency and detailed control sequences are not verified; the baseline gas total is constrained by annual utility calibration.

4.8. ASHP, DHW, and PV Scenario Boundaries

The ASHP scenarios are decomposed in Table 3 because they are not pure equipment replacements. Space-heating electrification is represented using a high-efficiency air-to-air heat-pump proxy. Because air-to-air systems do not provide DHW, the displacement of gas DHW in both ASHP variants was represented as a separate electrified DHW load (a heat-pump water heater or direct electric resistance, configured to match the baseline DHW demand). Cooling is either enabled and expanded or disabled, depending on the scenario. This distinction is essential because the heating-only case performs better in annual energy terms partly because it avoids cooling electricity. In a final detailed design, an air-to-water ASHP coupled to a hot-water cylinder, or a dedicated heat-pump water heater, would be the appropriate route to deliver the combined space-heating and DHW function [36]. The combined scenario should therefore be interpreted as space-heating electrification plus DHW fuel-switching, not as a single equipment substitution.

Table 3. ASHP, DHW, and cooling boundary decomposition. Values are model-derived scenario outputs, not equipment sizing recommendations.

Boundary Item	Baseline	ASHP Heat + Cool	ASHP Heat-Only
Space heating	Gas boiler/radiators, direct gas heaters, electric panels and local split heating	Gas space heating removed; electric heat-pump service represented	Gas space heating removed; electric heat-pump heating represented
DHW	Gas hot-water system	Gas DHW removed; separate electrified DHW load assumed	Gas DHW removed; separate electrified DHW load assumed
Cooling	Limited existing cooling in part of dining area	Cooling enabled and expanded; 16,983 kWh/yr standalone and 17,419 kWh/yr cumulative	Cooling disabled except residual model load; 22 kWh/yr standalone and 192 kWh/yr cumulative
Served zones	Partial and uneven service	Conditioning extended relative to baseline	Heating service improved without added cooling
Interpretation	Existing mixed service	Fuel switching plus service expansion	Fuel switching plus cooling exclusion

Two clarifications follow from this decomposition. First, neither ASHP scenario is a single equipment swap. Each represents space-heating electrification together with a separately electrified DHW assumption, namely a heat-pump water heater or direct electric resistance sized to match the baseline DHW demand, and, in the heating-and-cooling case, an explicit cooling-service decision. Because air-to-air systems do not provide DHW, the modelled carbon savings are conditional on delivering both the space-heating and the hot-water function, not on installing a single air-to-air unit; the real investment, spatial, and electrical implications of providing DHW separately are returned to in Section 7. Second, the 11 kWp PV array is modelled as full annual self-consumption, that is, as a feasibility-level annual import-offset in which annual PV generation is netted against annual electricity demand. This is an annual energy-balance assumption, not an hourly self-consumption result. It is plausible at feasibility stage because annual electricity demand is much larger than annual PV generation and restaurant trading hours overlap with much of the solar-generation window, but the exported fraction cannot be quantified without hourly load-yield matching; its effect on import, carbon, and economic estimates is therefore bounded as a limitation in Section 8.

The PV scenario uses an 11 kWp roof-mounted array with annual yield of 11,025 kWh/yr estimated using PVGIS [38]. PV is treated as grid-import offset, not demand reduction. The central result assumes full annual self-consumption because annual electricity demand is much larger than PV yield. This is an annual import-offset potential, not a verified hourly behind-the-meter result. Hourly or monthly load–yield matching would be required to confirm export and self-consumption. The system was sized by the available sloped roof area (approximately 55 m^2 at 4–6 m^2 per kWp planning ratio), not by demand or inverter capacity. Installation conforms to the MCS framework [40].

4.9. Energy, Carbon, and Residual-Load Equations

Annual operational carbon emissions were computed by applying static UK Government GHG Conversion Factors (2025 release) to the metered or simulated annual energy use of each fuel carrier [31]:

$$C_{annual} = \Sigma_i \left(E_i \times EF_i\right) \tag{1}$$

where E_i and EF_i are annual energy demand (kWh/yr) and emission factor (kgCO_2e/kWh) for carrier i. For this study, EF_{elec} = 0.177 and EF_{gas} = 0.183 kgCO_2e/kWh [29]. Energy-use intensity was computed as:

$$EUI = E_{total}/A_{floor} \tag{2}$$

with A_{floor} the gross internal floor area (655.82 m^2). Percentage savings against baseline were computed as:

$$\Delta E\ (\%) = (E_{baseline} - E_{scenario})/E_{baseline} \times 100 \tag{3}$$

$$\Delta C\ (\%) = (C_{baseline} - C_{scenario})/C_{baseline} \times 100 \tag{4}$$

PV generation offsets imported electricity rather than reducing underlying building demand. The *PV* offset fraction is computed against gross-baseline electricity demand to provide a stable reporting basis:

$$F_{PV}\ (\%) = E_{PV}/E_{electricity,gross} \times 100 \tag{5}$$

with E_{PV} the annual *PV* generation (kWh/yr), and $E_{electricity,gross}$ the annual gross-baseline electricity demand. To formalise the residual-load argument quantitatively, the Residual-Load Index (*RLI*) is defined as the share of total annual energy demand attributable to process and catering end uses:

$$RLI = E_{process}/E_{total} \tag{6}$$

where $E_{process}$ is the sum of kitchen and back-of-house electrical equipment and kitchen and catering gas (held constant in absolute terms across the building-focused scenarios because those measures do not address process loads), and E_{total} is the total annual energy demand of the relevant scenario (gross delivered energy in baseline and demand-side scenarios; net imported energy in *PV* cases). *RLI* varies between 0 (no process load) and 1 (process load equals total demand); higher *RLI* values indicate that further building-focused measures will deliver progressively smaller absolute and proportional carbon reductions. In this paper, $E_{process}$ is model-derived rather than sub-metered, so RLI is reported with ±15% process-allocation screening uncertainty (Section 4.10). The ±15% screening band is applied to $E_{process}$ only while the scenario total E_{total} is held constant. The band therefore tests process/non-process allocation uncertainty within the reported annual energy total, rather than a re-simulated change in whole-building demand.

The boundary of the RLI numerator is defined narrowly and conservatively. Kitchen ventilation and make-up air are process-driven in operation, but because the kitchen extract and supply fan electricity was not separately metered, it is carried within the HVAC and ventilation auxiliary energy and is not included in the process-load numerator. The RLI numerator is therefore restricted to kitchen and catering gas plus kitchen and back-of-house electrical equipment. This makes the RLI conservative: if separately metered ventilation-fan energy were added to the numerator, the effective process-driven share, and, hence, the residual constraint identified here, would increase rather than decrease. The same boundary is applied consistently in Section 3.5, Table 4, the residual-load results in Section 5.5, and the limitations in Section 8.

Table 4. Consolidated model-input register and provenance. Process values are model-derived allocations within the whole-building utility-calibrated model, not sub-metered end-use measurements.

Item	Value/Basis	Provenance Class	Use in Model
Floor area	655.82 m^2 (Section 3.2)	Reported survey/ source dataset	EUI denominator
Baseline electricity	117,008 kWh/yr	Measured annual utility total	Baseline calibration
Baseline gas	296,886 kWh/yr	Measured annual utility total	Baseline calibration
Baseline energy	413,895 kWh/yr	Derived from utilities	Baseline total
Existing wall U-value	1.19 W/m^2K (Section 3.2)	Visual survey/ reference [33]	Envelope input
Existing roof U-value	3.84 W/m^2K (Section 3.2)	Visual survey/ reference [33]	Envelope input
Existing glazing U-value	4.80 W/m^2K (Section 3.2)	Visual survey/ reference [33]	Envelope input
Existing glazing g-value	0.78 (Section 3.2)	Visual survey/ reference [33]	Solar gain input
Dining LPD	9.579 W/m^2 (Section 3.5)	Lighting audit/ source dataset	Internal gains/electricity
Kitchen LPD	18 W/m^2 (Section 3.5)	Lighting audit/ source dataset	Internal gains/electricity
Kitchen extract	20 ACH cooking; 10 ACH prep; 2 ACH standby	Screening assumption [15]	Ventilation/HVAC interaction
Front-of-house infiltration	0.5 ACH closed; 1.0 ACH active	Screening assumption	Heat-loss/air-exchange input
Process gas	167,317 kWh/yr	Model-derived allocation	RLI and residual load
Kitchen/BOH electricity	66,603 kWh/yr	Model-derived allocation	RLI and residual load
PV array	11 kWp; 11,025 kWh/yr	PVGIS [37]/source dataset	Grid-import offset
Electricity factor	0.177 $kgCO_2e/kWh$	DESNZ 2025 [31]	Carbon calculation
Gas factor	0.183 $kgCO_2e/kWh$	DESNZ 2025 [31]	Carbon calculation

4.10. Scenario Design and Uncertainty Method

Scenarios are defined in two families. Standalone cases test one measure against the baseline where possible. Cumulative cases layer measures sequentially to approximate a phased retrofit package. The ASHP cases are exceptions: they are bundled service scenarios, not pure equipment substitutions, and this composite-scenario caveat applies wherever Cases 4a and 4b appear and is not repeated in subsequent sections. PV is modelled as grid-import offset, not demand reduction, with gross demand before PV reported separately from net imported energy after PV.

Uncertainty is treated through analytical post-processing screening rather than re-simulated parametric modelling. The tested ranges are process-load allocation ±15%, ASHP and DHW electrical efficiency ±15%, kitchen extract and make-up air ±20%, envelope U-values ±20%, lighting-control persistence ±20%, and PV yield ±10%. These ranges are not probabilistic confidence intervals; they identify which assumptions dominate the interpretation. The central RLI conclusion is considered robust only if the optimised case remains process-load dominated (RLI > 0.5) under the low-process-load boundary.

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4.11. Modelled Inputs Register and Scenario Definitions

Table 4 consolidates the model inputs and their provenance for the modelled scenarios. Items already given in narrative form in Section 3 are included for reference only so that the input register is complete and machine-readable; the case-study description in Section 3 remains the single narrative source for as-built physical attributes. Table 5 defines the standalone and cumulative retrofit scenarios, separating intervention labels from mechanism classes. This distinction is retained to avoid collapsing demand reduction, fuel switching, service expansion, and generation offset into a single undifferentiated saving.

Table 5. Scenario definitions, mechanism class, and interpretation boundaries.

Scenario	Type	Measure Definition	Mechanism Class	Interpretation Caveat
Baseline	Reference	Existing fabric, systems, lighting and process loads	Reference	Whole-building utility-calibrated
Standalone 1	EEM	Wall and roof insulation	Demand reduction	U-values require intrusive confirmation
Standalone 2	EEM	Low-e double glazing	Demand reduction/comfort	Whole-building saving limited by process share
Standalone 3	EEM	LED lighting and controls	Electrical demand reduction	Lower lighting gains can slightly increase heating
Standalone 4a	Service scenario	ASHP heating and cooling plus DHW fuel switching	Fuel switching + service expansion	Not like-for-like
Standalone 4b	Service scenario	ASHP heating-only plus DHW fuel switching	Fuel switching + cooling exclusion	Summer comfort not demonstrated
Standalone 5	Generation	11 kWp PV	Electricity import offset	Not demand reduction
Cumulative 1	Package	Envelope only	Demand reduction	Phased retrofit
Cumulative 2	Package	Envelope + glazing	Demand reduction	Phased retrofit
Cumulative 3	Package	Envelope + glazing + LED/controls	Demand reduction	Phased retrofit
Cumulative 4a	Package	Cum. 3 + ASHP heat + cool + DHW	Combined	Service expansion in cooling
Cumulative 4b	Package	Cum. 3 + ASHP heat-only + DHW	Combined	Cooling exclusion; comfort caveat
Cumulative 5a	Package	Cum. 4a + PV	Combined + offset	Net imported energy reported
Cumulative 5b	Package	Cum. 4b + PV (analytical bound)	Combined + offset	Headline case
(Out of scope)	Process-side	Catering equipment/kitchen ventilation/cooking-fuel switching/refrigeration controls	Residual-load reduction	Not modelled in current scope

5. Results

5.1. Baseline Energy and Carbon Performance and Calibration Evidence

The whole-building utility-calibrated baseline is 413,895 kWh/yr (Table 6). Dividing by 655.82 m^2 gives 631.1 kWh/m^2·yr. This sits below the approximate CIBSE TM46 typical-practice restaurant benchmark (~800 kWh/m^2·yr) and above the approximate best-practice benchmark (~460 kWh/m^2·yr), indicating that the annual total is plausible for the use class [1]. The baseline carbon value retained for consistency with the source-reporting basis is 75,020 kgCO$_2$e/yr. The model-derived process-load allocation is 167,317 kWh/yr residual kitchen and catering gas plus 66,603 kWh/yr kitchen and back-of-house electricity. This gives $E_{process}$ = 233,920 kWh/yr and a baseline RLI = 0.57. The RLI value is not a sub-metered result; it is a model-derived indicator constrained by whole-building utility data and is reported with the uncertainty range in Section 5.5.

Table 6. Whole-building utility-calibrated evidence and baseline performance; modelled values are source-constrained totals, not sub-metered calibration statistics.

Carrier	Measured (kWh/yr)	Modelled (kWh/yr)	Difference	Calibration Status
Electricity	117,008	117,008	<1%	Whole-building utility-calibrated
Natural gas	296,886	296,886	<1%	Whole-building utility-calibrated
Total annual energy	413,895	413,895	<1%	Whole-building, feasibility-grade
Monthly utility profile	June 2024–May 2025	Used for calibration		Feasibility-grade
End-use sub-metering	Not available	–	–	Limitation

Source-reporting operational carbon: electricity = 20,710 kgCO$_2$e/yr and gas = 54,309 kgCO$_2$e/yr, giving 75,020 kgCO$_2$e/yr. Displayed conversion factors are rounded in the source feasibility dataset, so the source-reporting carbon values are retained for scenario comparison. EUI = 413,895/655.82 = 631.1 kWh/m^2·yr. Process-load share at baseline = (167,317 + 66,603)/413,895 = 56.5%, giving a baseline RLI of 0.57. Unmet hours at baseline: 7049 (4082 occupied).

5.2. Standalone Measure Results

Standalone results are summarised in Table 7. The largest single change is the ASHP heating-only service scenario, which reduces energy to 357,189 kWh/yr and carbon to 64,215 kgCO$_2$e/yr. This result must not be interpreted as a simple heat-pump efficiency claim. It combines removal of gas space heating, assumed DHW electrification, and avoidance of expanded cooling energy. The ASHP heating-and-cooling scenario reduces energy to 374,931 kWh/yr and carbon to 67,355 kgCO$_2$e/yr. It saves less because cooling provision and service coverage expand. Envelope insulation reduces total energy to 380,825 kWh/yr (an 8.0% saving), the largest building-related single-measure energy reduction, principally through reduced gas space-heating demand (from 107,125 to 77,017 kWh/yr). Glazing alone reduces energy by 1.3%, while LED with controls reduces energy by 2.2%; the small whole-building impact in both cases reflects that perimeter-zone heating gas and lighting electricity are modest shares of total demand. PV offsets 11,025 kWh/yr of grid import (9.4% of baseline electricity demand) and reduces carbon by approximately 1951 kgCO$_2$e/yr (2.6% of baseline operational emissions). The asymmetry between the 2.7% energy saving and 2.6% carbon saving for PV reflects the higher carbon factor of gas, which PV does not displace.

Table 7. Standalone scenario results. ASHP cases are bundled service scenarios; PV is an import-offset case, not demand reduction.

Scenario	Annual Energy (kWh/yr)	EUI (kWh/m^2·yr)	Energy Saving (%)	Carbon (kgCO_2e/yr)	Carbon Saving (%)
Baseline	413,895	631.1	0.0	75,020	0.0
Envelope	380,825	580.7	8.0	68,988	8.0
Glazing	408,592	623.0	1.3	74,059	1.3
LED/controls	404,942	617.5	2.2	73,449	2.1
ASHP heat + cool	374,931	571.7	9.4	67,355	10.2
ASHP heat-only	357,189	544.6	13.7	64,215	14.4
PV offset	402,870	614.3	2.7	73,068	2.6

Figures 2 and 3 are best read together. Figure 2 shows the baseline end-use structure and explains why process loads dominate, while Figure 3 shows why standalone building-focused measures have limited whole-building impact. The reason the envelope, glazing, and LED cases produce only modest whole-building savings in Figure 3 is visible in Figure 2: a large share of the baseline is process-related kitchen and catering gas and kitchen and back-of-house electricity, which lies outside the reach of those measures. The two largest single changes in Figure 3, the ASHP service scenarios, act on space heating, DHW, and cooling rather than on this process share, so even they leave the process block of Figure 2 substantially intact. The figures thus make the same point from two directions: the composition of baseline demand in Figure 2 sets an upper bound on what the building-focused measures in Figure 3 can achieve.

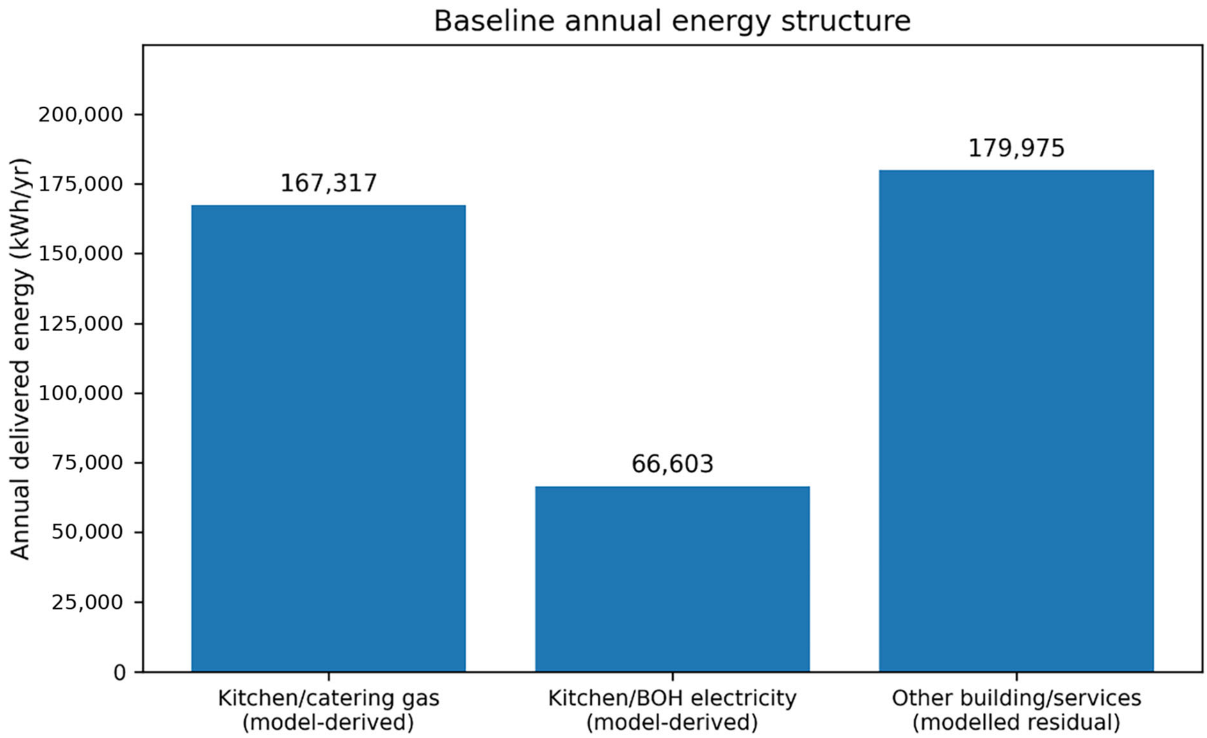

Figure 2. Baseline end-use energy structure. Process gas and kitchen/back-of-house electricity are model-derived allocations within the whole-building utility-calibrated model; other building/services demand is the modelled residual.

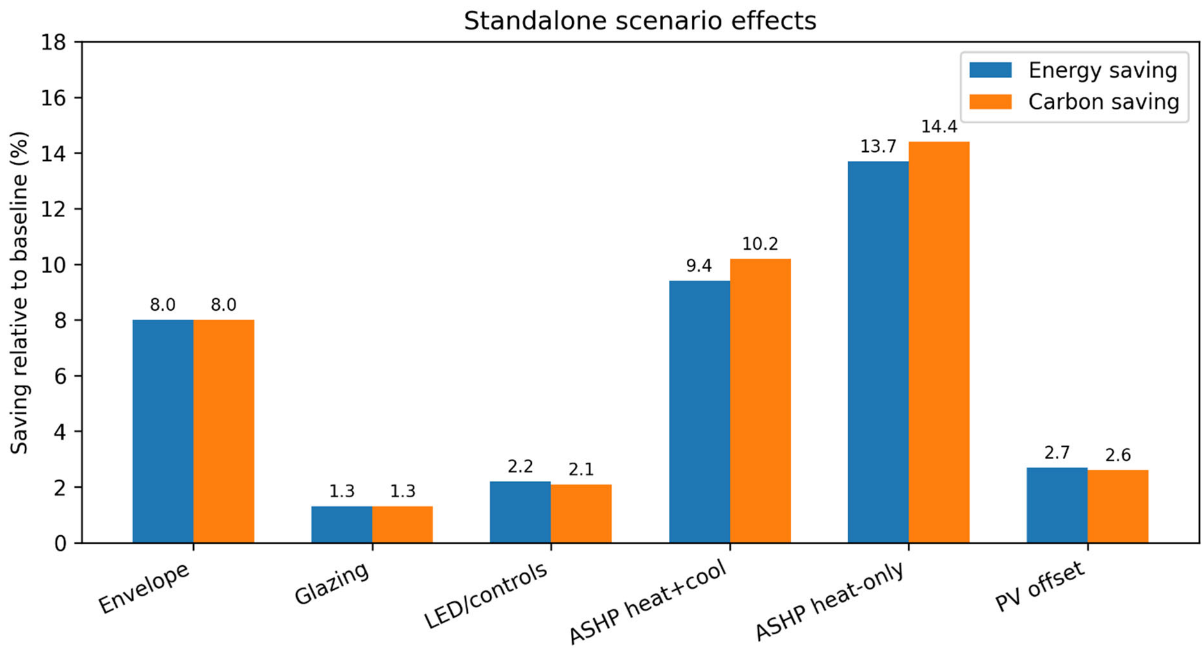

Figure 3. Standalone scenario effects on annual energy and operational carbon. ASHP cases are not like-for-like replacements because service coverage and DHW assumptions change.

5.3. Cumulative Package Results

The cumulative results show a staged reduction from 413,895 kWh/yr at baseline to 314,734 kWh/yr in the lowest-net-energy analytical case (Table 8). The pathway is not strictly additive because measures interact. The LED and controls step reduces lighting electricity but also reduces internal heat gains. The modelled gas value in that step is therefore interpreted as an interaction within the cumulative energy balance rather than an independent gas-saving measure; this reflects the heat-balance interaction captured by EnergyPlus. The best pre-PV analytical package is fabric + glazing + LED/controls + ASHP heating-only, with gross annual demand of 325,759 kWh/yr and carbon of 58,651 $kgCO_2e/yr$. Adding 11,025 kWh/yr of PV reduces net imported energy to 314,734 kWh/yr and carbon to 56,700 $kgCO_2e/yr$. The retained headline saving is 24.0% on the source-report basis. Gross demand before PV and net imported energy after PV are reported separately to avoid treating generation as demand reduction; the heating-only pathway is retained as an analytical lower-energy bound rather than a recommended final design.

Table 8. Cumulative package results. The 24.0% carbon reduction is retained consistently because it is the reporting basis of the source feasibility dataset (Please refer Figures 4 and 5 as well).

Cumulative Case	Energy Basis	Energy (kWh/yr)	EUI ($kWh/m^2 \cdot yr$)	Carbon ($kgCO_2e/yr$)	Carbon Saving (%)
Baseline	Delivered	413,895	631.1	75,020	0.0
Envelope	Delivered	380,825	580.7	68,988	8.0
+glazing	Delivered	373,817	570.0	67,722	9.7
+LED/controls	Delivered	364,853	556.3	66,148	11.8
+ASHP heat + cool	Delivered	343,964	524.5	61,874	17.5
+ASHP heat-only	Gross before PV	325,759	496.7	58,651	21.8
+PV (h + c)	Net after PV	332,939	507.7	59,922	20.1
+PV (h-only)	Net after PV	314,734	479.9	56,700	24.0

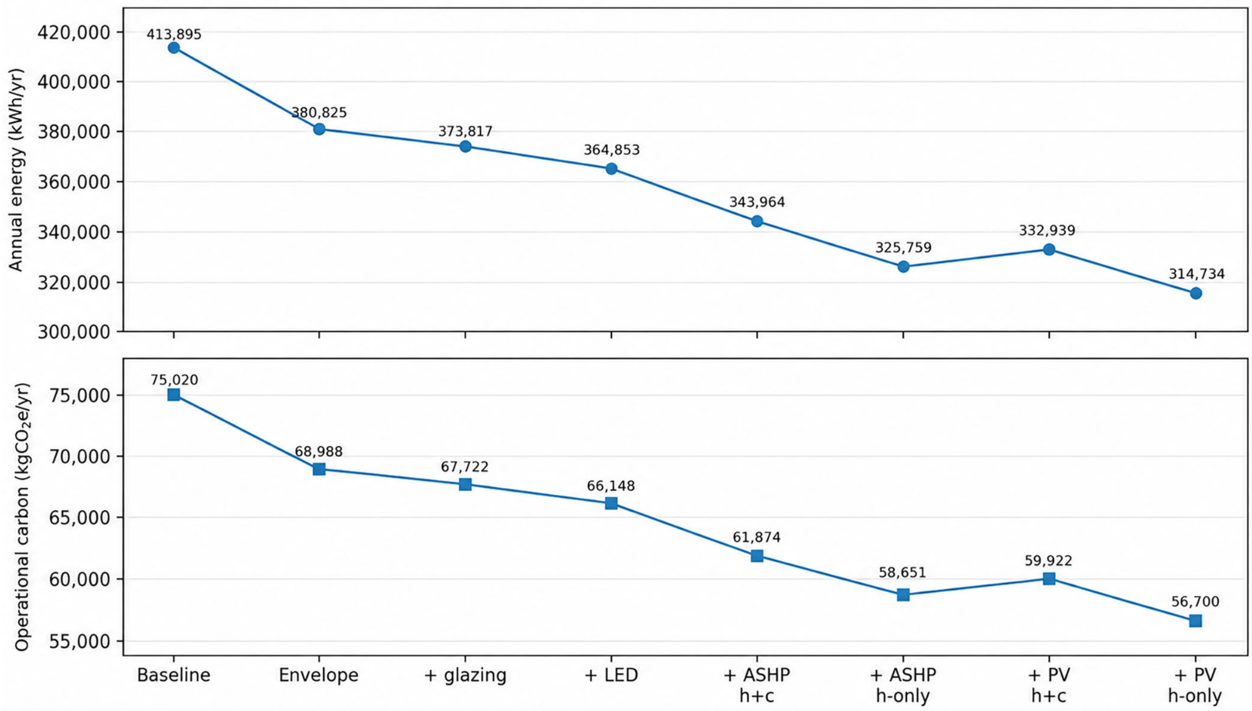

Figure 4. Cumulative package pathway for annual energy and operational carbon. Energy in PV cases is net imported energy after annual PV offset; the two panels use separate axes to avoid misleading overlap between energy and carbon series.

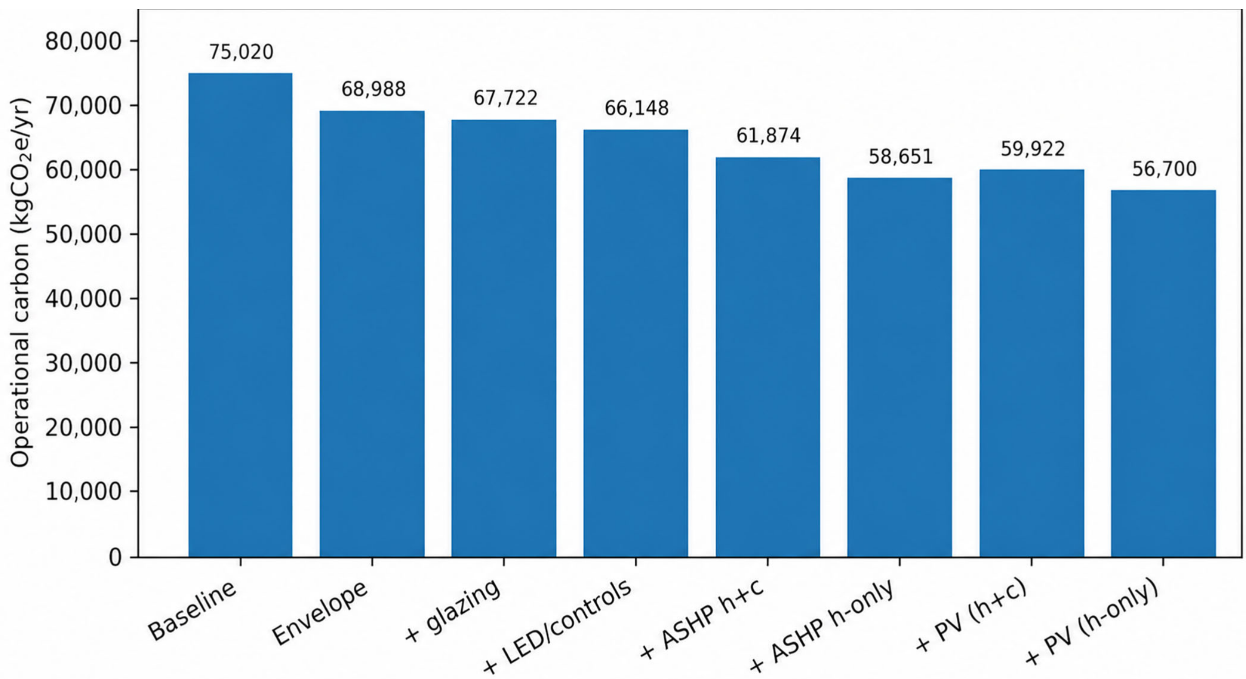

Figure 5. Operational carbon pathway from baseline to the optimised package. Incremental differences include interaction effects and should not be interpreted as isolated causal savings.

5.4. Fuel Switching and PV Offset

The baseline fuel split is approximately 28% electricity and 72% gas (Figure 6). In the optimised package, gross electricity demand before PV is 158,442 kWh/yr and residual gas demand is 167,317 kWh/yr. PV yield is 11,025 kWh/yr, equal to approximately 7.0% of optimised gross electricity demand and 3.4% of optimised gross total demand. After PV, net imported electricity is 147,417 kWh/yr and the optimised net split is approximately 47% gas and 53% electricity import. The PV offset fraction against gross-baseline electricity (Equation 5) is 9.4%. The PV calculation assumes full annual self-consumption because annual electricity demand is much larger than PV yield. This is a defensible feasibility assumption but not a verified hourly result. If hourly load profiles show export, the import reduction and economic benefit would be lower. The carbon result is therefore reported as annual import-offset potential, not measured behind-the-meter performance.

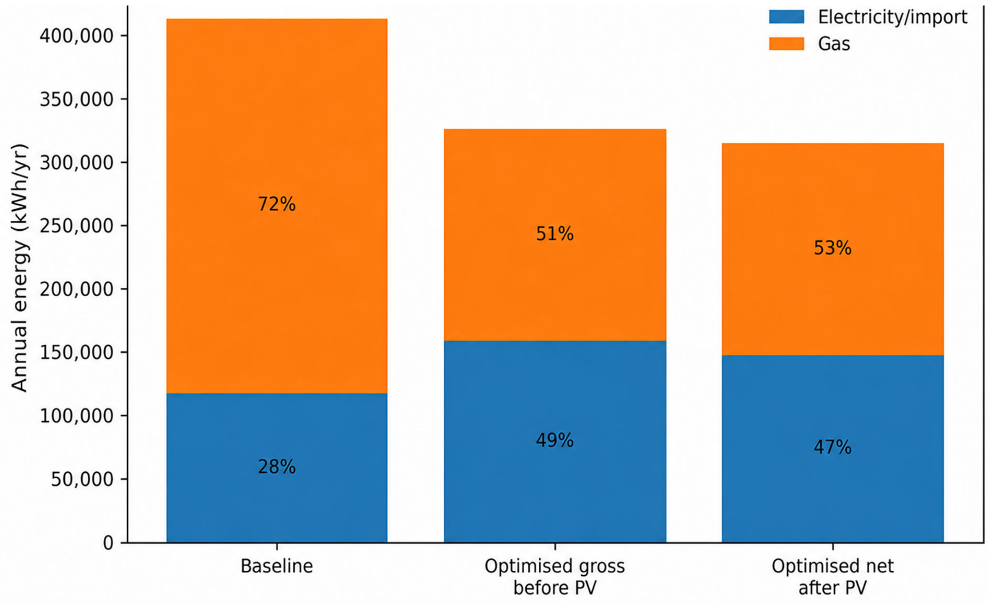

Figure 6. Fuel split in the baseline, optimised gross package before PV, and optimised net package after PV. The PV case reports grid electricity import after annual offset.

One caveat applies to the PV result, but it should be interpreted quantitatively rather than as a generic rejection of the assumption. A total annual electricity demand that exceeds annual PV generation does not guarantee full self-consumption because PV generation peaks around midday while restaurant electricity demand often peaks during evening service. The modelled annual import-offset therefore represents a feasibility-level upper-bound benefit: any generation in excess of the coincident load would be exported rather than self-consumed, reducing realised import, carbon, and economic savings. However, the 11 kWp array is small relative to the annual electricity demand of the restaurant (117,008 kWh/yr at baseline and 158,442 kWh/yr gross electricity demand in the optimised pre-PV case), and the restaurant has daytime trading, refrigeration, catering, and lighting loads. High self-consumption is therefore physically plausible but not proven. Resolving the exported fraction would require hourly load and PV-yield profiles together with export metering, which were not available; the uncertainty is stated explicitly in Section 8.

5.5. Residual-Load Index and Process-Load Constraint

The most important result is the change in load composition. The residual process energy remains 233,920 kWh/yr in the best package because the modelled building-focused measures do not replace cooking equipment, catering equipment, refrigeration, or process controls (Figure 7). Since total net energy falls, the process share rises. RLI rises from 0.57 in the baseline to 0.74 in the optimised net case (Table 9 and Figure 8). This is the decarbonisation ceiling demonstrated by the case. The package reduces annual carbon by 24.0%, but it leaves a residual process-dominated energy balance. Further reduction would require measures outside the conventional building-retrofit package: efficient catering equipment, induction or alternative cooking-fuel strategies, demand-controlled kitchen ventilation, heat recovery where hygienically and technically feasible, refrigeration optimisation, staff operating protocols, sub-metering, and demand-response.

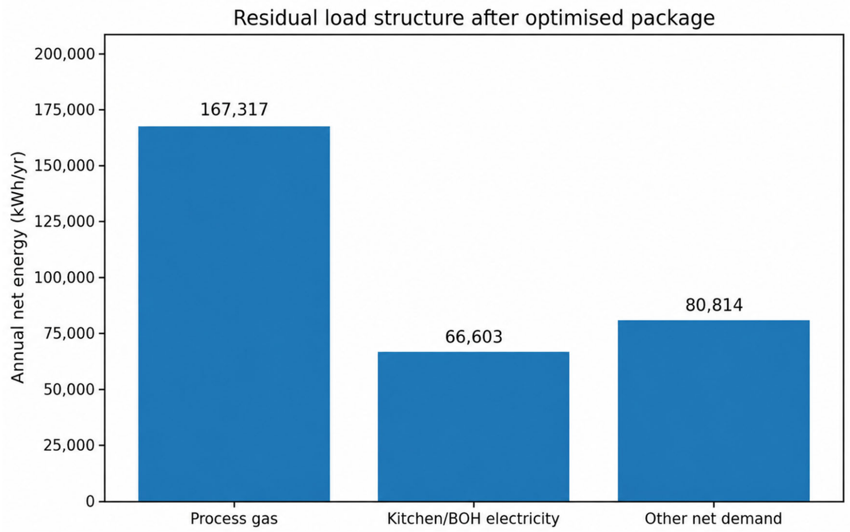

Figure 7. Residual-load structure after the best package. The dominant remaining loads are model-derived cooking and catering gas and kitchen/back-of-house electricity.

Table 9. Residual-Load Index and uncertainty range. Process values are model-derived, not sub-metered.

Metric	Baseline	Optimised Net Package	Provenance
Total annual energy	413,895 kWh/yr	314,734 kWh/yr	Utility-calibrated/modelled
Process gas	167,317 kWh/yr	167,317 kWh/yr	Model-derived allocation
Kitchen/BOH electricity	66,603 kWh/yr	66,603 kWh/yr	Model-derived allocation
$E_{process}$ total	233,920 kWh/yr	233,920 kWh/yr	Derived
RLI (central)	0.57	0.74	Derived
RLI (±15% screening band)	0.48–0.65	0.63–0.85	Analytical screening

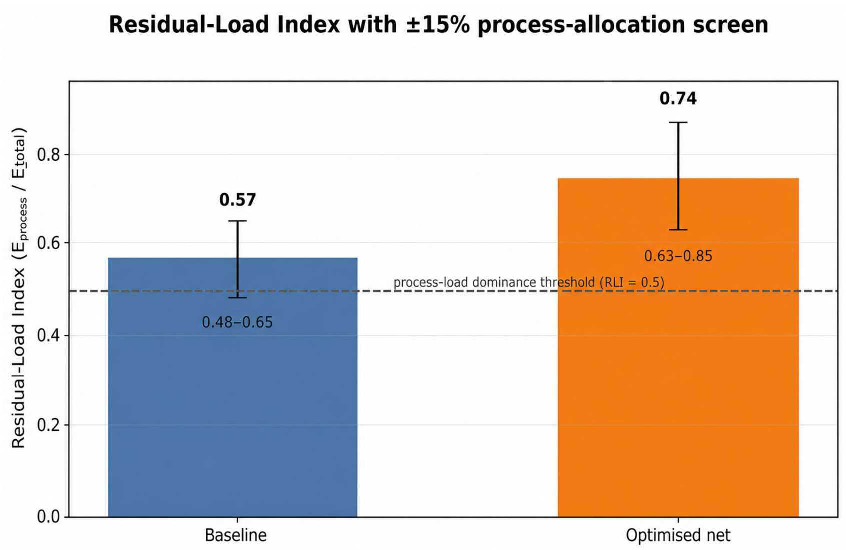

Figure 8. Residual-Load Index central values with ±15% process-load allocation uncertainty. Total scenario energy is held constant for the allocation screen; the process-load allocation is model-derived and not sub-metered.

5.6. Analytical Uncertainty Screening

The uncertainty screening identifies which assumptions matter most (Table 10 and Figure 9). Process-load allocation dominates the result. For RLI, the ±15% test is an allocation screen that holds total scenario energy constant and shifts the process/non-process split. Read as a physical demand sensitivity rather than an allocation test, the same ±15% change would be equivalent to approximately ±35,088 kWh/yr of process energy and ±6361 kgCO_2e/yr. The carbon swing is calculated by applying the same ±15% change to model-derived process gas and kitchen and back-of-house electricity separately, then multiplying by their respective emission factors: 0.15 × (167,317 × 0.183 + 66,603 × 0.177) = 0.15 × 42,408 = 6361 kgCO_2e/yr. This does not overturn the conclusion: even at the low-process case, the optimised RLI remains approximately 0.63, well above the 0.5 threshold for process-load dominance. PV yield uncertainty is much smaller, with ±10% PV yield changing carbon by about ±195 kgCO_2e/yr. Lighting persistence and envelope U-value uncertainty are also smaller than process-load and ventilation uncertainty. Kitchen extract and make-up air sensitivity is reported as post-processing screening only; measured extract rates were not available.

Table 10. Analytical post-processing uncertainty screening around the optimised package. These are screening bands, not re-simulated probabilistic confidence intervals.

Uncertainty Parameter	Tested Range	Approx. Allocation or Demand-Equivalent Swing	Approx. Carbon Swing	Interpretation
Process-load allocation	±15%	±35,088 kWh/yr	±6361 kgCO_2e/yr	Dominant; RLI remains >0.5
ASHP/DHW electrical efficiency	±15%	±8730 kWh/yr	±1545 kgCO_2e/yr	Affects electrified service scenario
Kitchen extract/make-up air	±20%	±10,000 kWh/yr	±1800 kgCO_2e/yr	Post-processing screening only
Envelope U-values	±20%	±8015 kWh/yr	±1465 kgCO_2e/yr	Affects heating saving
Lighting-control persistence	±20%	±2265 kWh/yr	±401 kgCO_2e/yr	Includes internal-gain interaction
PV yield	±10%	±1103 kWh/yr	±195 kgCO_2e/yr	Minor relative to total demand

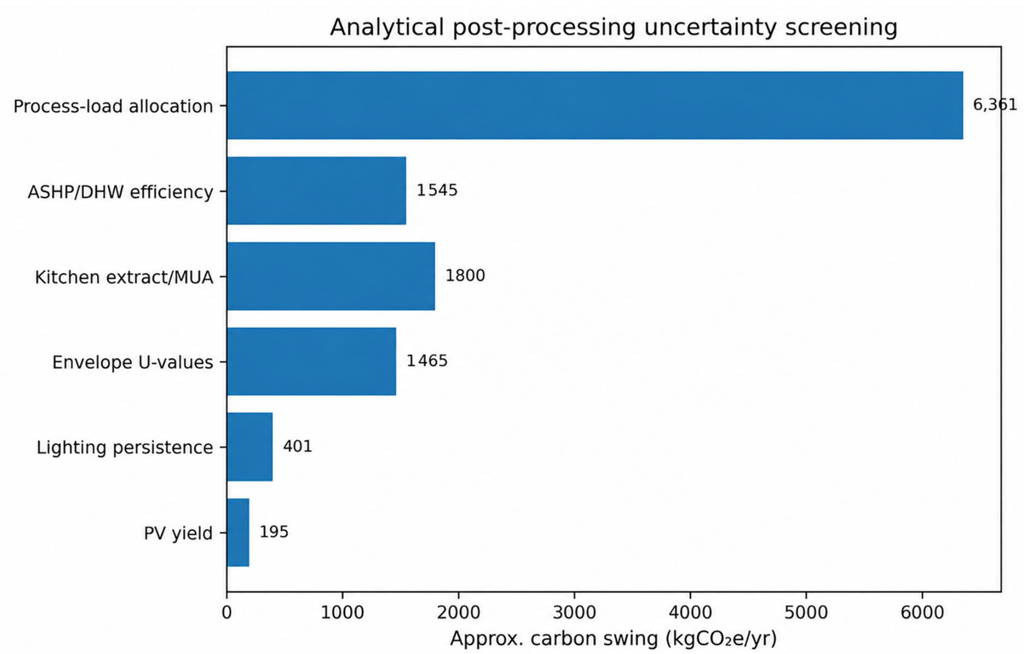

Figure 9. Analytical post-processing uncertainty screening around the optimised package. Values are post-processing screening bands, not re-simulated probabilistic confidence intervals; process-load allocation is the dominant uncertainty.

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5.7. Comfort and Unmet-Hours Interpretation

The source model reports baseline unmet hours of 7049 total hours, including 4082 occupied hours. The ASHP heating-and-cooling scenario reduces these to 1341 total hours and 746 occupied hours. The heating-only ASHP case reduces heating-related unmet hours to 1040 total hours and 451 occupied hours. The occupied-hour definition follows the restaurant operating schedule in Table 2; the screening heating setpoint is 20–21 °C for occupied front-of-house areas and 18 °C for served back-of-house zones, while cooling-enabled zones use a 24–26 °C cooling setpoint. These values indicate improved modelled heating service, but they do not establish summer comfort under the heating-only case. The manuscript does not claim compliance with CIBSE TM52 [41] or any non-domestic overheating criterion. A comfort–compliant design would require zone-level operative temperatures, adaptive-comfort criteria, internal-gain schedules, ventilation assumptions, shading assumptions, and summer weather assessment. The heating-only ASHP option is an annual-energy result, not a complete comfort design conclusion; summer comfort under that scenario must be evidenced through a separate TM52-style adaptive-comfort assessment, which lies outside the scope of this study.

The unmet hours reported here are EnergyPlus unmet-setpoint hours, that is, the hours in which the model could not maintain the heating or cooling control setpoint within the simulation tolerance; they are not CIBSE TM52 overheating hours and are not an adaptive thermal-comfort assessment. Two counts are reported for each scenario: total hours across the full year, and occupied hours, where occupancy follows the restaurant operating schedule in Table 2. The values are reported as source-model outputs and should be treated as comparative feasibility indicators between scenarios rather than as compliance metrics; the baseline and ASHP-scenario counts are therefore meaningful relative to one another, but not as an absolute statement of comfort. On this basis the heating-and-cooling and heating-only ASHP scenarios both reduce modelled unmet hours relative to the baseline, indicating improved heating service while leaving summer comfort under the heating-only case unresolved, as discussed below.

5.8. Cost and Payback

Indicative simple paybacks were derived where cost data were considered sufficiently robust. Lighting with controls offers the shortest indicative payback among the building-focused measures, consistent with widespread commercial-sector evidence. Cavity-fill insulation paybacks depend strongly on confirmed wall build-up and installation cost; roof-quilt and double-glazing paybacks are sensitive to the alternative depreciation schedule of the existing assets. ASHP retrofit paybacks (including the separately electrified DHW load) are sensitive to the relative price of electricity and gas, the availability of grant support for eligible non-domestic buildings, and electrical-supply upgrade costs. PV paybacks depend on tariff, self-consumption fraction and any export agreement [38,39]. Cost figures are reported as indicative and are not used to support the central decarbonisation argument of the paper, which is intentionally framed in physical energy and carbon terms.

6. Discussion

6.1. Why the Baseline EUI Is High but Plausible

The baseline EUI of 631.1 kWh/m^2·yr is high compared with many commercial building types but plausible for a restaurant. The value sits between the approximate TM46 typical-practice and best-practice restaurant benchmark values [1]. Its plausibility is also supported by the underlying end-use structure: long operating hours, mixed gas and electricity use, catering process loads, lighting, and partial conditioning. The plausibility of the baseline therefore strengthens, rather than weakens, the residual-load argument: the elevated EUI is structural to the typology rather than an artefact of poor operation [5,14].

6.2. Why Fabric and Glazing Do Not Dominate the Result

The existing wall, roof, and glazing values are poor by modern standards (Section 3.2), so fabric measures do reduce energy. However, the whole-building saving is limited because a large share of annual demand is not envelope-driven. Glazing performs particularly weakly in whole-building terms because perimeter heat loss is only one component of a restaurant energy balance. These results do not mean envelope measures are irrelevant: reduced peak heating loads, lower plant sizes, improved winter comfort, improved internal-surface temperatures, and heat-pump readiness all matter [22,33]. They mean that envelope savings should be interpreted within the whole end-use composition, and that envelope-only retrofit programmes will under-perform when applied to restaurants.

6.3. Lighting Savings and Internal-Gain Interaction

The lighting scenario reduces electricity demand, but the whole-building impact is constrained by the size of process energy. The cumulative LED step also illustrates a standard dynamic-simulation interaction: reduced lighting power reduces internal heat gains, which can modestly alter heating demand in heating-dominated periods [23,24]. This is why EnergyPlus-style dynamic analysis is preferable to static subtraction of lighting kWh. In this case, lighting remains useful, but it is not a dominant decarbonisation pathway in absolute or proportional terms [34,35].

6.4. ASHP Cases as Service Scenarios, Not Pure Technology Swaps

The ASHP scenarios require careful interpretation. The heating-and-cooling case expands service coverage and introduces or increases cooling. The heating-only case avoids that cooling demand and therefore performs better in annual energy terms. However, the result combines several mechanisms: space-heating fuel switching, assumed DHW fuel switching represented as a separately electrified load (Section 4.8), service coverage, and cooling exclusion. It does not prove that heating-only operation is always preferable. It shows that cooling provision must be treated as an explicit service-level decision (which zones, what comfort target, what schedule), not as an incidental feature of heat-pump replacement [21,22]. The DHW provision in both ASHP variants is conditioned on a separately electrified DHW load (HPWH or direct electric); a final detailed design would typically use an air-to-water ASHP with a coupled cylinder, or a dedicated heat-pump water heater [36].

6.5. PV Contribution and Roof-Area Constraint

The 11 kWp PV array produces 11,025 kWh/yr. This is useful but small relative to total annual demand. PV reduces grid import, not underlying demand. Its impact is limited by available roof area (approximately 55 m^2 of sloped roof at 4–6 m^2 per kWp) and by the high residual annual load. In this case, PV is a supporting measure rather than the primary decarbonisation mechanism. Hourly self-consumption should be tested before final design because annual yield alone cannot quantify export or coincidence [38,39].

6.6. The Residual-Load Mechanism

The main insight is compositional. When building-related loads are reduced, unchanged process loads account for a larger share of the remaining total. The RLI increases from 0.57 to 0.74, with an optimised screening range of 0.63–0.85 under $\pm$15% process-load allocation uncertainty. This does not mean the retrofit has failed. It means the first retrofit package has shifted the constraint. After fabric, lighting, heat electrification, and PV, the limiting loads are cooking gas and kitchen and back-of-house electricity. This is the point at which standard building–retrofit measures reach diminishing returns. RLI is therefore proposed as a transferable analytical metric to be reported alongside EUI and operational carbon for any food-service building, supporting comparison across future restaurant and food-service cases, and policy targeting.

6.7. Transferability

The result should not be statistically generalised to all restaurants. Its transferability lies in the mechanism: where process loads dominate the baseline, conventional building measures reduce the non-process fraction first, causing residual process loads to become the binding constraint. The mechanism is likely relevant to restaurants, cafes, food halls, and small food-production premises with long operating hours and mixed-fuel catering equipment, but the magnitude will depend on menu, equipment, ventilation, occupancy, and roof area [5,14,16]. The findings are most directly transferable to other UK converted-shell restaurants from the 1970s–1980s era with mixed-fuel HVAC, single glazing and high catering loads, and less directly transferable to purpose-built modern restaurants with all-electric kitchens, stronger envelopes, and integrated MVHR.

6.8. Reporting Implications and the RLI Framing

The RLI framing also makes clear why the apparent success of a retrofit package can become harder to communicate after implementation. In the baseline, process loads and building loads are mixed within the same utility bills. After fabric and HVAC measures, the remaining utility profile may look stubbornly high even when the building-related measures have performed as intended. Without residual-load reporting, this can be misread as a failed retrofit. With residual-load reporting, the interpretation is different: the first package has shifted the decarbonisation problem from the envelope and space-conditioning system towards the catering process. This matters for design sequencing. A conventional first stage should still reduce avoidable fabric, lighting, and heating demand. A second stage should then be explicitly process-focused. For this case, the next-stage options would include equipment-level cooking energy audits, induction, or other lower-carbon cooking trials where acceptable to the operator, demand-controlled kitchen ventilation [15], heat recovery subject to hygiene and grease-management constraints, refrigeration controls, staff shutdown procedures, and load-shifting where it does not affect service quality. These measures were not modelled in the current paper because the source data do not include equipment-level metering or extract-rate measurements. Their exclusion is therefore a boundary condition, not a claim that they are unimportant. RLI provides a reporting structure that makes this division of labour visible to operators, designers, and policymakers alike.

7. Practical and Policy Implications

Building-focused packages remain necessary. Poor fabric, inefficient lighting, and gas-fired heating still create avoidable energy and carbon demand. However, for high-process-load hospitality premises, grant programmes and design briefs should not stop at fabric, heat pumps, and PV. They should separately budget and monitor building loads and process loads.

For an SME restaurant, the ASHP and DHW electrification scenarios are not a single procurement decision but a set of physical and contractual commitments, summarised in Table 11. Delivering hot water alongside electrified space heating requires either a dedicated heat-pump water heater, an air-to-water system with a hot-water cylinder, a hybrid system, or a direct electric cylinder, each needing cylinder or plant-room space that converted-shell premises rarely have spare. The associated electrical load often triggers a supply-capacity or distribution-board upgrade, and external condensers can require acoustic and planning assessment, as well as landlord consent in leased premises. Installation typically involves business downtime and disruption during a trading operation, ongoing maintenance obligations, and capital-cost risk. The practical implication is that the theoretical carbon savings reported in Section 5 may be delayed, reduced, or, on constrained sites, only partially deliverable; the modelled electrification should therefore be read as a feasibility-stage ceiling that is conditional on these site-specific constraints being resolved, rather than as a turnkey recommendation for this specific restaurant.

Table 11. Implementation constraints and uncertainty sources in leased hospitality premises.

Constraint/Uncertainty	Issue	Research/Design Implication
Whole-building calibration	No sub-metered or post-retrofit M&V calibration	Feasibility-stage scenario comparison; not IPMVP-grade validation
Process-load uncertainty	Kitchen appliances and extract/MUA rates not directly measured	Residual-load split should be tested using sub-metering and extract-flow logging
Envelope uncertainty	U-values inferred from visual survey and CIBSE reference assemblies	Intrusive survey and calculated U-values needed before detailed design
ASHP service coverage and DHW	ASHP cases alter served zones, cooling provision, and require separate electrified DHW	Not a strict like-for-like one-measure replacement
PV implementation	Roof structure, shading, landlord consent, grid/export arrangements unresolved	PV output and self-consumption to be confirmed in detailed design
Leased premises tenure	Tenant may not control fabric, roof, external plant, electrical infrastructure	Requires landlord-tenant governance and capital/benefit allocation
Acoustics and planning	External ASHP condensers may trigger acoustic and planning assessments	Plant location and attenuation are deployment barriers
Hourly load profiles	No half-hourly electricity or PV self-consumption data	Required for self-consumption and demand-response analysis
Comfort assessment	No CIBSE TM52 overheating evaluation undertaken	Heating-only ASHP requires separate summer comfort study

For designers, the first implication is diagnostic: sub-metering should be installed before or alongside retrofit. Whole-building utility bills cannot identify whether savings are being lost through cooking equipment, ventilation, controls, or HVAC operation. At minimum, future M&V should separate whole-building electricity, whole-building gas, heat-pump electricity, kitchen and catering circuits, refrigeration where practicable, ventilation fans and PV generation, and export [7,8].

For local authorities and place-based programmes such as the UKRI Park Royal Net Zero Food Systems initiative [17,18], SME decarbonisation support should distinguish conventional building measures from catering and process measures. Heat-pump support must include electrical-capacity checks, acoustic assessment, and landlord consent, and it must specify whether DHW is included in the package and through which technology route. PV support must include structural assessment, roof access, fire strategy, and grid and export assumptions. Restaurant-specific support should also consider demand-controlled kitchen ventilation [8], efficient catering equipment, cooking-fuel transition, and operational training. Reporting RLI alongside EUI and operational carbon would allow programme-level comparison of where each business sits on the building-versus-process trade-off curve.

For researchers, this case shows that residual-load reporting should become routine in process-load-heavy building studies. A single total-saving percentage is insufficient.

Reporting RLI before and after retrofit makes the limiting load visible and prevents over-claiming progress towards operational net zero.

8. Limitations

The study has nine main limitations. First, the baseline is whole-building utility-calibrated at feasibility level rather than sub-metered or IPMVP-grade. Its confidence remains limited by the absence of end-use metering and post-retrofit M&V data [7,8,26]. Second, no sub-metered process, HVAC, refrigeration, lighting, or DHW data were available, and no hourly measured load profiles or metered PV self-consumption profiles were available. Third, process-load values are model-derived allocations within annual utility totals, not direct measurements. Fourth, kitchen extract and make-up air rates are screening assumptions rather than measured design values [15]. Fifth, fabric U-values are based on visual survey and CIBSE Guide A reference constructions [33]; no intrusive survey, airtightness test, or thermal-bridge calculation was undertaken. Sixth, ASHP scenarios combine space-heating electrification, separately electrified DHW assumptions, and service-coverage changes; cross-scenario comparison must distinguish demand reduction from coverage change and from carrier substitution. Seventh, PV is assessed with annual yield and a full annual self-consumption assumption [38,39]; hourly coincidence and export are not modelled. Eighth, static annual carbon factors are used [31]; time-varying grid carbon is outside the scope. Ninth, the case is single-site and should be analytically, not statistically, generalised [21]. These limitations do not invalidate the central mechanism, but they constrain the precision of the numerical savings. The strongest next step would be a monitored follow-up study with end-use sub-metering, measured kitchen ventilation rates, archived model files, and post-retrofit M&V.

The seventh limitation warrants a sharper statement. The annual self-consumption assumption may overestimate import reduction, carbon reduction, and economic benefit if midday PV generation exceeds the coincident load and is exported. To first order, the magnitude of the carbon-accounting error equals the exported fraction of PV generation multiplied by the electricity emission factor; the economic error depends on the exported fraction multiplied by the import–export tariff spread. Hourly load data, PV-yield profiles, and export metering would be required to validate this. In this specific case, the overestimate is likely bounded by the small scale of the 11 kWp array relative to annual electricity demand and by the presence of daytime restaurant loads, but the exported fraction is not measured and is not assumed to be zero in the interpretation. The PV result is therefore reported as feasibility-stage annual import-offset potential, not as a metered self-consumption result.

Please refer Table 12 for benchmark value comparison with prior literature.

Table 12. Comparison with benchmark values and prior literature.

Comparator	Value/Evidence	Interpretation
This case baseline	631.1 $kWh/m^2·yr$; 75,020 $kgCO_2e/yr$; RLI 0.57	High but plausible for long-hours restaurant
CIBSE TM46 restaurant typical practice [1]	Approx. 800 $kWh/m^2·yr$	Used as contextual benchmark only
CIBSE TM46 restaurant best practice [1]	Approx. 460 $kWh/m^2·yr$	Optimised package reaches 480 $kWh/m^2·yr$, close to this benchmark
Mudie et al. [5,14]	High catering electricity share in UK kitchens	Supports residual-load thesis
Zhang et al. [15]	Demand-controlled kitchen ventilation savings	Supports next-step process-side interventions

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Table 12. *Cont.*

Comparator	Value/Evidence	Interpretation
Gunasegaran et al. [16]	PV in commercial restaurants offsets a fraction only	Supports the PV roof-area constraint observation
Heo et al. [25]	Bayesian calibration of retrofit models under data sparsity	Frames the appropriate level of confidence under data sparsity
de Wilde [12]; performance-gap literature	Predicted vs. measured energy gap in non-domestic buildings	Reinforces that aggregate utility agreement $\neq$ correct end-use disaggregation

9. Conclusions

This paper presents a whole-building utility-calibrated building-energy case study of a high-process-load UK restaurant. The main conclusions are as follows:

1. The baseline annual demand is 413,895 kWh/yr, equivalent to 631.1 kWh/m^2·yr and 75,020 kgCO$_2$e/yr. The value is plausible against CIBSE TM46 restaurant benchmarks [10], and the baseline Residual-Load Index of 0.57 indicates that process loads already account for over half of total demand.
2. The lowest-net-energy analytical package (envelope insulation, low-emissivity double glazing, LED lighting and controls, ASHP heating-only with separately electrified DHW, and 11 kWp PV) reduces net annual energy to 314,734 kWh/yr (479.9 kWh/m^2·yr) and operational carbon to 56,700 kgCO$_2$e/yr. The retained headline carbon reduction is 24.0% on the source-reporting basis. This is meaningful but not operational net zero, and the heating-only pathway should be interpreted as an analytical lower-energy bound rather than as the recommended final design.
3. The ASHP heating-only variant outperforms the heating-and-cooling variant in both annual energy and carbon terms because the heating-and-cooling case introduces or expands cooling provision in zones not previously cooled; the DHW provision in both variants is modelled as a separately electrified load because air-to-air systems do not provide DHW.
4. The heating-only ASHP pathway gives the lowest annual energy and carbon result only within the modelled boundary, principally because it excludes cooling. It should therefore not be read as a recommended final design without a separate CIBSE TM52 or equivalent summer-comfort and overheating assessment, especially because commercial kitchens have high internal gains and strong ventilation interactions. For this premise, the heating-and-cooling ASHP scenario is the design-relevant pathway, and the heating-only case is reported as an analytical bound rather than a recommendation.
5. Model-derived kitchen and catering gas and kitchen and back-of-house electricity remain 233,920 kWh/yr in absolute terms across the building-focused scenarios. RLI rises from 0.57 in the baseline to 0.74 in the optimised net case. Even under a ±15% process-load allocation screening band, the optimised RLI range is 0.63–0.85, so the post-retrofit balance remains process-load dominated.
6. In this case, and likely in similar high-process-load hospitality premises, building-focused decarbonisation alone cannot reach operational net zero. The residual catering and process loads constitute the principal practical limit on carbon reduction through fabric, HVAC, and on-site PV alone. RLI is proposed as a transferable analytical metric to be reported alongside EUI and operational carbon for food-service buildings.
7. Future work should integrate sub-metered M&V, monthly calibration statistics, kitchen-equipment efficiency strategies, demand-controlled kitchen ventilation, heat recovery, refrigeration and controls optimisation, cooking-fuel switching, PV and load

matching, and demand-response evaluation, and should be tested across multiple food-service typologies to support sub-sector-specific decarbonisation policy.

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Nomenclature

ASHP	Air-source heat pump
BES	Building energy simulation
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of performance (heating)
CV(RMSE)	Coefficient of variation of the root mean square error
DESNZ	Department for Energy Security and Net Zero (UK)
DHW	Domestic hot water
EEM	Energy efficiency measure
EER	Energy efficiency ratio (cooling)
EUI	Energy use intensity (kWh/m^2·yr)
HPWH	Heat-pump water heater
HVAC	Heating, ventilation and air conditioning
IPMVP	International Performance Measurement and Verification Protocol
LPD	Lighting power density (W/m^2)
M&V	Measurement and verification
MUA	Make-up air
NMBE	Normalised mean bias error
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System (EC JRC)
RLI	Residual-Load Index = $E_{process}/E_{total}$
SCOP	Seasonal coefficient of performance
SME	Small and medium-sized enterprise
TM46/TM52/TM54	CIBSE Technical Memoranda 46/52/54
WWR	Window-to-wall ratio

Appendix A. Carbon-Factor and Boundary Statement

Annual operational carbon is computed using static UK DESNZ 2025 GHG Conversion Factors [31]: 0.177 $kgCO_2e/kWh$ for grid electricity and 0.183 $kgCO_2e/kWh$ for natural gas. Factors are applied consistently to baseline and scenario energy values to enable like-for-like comparison. Time-varying grid carbon and projected grid decarbonisation are outside the scope of this paper. Embodied carbon, refrigerant leakage from heat-pump scenarios, construction-stage emissions, and exported PV electricity are also outside the operational boundary used here. The scope is delivered-energy operational carbon on a location-based annual basis.

Table A1. Carbon-accounting boundary and factor assumptions.

Item	Treatment in This Study	Source/Justification
Electricity factor	0.177 $kgCO_2e/kWh$	DESNZ 2025 [29]
Gas factor	0.183 $kgCO_2e/kWh$	DESNZ 2025 [29]
Calculation basis	Location-based annual operational carbon	Operational scope
Source-reporting carbon basis	Retained for scenario comparison	Avoids round-trip rounding error
Time-varying factors	Not modelled	Out of scope
PV treatment	Grid-import offset; not demand reduction	This study/[37,38]
Embodied carbon	Excluded	Boundary decision
Refrigerant leakage	Excluded	Boundary decision
Exported electricity	Not separately modelled	Limitation
Future grid factors	Not modelled (static factors held constant)	Limitation

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