

Article

Evaluating Envelope, Heating System and Thermal-Mass Retrofits for Indoor Air Temperature Control and Energy Saving in a UK Residential Building

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Abstract

Residential buildings are central to decarbonisation because existing dwellings combine long service lives, high heating demand and heterogeneous constraints for retrofitting. This study investigates some retrofit strategies for a terraced house in Oxford, UK, to achieve the winter indoor air temperature set-point while reducing energy use, costs and CO₂ emissions. A calibrated dynamic simulation model was developed from on-site inspections, monitored temperatures, occupant schedules and energy-bill data. The analysis compares baseline configuration with scenarios including radiator power upgrading, envelope insulation, increased internal thermal mass and replacement of the condensing boiler with a high-temperature ground-source heat pump (GSHP). The results show that radiator upgrading enables the most critical rooms to reach the 20 °C set-point, while envelope insulation reduces heating energy and costs. Increased thermal mass improves night-time temperature stability, although its effect on annual energy demand is limited. The GSHP provides the largest primary energy reduction, lowering operational primary energy by 66.3% compared to the reference case and by 70.4% when combined with envelope and thermal-mass measures. Operational CO₂ emissions are reduced by 35.0–84.3%. The study highlights the need to evaluate the capacity of heat emitters, building envelope performance, thermal inertia and heat generator efficiency within a dynamic framework.

Keywords: energy retrofit; building; indoor temperature; thermal insulation; heating system; thermal mass

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1. Introduction

Buildings account for a substantial share of final energy consumption and energy-related greenhouse gas emissions, with several end uses contributing to their overall energy balance [1]. Therefore, the decarbonisation of the residential building stock depends strongly on the retrofit of existing dwellings, which offer major opportunities for reducing energy use and emissions [2], especially because the low replacement rate of the building stock makes renovation essential for future performance improvements [3]. Research on building retrofit has consequently focused on the selection of measures according to building-specific constraints and objectives [2,4], including passive design, envelope improvement, regulatory compliance and techno-economic assessment [3,5]. Envelope-ori-

ented case studies show that wall, roof and fabric interventions can reduce annual energy demand [6], while simulation analyses indicate that savings also depend on construction period, heating source [7], climate, baseline building type and retrofit package [8]. At the same time, retrofit strategies should not be evaluated only in terms of energy savings, because the optimization of building operation must also preserve thermal comfort and indoor environmental quality [9,10]. Within this framework, the UK residential stock represents a relevant context in which policy targets, retrofit barriers, comfort requirements and building-specific performance constraints intersect.

1.1. Residential Building Retrofit in the UK Decarbonisation Context

In the UK, residential building stock plays a key role in the achievement of national decarbonisation objectives. The Future Homes Standard [11] aims to reduce the energy and carbon intensity of new dwellings by improving building thermal performance, heating and domestic hot water systems, although its direct regulatory scope is mainly oriented towards new homes rather than the existing stock. For existing buildings, retrofit-oriented policy instruments such as the Green Deal and the Energy Company Obligation [12] were introduced to support energy-efficiency improvements and reduce household energy use, with repayment mechanisms linked to the expected savings on energy bills. However, UK retrofit decisions are strongly affected by uncertainty in costs, predicted savings, occupant response and financial risk [13]. Some studies emphasized that low-carbon dwellings require innovative models of finance and service provision, because technical potential alone is insufficient to overcome household-level barriers [14]. Similarly, Dowson et al. identified technical, economic and policy barriers to deep reductions in energy use and CO₂ emissions in the UK housing stock [15]. Recent guidance and studies on traditional, historic and heritage buildings in the UK further highlighted that retrofit decisions must balance energy-efficiency improvements with building-specific constraints, conservation requirements, moisture risk, occupant needs and practical feasibility [16,17]. Studies on the supply chain also showed that the spread of energy retrofit interventions depends on the evolution of services, policy demand and market organization [18], while ex post evaluations indicated that the achieved savings can differ from the expected values due to rebound effects, family practices and modelling assumptions [19,20].

Furthermore, building energy performance depends on the interaction between technical systems, envelope characteristics, occupant operation and climatic boundary conditions. Climatic conditions have a direct impact on energy needs because outdoor temperature, solar gains, wind exposure and seasonal variability affect both heating demand and the ability of passive or active retrofit measures to maintain indoor thermal comfort [21]. In the UK regulatory context, government acts define requirements for the conservation of fuel and energy and provide reference for limiting heat losses through the building envelope [22]. But thermal comfort requirements must also be considered when evaluating retrofit performance, because energy reductions are only meaningful if acceptable indoor environmental conditions are maintained [23]. Therefore, retrofit design should not be limited to reducing annual energy consumption, but should also assess whether the building can achieve and maintain target indoor temperatures under dynamic operating schedules.

1.2. Energy Assessment of Retrofit Strategies Regarding Building Envelope, Heat Pumps, and Thermal Mass

Considering the dynamic energy behaviours of buildings, retrofit evaluation cannot be limited to steady-state heat-loss calculations. Dynamic energy simulation is required when the objective is to represent thermal transients, heat storage in the building fabric, intermittent heating schedules and plant operation. Dynamic building energy simulation

is widely used to evaluate interactions between building fabric, HVAC (Heating, Ventilation and Air Conditioning) systems, controls and operating schedules [24,25]. The need to represent the transient operation of heating systems is also supported by recent research on heat pump modelling. For example, Yousaf et al. [26] developed a reduced-order transient model for air-source heat pumps, showing that start-up, cycling operation and part-load behaviour can influence heating capacity and compressor power. Although the present study uses a whole-building dynamic simulation approach rather than a reduced-order heat pump model, this recent contribution reinforces the importance of considering the system's temporal behaviour when evaluating heat pump-based retrofits.

However, the performance gap between predicted and measured building energy use remains a key issue, especially when design assumptions differ from actual operation [27]. Heating schedules and control practices are important sources of uncertainty in energy modelling of residential buildings, as shown by survey evidence on UK homes [28]. Accordingly, schedules, set-points, internal gains, plant assumptions and calibration indicators should be considered when dynamic simulation is used to compare retrofit scenarios [29,30]. Calibration is, therefore, particularly important when building energy models are used to support retrofit analysis for existing buildings [31]. Reviews of calibration methods showed that measured data, uncertainty treatment and model-adjustment procedures strongly influence the credibility of simulation results [29,32]. Intercomparison studies also showed that different monitoring datasets, modelling choices and calibration procedures can lead to different calibrated models [30]. Therefore, monitoring data should be carefully chosen, and simulation outputs should be interpreted as comparative scenario indicators rather than as fully predictive annual estimates, when calibration is limited [29].

Among the several relevant energy aspects concerning the building, the envelope remains one of the most widely investigated retrofit domains. Dynamic simulation studies have shown that envelope interventions can improve the energy performance of existing buildings [33], while optimized insulation analyses demonstrated the importance of climate-specific envelope design [34]. Studies on retrofit of residential buildings also confirmed that envelope performance and economic outcomes depend on the selected regulatory, climatic and construction context [35]. Nevertheless, envelope measures should not be assessed in isolation. Indeed, the marginal energy benefit of additional insulation decreases when the envelope already has moderate thermal performance or when the heating system is highly efficient [7]. Moreover, construction solutions influence thermal comfort as well as energy use [36], and retrofit packages need to be assessed together with heating technologies and control strategies [37,38]. This point is particularly important for existing residential buildings with intermittent heating schedules [28], where the envelope insulation may reduce the seasonal heating demand [7], but may not by itself ensure a rapid return to the indoor set-point temperature after night-time setback if the heating system is not properly designed.

Heating-system electrification is another key retrofit pathway. Heat pumps are frequently presented as low-carbon heating technologies for dwellings [39], and their interaction with electricity networks has been widely discussed in relation to smart-grid operation and demand-side flexibility [40]. Field-study reviews showed that heat pump performance is affected by system management, defrosting operation and real operating conditions [39]. Recent studies further confirmed the importance of evaluating heat pump retrofits under real operating and building-specific conditions. Rosenow et al. [41] analyzed UK heat pump monitoring data and showed that real seasonal performance is strongly affected by flow, temperature, weather compensation settings, cycling and commissioning quality. Pochampalli et al. [42] showed, for a pre-1930s UK mid-terrace house, that low-carbon heating systems should be assessed together with fabric retrofit measures

because envelope performance affects heating demand, carbon reduction and running costs.

Retrofit simulation and monitoring studies further show that heat pump performance must be assessed in relation to the whole building and heating system, rather than to the generator alone [43]. This is particularly important in existing dwellings, where the heating distribution system may not have been designed for low-temperature operation [43]. In such cases, acceptable performance may require reducing building heat loss, adapting heat emitters or operating the heat pump at higher supply temperature; these choices affect the overall retrofit performance and should therefore be analyzed at building-system level [43,44].

A further issue concerns the role of thermal mass. Thermal inertia can time-shift and dampen indoor temperature fluctuations, but its effect on annual heating and cooling energy is not universal and depends on climate, building use and operation [45]. Reilly and Kinnane showed that the interaction between intermittent occupancy and thermal mass can significantly affect energy use [46]. In intermittently heated buildings, additional internal mass may store heat during occupied periods and release it during heating-off periods, thereby reducing the rate of night-time temperature decay [46]. However, the position and exposure of the mass are important: if insulation layers reduce the effective coupling between room air and the massive element, the contribution of thermal mass to indoor temperature stability may be reduced or modified [47]. Building thermal capacity has also been considered as a source of demand-side flexibility, especially when heating demand can be shifted over time [48,49]. Therefore, thermal mass should not be treated automatically as an energy-saving measure; it should be evaluated as a transient parameter of thermal comfort and flexibility whose effect depends on operation and control.

1.3. Aim, Research Gap and Contributions

Against this background, the present study investigates the thermal and energy performance of an existing terraced dwelling located in Oxford, UK. Oxford is located in a temperate UK climate, where winter heating remains a major residential energy need, while building-stock decarbonisation policies reinforce the relevance of retrofit strategies able to combine indoor comfort with reduced energy use and emissions [11,22]. The dwelling is analyzed using a calibrated dynamic simulation model developed from on-site inspections, measured indoor air temperature profiles, occupant schedules and energy-bill data. The study evaluates retrofit scenarios involving radiator power upgrading, building envelope thermal insulation, the combination of heat-emitter and envelope measures, modification of internal thermal mass, and replacement of the existing condensing boiler with a high-temperature ground-source heat pump. The analysis considers both the achievement of the winter indoor air temperature set-point and the reduction in final energy use, primary energy demand, operating cost and carbon emissions.

The scientific gap addressed is the limited integration, within a single calibrated residential case study, of four aspects that are often treated separately in the retrofit literature: heat-emitter capacity adequacy, envelope heat-loss reduction, internal thermal-mass modification and replacement of the boiler with a heat pump. Previous studies have extensively examined envelope retrofit strategies [7], heat pump-based heating system replacement [43,44], and the effect of thermal mass on building energy behaviour [45,46]. However, few studies explicitly distinguish between measures that restore thermal comfort by increasing heat-emission capacity and measures that directly reduce heating energy demand or carbon emissions. This distinction is particularly relevant under intermittent heating operation, where a building may show reduced seasonal heat losses but still fail to recover the indoor set-point rapidly if the heat emitters are undersized. The present

study therefore examines how these measures interact in terms of indoor temperature control and energy performance.

The main contributions of the paper are as follows.

- This study develops and applies a calibrated dynamic simulation model of an existing UK residential building, using monitored indoor air temperatures and energy-bill data to support the baseline energy model.
- It compares radiator power upgrading as a comfort upgrade intervention to building envelope and heat pump measures that may also improve energy efficiency and reduce carbon emissions.
- It evaluates whether envelope thermal insulation alone is sufficient to restore the winter indoor set-point in the most critical rooms, or whether heat-emitter capacity remains a limiting factor.
- It analyses the effect of increasing internal thermal mass on night-time temperature decay and daytime temperature stability.
- It compares boiler-based and heat pump-based retrofit solutions using final energy, primary energy, carbon emissions and operating cost as separate indicators.
- It provides a case study contribution to residential retrofit design in UK temperate climates, showing the need to evaluate heat demand, heat-emission capacity, building thermal inertia and heat generator efficiency within the same dynamic framework.

2. Methodology, Case Study, Calibration of the Model and Proposed Retrofit Solutions

2.1. Methodology, Case Study and Calibration of the Model

The dynamic energy simulation of the building, performed with the DesignBuilder software v. 2025.1 [50], exploits the dynamic calculation method, which allows simulations of the building's behaviour to be carried out on an hourly or sub-hourly basis, also considering the accumulation and release of thermal energy by the structure. This requires a certain specificity of the data to be provided as input for the calculation; in particular, it is necessary to enter climatic data on an hourly basis, as well as precise information on the building envelope components, on the characteristics of the heating system and on the hourly profiles of occupancy and uses. Prior to the simulation analysis, on-site inspections were carried out to assess the characteristics of the building envelope and heating system, collect information on operating schedules, and gather data from energy bills. These data were used to develop and calibrate a reliable baseline energy model of the existing building.

The data-collection phase consisted of two on-site inspections. During the inspections, the building geometry, envelope stratigraphy, radiator locations and nominal heating powers, boiler characteristics, thermostat settings and heating schedules were recorded. Indoor air temperature monitoring was available for the kitchen and sitting room on 12 December 2022. Energy-bill information was available for the period from 3 January to 7 February 2023 and was used as an additional check of the gas and electric energy consumption obtained by simulation. The duration of the monitoring and billing data are limited. Therefore, the model should be interpreted as a measurement-informed baseline model calibrated on limited short-term monitoring and a single winter billing period.

Figure 1 summarizes the workflow adopted for the dynamic assessment of the retrofit scenarios. The process starts with the collection of input data from on-site inspections, building geometry, envelope characteristics, heating system information, occupant schedules, energy bills, indoor air temperature monitoring and local weather data. These inputs are used to develop the baseline dynamic simulation model of the existing dwelling,

which is then calibrated by comparing simulated and measured indoor temperatures and energy consumption. After calibration, the retrofit scenarios (described in more detail in Section 2.2) are defined, including radiator power upgrading, building envelope thermal insulation, combined envelope and heating system improvements, increased internal thermal mass and replacement of the existing boiler with a high-temperature ground-source heat pump (GSHP). Each scenario is simulated under consistent boundary conditions, and the results are assessed in terms of indoor temperature achievement, final energy use, primary energy demand, CO₂ emissions and operating costs. Finally, the scenarios are compared with the baseline and with the comfort-normalized reference case (i.e., scenario S1 including only radiator power upgrading) to identify the main trade-offs between comfort recovery, energy reduction, emission reduction and cost implications.

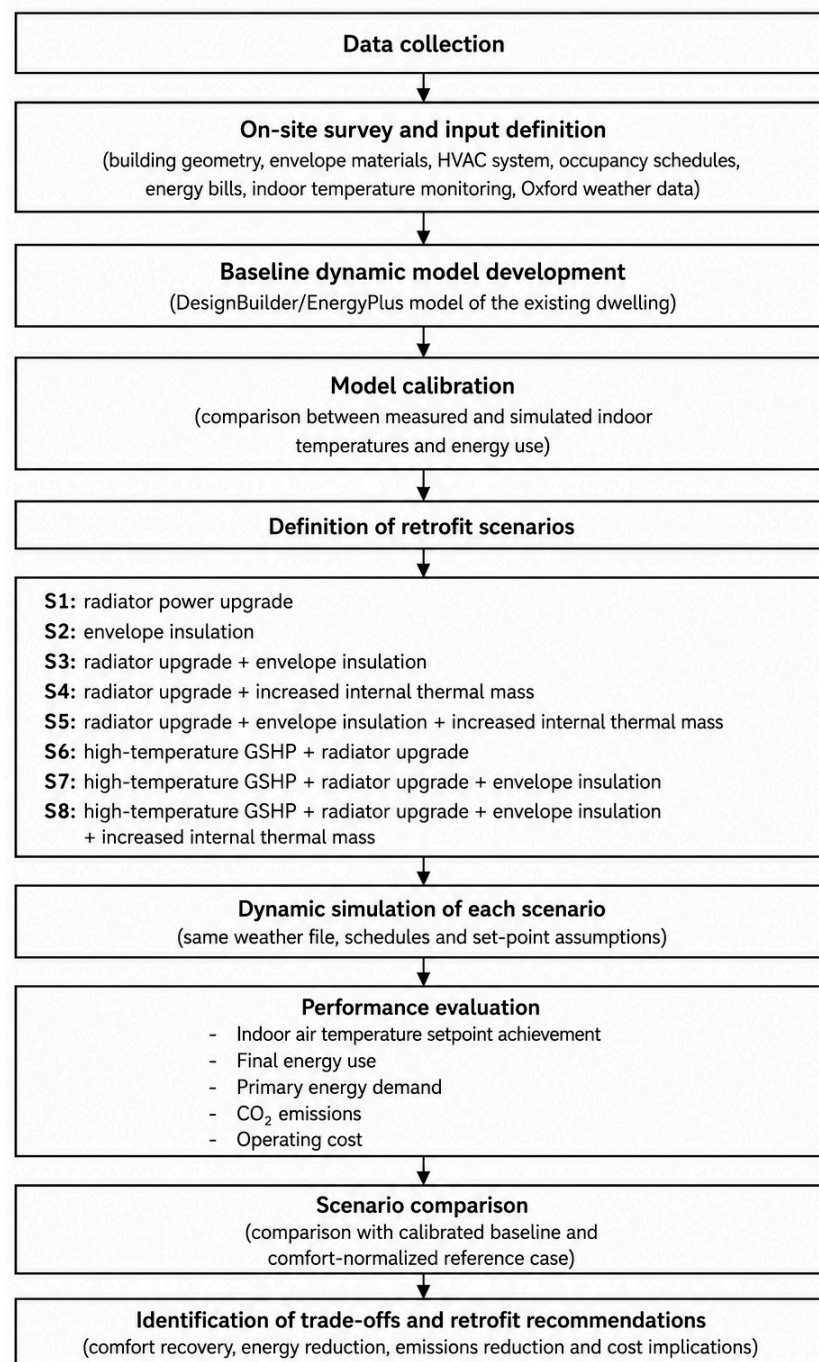


Figure 1. Workflow adopted for the assessment of the retrofit scenarios for the Oxford residential case study.

The simulation analysis for the building energy retrofit was then structured into the following main steps: comparison of the first three improvement hypotheses (scenarios S1, S2 and S3), implementation of massive envelope elements (scenarios S4 and S5), subsequent replacement of the heat generator (scenarios S6, S7 and S8), and final analysis and comparison in terms of primary energy consumption and carbon emissions.

The case study refers to a real terraced house located in Oxford (England), a city belonging to ASHRAE climate zone 4A [51] with a winter design external temperature of -3.5°C . Built around the beginning of the eighties, the building has an almost rectangular shape with a large garden in the rear area and a double-pitched roof of different inclinations, typical of English terraced dwellings (Figure 2).

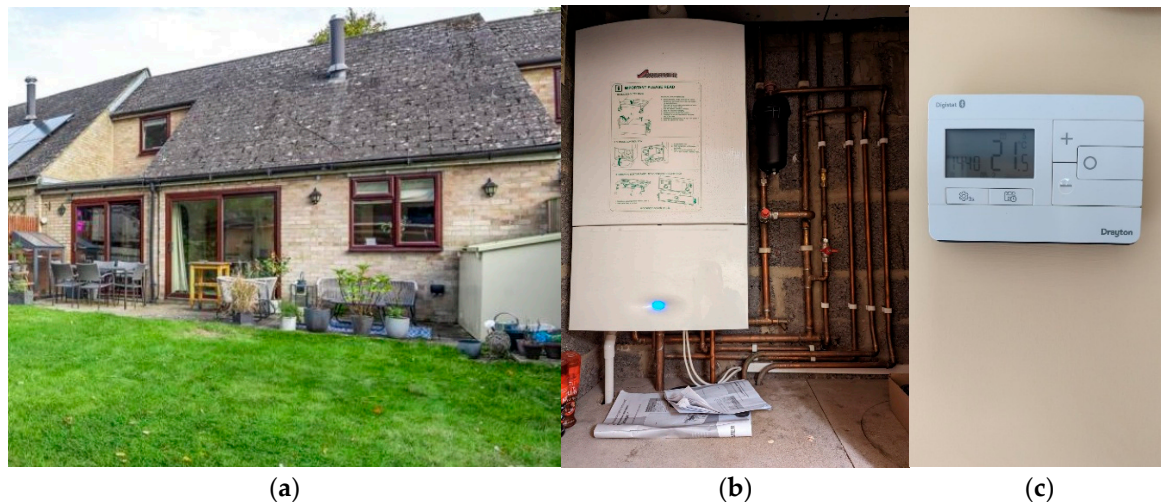


Figure 2. Existing case study building located in Oxford, UK (a) external view; (b) boiler; (c) indoor thermostat.

The building is spread over two floors: the ground floor, which includes the kitchen, sitting room, one bedroom, veranda, bathroom and stair septum, and has an area of about 60 m^2 with a heated usable area of 46 m^2 and a heated usable volume of 108 m^3 ; and the first floor, where there is a sleeping area with three bedrooms, a bathroom and a closet. This part of the house has an area of 39 m^2 with a heated usable area of 34 m^2 and a heated usable volume of 79 m^3 . The total heated usable area and volume are, respectively, 80 m^2 and 187 m^3 (Figure 3).

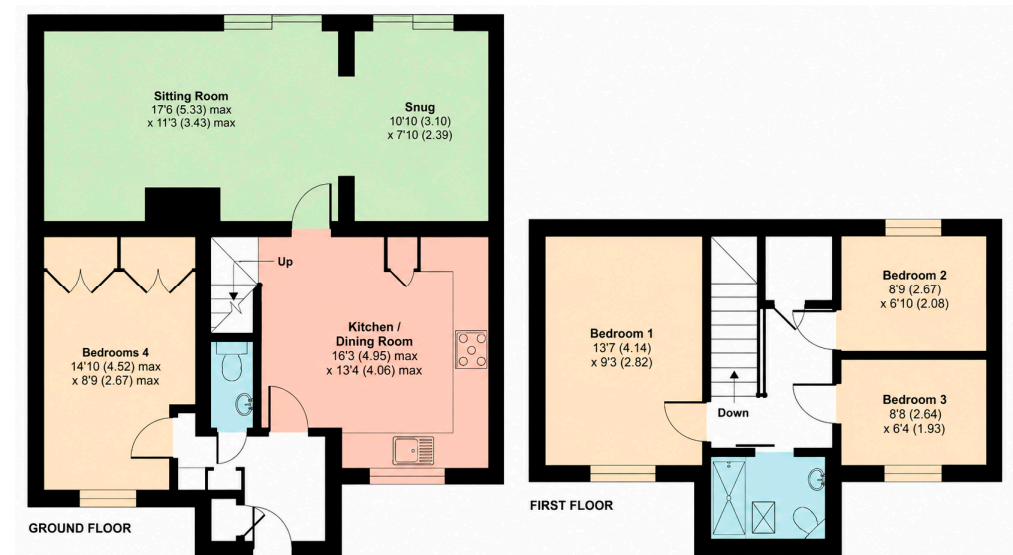


Figure 3. Ground and first floor plans of the examined building.

The heating system consists of a wall-mounted condensing boiler located in a room adjacent to the entrance area, with a thermal power of 30 kW and 92% as nominal efficiency, connected to aluminum radiators. These radiators are positioned as follows: three on the ground floor (Figure 4a), in the kitchen, sitting room and bedroom, with a total installed heating power of 3.4 kW, and four in the sleeping area (Figure 4b), i.e., in the three bedrooms and bathroom, with a total installed heating power of 4.1 kW. Their main characteristics are shown in Table 1.

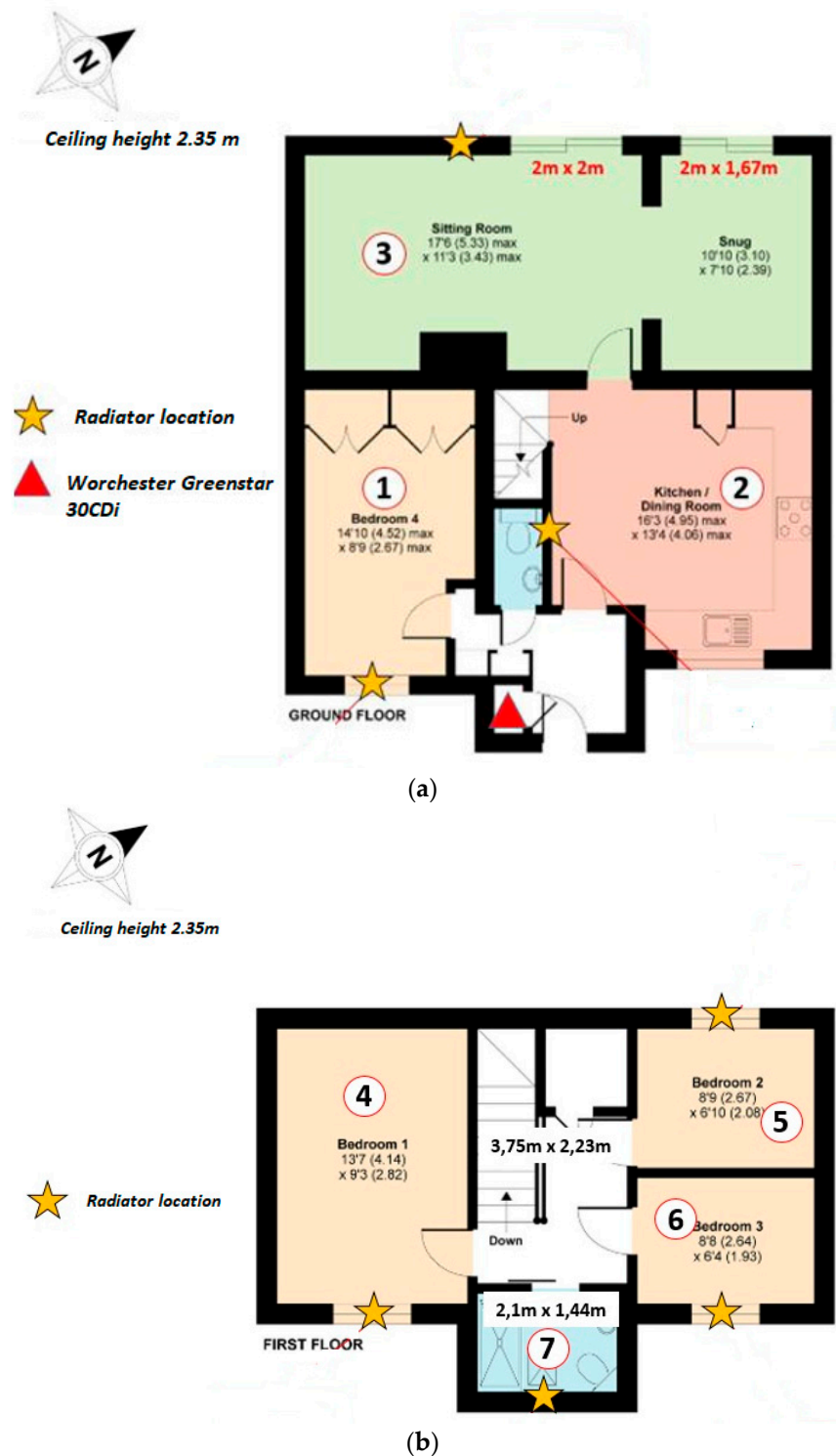


Figure 4. Location of the radiators on the ground floor (a) and on the first floor (b).

Table 1. Main characteristics of the radiators installed in the house.

Floor	Location	Size	Heating Power
Ground floor	Sitting Room	1600 mm × 420 × 47 mm—1 rank	0.974 kW
	Kitchen/Dining room	635 mm × 826 × 56 mm—1 rank	0.926 kW
	Bedroom 4	600 mm × 800 × 72.5 mm—1 rank	1.508 kW
First floor	Bedroom 1	635 mm × 826 × 78 mm—2 ranks	1.447 kW
	Bedroom 2	635 mm × 590 × 78 mm—2 ranks	1.034 kW
	Bedroom 3	635 mm × 590 × 78 mm—2 ranks	1.034 kW
	Bathroom	1200 mm × 400 mm × 30 mm	0.558 kW

Based on air temperature measurements obtained using indoor and outdoor sensors, the temperature profiles were recorded. Table 2 shows the hourly values of the indoor air temperature logged on 12 December 2022 in the kitchen and sitting room. The kitchen is the room in which there is the most dissatisfaction in terms of maintenance of the indoor air temperature set-point (20 °C). It should also be noted that in both the rooms, the system needs a considerable number of operation hours before the room winter setpoint air temperature of 20 °C (minimum thermal comfort temperature in winter) is reached or approached.

Table 2. Hourly values of the internal air temperature recorded on 12 December 2022 in the kitchen and sitting room.

Time (Hours)	T _{KITCHEN} (°C)	T _{SITTING ROOM} (°C)
7:30	16.3	-
9	17.7	17.2
10	18.5	18
11	18.9	18.9
12	19.3	19.3
13	19.7	19.6
14	19.7	19.6
15	19.5	19.4
16	19.1	19.1
17	19.6	19.3
18	20	19.4
23:30	20	19.4

Figure 5 shows a typical monthly winter energy bill for the examined building, which is considerably expensive due to the high energy consumption of natural gas compared to standard monthly energy consumption (an average monthly cost of gas of 75.08 £, equal to about 86 €; and a monthly electric energy cost of 77.6 £, equal to about 89 €) [52].

Statement period 03 Jan 23 · 07 Feb 23		
	Gas statement	
Your total new gas charges	£205.91	kWh 1881.885
	Electricity statement	
Your total new electricity charges	£65.63	kWh 150.000

Figure 5. Representative winter monthly energy consumption and costs (kWh and GBP) for the examined building.

Based on this information, it was possible to calibrate the energy model of the building using the software DesignBuilder [50]. Subsequently, through detailed modelling, the existing heating system was defined, specifying the characteristics of the boiler and the individual radiators and setting the flow temperatures in the general sheet. Furthermore, based on the actual occupants' uses, an operating profile for heating was set from October to April and, in terms of time, the same as those used by the users (from 7:00 to 23:30).

To evaluate the agreement between measured and simulated data, the baseline model outputs were compared with monitored indoor air temperature in the kitchen on 12 December 2022 and with gas and electric energy consumption from the available winter bill period. The calibration check reports absolute errors in °C and standard error metrics, including mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), normalized mean bias error (NMBE) and coefficient of variation in the root mean square error (CV(RMSE)). The following expressions were used:

$$MBE = \frac{1}{n} \sum_{i=1}^n (T_{sim,i} - T_{meas,i})$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |T_{sim,i} - T_{meas,i}|$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (T_{sim,i} - T_{meas,i})^2}$$

$$NMBE = 100 \cdot \frac{MBE}{\bar{T}_{meas}}$$

$$CV(RMSE) = 100 \cdot \frac{RMSE}{\bar{T}_{meas}}$$

where $T_{sim,i}$ and $T_{meas,i}$ are the simulated and measured indoor air temperatures at time step i , respectively; n is the number of compared time steps; and $\bar{T}_{meas}$ is the mean measured indoor air temperature. The same logic was used for the energy-bill comparison, although the availability of a single billing period prevents a full monthly calibration according to ASHRAE Guideline 14 [53].

Therefore, the calibration with reference to the internal temperature (Table 3 and Figure 6) and energy consumption (Figure 7) should be considered a short-term validation check of the baseline model rather than a complete seasonal calibration.

Table 3. Detected and simulated indoor air temperatures on December 12, 2022, in the kitchen.

Time	Kitchen T Detected	Kitchen T Simulated	Deviation	Error	Absolute Error
Hour	°C	°C	%	°C	°C
07:30	16.3	16.2	−1%	−0.10	0.10
9	17.7	17.3	−2%	−0.40	0.40
10	18.5	18.5	0%	0.00	0.00
11	18.9	18.8	−1%	−0.10	0.10
12	19.3	19.1	−1%	−0.20	0.20
13	19.7	19.8	1%	0.10	0.10
14	19.7	19.85	1%	0.15	0.15
15	19.5	19.9	2%	0.40	0.40
16	19.1	19.3	1%	0.20	0.20
17	19.6	19.9	2%	0.30	0.30

18	20	20	0%	0.00	0.00
23:30	20	19.8	−1%	−0.20	0.20

The resulting short-term temperature validation metrics are as follows: MBE = 0.013 °C, MAE = 0.179 °C, RMSE = 0.220 °C, NMBE = 0.066%, CVRMSE = 1.16%, and maximum absolute error = 0.4 °C. These values indicate a good agreement for the monitored day.

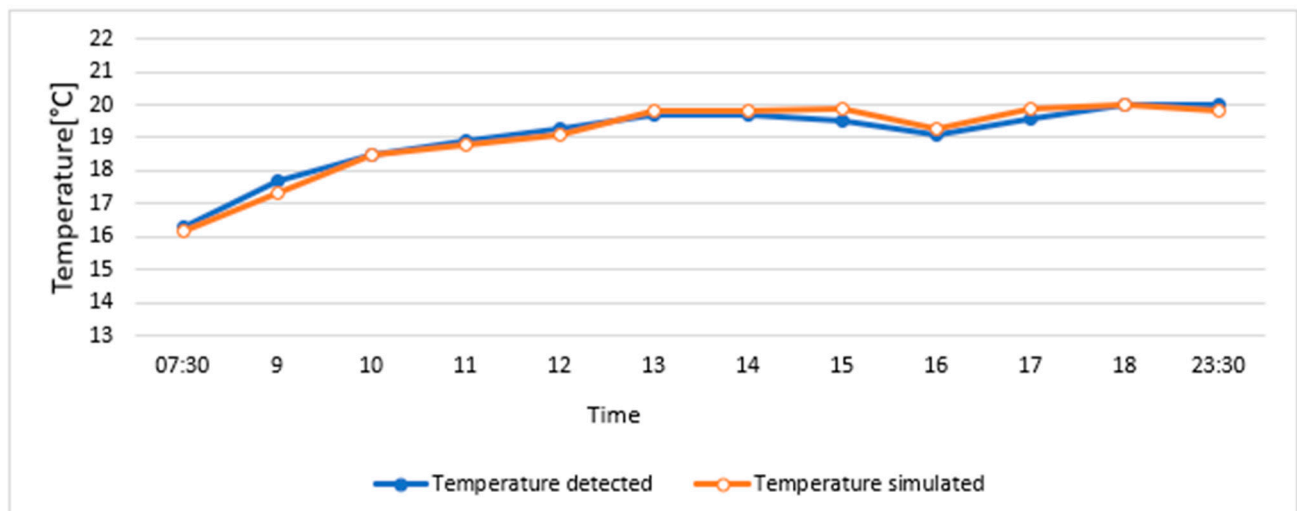


Figure 6. Comparison between detected and simulated indoor air temperatures on 12 December 2022, in the kitchen.

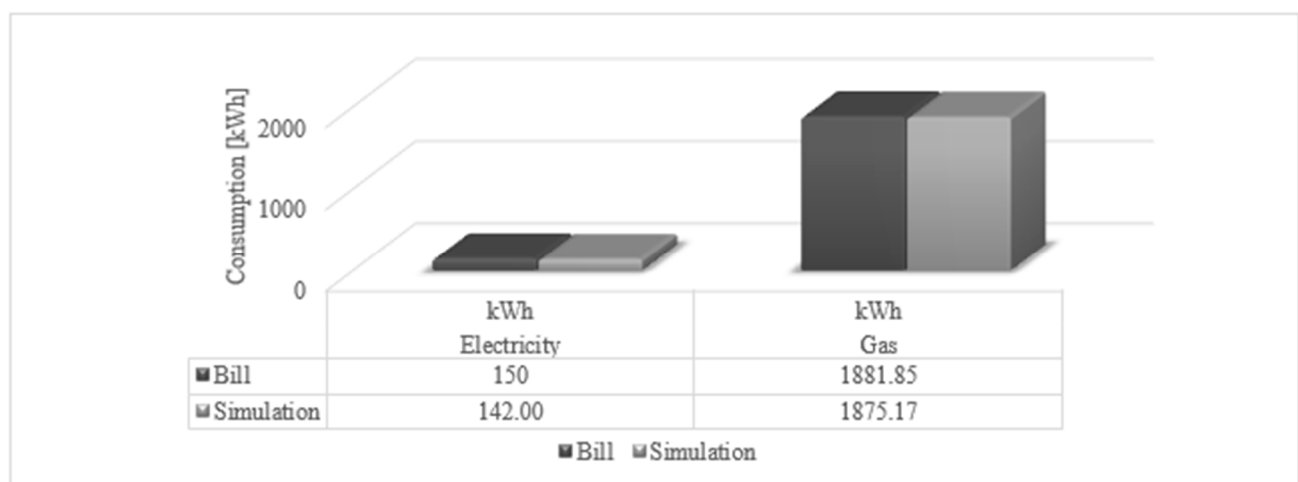


Figure 7. Comparison between real and simulated data on energy consumption for the period from 3 January to 7 February 2023.

For the available billing period from 3 January to 7 February 2023, the measured electric energy consumption was 150 kWh, while the simulated value was 142.0 kWh, corresponding to a deviation of −5.33%. The measured gas consumption was 1881.85 kWh, while the simulated value was 1875.17 kWh, corresponding to a deviation of −0.35%. Considering gas and electricity together, the total deviation was −0.72%. Since only one billing interval was available, these values were used as a supporting consistency check rather than as a full monthly or seasonal calibration dataset.

The energy consumption relating to the entire heating season (1 October–30 April) is reported in Figure 8.

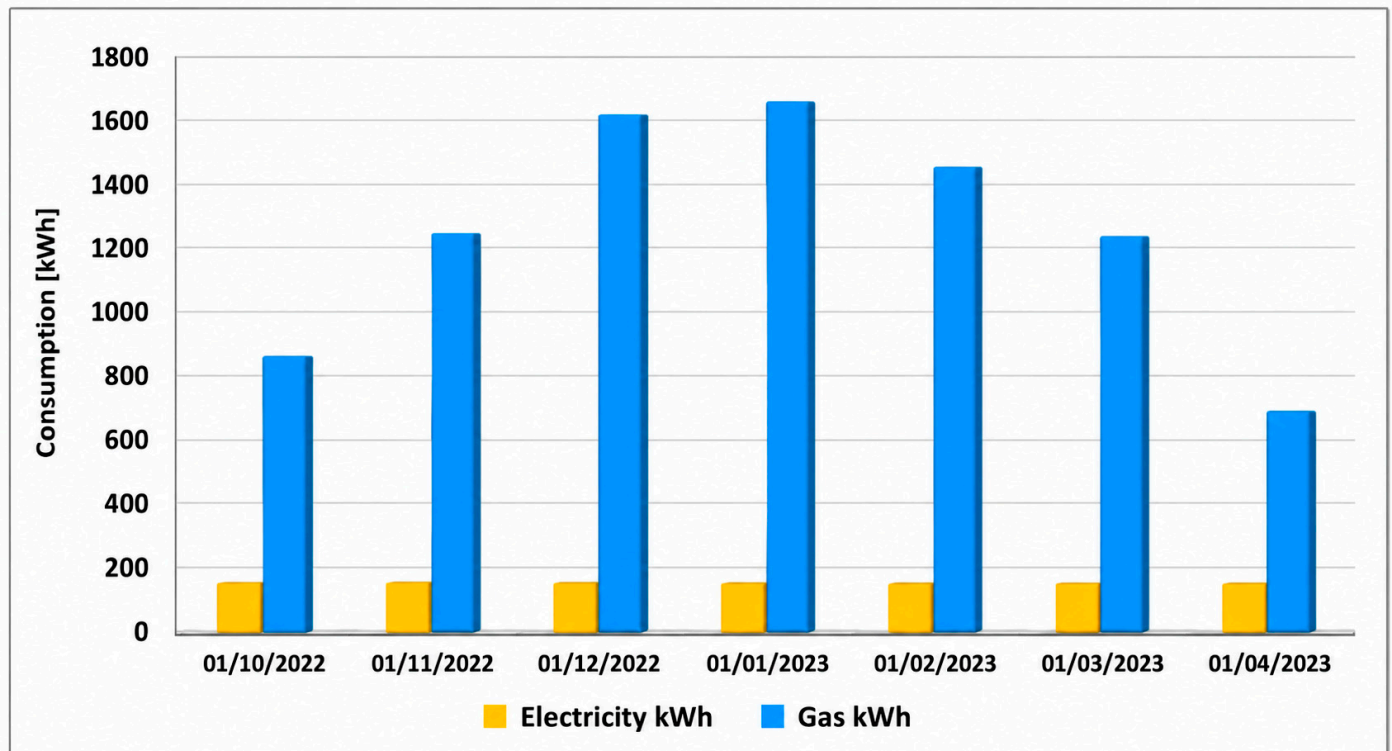


Figure 8. Energy consumption calculated for the heating season of the examined terraced house (from 1 October to 30 April).

The main comfort-related target used in this study is the achievement of a 20 °C winter indoor air-temperature set-point in the occupied rooms. This value was selected because it corresponded to the occupants' thermostat setting and was used as a practical target for evaluating whether the existing heating system could restore acceptable indoor thermal conditions during the occupied heating period. The focus on air-temperature set-point achievement is consistent with the objective of the paper, which is not to perform a full indoor environmental quality assessment, but to test whether the building and heating system can reach the intended winter indoor air temperature under intermittent heating.

Also two additional temperature-based comfort indicators have been analyzed for the critical room: the number of monitored or simulated time steps in which the indoor air temperature was below 20 °C, and the cumulative temperature deficit below the set-point, calculated as:

$$D_T = \sum_{i=1}^n \max(0, 20 - T_{\text{air},i})$$

where D_T is the cumulative temperature deficit (K·h), $T_{\text{air},i}$ is the indoor air temperature at time step i , and n is the number of monitored or simulated time steps.

These indicators quantify both the frequency and magnitude of set-point non-attainment.

The present study focuses on indoor air-temperature set-point attainment because the main observed problem in the dwelling was the inability of the heating system to reach the occupants' winter indoor air temperature set-point. Full PMV/PPD assessment was not included because measured mean radiant temperature and air velocity were not available for the monitoring period.

The operational CO₂ emissions and primary energy values were calculated by applying fuel-specific conversion factors to the simulated gas and electric energy consumption.

Table 4 reports the factors used in the analysis. The energy tariffs were derived from the occupants' bills and were used only for operating-cost calculations. Investment cost, replacement cost, maintenance cost and residual value were not included; therefore, the economic results should be interpreted as operating-cost comparisons rather than as a full techno-economic feasibility assessment.

Table 4. Conversion factors and tariffs used for operating cost, primary energy and CO₂-emission calculations.

Parameter	Natural Gas	Electric Energy	Source
Operating tariff (£/kWh)	0.099	0.326	Occupants' bill
Standing/fixed charge	£19.60 per billing period	£16.73 per billing period	Occupants' bill
CO ₂ emission factor (kg _{CO₂-eq} /kWh)	0.210	0.136	SAP 10.2 [54]
Primary energy factor (kWh _{primary} /kWh _{final})	1.130	1.501	SAP 10.2 [54]

The operating tariffs were derived from the occupants' bill. The fixed charges were obtained as the difference between the total bill amount and the variable energy charge calculated from the reported consumption and unit tariff. Therefore, the economic results should be interpreted as operating-cost comparisons, while the environmental results refer to operational CO₂ emissions only. The CO₂ emission factors and primary-energy factors were taken from Table 12 of SAP 10.2, using the values for mains gas and standard-tariff electricity [54].

2.2. Proposed Retrofit Solutions

The study focuses on achieving the target indoor air temperatures while reducing heating-related energy consumption, operating costs and CO₂ emissions. To this end, a set of retrofit scenarios was defined to progressively assess the effects of heat-emission capacity, envelope insulation, internal thermal mass and heat generator replacement. In addition to the existing baseline configuration, the following retrofit scenarios were considered:

- S1: upgrading of the heat-emission system through an increase in radiator nominal power.
- S2: reducing the thermal transmittance of the building opaque envelope components.
- S3: combined upgrade of the radiator nominal power and building envelope thermal insulation.
- S4: increase in internal thermal mass, including the modification of internal partitions and the intermediate floor, combined with the upgraded radiator configuration.
- S5: combined envelope insulation and increased internal thermal mass, including the modified internal partitions and intermediate floor, combined with the upgraded radiator configuration.
- S6: replacement of the existing condensing boiler with a high-temperature ground-source heat pump (GSHP), with maximum supply temperature of 80 °C, combined with upgraded radiators.
- S7: high-temperature GSHP combined with upgraded radiators and improved building envelope insulation.
- S8: high-temperature GSHP combined with upgraded radiators, improved building envelope insulation and increased internal thermal mass.

As reported in Table 5, a scenario matrix is used to clarify the configuration of each case in terms of heat generator, radiator configuration, envelope performance and internal thermal mass. The existing baseline, denoted as B0, represents the current configuration of the dwelling, including the existing boiler, radiators, envelope and internal thermal

mass. Since the monitored data showed that the kitchen and sitting room had difficulty reaching the winter indoor air temperature set-point, the radiator-upgrade scenario S1 was defined as a comfort-normalized reference case rather than as a direct energy-saving intervention. Consequently, B0 is used as the reference condition to evaluate the improvement in indoor air temperature set-point achievement, while S1 is used as the reference condition for comparing energy consumption, primary energy demand, CO₂ emissions and operating costs under comparable comfort conditions.

Table 5. Scenario matrix adopted for the retrofit analysis.

Code	Description	Heat Generator	Radiators	Building Envelope	Thermal Mass
B0	Existing baseline	Existing Boiler	Existing	Existing	Existing
S1	Radiator upgrade	Existing Boiler	Upgraded	Existing	Existing
S2	Envelope upgrade	Existing Boiler	Existing	Improved	Existing
S3	Radiator upgrade + envelope upgrade	Existing Boiler	Upgraded	Improved	Existing
S4	Radiator upgrade + increased thermal mass	Existing Boiler	Upgraded	Existing	Increased
S5	Radiator upgrade + envelope upgrade + increased thermal mass	Existing Boiler	Upgraded	Improved	Increased
S6	GSHP + radiator upgrade	GSHP	Upgraded	Existing	Existing
S7	GSHP + radiator upgrade + envelope upgrade	GSHP	Upgraded	Improved	Existing
S8	GSHP + radiator upgrade + envelope upgrade + increased thermal mass	GSHP	Upgraded	Improved	Increased

As mentioned, the first scenario (S1) aims only to improve the existing heating system, considering that it takes about six hours to reach full capacity, causing thermal discomfort for users. As a solution, the replacement of the existing radiators with new ones with higher thermal power (or, almost equivalently, the enhancement of the existing radiators with the addition of new elements) was envisaged to reduce the latency time of the system to about an hour.

The winter design thermal load of each room, calculated by DesignBuilder ($Q_{h,simulation}$), was compared with the installed radiator thermal power to evaluate the adequacy of existing heating terminals in meeting the required thermal demand.

$$\dot{Q}_h = \dot{Q}_{h,simulation} + \Phi_{RH,i}$$

where

- $\dot{Q}_h$: total thermal power required, [kW];
- $\dot{Q}_{h,simulation}$: thermal power obtained from the simulation, [kW];
- $\Phi_{RH,i}$: additional thermal power to consider the intermittent operation of the heating system

$$\Phi_{RH,i} = A_i \cdot f_{RH} \quad [W]$$

where:

- A_i = is the area of the heated space [m²];

- f_{RH} is the recovery factor that is a function of the time required for the indoor air to return to the design temperature and the drop in temperature during the period of inactivity [W/m²].

The results (Table 6) show that this balance is not satisfied for the kitchen and the sitting room, as confirmed by users (feeling cold at times). It is therefore envisaged that the existing radiators will be replaced with new ones with thermal power increased by 56% for the kitchen and 97% for the sitting room.

Table 6. Thermal power of the radiators (required $\dot{Q}_h$, currently installed $\dot{Q}_{radiators}$, proposed $\dot{Q}_{new}$).

Floor	Room	$\dot{Q}_h$	$\dot{Q}_{radiators}$	$\dot{Q}_{new \text{ thermal power}}$	Percentage Deviation
		kW	kW	kW	%
Ground floor	Kitchen	1.4	0.926	1.4	56.3
	Sitting room	1.8	0.974	1.9	96.7
	Bedroom 4	1.1	1.508	-	-
First floor	Bedroom 1	0.5	1.447	-	-
	Bedroom 3	0.2	1.034	-	-
	Bedroom 2	0.3	1.034	-	-
	Bathroom	0.1	0.558	-	-

The second scenario (S2), aimed at complying with the requirements of English legislation [22], refers to the enhancement of the thermal insulation of the building components, specifically the external walls and attic floor. For the external walls, the existing plasterboard layer is replaced with insulated plasterboard panels incorporating high-performance rigid thermosetting phenolic insulation; the insulated plasterboard consists of an internal glass fabric-based facing with a thickness of 3 cm and a thermal conductivity of 0.021 W/(m·K), coupled with an external plasterboard layer that is 1.25 cm thick with a thermal conductivity of 0.017 W/(m·K).

For the building roof, glass mineral wool insulation rolls with a thickness of 30 cm and a thermal conductivity of 0.035 W/(m·K) are suggested. These measures ensure compliance with the thermal transmittance limits prescribed by English legislation (Table 7). It is worth noting that, in the existing configuration, the perimeter walls already exhibit relatively low steady-state thermal transmittance values, whereas the attic floor shows significantly poorer performance. Consequently, only a limited insulation thickness is required for the external walls, while a substantially greater thickness is necessary for the building roof.

Table 7. Thermal transmittance of the perimeter wall and building roof before and after retrofit interventions compared with the legislation values.

	$U_{existing \text{ baseline}}$	$U_{retrofit}$	$U_{max, legislation}$
	W/m ² K	W/m ² K	W/m ² K
Perimeter wall	0.36	0.22	0.30
Building roof	1.66	0.22	0.25

The insulation thicknesses were selected to achieve compliance with the relevant thermal-transmittance limits and to represent technically plausible retrofit packages for the case study dwelling. They were not obtained through a cost-optimal insulation-thickness optimization. An economic optimization would require investment costs, installation costs, service life, discount rate, maintenance assumptions, future fuel prices and possible incentives, which were outside the scope of the present work. Therefore, the envelope

scenario should be interpreted as regulatory/performance-driven retrofit case rather than an economically optimized solution.

The third scenario (S3) simply provides for the integration of the two previous hypotheses.

A further scenario (S4) explores an unconventional intervention designed to modify the building's thermal behaviour by enhancing the thermal capacity of internal partitions. The principal aim of this strategy is to evaluate its impact on indoor temperature stability during periods when the heating system is inactive at night. This approach is based on the principle that when a room is heated, part of the energy is absorbed by the building structures: the higher the thermal capacity of the walls, the more energy is stored within them, which is then gradually released back into the rooms during night-time system shutdowns. Although this can lead to higher initial energy consumption to 'charge' the walls, it contributes to maintaining indoor set-point during off periods. Finally, this intervention is integrated with the previously described enhancement of the building envelope (second scenario) in terms of thermal insulation, defining scenario S5. In this context, insulation materials with both high thermal capacity and low thermal conductivity have been selected. The modified partition walls are composed of a layered configuration designed to enhance thermal performance. The layers are as follows: a 1.25 cm insulated plasterboard panel, a 4 cm layer of rock wool insulation, a 10 cm lightweight concrete block, a second 4 cm rock wool insulation layer, and a final insulated plasterboard panel. This arrangement, essentially a sandwich structure with insulated plasterboard on both sides, is intended to maximize thermal storage and reduce heat losses through the partitions. In Table 8, the thermal characteristics of the modified partitions are reported.

Table 8. Specific thermal capacity c_p and thermal conductivity λ of the single elements used for the modified partitions.

Layer	Thickness	λ	c_p
	cm	W/(m·K)	J/(kg·K)
Plasterboard panel	1.25	0.16	1000
Insulation in rock wool	4	0.035	1030
Concrete block	10	0.19	1000
Insulation in rock wool	4	0.035	1030
Plasterboard panel	1.25	0.16	1000

For the intermediate floor insulation, a 10 cm layer of rock mineral wool and a 0.25 cm vapour barrier are positioned between the floor beams. The modified floor structure consists, from bottom to top, of a 3 cm plywood layer, the rock wool insulation, the vapour barrier, a second 3 cm plywood layer, and a 1 cm carpet layer. The thermal properties of the modified intermediate floor are reported in Table 9.

Table 9. Specific thermal capacity c_p and thermal conductivity λ of the single elements used for the modified intermediate floor.

Layer	Thickness	λ	c_p
	cm	W/(m·K)	J/(kg·K)
Plywood	3	0.13	1500
Insulation in rock wool	10	0.035	1030
Vapour barrier	0.25	0.14	1200
Plywood	3	0.13	1500
Moquette	1	0.06	1360

The thermal-mass scenarios (S4 and S5) were included as exploratory cases rather than as standard residential retrofit recommendations. In practice, increasing the thermal capacity of internal partitions and intermediate floors is less common than envelope insulation or heat-emitter replacement because it can be disruptive, costly and difficult to implement in an occupied dwelling. The aim of S4 and S5 is therefore to test the sensitivity of night-time temperature decay and daytime temperature stability to increased internal thermal capacity under intermittent heating operation.

From a practical implementation perspective, the proposed internal thermal-mass retrofit would require careful assessment of constructability, moisture risk, fire safety, acoustic performance, additional structural loads, loss of internal floor area and disruption to occupants. In an occupied dwelling, such works may require room-by-room phasing or temporary relocation. Consequently, the thermal-mass scenarios should be considered primarily as parametric cases used to understand transient thermal behaviour, rather than as universally recommended retrofit measures.

As the last intervention, the condensing boiler is replaced with a high-temperature GSHP with a nominal heating power of 9.6 kW and a maximum supply temperature of 80 °C. In the DesignBuilder/EnergyPlus model, the electric energy consumption of the heat pump was calculated dynamically according to the simulated heating load and the heat pump performance data (rather than by applying a single constant annual seasonal performance factor to the final heating demand). Three application cases are analyzed:

- Scenario 6 (S6): scenario with upgraded radiators (S1) + GSHP;
- Scenario 7 (S7): upgraded radiators + improvement of the building envelope + GSHP;
- Scenario 8 (S8): upgraded radiators + improvement of the envelope + increase in thermal capacity + GSHP.

3. Results

For each proposed improvement scenario, both achievement of the target indoor air temperature set-point (mainly in the kitchen) and energy efficiency were evaluated. The energy-related results are expressed both in terms of gas and electric energy consumption and in primary energy.

3.1. Results Relating to the First Three Retrofit Scenarios (S1, S2 and S3)

Considering the first three retrofit scenarios, S1-S3, these cases are compared with the existing baseline B0, assuming an indoor air temperature setpoint of 20 °C. Using dynamic building energy simulation, indoor air temperatures were obtained (particularly for the rooms where thermal discomfort was most pronounced) and are reported in Figure 9 and Table 10.

Based on the indoor air temperature profiles obtained for B0–S3, Table 11 summarizes the temperature-based comfort indicators calculated for the kitchen on 12 December 2022, namely the number of reported time points in which the indoor air temperature was below the 20 °C set-point and the cumulative temperature deficit below this set-point (considering both the case of all the 24 h and the case of only system operating time 7:00–23:00).

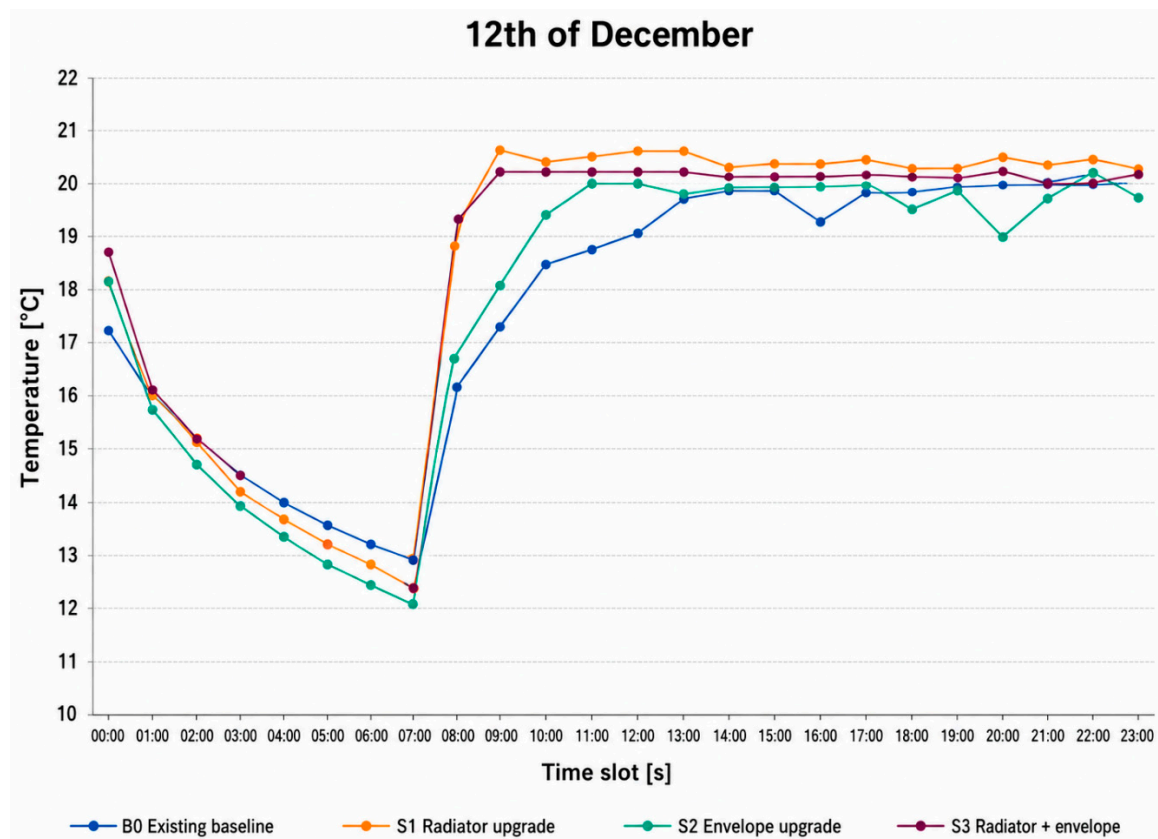


Figure 9. Comparison between indoor air temperatures for existing baseline case B0 and scenarios S1–S3, for 12 December 2022 (over 24 h).

Table 10. Values of the indoor air temperatures in the kitchen for cases B0–S3 (for 12 December 2022, over 24 h).

Time	B0 Existing Baseline	S1—Radiator Upgrade	S2—Envelope Upgrade	S3—Radiator + Envelope
	°C	°C	°C	°C
00:00	17.3	18.2	18.2	18.7
01:00	16.0	16.0	15.7	16.1
02:00	15.1	15.1	14.7	15.2
03:00	14.5	14.2	14.0	14.5
04:00	14.0	13.7	13.4	13.9
05:00	13.6	13.2	12.9	13.4
06:00	13.2	12.8	12.5	12.9
07:00	12.9	12.3	12.1	12.5
08:00	16.2	18.8	16.7	19.3
09:00	17.3	20.6	18.1	20.2
10:00	18.5	20.4	19.4	20.2
11:00	18.8	20.5	20.0	20.2
12:00	19.1	20.6	20.0	20.2
13:00	19.8	20.6	19.8	20.2
14:00	19.9	20.3	20.0	20.1
15:00	19.9	20.4	20.0	20.1
16:00	19.3	20.4	20.0	20.1
17:00	19.9	20.5	20.0	20.1
18:00	20.0	20.3	19.5	20.1
19:00	20.0	20.3	19.9	20.1
20:00	20.0	20.5	19.0	20.4
21:00	20.0	20.4	19.8	20.0

22:00	20.0	20.5	20.3	20.1
23:00	20.0	20.3	19.8	20.2

Table 11. Temperature-based comfort indicators for the kitchen on 12 December 2022.

Scenario	Number of Reported Time Points Below 20 °C	Cumulative Temperature Deficit Below 20 °C (24 h)	Cumulative Temperature Deficit Below 20 °C (System Operating Time 7:00–23:00)
		(K·h)	(K·h)
B0—Existing baseline	18	54.7	11.3
S1—Radiator upgrade	9	45.7	1.2
S2—Envelope upgrade	17	54.5	8.0
S3—Radiator + envelope	9	43.5	0.7

The comfort indicators confirm that the radiator upgrade (S1) removes the set-point non-attainment observed in the baseline case B0 during the reported period, while S2 reduces but does not fully eliminate the temperature deficit. This supports the use of S1 as the comfort-normalized reference case for subsequent energy, cost and emission comparisons. Considering only the heating system operating period (from 07:00 to 23:00), the cumulative temperature deficit below the 20 °C set-point decreases from 11.3 K·h in B0 to 1.2 K·h in S1 and 0.7 K·h in S3. The envelope only scenario S2 reduces the operating period deficit to 8.0 K·h, but it remains less effective than the radiator-based scenarios because it does not directly increase heat-emission capacity. These results confirm that radiator upgrading mainly improves set-point recovery during the operating period, while the combined radiator and envelope scenario provides the best performance in terms of both recovery and temperature stability.

The improved envelope contributes to reducing indoor air temperature swings and helps maintain the kitchen temperature closer to the 20 °C set-point throughout the monitored period. The results reported in Figure 9, Tables 10 and 11 indicate that the increase in radiator thermal power enables indoor temperatures to remain within the 20–21 °C range, a condition that was not met before this intervention. It is worth noting that, in the early morning hours, scenario S1 (Radiator upgrade) reaches slightly higher indoor temperatures than scenario S3 (Radiator + envelope). Compared with S1, the combined S3 scenario reduces temperature fluctuations and maintains the indoor air temperature closer to the set-point, because the envelope improvement limits heat losses while the radiator upgrade ensures sufficient heating capacity.

The energy comparison with the case B0 was then evaluated (Figure 10). Based on electric energy and gas tariffs of 0.326 £/kWh and 0.099 £/kWh, respectively, derived from the bills provided by the occupants, the energy costs associated with scenarios S1–S3 were evaluated (including fixed costs), allowing a comparison of the economic impact of the different retrofit interventions (Figure 11).

Only operating costs were considered in this study because reliable project-specific quotations for radiator replacement, thermal insulation, partition reconstruction and GSHP installation were not available. Therefore, simple payback period, net present value and life-cycle cost were not calculated. This is a limitation of the present analysis, because real retrofit feasibility depends also on investment cost, installation constraints, maintenance costs, available incentives and energy price uncertainty.

The results reported in Figure 10 show that, compared with B0, gas consumption decreases by 37.6% in S2 and by 29.4% in S3, while electric energy consumption changes only slightly, with reductions of about 1.6% and 1.5%, respectively. Figure 11 shows that the corresponding gas-related operating costs decrease by 35.2% in S2 and by 27.6% in S3, while electric energy costs decrease by about 1.1% in both cases.

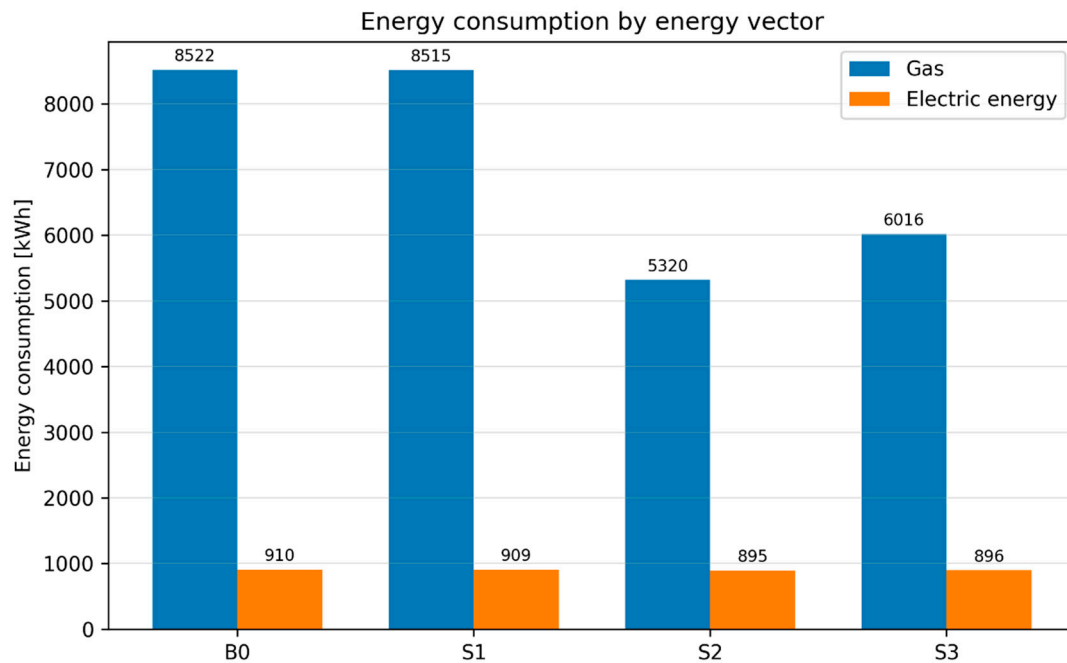


Figure 10. Energy consumption during winter season (1 October–30 April) for cases B0–S3. (B0: existing baseline; S1: radiator power upgrade/comfort-normalized boiler reference; S2: envelope upgrade only; S3: combined radiator power upgrade and envelope improvement).

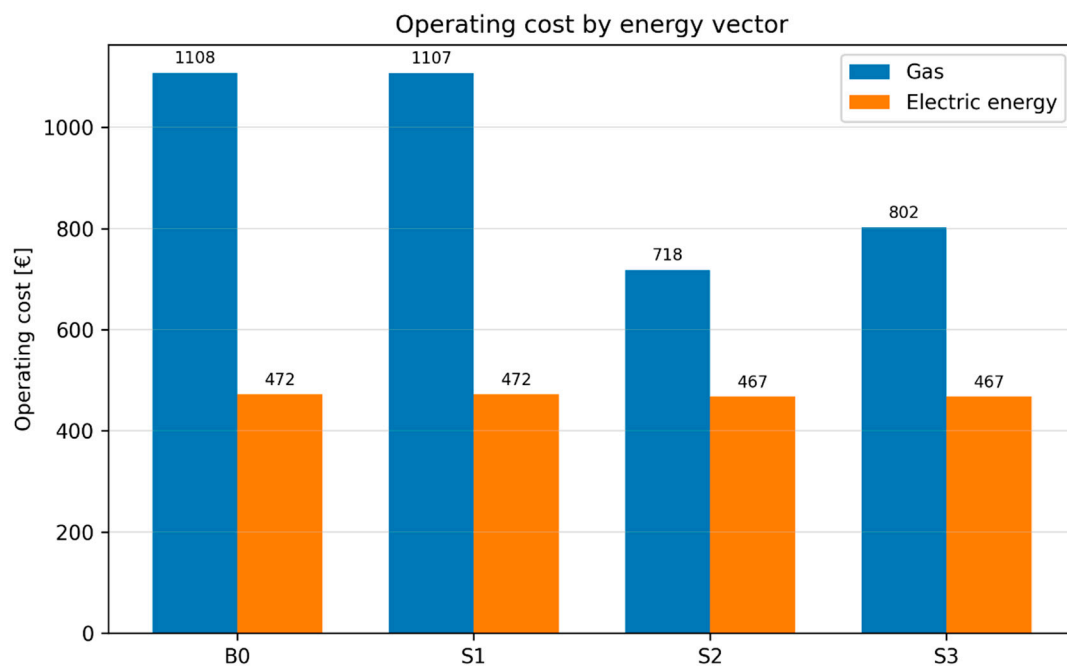


Figure 11. Energy costs during winter season (1 October–30 April) for cases B0–S3. (B0: existing baseline; S1: radiator power upgrade/comfort-normalized boiler reference; S2: envelope upgrade only; S3: combined radiator power upgrade and envelope improvement).

3.2. Results Relating to Scenarios S4 and S5 (Increase in the Thermal Capacity of the Partition Walls)

The results (Table 12) show that, with this intervention, indoor air temperatures during night-time (when the heating system is inactive) are maintained approximately 1 °C higher than in case B0, thus reducing early-morning discomfort. During daytime, the combination of increased wall thermal mass and an improved building envelope (S5) stabi-

lizes indoor temperatures around 20–20.3 °C, reducing daily temperature fluctuations. Overall, enhancing the wall's thermal mass contributes to a more stable and comfortable indoor environment. When only the internal thermal mass is increased (S4), the thermal response becomes more gradual, allowing heat stored during the heating period to be released progressively during the following hours. When this intervention is combined with envelope insulation (S5), the reduction in heat losses further lengthens the thermal response time of the building, producing a smoother indoor temperature profile. As a result, indoor air temperature is maintained more steadily, and the night-time temperature decay is reduced compared with the existing baseline.

More in details, the minimum night-time temperature increases from 12.9 °C in B0 to 14.4 °C in S4 and 13.8 °C in S5. The average night-time temperature over the 00:00–07:00 period increases from 14.6 °C in B0 to 15.8 °C in S4 and 15.6 °C in S5. Therefore, the main benefit is a reduction in early-morning discomfort and a smoother indoor temperature profile. The final interpretation is, therefore, that scenarios S4 and S5 primarily lead to a transient indoor temperature stability rather than an annual energy reduction.

It should be noted that S5 does not show higher temperatures than S4 during all night-time hours. In particular, between 02:00 and 07:00, indoor air temperature in S5 is slightly lower than S4 (although in both scenarios it remains higher than B0), because the combined effect of insulation layers and added mass modifies the coupling between room air and internal surfaces. Moreover, additional thermal mass must be heated during occupied periods before it can release heat during the heating-off period. Therefore, the thermal mass scenarios should be interpreted mainly as a measure for improving temperature stability relative to the existing baseline, rather than as a uniformly superior solution in all hourly conditions, neither as a direct energy-saving intervention.

Table 12. Comparison between the indoor air temperatures for baseline case B0 and the thermal-mass scenarios S4 and S5 (12 December 2022).

Time	T_{B0} (B0—Existing Base-line)	T_{S4} (S4—Thermal Mass)	T_{S5} (S5—Envelope + Thermal Mass)
	°C	°C	°C
00:00	17.3	18.2	18.3
01:00	16.0	16.9	17.0
02:00	15.1	16.3	16.2
03:00	14.5	15.8	15.6
04:00	14.0	15.4	15.1
05:00	13.6	15.0	14.6
06:00	13.2	14.7	14.2
07:00	12.9	14.4	13.8
08:00	16.2	20.0	20.2
09:00	17.3	20.5	20.3
10:00	18.5	20.3	20.3
11:00	18.8	20.4	20.3
12:00	19.1	20.3	20.3
13:00	19.8	20.6	20.2
14:00	19.9	20.3	20.2
15:00	19.9	20.4	20.2
16:00	19.3	20.4	20.2
17:00	19.9	20.5	20.2
18:00	20.0	20.5	20.1
19:00	20.0	20.4	20.1
20:00	20.0	20.3	20.1

21:00	20.0	20.3	20.3
22:00	20.0	20.4	20.3
23:00	20.0	20.4	20.4

Moreover, the cumulative temperature deficit below 20 °C over the 24 h profile decreases from 54.7 K·h in the B0 scenario to 33.3 K·h and 35.2 K·h in the S4 and S5 scenarios, respectively. This confirms that the thermal mass intervention improves temperature stability compared to the baseline B0. If only the heating system operating period (from 07:00 to 23:00) is considered, the cumulative deficit decreases from 11.3 K·h in B0 to 0.0 K·h in both S4 and S5. This confirms that the thermal-mass scenarios improve temperature stability compared to the baseline and, during the operating period, allow the kitchen temperature to remain always at or above the 20 °C set-point.

3.3. Results Relating to Scenarios S6–S8 (Replacement of the Heat Generator)

The first results (not reported in detail) show negligible variations in indoor air temperatures compared with the boiler case.

From an energy perspective, the GSHP-based scenarios substantially reduce the final heating energy by replacing gas consumption in the comfort-normalized reference case S1 with electric energy use for the high-temperature GSHP. In Figure 12, the boiler reference scenario S1 shows a heating energy consumption of 8515 kWh (from gas), whereas the GSHP scenario with upgraded radiators only (S6) requires 2773 kWh of electric energy for heating. When envelope insulation is added (S7), the electric energy consumption decreases further to 2405 kWh, corresponding to a reduction of about 13.3% compared with S6. Finally, when increased internal thermal mass is also included (S8), the heating electric energy consumption decreases to 2286 kWh, corresponding to a further reduction of about 4.9% compared with S7. Overall, Figure 12 shows that the combined GSHP, envelope and thermal-mass retrofit measure provides the lowest final heating energy demand among the GSHP-based scenarios.

However, final energy and primary energy must be interpreted separately because they depend on the energy vector and on the adopted conversion factors. Therefore, the comparison between S1 and S6–S8 must also be performed in terms of primary energy (Table 13) using the SAP 10.2 factors reported in Table 4. In terms of total operational primary energy, adding envelope improvement to the radiator-upgrade reference case (S3) reduces primary energy from 12,115 kWh in S1 (comfort normalized boiler reference case) to 8205 kWh in S3, corresponding to a 32.3% reduction. When increased internal thermal mass is also included in the boiler reference case (S5), the primary energy consumption reaches 7790 kWh, corresponding to a 35.7% reduction compared with S1.

Considering the replacement of the heat generator, primary energy decreases from 12,115 kWh in S1 to 4077 kWh in S6, corresponding to a 66.3% reduction. When envelope insulation is added (S7), primary energy decreases to 3667 kWh, corresponding to a 69.7% reduction compared with S1. The combination of all measures (S8), namely radiator upgrade, GSHP, envelope insulation and increased internal thermal mass, further reduces primary energy to 3581 kWh, corresponding to a 70.4% reduction. These results confirm that replacing the conventional boiler with a heat pump provides the largest reduction in primary energy. At the same time, the additional contribution of increased internal thermal mass to annual energy reduction remains relatively limited compared with the effect of heat pump introduction and envelope insulation; its main benefit remains the improvement of indoor temperature stability and the reduction in night-time temperature decay.

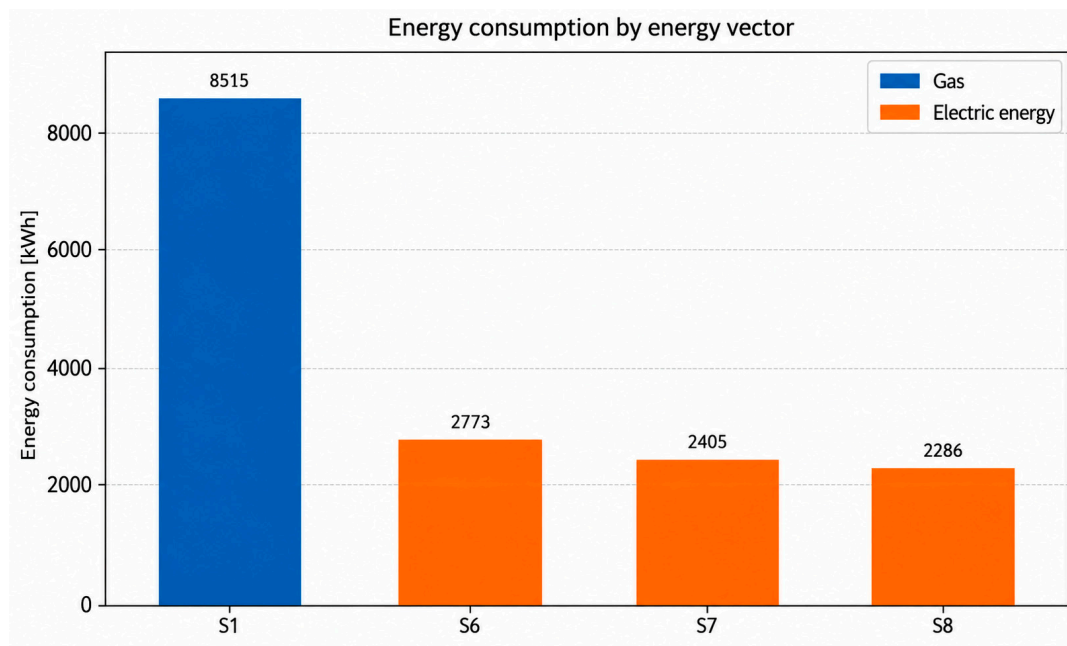


Figure 12. Energy consumption by energy vector for the boiler reference case and GSHP-based scenarios. (S1: boiler with radiator power upgrade; S6: high-temperature GSHP with radiator power upgrade; S7: high-temperature GSHP with radiator power upgrade and envelope improvement; S8: high-temperature GSHP with radiator power upgrade, envelope improvement and increased thermal mass. Gas consumption is reported for the boiler-based reference scenario, while electric energy consumption is reported for the GSHP-based scenarios).

Table 13. Annual primary energy consumption for the selected retrofit scenarios, considering the overall energy consumption of the dwelling, including all building services accounted for in the model.

Ref	Description	Primary Energy Consumption from Gas	Primary Energy Consumption from Electric Energy	Total Primary Energy	Reduction
		kWh	kWh	kWh	%
S1	Radiator upgrade	10,228	1887	12,115	–
S3	Radiator upgrade + envelope upgrade	6339	1866	8205	32.3
S5	Radiator upgrade + envelope upgrade + increased thermal mass	5930	1859	7790	35.7
S6	GSHP + radiator upgrade	0	4077	4077	66.3
S7	GSHP + radiator upgrade + envelope upgrade	0	3667	3667	69.7
S8	GSHP + radiator upgrade + envelope upgrade + increased thermal mass	0	3581	3581	70.4

As a final analysis, the environmental impact was examined through the calculation of carbon emissions (Table 14). The CO₂ assessment refers to the overall energy consumption of the dwelling, including all building services considered in the model. Therefore, both gas consumption and electric energy consumption are included, with the latter accounting not only for the GSHP where present, but also for the other electric uses associ-

ated with the building operation. The CO₂ emissions data therefore reflect the overall operational environmental impact of the different retrofit scenarios.

Table 14. Annual operational CO₂ emission values and comparisons for the selected retrofit scenarios, considering the overall energy consumption of the dwelling, including all building services accounted for in the model.

Ref	Description	CO ₂ Emissions from Gas	CO ₂ Emissions from Electric En- ergy	Total Emissions	Reduction
		kg CO ₂	kg CO ₂	kg CO ₂	%
S1	Radiator upgrade	1900.8	170.9	2071.8	–
S3	Radiator upgrade + envelope up- grade	1178.1	169.1	1347.2	35
S5	Radiator upgrade + envelope up- grade + increased thermal mass	1102.1	168.5	1270.6	38.7
S6	GSHP + radiator upgrade	0	369.4	369.4	82.2
S7	GSHP + radiator upgrade + enve- lope upgrade	0	332.2	332.2	84
S8	GSHP + radiator upgrade + enve- lope upgrade + increased thermal mass	0	324.4	324.4	84.3

Compared with the boiler-based comfort-normalized reference case (S1), the combined radiator and envelope upgrade S3 reduces operational CO₂ emissions by 35.0%, while the addition of increased internal thermal mass in S5 increases the reduction to 38.7%. The transition from the gas boiler to the high-temperature GSHP produces a much larger reduction because the SAP 10.2 electricity emission factor is significantly lower than the gas emission factor. In particular, S6 reduces operational CO₂ emissions by 82.2%, S7 by 84.0% and S8 by 84.3% compared with S1. The greatest reduction is therefore obtained by combining the high-temperature GSHP with radiator upgrading, envelope improvement and increased internal thermal mass. These results show that, under SAP 10.2 conversion factors, heating electrification strongly reduces operational CO₂ emissions, especially when combined with envelope measures that reduce heating demand. Moreover, improvements in the building envelope and thermal capacity effectively lower overall CO₂ emissions. The synergy of all interventions (advanced heating technology, enhanced insulation, and increased thermal mass) yields the most significant environmental benefits, substantially reducing the building's carbon footprint compared to the boiler-based scenario.

4. Discussion

The results of this study are consistent with the broader retrofit literature, which shows that the effectiveness of residential renovation depends strongly on the initial building condition, the selected retrofit solutions and the interaction between building envelope and HVAC systems. The reduction in heating energy obtained through envelope improvement agrees with previous envelope-oriented case studies, where wall, roof and fabric interventions were shown to produce relevant reductions in annual energy demand [6]. The result is also coherent with simulation-based studies showing that the benefits of envelope retrofit are not fixed but depend on the original construction features and on the heating source considered [7].

However, the present case study adds a more specific contribution by showing that envelope improvement should be interpreted together with heat-emitter adequacy. In this

case, the high initial transmittance of the building roof explains why the insulation package produces a significant reduction in heating demand, while the already moderate wall U-value limits the marginal benefit of wall insulation. At the same time, intervention only on the opaque envelope of the building does not completely solve the problem of morning recovery of the internal temperature, confirming that the reduction in heat losses and achieving the indoor air temperature set-point are related but not equivalent results.

The findings therefore show that retrofit assessment should not be based only on annual energy demand. Although envelope insulation reduces heat losses, the simulations indicate that it does not fully solve the issue related to the morning recovery of the internal temperature, when the original heat emitters are undersized. This agrees with studies emphasizing that building performance is affected by heating schedules, control practices and user operation, especially in UK dwellings with intermittent heating patterns [28]. The contribution of the present work is to make this distinction explicit through the use of a comfort-normalized reference scenario. Radiator power upgrading is not treated as a conventional energy-saving measure, but as a comfort-capacity intervention that allows the building to reach the prescribed indoor air temperature set-point. This provides a clearer basis for comparing subsequent envelope, thermal-mass and heat-pump measures under more comparable comfort conditions.

It should also be noted that radiator upgrading solves the set-point recovery problem by increasing heat-emission capacity, but it also increases peak heat demand, mainly during morning temperature recovery. If this strategy is combined with electrified heating, such as a heat pump-based system, the higher recovery load may translate into higher electricity demand peaks. This issue was not explicitly simulated in the present work and should be addressed in future studies through detailed control and demand-response analysis.

The heat pump scenarios are also consistent with previous studies showing that heat pump performance must be assessed at building-system level rather than as a simple generator substitution. Field-study reviews have shown that real heat pump performance is affected by operating conditions, system management and installation quality [39]. Similarly, retrofit simulation studies indicate that heat pump performance depends on the integration between the heat pump, the building fabric and the heating distribution system [43]. In the present case, the GSHP substantially reduces final heating energy consumption compared with the boiler-based solution, but its performance and cost-effectiveness remain linked to the assumed supply temperature, heat-emitter capacity and electricity-to-gas price ratio. The analysis therefore reinforces one of the main messages of this paper: the replacement of a boiler with a heat pump should be assessed together with heat-emission capacity and envelope demand, because these elements jointly determine thermal comfort recovery, energy use and operational emissions.

The results regarding thermal mass also support a more nuanced interpretation of retrofit benefits. Verbeke and Audenaert reported that the impact of thermal inertia varies with climate, building use and operation [45], while Reilly and Kinnane showed that the interaction between intermittent occupancy and thermal mass can significantly modify energy consumption [46]. In the present study, increasing internal thermal mass improves indoor air temperature stability and reduces night-time temperature decay, while its direct effect on annual energy consumption remains limited compared with the effect of envelope improvement and heat generator replacement. This is an important outcome because it prevents thermal mass from being presented as an automatic energy-saving measure. Instead, the results position it mainly as a transient comfort-stability strategy and, potentially, as a flexibility-related measure. This interpretation is coherent with recent studies framing building thermal capacity as a source of demand-side flexibility [48,49].

From a methodological perspective, the use of a calibrated dynamic simulation model allowed us to evaluate energy retrofit measures that affect both annual energy demand and transient indoor temperature behaviour. Previous research has shown that calibration is especially important when building energy models are used for retrofit analysis [31], while reviews of calibration methods highlight the influence of measured data, model-adjustment procedures and uncertainty treatment on simulation reliability [29,32]. However, the outcomes obtained in this analysis remain limited to the analyzed case study; therefore, the results should be interpreted primarily as comparative indicators among retrofit scenarios rather than as fully generalizable predictions. This is consistent with the broader discussion on the performance gap between predicted and measured energy use in buildings [27]. Within these limits, the paper contributes a structured retrofit assessment in which comfort restoration, heat-loss reduction, thermal inertia and heat generator efficiency are analyzed as interacting components of the same dynamic framework. Overall, the study adds to the literature by explicitly separating comfort-restoration measures, such as radiator power upgrading, from energy- and carbon-reduction measures, such as the building envelope insulation and the replacement of a boiler with a heat pump. This distinction is particularly relevant for existing dwellings where the baseline heating system may not adequately reach the winter set-point and where retrofit decisions should therefore be guided by both energy indicators and indoor temperature achievement.

5. Conclusions

Several energy retrofit scenarios for the building-plant system of a terraced house in Oxford, England, were evaluated using dynamic simulation software after model calibration. Considering the first three scenarios (enhancement of the radiator thermal power S1, improvement of the building envelope insulation S2, and their combination S3) it is evident that even a minimally invasive intervention, such as increasing radiator thermal power, can significantly improve indoor air temperature, when the existing system is unable to provide sufficient heat-emission capacity to rapidly reach the prescribed winter set-point under intermittent operation. In this sense, S1 should be interpreted mainly as a comfort restoration intervention and as a thermal comfort normalized reference, rather than as a direct energy-saving measure. Thermal insulation of the building envelope, although more invasive, yields very satisfactory results in terms of energy consumption and operating costs, with gas savings ranging between 29.4% and 37.6%. Among the boiler-based scenarios, S2 provides the lowest operating cost, while S3 offers a better compromise between energy reduction and indoor air temperature set-point achievement.

The fourth scenario S4, involving an increase in the thermal capacity of internal partition walls and the intermediate floor, also produces positive outcomes. Night-time temperatures are maintained approximately 1 °C higher than in the baseline case B0, reducing early-morning discomfort, while daytime temperatures are stabilized around 20 °C, limiting daily fluctuations. However, the direct impact of enhanced thermal mass on annual energy consumption is limited; therefore, this measure should be interpreted mainly as a strategy for improving transient indoor temperature stability rather than as a conventional energy-saving intervention.

Moreover, replacing the existing condensing boiler with a high-temperature geothermal heat pump (GSHP) provides the most substantial reductions in energy demand, primary energy use and carbon emissions. Winter heating energy consumption decreases from 8515 kWh in S1 (the radiator-upgrade boiler reference), to 2773 kWh in S6 (GSHP with upgraded radiators). Additional envelope improvement reduces consumption to 2405 kWh, while further inclusion increased thermal mass reduces it to 2286 kWh.

In terms of primary energy, the GSHP with upgraded radiators reduces total primary energy consumption by 66.3% compared with S1, while the integrated approach combining GSHP, improved envelope insulation and increased thermal mass achieves a 70.4% reduction in primary energy consumption. These results confirm the importance of assessing the replacement of the existing boiler with a high-efficiency heat pump together with heat-emitter adequacy and envelope performance.

All the selected retrofit scenarios show reductions in operational CO₂ emissions ranging from 35.0% to 84.3%, with the highest reduction obtained when the GSHP is combined with envelope improvement and increased internal thermal mass.

Finally, the operating cost analysis confirms that envelope insulation substantially reduces the gas-related operating cost in the boiler-based scenarios, although the overall economic performance depends on the balance between gas and electric energy prices. Since investment costs, payback period and life-cycle costs were not included, these economic results should be interpreted as operating cost comparisons only.

6. Limitations and Further Development

This study is based on a single terraced dwelling in Oxford and relies on dynamic simulation results supported by limited monitoring data. Therefore, the outcomes should not be generalized directly to other building typologies or climatic contexts. The results depend on the specific geometry, wall configuration, roof heat losses, radiator sizing, heating schedule, occupant behaviour, boiler characteristics, assumed GSHP performance and local climate. Detached houses may show higher heat losses because of larger exposed envelope areas, while mid-floor apartments may have lower heating demand due to heat transfer from adjacent dwellings. End-row terrace houses may perform differently from the mid-terrace case because of additional exposed walls. Buildings in colder UK climate regions may show higher peak loads, longer heating seasons and different heat pump seasonal performance. Consequently, the conclusions should be interpreted as a case-study contribution illustrating the interaction among building envelope performance, heat emitter adequacy, thermal mass and heat generator efficiency, rather than as a universal ranking of retrofit measures.

Moreover, the assessment of indoor comfort is mainly limited to indoor air temperature, while other relevant comfort indicators are not explicitly considered. Future work may extend the present analysis by including a comprehensive evaluation of indoor comfort parameters, including PMV, PPD or adaptive comfort models, humidity levels and indoor air quality indicators.

The economic assessment is also limited to operating costs calculated using the gas and electric energy tariffs available from the occupants' bills. Therefore, the study does not provide simple payback period, net present value or life-cycle cost results. This limitation is particularly important for the GSHP and internal thermal mass scenarios, which may require substantial capital investment and disruption.

Further developments should also include longer monitoring campaigns, additional dwelling typologies, sensitivity analyses on heat pump seasonal performance, life-cycle carbon assessment and full techno-economic optimization. This would allow a more holistic assessment of retrofit strategies by linking energy performance, operational and embodied emissions, economic feasibility and occupants' comfort and well-being.

The environmental assessment is limited to operational CO₂ emissions. Embodied energy and embodied carbon associated with insulation materials, radiator replacement, internal partition reconstruction and GSHP installation were not included. This limitation is relevant because measures with strong operational benefits may also involve non-negligible embodied impacts, especially when large quantities of insulation or new plant components are required. A full life-cycle assessment based on environmental product declara-

rations, replacement cycles and end-of-life assumptions is therefore needed in future work to evaluate whether the operational CO₂ savings offset the embodied impacts over the retrofit lifetime.

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