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Heat, homes and hidden impacts: Life cycle sustainability assessment of low-carbon heating in the built environment

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ABSTRACT

Decarbonising heating in the built environment is one of the most complex challenges in achieving net-zero, yet current research inadequately addresses its full sustainability scope. Existing studies predominantly focus on operational performance while overlooking life cycle impacts, disproportionately emphasise environmental factors, and lack meaningful stakeholder engagement. To address these gaps, this study develops a novel framework integrating Triple Bottom Line sustainability principles, life cycle assessment, and multi-criteria analysis to define what sustainability entails in building heating systems and how it can be evaluated. Applied to eight heating technologies in UK housing, the framework reveals that no single technology dominates across all sustainability dimensions, with significant trade-offs between environmental, economic, and social performance. Heat pumps emerged as the most sustainable option overall, delivering clear environmental and social benefits, though with a challenging economic outlook driven by the unbalanced electricity:gas price ratio. Direct electric systems and biomass boilers ranked poorest, failing to mitigate environmental impacts while inflating life cycle costs and posing broader social burdens, particularly around fuel poverty and public health. This research contributes a practical and transferable assessment framework that integrates life cycle thinking, multidimensional sustainability, and stakeholder priorities into heating system design and decision-making, with broader applicability for informing policy interventions towards a just and sustainable heat transition.

Glossary

Acronyms	
AHP	Analytic hierarchy process
BHS	Building heating system
CSI	Composite sustainability index
E-LCA	Environmental life cycle assessment
EPD	Environmental product declaration
GHG	Greenhouse gas emissions
GSHP	Ground-source heat pump
GWP	Global warming potential
HP	Heat pump
LCA	Life cycle assessment
LCC	Life cycle costing
LCSA	Life cycle sustainability assessment
MCDA	Multi-criteria decision analysis
NPV	Net present value
O&M	Operating and maintenance
PM	Particulate matter
PVT	Photovoltaic thermal
RES	Renewable energy sources
SI	Sustainability indicator
S-LCA	Social life cycle assessment
TBL	Triple bottom line
TOPSIS	Technique for order preference by similarity to ideal solution
WLC	Whole life carbon
WSM	Weighted sum method

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1. Introduction

1.1. Background and motivation

Heating accounts for nearly half of global final energy use and is the primary contributor to greenhouse gas (GHG) emissions from the building industry [1]. Fossil fuels continue to dominate heat supply, with renewable resources meeting only 10% of global heat demand [2]. In the UK, renewables and low-carbon heating technologies barely reach 10% market share [3], while nearly 85% of British households rely on gas for heat and hot water [4]. Despite a 67% emissions reduction in electricity generation between 2010 and 2018, heat decarbonisation has progressed slowly, with negligible emissions reductions over the same period [5].

The UK government has committed to fully decarbonising its building sector by 2050, requiring the transformation of over 28 million homes [6]. This is particularly challenging given that approximately 57% of UK homes were built before 1965, making British housing stock one of Europe's least energy-efficient [7]. Strategic initiatives such as the 'Clean Growth: Transforming Heating' [8] and the 'Heat and Buildings Strategy' [9], outline a comprehensive roadmap for the transition. This roadmap encompasses targets including 600,000 annual heat pump (HP) installations, 400,000 annual retrofits by 2028, meaningful HP cost reduction, and many more end-user financial support, ultimately preparing an on gas boilers in new homes from 2035 [9].

The heat transition extends well beyond adopting lower-carbon technologies; it carries profound social, economic, and environmental consequences. Domestic heat decarbonisation is uniquely challenging because of its direct links with household health, well-being, and living standards. Many in Britain still recall the widespread impacts of shifting from wood and coal to central heating, yet efforts to learn from this experience for smoother, fairer future transitions remain limited [10]. Understanding these social ties and their community-wide implications is crucial for a just and sustainable transition [11]. Fuel poverty, affecting over 11% of UK households (34% in Scotland) [12], is one critical social issue often overlooked in heating interventions. Evidence suggests that low-carbon transitions may escalate energy costs, placing additional burden on vulnerable households [13].

At the same time, the transition demands substantial upgrades across energy networks, supply chains, and regulatory frameworks. The transition's complexity is further amplified by constraints within the broader energy system and the building industry, requiring parallel advancements in grid decarbonisation and building fabric improvements [14]. These interconnected challenges underline the need for a holistic approach to evaluating heating system sustainability, one that goes beyond technical and environmental metrics to capture economic viability and social dynamics.

1.2. Literature review and research gaps

The growing body of research on heat decarbonisation demonstrates increasing recognition of heat's role in achieving climate targets. Since the early 2010s, key research areas have expanded to include transition pathway assessments [15,16], heat demand reductions [17,18], market policies and adoption incentives [19,20], and real-world pilot projects [21,22]. In the UK, dedicated initiatives such as UKERC's 'Decarbonisation of Heat' [23], the 'Leeds Heat Planning Tool' [24], and the 'Just Heat' project [25] have an advanced understanding of technological pathways, heat demand mapping, and social equity dimensions of the transition.

This research growth has paralleled the development of low-carbon alternatives. A study by the 'Net-Zero Infrastructure Industry Coalition' [26] identified three pathways for the heat decarbonisation, each combining various low-carbon technologies, storage systems and smart solutions. However, no single technology is likely to achieve gas boilers' current market dominance; therefore, a diverse portfolio of technologies is needed to serve varied building types, consumer needs, and local contexts [27]. To examine these technological pathways and their sustainability performance, life cycle sustainability assessment (LCSA) has emerged as the dominant approach, evaluating impacts across the full life cycle of energy systems [28]. While LCSA studies employ diverse tools and methods [29,30], the approach is consistently defined as:

$$LCSA = E\_LCA + LCC + S\_LCA$$

This reflects the Triple Bottom Line (TBL) definition of sustainability, where sustainability is evaluated through environmental life cycle assessment (E-LCA), social life cycle assessment (S-LCA), and life cycle costing (LCC). While the TBL approach has facilitated holistic sustainability studies, reviewing the literature with a focus on heating technologies reveals three persistent gaps.

a) **Limited life cycle scope:** Current research inadequately addresses the full life cycle impacts of building heating services. Assessments typically focus on operational energy, costs, and emissions [31], yet building services contribute 40–70% of total embodied carbon in buildings, averaging 11% of a building's life cycle emissions [32].
b) **Imbalanced sustainability dimensions:** Studies often overlook multi-dimensional analysis of the building heating services or fail to equitably consider all facets of sustainability. The predominance of environmental factors has been noted by scholars in studies on heating technologies [33], building interventions [34] and energy systems [35].
c) **Overlooked social sustainability:** The social dimension is consistently underrepresented, often reduced to brief qualitative commentary or embedded implicitly within environmental analyses. As a result, no consensus exists on how to measure or evaluate social sustainability in this sector [36,37].

1.3. Aims and objectives

To address these gaps, this paper integrates life cycle thinking and multidimensional sustainability into early-stage design and decision-making for domestic heat decarbonisation. A purpose-built LCSA framework is developed to evaluate the life cycle performance and sustainability implications of low-carbon building heating systems (BHSs), then applied to single-family houses in the UK to demonstrate its functionality and practical value. The study objectives are.

a) Develop a holistic and practical life cycle sustainability assessment framework for BHSs.
b) Apply the framework to a UK case study to evaluate low-carbon BHSs and demonstrate its application in practice.

This paper advances existing studies by integrating TBL dimensions into a unified framework, recognising the interconnectivity of economic viability, environmental protection, and social sustainability. Using multi-criteria decision analysis (MCDA), it enables trade-offs across sustainability indicators (SIs), ensuring all sustainability dimensions are proportionally represented and stakeholder priorities are reflected. This work offers a foundation for understanding the heat decarbonisation complexity, supporting more targeted and sustainable decision-making.

The remainder of this paper is structured as follows: Section 2 details the materials and methods used to develop the LCSA framework; Section 3 presents results from the case study application; Section 4 discusses and interprets findings; and Section 5 summarises conclusions, contributions, and limitations.

2. Materials and methods

2.1. Methodology stages

The theoretical foundation and methodology follow life cycle assessment (LCA) guidelines established in ISO 14040 [38] and ISO 14044 [39] standards. While these provide a reference framework for environmental analysis, they cannot deliver a comprehensive sustainability evaluation alone. The publication of ISO 14075 [40] in October 2024, a significant milestone was marked, introducing a standardised approach for social life cycle assessment (S-LCA) and enabling evaluation of social and socio-economic impacts linked to products, services, and organisations. This development supports more complete LCSA studies while reducing inconsistencies in modelling approaches and assumptions, such as system boundaries and impact categories [41].

Both LCA and S-LCA follow identical principles comprising four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. The present study adopts this structure accordingly. It begins with defining objectives, scope, and system boundaries (Section 2.2), followed by identifying key SIs and establishing quantification methods and datasets for measuring them (Section 2.3), which are then combined with an MCDA approach to construct the LCSA framework (Section 2.4). The framework's robustness is validated through sensitivity analysis (Section 2.5). The final stage applies the framework to a case study to validate its functionality in practice (Section 2.5).

2.2. Scope and boundaries

To establish a clear LCSA framework, the life cycle scope and system boundaries must be defined. A cradle-to-grave life cycle scope is adopted to comprehensively account for impacts across all stages from raw material extraction to end-of-life. Following CIBSE TM65 [42] for embodied carbon in building services, system boundaries are set at the product level, meaning that individual heating systems are assessed independently of the buildings they serve. To ensure applicability at early design stages, impact categories and indicators are constrained by data available during initial project phases, avoiding dependence on detailed technical designs or post-construction surveys and monitoring.

2.3. Sustainability indicators

A critical initial step for LCSA is identifying all factors that impact sustainability, known as sustainability indicators (SIs), or impact categories in LCA terminology. These indicators enable quantifying, analysing, and communicating complex sustainability information. Therefore, identifying an effective set of SIs that represents system dynamics and complexity is crucial for assessments. However, SI sets used for BHSs in the literature often face significant limitations, including insufficient stakeholder participation, environmental factor predominance, and inconsistency across frameworks [33].

Addressing these limitations, Abbasi et al. [33] identified a set of SIs and their weight factors to effectively portray BHS sustainability, using a combination of desk research and participatory techniques. Through a three-phase process of identification, refinement, and prioritisation, they established 22 key SIs comprising 8 environmental, 4 economic, and 10 social indicators, presented in Table 1 and illustrated in Appendix Figure A. 1. Importantly, this SI set was developed specifically for individual household-scale sustainability assessments of BHSs in UK, meaning its context and scope align closely with the present study. It is therefore adopted as the foundation of the LCSA framework developed in the present study.

To utilise these SIs, a series of quantification methods is required; that is, quantitative or semi-quantitative approaches to derive SI values using data accessible at early project stages. These quantification methods and their associated datasets provide the necessary information for inventory analysis, following the ISO LCA methodology [40], and are detailed in Appendix A, Table A. 1 to Table A. 8. This information is collected from different standards, databases, and literature which are cited accordingly.

Table 1
Selected sustainability indicators and their importance weight [33].

Sustainability dimensions	Importance weight	Rank	Sustainability indicators	Importance weight	Rank
Environmental	0.395	1	Operational carbon emissions	0.097	3
			Primary energy consumption	0.082	4
			Embodied carbon emissions	0.049	7
			Share of renewable energy	0.049	8
			Energy efficiency	0.041	10
			Water consumption	0.034	12
			Land requirement	0.025	16
			Acidification potential	0.017	19
Economic	0.332	2	Operation & maintenance cost	0.118	1
			Net present value	0.113	2
			Upfront cost	0.067	5
			Economic lifetime	0.034	13
Social	0.273	3	Health impacts	0.058	6
			Fuel poverty	0.044	9
			Thermal comfort	0.036	11
			Safety	0.029	14
			Employment impact	0.027	15
			Reliability	0.022	17
			Usability and functionality	0.018	18
			Social acceptance	0.017	20
			Acoustic performance	0.014	21
			Aesthetic aspects	0.008	22

2.4. Framework architecture

With data requirements and quantification methods established, this section develops the LCSA framework's operational workflow. LCSAs require integrated analysis of diverse information, parameters, and uncertainties, and MCDA provides reliable methods for handling this complexity. MCDA incorporates the three sustainability dimensions within a unified process, evaluating trade-offs between conflicting criteria to identify optimal solutions [43]. MCDA methods are increasingly applied in sustainability assessments due to their ability to handle multi-faceted problems [44].

Among MCDA approaches applied in sustainability studies, AHP, WSM, TOPSIS, Fuzzy set, and ELECTRE are the most prevalent [44]. This study uses Weighted Sum Method (WSM) as the primary method, with TOPSIS as a secondary approach for validation. Both methods are widely used in technology assessments and sustainable decision-making [43–45]. Step-by-step implementation is described in Refs. [46,47] for WSM, and [43,48] for TOPSIS.

WSM is selected as the primary method because it uses a criteria hierarchy and importance weightings to obtain overall scores for alternatives [44]. The heterogeneous nature of SIs with different measurement units prevents meaningful comparisons merely based on indicator values. Using normalisation and weighted models, WSM effectively captures the relative magnitude of indicators and their trade-offs within the system. Normalised weighted scores are then aggregated into a composite sustainability index (CSI) for each dimension [46,47], which can be summed into an overall sustainability score (CSI^{OA}). This approach consolidates all evaluations into a unified score, enabling overall ranking and interpretations.

Based on this MCDA method, a tailored LCSA workflow specifically for evaluating BHSs is developed (Fig. 1). User inputs define technology alternatives and decision-making parameters, alongside building energy estimates from simulation or benchmarking. These couple with source datasets mentioned in Fig. 1, to supply analyses throughout. The framework then applies quantification methods to conduct E-LCA, S-LCA, and LCC. Results then feed into MCDA, where alternatives are rated on environmental, economic, and social performance, yielding overall sustainability scores.

2.5. Validation method

The decision model's validity must be checked to ensure MCDA robustness. Although various validation techniques exist, including expert evaluation, sensitivity analysis, real-world measurement, and benchmarking, sensitivity analysis offers the most practical approach for this study. This method determines how input parameter changes affect model outputs, identifying critical factors that significantly influence overall sustainability. The outcome can identify unrealistic behaviour, adjust decision parameters, reformulate the model, and help better interpretation of the results [49].

Sensitivity analyses typically encompass three approaches: dynamic analysis (altering criteria weights), performance analysis (changing input parameters), and using different MCDA models [50,51]. All three approaches are utilised here to investigate limitations and uncertainties embedded in the MCDA model.

Dynamic sensitivity analysis illustrates how changing criteria priorities affects outcomes [52], implemented through four scenarios with distinct weighting profiles based on [43]. Performance sensitivity analysis examines how varying system parameters impact final rankings [51]. This analysis targets the most important uncertain parameters, including conversion factors of the energy sources, grid renewable ratio, energy prices, and HP refrigerants. Finally, comparing results between different decision methods validates the rankings [51], which is why TOPSIS is used to verify WSM outcomes. These scenarios, detailed in Table 2, cover all critical model variations.

2.6. Case study

The final step is to demonstrate the framework's functionality and robustness through a case study application. The selected case is a two-floor, three-bedroom, semi-detached house (102 m^2 floor area) in Liverpool. This represents a typical UK single-family dwelling, as nearly half of UK properties share similar size and structure [54]. The building model complies with 2025 standards per Building Regulations Part L1 [55]. Further building specifications are provided in Appendix B, Figure B. 1, Figure B. 2, and Table B. 1.

Eight BHSs representing the most prevalent UK market technologies are evaluated in this study; their configurations are outlined in Table 3. The material composition of each BHS, detailed in Appendix Table B. 2, is another critical input. According to CIBSE TM65 [42], where Environmental Product Declarations (EPDs) are unavailable, whole life carbon is estimated using product weight and material composition. Due to limited BHS data availability, sourcing this data presented a significant challenge, requiring extensive searches across industry databases, manufacturer reports, and comparable product data.

3. Results

3.1. Building energy simulation

Building models are created in the IES-VE 2023, generating hourly heating loads across the full year. These loads are validated against both real-world case data and UK average figures. Appendix Figure C. 1 and Figure C. 2 show monthly and hourly load for space heating and domestic hot water (DHW), calculated based on the building's thermal properties independently from the BHS. Next, the case study building is simulated with eight different BHSs. Fig. 2 illustrates annual energy consumption by end-use type, clearly distinguishing HP-based systems from others, with the gap primarily driven by space heating demand. A breakdown of energy consumption by energy source appears in Appendix Figure C. 3.

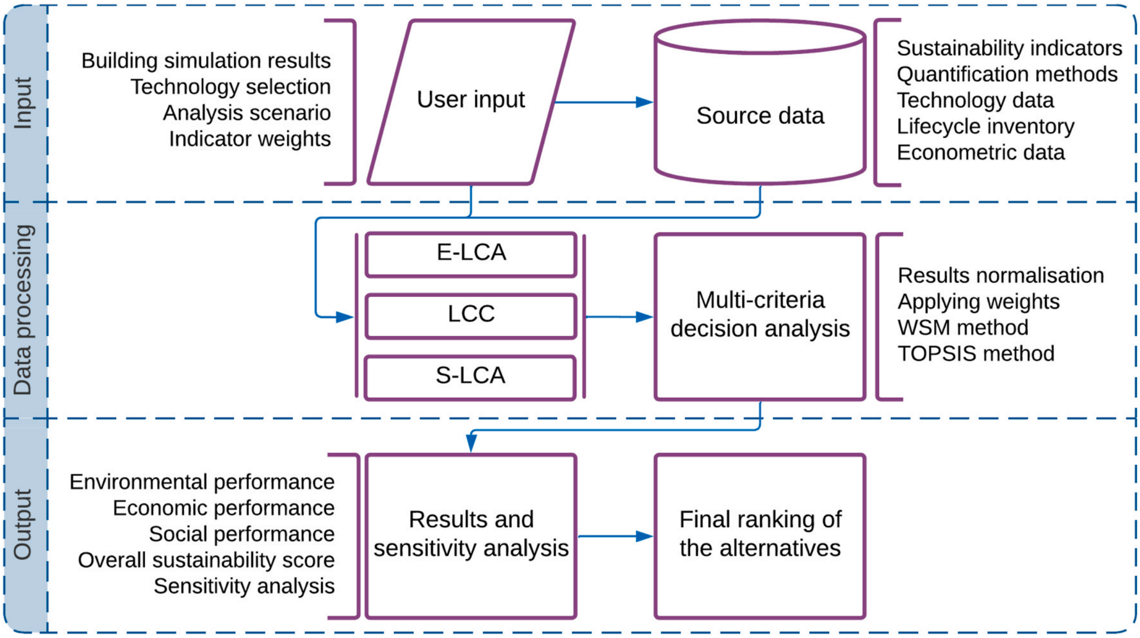


Fig. 1. Architecture of the developed LCSA framework.

Table 2

Sensitivity analysis scenarios.

Method	Code	Scenario	Description	Applied variations
Dynamic analysis	Sce1	Equal dimensions of sustainability	All three sustainability dimensions are weighted equally.	$w_{Env} = 0.33$; $w_{Eco} = 0.33$; $w_{Soc} = 0.33$
	Sce2	Priority of the environmental aspect	Environmental dimension receives highest importance; economic and social dimensions weighted equally.	$w_{Env} = 0.50$; $w_{Eco} = 0.25$; $w_{Soc} = 0.25$
	Sce3	Priority of the economic aspect	Economic dimension receives highest importance; environmental and social dimensions weighted equally.	$w_{Env} = 0.25$; $w_{Eco} = 0.50$; $w_{Soc} = 0.25$
	Sce4	Priority of the social aspect	Social dimension receives highest importance; environmental and economic dimensions weighted equally.	$w_{Env} = 0.25$; $w_{Eco} = 0.25$; $w_{Soc} = 0.50$
Performance analyses	Sce5	Decarbonisation of the power supply	Assumes 2030 grid decarbonisation targets are achieved, with emission and energy factors adjusted accordingly.	$CF^{E}_{Ovr} = 0.10$ kgCO$_{2eq}$/kWh [a]; $r_g = 0.8$[b]
	Sce6	Adjustment of the energy tariffs	Applies 2030 energy prices based on UK Green Book projections.	$UC^{E} = 19.39$ p/kWh; $UC^{NG} = 8.04$ p/kWh; $UC^{WP} = 30.96$ p/kWh[c]
	Sce7	Using refrigerants with low global warming potential (GWP)	Replaces base case R134a refrigerant with R32 in heat pumps.	$GWP_{\mathrm{R134a}} = 1430$ kgCO$_{2eq}$/kg $GWP_{R32} = 677$ kgCO$_{2eq}$/kg
Decision analysis sensitivity	Sce8	Using a different MCDA method	Applies TOPSIS method to cross-check rankings obtained through WSM.	TOPSIS is utilised as the secondary decision analysis approach.

[a] 2030 electricity GHG conversion factor based on Long-run Marginal Projection scenario from UK Green Book supplementary guidance [53].

[b] Grid renewable energy ratio based on UK national grid target of 80% decarbonisation by 2030.

[c] The 2030 prices are based on projected retail energy prices in the Supplementary guidance to Treasury's Green Book [53].

Table 3

Configuration of the studied heating systems.

Heating system	Space heating	Heat distribution	Hot water	Cooking
Gas condensing boiler	Low-temperature gas boiler	Central heating with convector radiators	Gas boiler	Gas
Biomass wood pellet boiler	Low-temperature biomass boiler	Central heating with convector radiators	Biomass boiler	Electricity
Solar thermal + Gas boiler	Photovoltaic thermal (PVT) collector + Gas boiler	Central heating with convector radiators	PVT + gas boiler	Electricity
Direct electric heating + Electric boiler	Electric panel heaters	Local unfanned radiator panels	Electric boiler	Electricity
Air-water HP	Air-water individual HP	Central heating with convector radiators	Air-water HP	Electricity
Air-air HP + Electric boiler	Multi-split air-air HP	Local indoor fan-coil units	Electric boiler	Electricity
Ground-source HP	Ground-source individual HP	Central heating with convector radiators	Ground-source HP	Electricity
Gas hybrid HP	Air-water HP	Central heating with convector radiators	Gas boiler	Electricity

3.2. LCSA results

Building simulation results provide the final essential input for the LCSA framework. Combined with source data (Fig. 1), these enable SI calculations for each BHS. Appendix Table D. 1 presents initial E-LCA, S-LCA, and LCC results before normalisation and applying weights, with colour-coding to aid preliminary comparison. SI values are then converted into dimensionless scale using the distance-based normalisation method [46,47]. After normalisation, expert-derived weighting factors (Table 1) are applied to reflect the importance weights. Appendix Figure D. 1 presents the weighted and normalised SI values on a 0-100 scale, illustrating each indicator's contribution across sustainability dimensions. While these weighted models capture relative magnitudes and trade-offs within each dimension, they do not support an overall interpretation across all SIs collectively.

3.3. Decision analysis results

Decision-making is conducted using the WSM method, which aggregates normalised weighted scores of SIs into composite sustainability indices (CSI) for each dimension and the overall sustainability score (CSI^{OA}) for each technology [46,47]. Table 4 presents the final CSI and CSI^{OA} scores, and Fig. 3 provides a multi-actor visualisation of the MCDA results for the baseline scenario.

The analysis identifies the ground-source heat pump (GSHP) as the preferred alternative, ranking highest across all dimensions except economic sustainability, where gas boilers lead. Results confirm the broader sustainability advantages of HPs, with ground-source variants marginally outperforming air-source systems. Biomass boilers emerge as the least sustainable option, with direct electric systems performing only marginally better. Detailed interpretation of these ratings is provided in Section 4. It should be noted that these findings are specific to this case study and its location and should be interpreted within its defined scope. Also, relying solely on CSI scores for decision-making risks oversimplification, as important trade-offs between individual sustainability criteria may be concealed.

3.4. Sensitivity analysis results

Sensitivity analysis is conducted using eight scenarios defined in Section 2.5, examining the framework's robustness across varying assumptions and parameter values. At first, dynamic sensitivity analysis evaluates the impact of changing sustainability dimension weights. Using the alternative weighting schemes given in Table 2, the WSM is recalculated for each scenario to obtain new scores and rankings, as presented in Fig. 4.

Results demonstrate that weighting changes have minimal impact on final MCDA outcomes. Consistent ranking of top three alternatives (GSHP, air-air HP, and air-water HP) is maintained across all scenarios. However, some variations occur among lower-ranked options. The gas boiler shows high sensitivity to weight changes, fluctuating between ranks 4 and 6 across different weighting scenarios. The biomass boiler consistently ranks as the least attractive option under most scenarios, except when environmental criteria are prioritised.

The next validation approach is the performance sensitivity analysis that examines the key variable parameters. In this paper, three key parameters, the electricity conversion factor, energy prices, and HP refrigerant type, are examined according to Table 2, and the results are given in Fig. 5.

In the case of a decarbonised power supply (Scenario 5), if UK grid

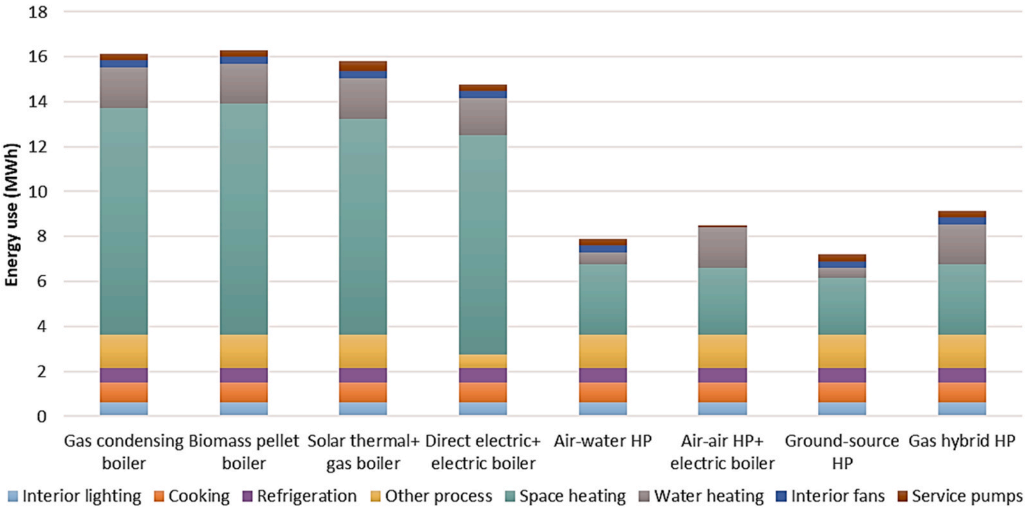


Fig. 2. Building's annual energy consumption broken down by end-use.

Table 4
CSI scores and ranks of alternatives based on the WSM method.

Assessment category	Item	Building heating system							
		Gas condensing boiler	Biomass pellet boiler	Solar thermal + Gas boiler	Direct electric + Electric boiler	Air-water HP	Air-air HP + Electric boiler	Ground-source HP	Gas hybrid HP
E-LCA	CSI^{Env}	0.1448	0.2300	0.1377	0.1522	0.2602	0.2505	0.2813	0.2303
	E-LCA rank	7	5	8	6	2	3	1	4
LCC	CSI^{Eco}	0.3150	0.1535	0.2815	0.1637	0.2536	0.2807	0.2836	0.2391
	LCC rank	1	8	3	7	5	4	2	6
S-LCA	CSI^{Soc}	0.1659	0.1098	0.1875	0.1806	0.2000	0.1942	0.2034	0.1790
	S-LCA rank	7	8	4	5	2	3	1	6
LCSA	CSI^{OA}	0.6257	0.4933	0.6066	0.4966	0.7138	0.7254	0.7683	0.6485
	Overall rank	5	8	6	7	3	2	1	4

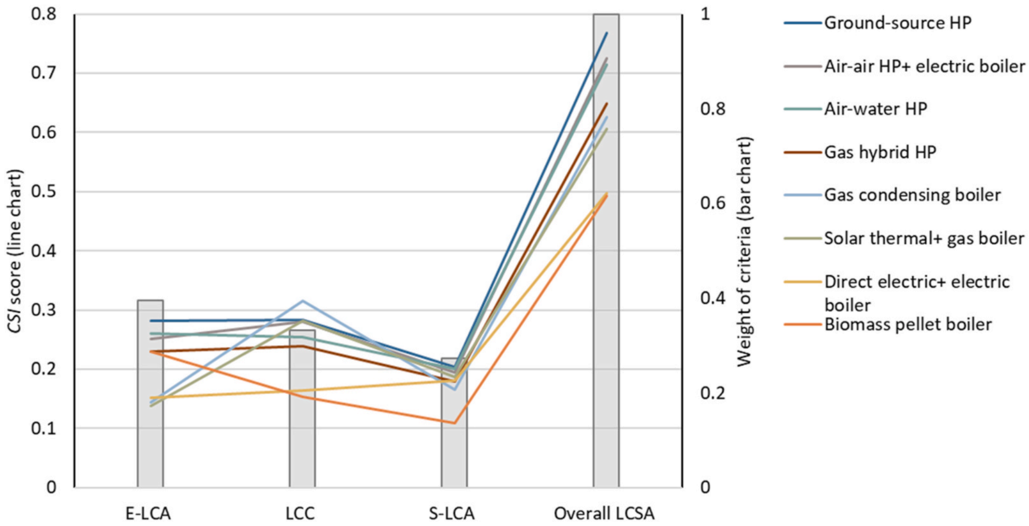


Fig. 3. CSI scores of alternatives and the weight of criteria in the baseline scenario.

emissions decrease from 0.26 kg CO2eq/kWh to the targeted 0.1 kg CO2eq/kWh by 2030, the GSHP's whole life carbon (WLC) footprint would reduce by 51%. This scenario also incorporates increased renewable energy penetration in the national grid. Despite these substantial improvements, technology rankings remained unchanged. In fact, decarbonised electricity supply further strengthens the sustainability advantage of HP technologies.

Under revised energy tariffs (Scenario 6), life cycle costs for GSHPs and air-air heat pumps decrease by 33% and 42% respectively, significantly enhancing their economic competitiveness relative to gas boilers.

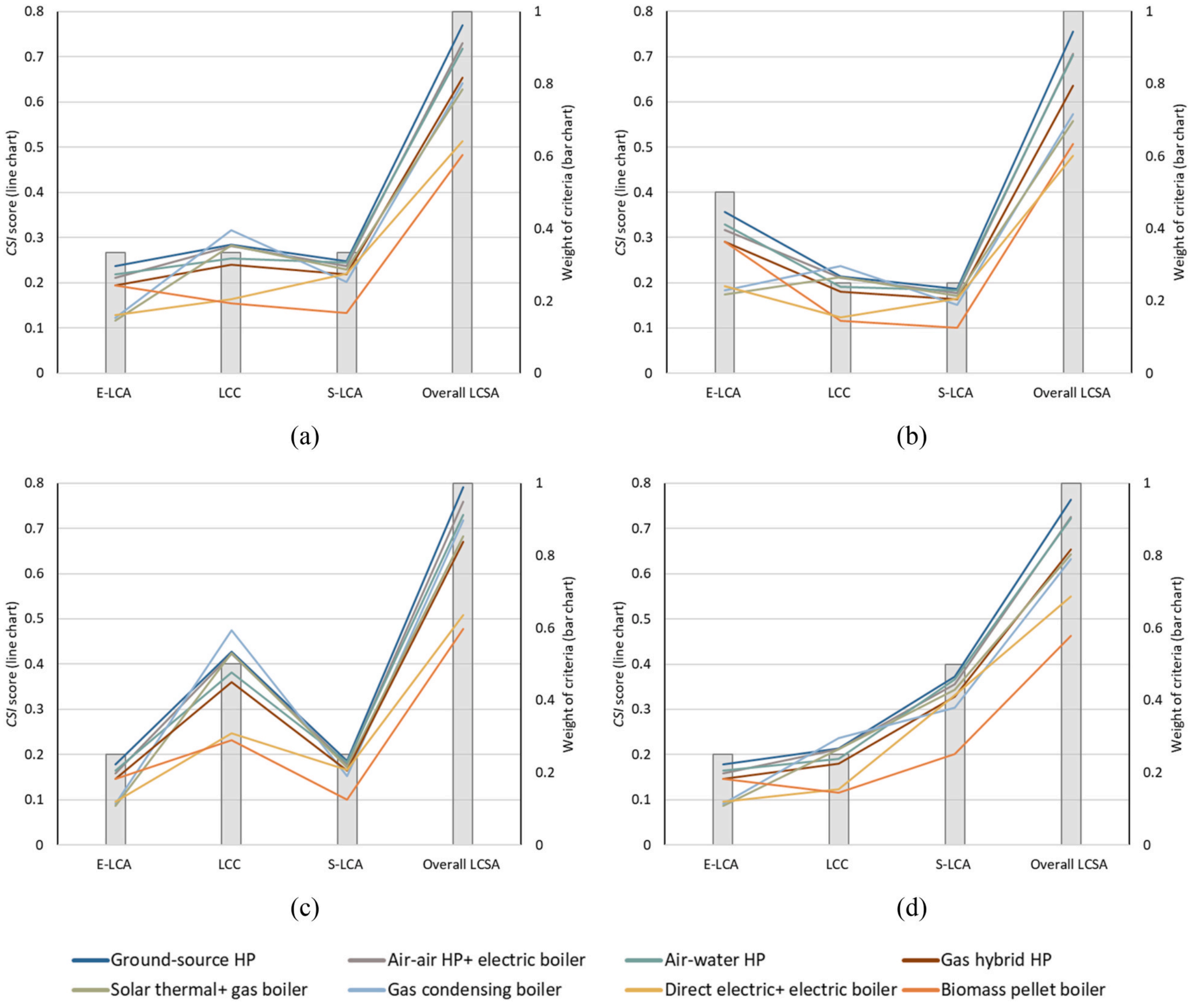


Fig. 4. CSI scores and criteria weights for (a) Scenario 1: Equal weighting; (b) Scenario 2: Environmental priority; (c) Scenario 3: Economic priority; (d) Scenario 4: Social priority.

Energy price changes also significantly reduce fuel poverty risk by approximately 50% for HP-equipped systems, highlighting the critical importance of electricity:gas price ratios for future energy policy. However, despite considerable cost variations, final rankings remain consistent.

The final parameter examined using performance sensitivity analysis is refrigerant impact, which represents a critical factor in embodied carbon calculations. Switching from R134a to R32 (which has 52% lower GWP), in scenario 7, reduces the embodied emissions of the air-water HP by 7%. However, on a scale of the WLC footprint, switching refrigerants reduces the WLC by only 1%, assuming constant leakage rates throughout the technology's lifespan. This small impact is barely reflected in the E-LCA scores and does not affect the alternative rankings.

Finally, decision model validity is assessed using TOPSIS as an alternative MCDA method. Following the TOPSIS methodology [43,48], decision analysis elements are calculated and presented in Table 5. TOPSIS scores lead to some ranking variations compared to WSM results, i.e. rank reversals between the 1st and 2nd alternatives, and between the 3rd and 4th positions. Despite these differences, both methods consistently favour HP-based alternatives over gas- or biomass-based systems.

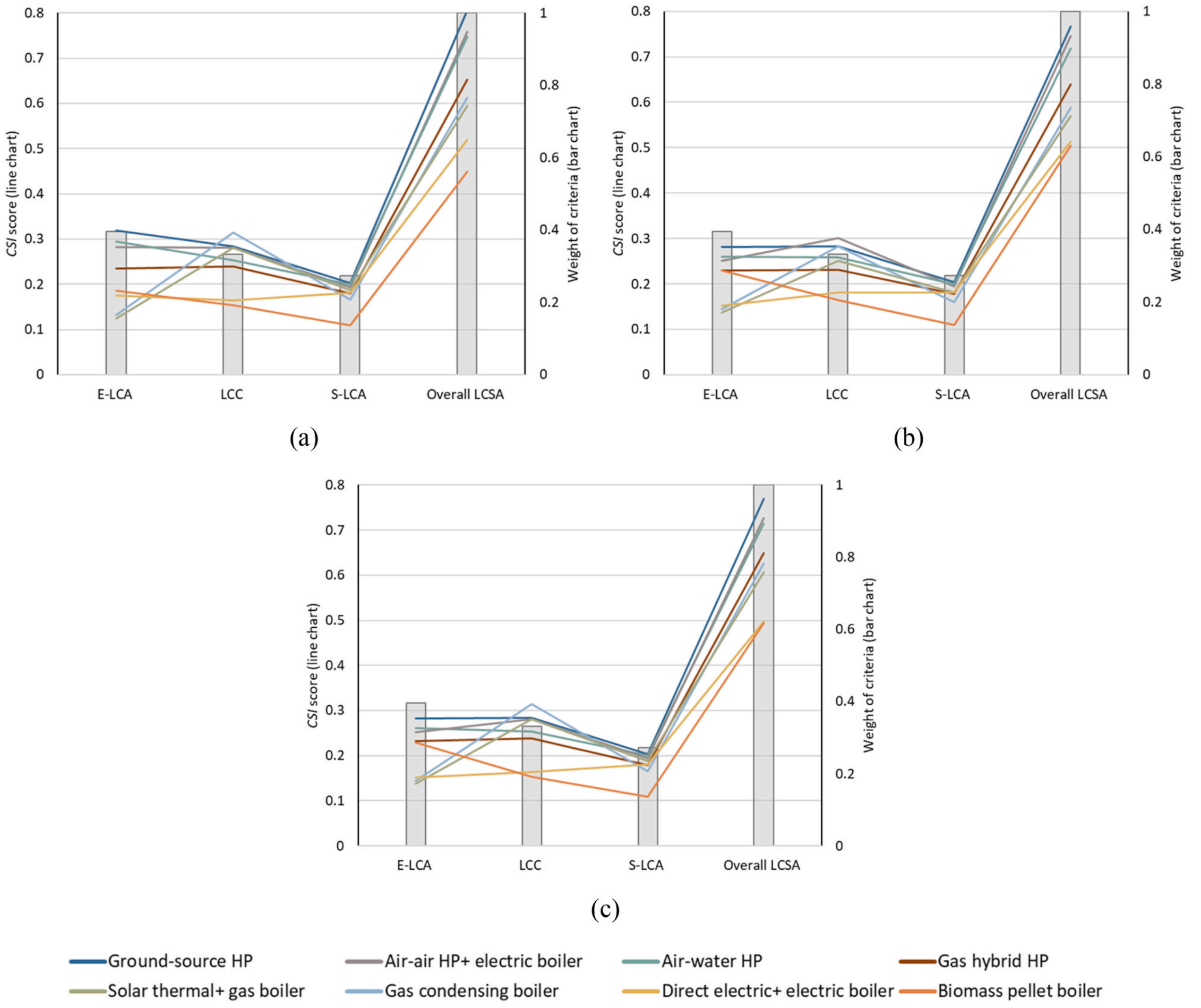
For this study, WSM is prioritised over TOPSIS for two key reasons. First, the assessment framework employs a two-level hierarchical structure comprising main criteria (sustainability dimensions) and sub-criteria (sustainability indicators). WSM proves well-suited to hierarchical problems because it processes weights at each level separately, enabling meaningful analysis of significant factors within each level while avoiding the bias where main criteria weights implicitly depend on sub-criteria quantity [56]. TOPSIS, however, treats all criteria at a single analytical layer, without recognising hierarchical relationships. Second, using WSM, introducing or removing alternatives does not affect the relative rankings of remaining options [57].

4. Discussion

4.1. Insights into heating systems

The sustainability assessment reveals significant trade-offs between sustainability indicators across BHS alternatives. While WSM provides a straightforward aggregation approach, it obscures the specific strengths and limitations of each technology. Disaggregated SI results offer better insights into critical trade-offs between indicators in individual BHSs, enabling more nuanced comparisons between them. Fig. 6 illustrates the contribution of each SI to the final CSI score on a polar graph for each heating system, revealing the underlying performance patterns that drive the overall rankings.

GSHPs emerge as the most sustainable heating system overall,



(a)

(b)

(c)

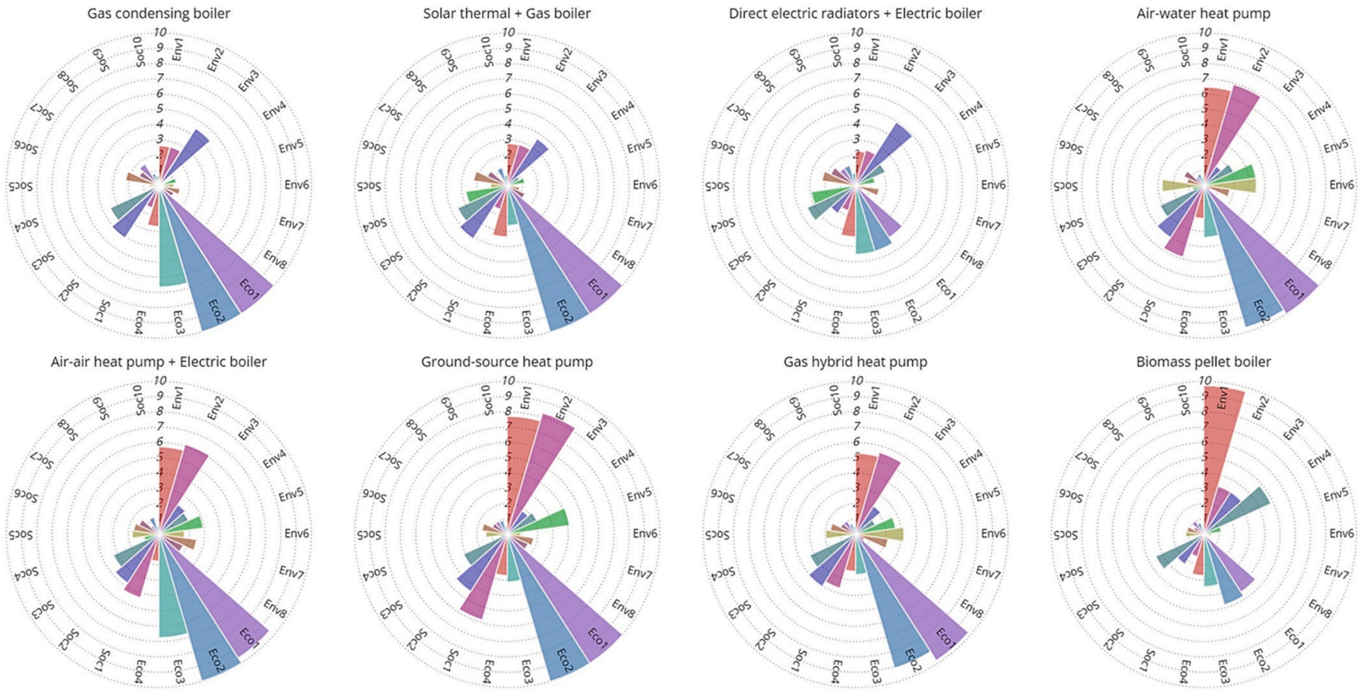
Fig. 5. CSI scores and criteria weights for (a) Scenario 5: Decarbonised grid; (b) Scenario 6: Adjusted energy prices; (c) Scenario 7: Lower-GWP refrigerants.

Table 5
Scores and ranks of alternatives based on the TOPSIS method.

TOPSIS elements	Description	Building heating system							
		Gas condensing boiler	Biomass pellet boiler	Solar thermal + Gas boiler	Direct electric + Electric boiler	Air-water HP	Air-air HP + Electric boiler	Ground-source HP	Gas hybrid HP
Si^+	**Euclidean distance from the ideal best**	0.0529	0.0941	0.0485	0.0882	0.0358	0.0260	0.0326	0.0337
Si^-	**Euclidean distance from the ideal worst**	0.1016	0.0589	0.1002	0.0765	0.1053	0.1058	0.1092	0.1012
CD_i	**Closeness degree**	0.6576	0.3848	0.6740	0.4644	0.7460	0.8026	0.7702	0.7503
Rank	**TOPSIS rank**	6	8	5	7	4	1	2	3

consistent with some previous research [58,59]. They demonstrate 40% higher efficiency and 26% lower operational carbon than air-air HPs. Compared to gas boilers, they rank competitively in terms of economic performance and deliver 73% lower health impacts. Despite this strong performance, GSHPs face significant adoption barriers in single-family houses, including high upfront costs, substantial land requirements for ground loops, and technical restrictions related to excavation and soil conditions. This highlights an important limitation of the current framework: technical feasibility is not explicitly captured within the TBL dimensions. While this framework evaluates environmental, economic, and social performance, technical constraints can rule out theoretically optimal solutions, suggesting it should be considered as a fourth dimension in future holistic assessments.

Air-air HPs emerge as the second most sustainable option for the case study building. Their main advantages are competitive costs with gas boilers, along with rapid and targeted climate management, resulting in better thermal comfort for individual spaces. However, these systems are less popular in UK houses, partly because they do not supply hot water and require supplementary boilers. This reflects the historic prevalence of central heating in Britain, where 74% of households in England and Wales rely on gas central heating [60]. Their limited uptake was also compounded by a lack of government financial support; until the expansion of the Boiler Upgrade Scheme in November 2025, air-air HPs were effectively excluded from any support schemes, limiting their



Gas condensing boiler

Solar thermal + Gas boiler

Direct electric radiators + Electric boiler

Air-water heat pump

Air-air heat pump + Electric boiler

Ground-source heat pump

Gas hybrid heat pump

Biomass pellet boiler

Fig. 6. Breakdown of SI contributions to overall CSI scores.

role in the heat transition for several years.

For houses with existing central heating infrastructure, air-water HPs represent a more natural technological fit. These systems can be retrofitted as standalone units, though at higher upfront costs than air-air alternatives. They perform well socially, achieving 68% lower health impacts and 345% higher job creation compared to gas boilers. However, valid concerns remain regarding thermal comfort, noise, and public acceptance [61]. Air-water HPs can also operate in hybrid configurations alongside gas boilers, which the Committee on Climate Change views as a viable transitional pathway [62]. This study challenges that view; the findings show hybrid systems perform worse than standalone HPs across all sustainability dimensions in the long term.

Direct electric systems do not represent a viable low-carbon alternative. This analysis shows their environmental footprint is not significantly better than gas boilers, and some research suggests direct electric boilers can yield higher life cycle carbon than gas boilers where renewable electricity generation is limited [63]. From the end-user perspective, advantages like low upfront cost, decent reliability, and minimal visual impact are undermined by high operational costs. Despite being widely adopted as an electrification measure in UK new-build flats, these systems impose significant economic and social burdens on future householders and do not represent a long-term solution for heating electrification.

Supplementary solar thermal performs poorly in this study. Adding PVT panels to gas-based systems imposes additional upfront costs without yielding significant benefits, achieving only around 4.5% carbon savings over a 25-year lifespan. This is largely attributable to poor solar intensity at the case study location, and also the fact that for residential purposes sunshine and heat demand coincide poorly. These systems may perform better in higher solar gain regions [64], but the evidence here suggests limited value for typical UK households.

The findings regarding biomass boilers are unexpected, as this system emerges as the least attractive option under most scenarios. The most critical issues are high operational costs and elevated emissions of PM, SO_2, and NOx, resulting in adverse health impacts and ecosystem acidification, consistent with Yang et al. [64] and Nyborg and Røpke [65]. Their emission performance could potentially improve through advanced emission controls such as scrubbers and catalytic converters. Biomass systems also carry substantial land-use implications, potentially competing with agricultural land and crop cultivation. That said, this technology performs well in terms of whole life carbon, suggesting it may remain a viable low-carbon option in specific circumstances, such as off-grid rural locations.

4.2. *Insights into environmental performance*

In response to the long-standing scholarly debate about HPs environmental impact compared to gas boilers [58,66], this analysis demonstrates that HPs achieve the lowest overall environmental impact. In terms of operational emissions, the assessed HPs achieve substantial reductions by 66%, declining from 2.7 tCO_2eq for conventional gas boilers to 0.92 tCO_2eq for GSHP installations. Whereas the embodied carbon footprint of HPs substantially exceeds that of gas boilers, climbing to 5.4 tCO_2eq for air-water variants (198% increase compared to gas boilers) due to their complex material content and refrigerant use.

Whole life carbon (WLC) offers a fairer comparison by aggregating both embodied and operational emissions. Fig. 7 shows biomass boilers achieve the largest WLC reduction (71%), followed by GSHPs (61%) and air-water HPs (56%) over 25 years. However, sensitivity analysis shows HPs can outperform biomass if 2030 grid decarbonisation targets are met. PVT-assisted and direct electric systems carry the highest lifetime carbon burden, driven by grid electricity reliance.

4.3. *Insights into economic performance*

HP's economic superiority is not evident under current tariffs. Baseline scenario analysis shows most low-carbon alternatives carry higher running costs, except GSHPs and solar-assisted systems, which save up to £142 annually (8% reduction). Low-carbon options also generally require higher upfront investment [31], with air-air HPs being the exception. NPV analysis over 25 years (Fig. 8) provides a clearer picture: GSHPs (£34 k) and PVT-assisted systems (£35 k) carry the lowest long-term financial burden, only marginally above gas boilers (£33 k), while biomass (£82 k) and direct electric (£77 k) systems represent the worst financial outcomes.

Another finding is obtained through the sensitivity analysis (scenario

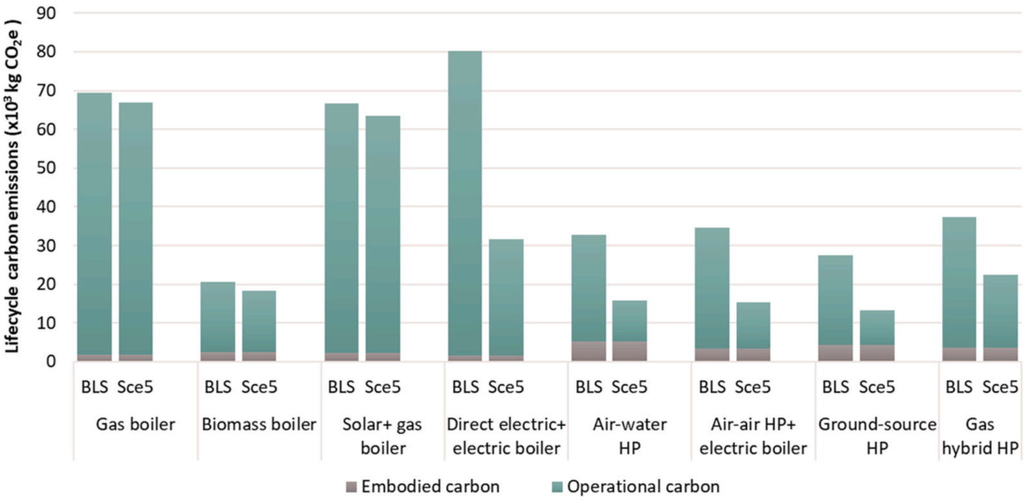


Fig. 7. WLC of heating systems under the baseline scenario (BLS – current grid) and scenario 5 (Sce5 – 2030 decarbonised grid).

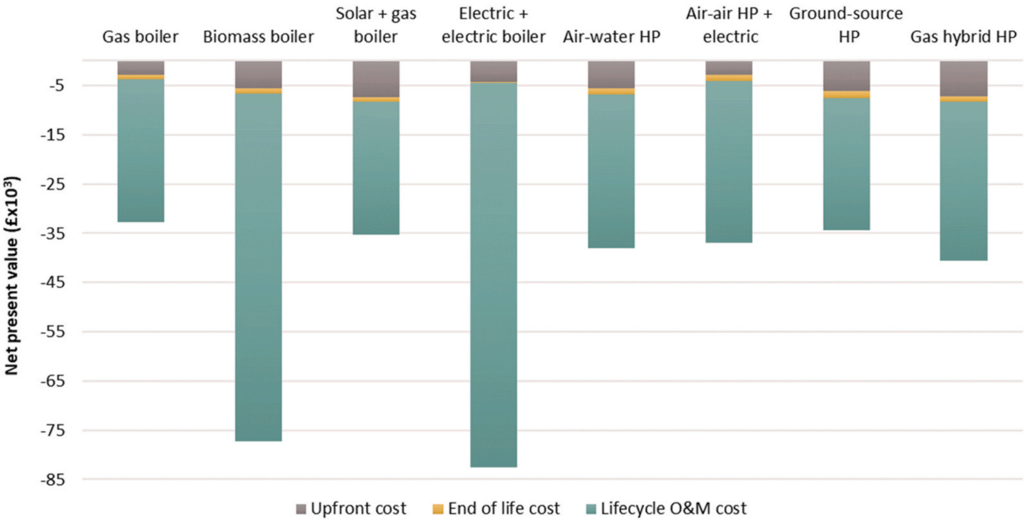


Fig. 8. Net present value of the heating systems (life cycle cost over 25 years).

6) where the electricity:gas price ratio emerges as a critical factor in HP economic viability. Historically, UK electricity tariffs have been considerably higher than gas prices, creating a barrier to heating decarbonisation [67]. For air-water HPs, the breakeven ratio is 2.9; above this level, this technology becomes more expensive to operate than gas boilers. At the current ratio of approximately 3.4 (based on 2024 pricing), HPs can hardly offer any economic advantage without subsidies. Reducing this ratio is therefore essential to improving the financial case for electrified heating.

4.4. Insights into social performance

The main reflection from the social perspective is the vital role this aspect plays in shaping equitable transition pathways, yet it is frequently overlooked. Biomass boilers illustrate this well; despite reasonable environmental performance, poor reliability, usability, and significant NOx, PM2.5, and SO2 health impacts push them to last place in overall sustainability. In contrast, social factors strengthen HPs' rankings considerably. Each air-water HP creates 0.005 jobs, 4.5 times more than gas boilers. With the government targeting 600,000 HP installations per year by 2028 [68], air-water HPs alone could generate approximately 3000 jobs annually in residential applications.

The social consequences of low-carbon transitions can be managed through careful, proactive design. Integrating social factors as design parameters enables early identification of potential impacts on households at early stages. For instance, fuel poverty is explicitly defined here as an SI, analysed alongside environmental and economic parameters. This ensures that decision makers can check that their designed decarbonisation interventions do not deepen energy deprivation for vulnerable households and enables more informed and targeted interventions.

5. Conclusion

Despite heating's pivotal role in achieving net-zero targets, existing literature lacks a robust framework for evaluating heating system sustainability in buildings. This gap stems from inconsistent representation of sustainability dimensions, neglect of stakeholder perspectives, and disregard for life cycle impacts at the household and community level. Building heating systems also have particularly close links with end-users, creating broader health, comfort, and well-being impacts that are often overlooked in heat transition interventions. This study addresses these gaps by combining multi-criteria analysis, life cycle assessment, and participatory approaches into a unified sustainability assessment framework.

In response to the first research objective, the proposed framework advances existing studies by encompassing E-LCA, S-LCA, and LCC, processed through MCDA models to deliver a life cycle, multi-dimensional sustainability assessment. This enables trade-offs between environmental, economic, and social costs and benefits while reflecting stakeholder priorities. Through sensitivity analysis, key uncertainties in the LCSA model are explored and critical interactions between indicators identified.

Applied to eight prevalent BHSs in a typical UK house, results show no single technology achieves superiority across all sustainability dimensions, explaining why no alternative is likely to dominate the market as gas boilers do today. HP-based systems are identified as the most favourable overall, with GSHPs demonstrating the best sustainability performance. Air-water and air-air HPs also rank competitively, with clear environmental and social benefits, though challenging economic viability under current tariffs. HPs' performance depends critically on the electricity:gas price ratio and on continued grid decarbonisation, underlining the interconnected nature of heating electrification with broader energy systems. Direct electric systems and biomass boilers prove least sustainable, failing to mitigate environmental impacts while inflating household costs. While the framework offers a methodology applicable to various contexts, these findings are specific to this UK case study. Applying them to other locations, building types, or market conditions requires adjusted input data and re-evaluation.

This study offers key recommendations to practitioners and policymakers, emphasising that multidisciplinary, participatory, and life cycle approaches are crucial for sustainable design and decision-making. Low-carbon technologies should be viewed as complementary components of a future energy system, requiring more comprehensive and targeted support schemes tailored to diverse household demands, building types, and local conditions. Current schemes such as the Boiler Upgrade Scheme do not serve all households and technologies, highlighting the need for broader policy approaches coupled with continued reduction of the electricity:gas price ratio to accelerate the transition from gas heating.

Regarding limitations, the SIs and their weights are validated for the UK context and may not fully reflect the nuances of other regions or application types; broader stakeholder engagement would be needed to derive context-specific weightings elsewhere. It should also be acknowledged that social sustainability is inherently complex, such as physiological and psychological differences between households, which make it difficult to fully capture through simple metrics. Nonetheless, the proposed method facilitates the integration of key social factors into early design and decision-making stages, supporting a shift from reactive to proactive approaches. Finally, data scarcity and inconsistencies across BHS life cycle inventories remain a persistent challenge, reinforcing the importance of engaging supply chains and encouraging manufacturers to provide EPDs.

Future research should expand this framework to evaluate heating transitions at larger scales, incorporating macro-level factors such as energy security and infrastructure capacity. Technical factors, such as technology integrability in existing homes, should also be included in evaluations. Technical constraints can rule out theoretically optimal solutions under the TBL framework, suggesting technical feasibility should be considered as a fourth dimension in future assessments. Finally, this study contributes to the growing recognition that social sustainability and energy justice are foundational to energy research and policy, supporting a paradigm shift towards more transdisciplinary and people-focused approaches.

CRediT authorship contribution statement

Mohammad Hosein Abbasi: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Waseem Ahmad:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Badr Abdullah:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Ali Rostami:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Raúl Castaño-Rosa:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Claude (Anthropic) to assist with summarisation and language refinement. The authors reviewed and edited all the content and take full responsibility for the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices.

A. Sustainability indicators

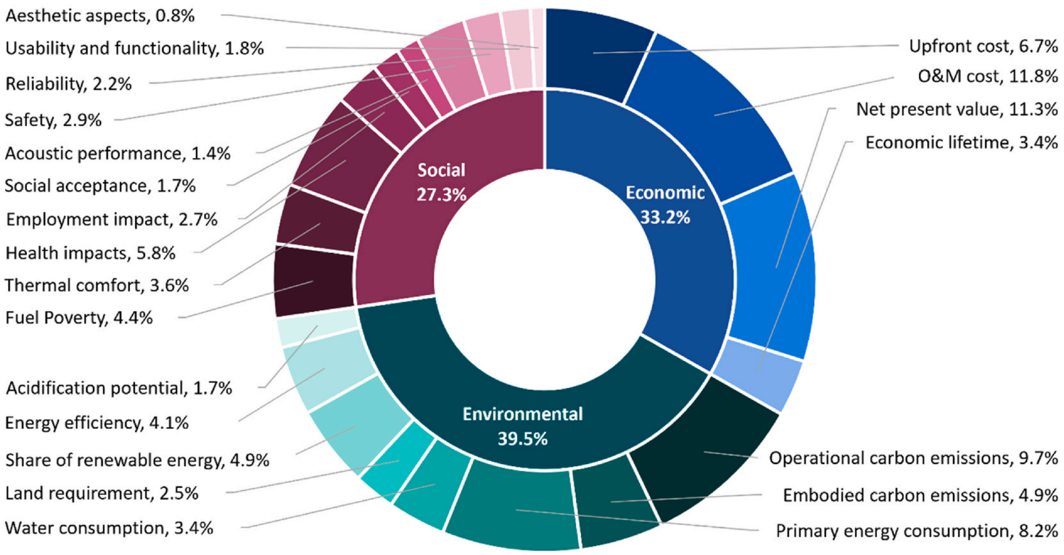


Figure A. 1 Selected sustainability indicators and their importance weight [33]

Table A. 1
Quantification methods for the sustainability indicators

Indicator	Description	Index (unit)	Quantification method	Notes
Operational carbon emissions	Operational GHG emissions of the heating system over its service life.	OCE ($kgCO_{2eq}$/year)	$OCE = EC_{BHS}.CF^{E}_{Ovr} + FC_{BHS}.CF^{F}_{Ovr}$	EC_{BHS}: Annual electricity consumption of the BHS (building energy model) FC_{BHS}: Annual fuel consumption of the BHS (building energy model) CF^{E}_{Ovr}: Electricity conversion factors (Table A. 2) CF^{F}_{Ovr}: Fuel conversion factors (Table A. 2)
Primary energy consumption	Annual energy demand measured in its raw, untransformed state prior to any conversion processes.	PEC (kWh/year)	$PEC = EC_{BHS}.PEF^{E} + FC_{BHS}.PEF^{F}$	PEF^{E}: Electricity primary energy factor (Table A. 2) PEF^{F}: Fuel primary energy factor (Table A. 2)
Embodied carbon emissions	GHG emissions from manufacturing, transportation, installation, and end-of-life disposal of the heating system.	ECE ($kgCO_{2eq}$)	$ECE = \left[\left(\sum_j M_j.ECC_j + 0.1 \times \sum_j M_j.ECC_j\right) \times f_s \times f_b \times HC_{BHS}\right] + [RC \times GWP_R \times LR \times N] + [RC \times GWP_R \times (1 - RR)]$	M_j: Weight of BHS material (Table B. 2) ECC_j: Embodied carbon coefficient (Table B. 2) HC_{BHS}: BHS heating capacity (building energy model) f_s: Scale-up factor (Table A. 3) f_b: Buffer factor (Table A. 3) RC: Refrigerant charge (Table B. 2) GWP_R: Refrigerant global warming potential [42] LR: Annual leakage rate (Table A. 3) RR: Refrigerant end-of-life recovery rate (Table A. 3) N: Product service life (Table A. 5)
Share of renewable energy	Ratio of consumed energy from renewable sources to the total energy consumption.	SOR (−)	$SOR = \frac{E_{sol} + E_{bio} + E_{geo} + (EC_{BHS}.r_g)}{E_{Tot}}$	E_{sol}: Total energy input from solar E_{bio}: Total energy input from biofuels E_{geo}: Total energy input from geothermal E_{Tot}: Total energy consumption r_g: Renewable energy ratio of the national grid, averaging 51% during 2024 [69]
Energy efficiency	Ratio of produced heat to the total energy consumption.	OE (−)	$OE = \frac{H_{Gen}}{E_{Tot}}$	H_{Gen}: Total heat generated (building energy model)
Water consumption	Freshwater consumption during the overall life cycle of the heating system.	FWC (m^3)	$FWC = HC_{BHS}.WCC$	WCC: Water consumption coefficient (Table A. 4)

(continued on next page)

Table A. 1 (*continued*)

Indicator	Description	Index (unit)	Quantification method	Notes
Land requirement	Direct and indirect land use of the heating technology over its life cycle.	*LR* (m^2)	$LR = HC_{BHS}.LRC$	*LRC*: Land requirement coefficient (Table A. 4)
Acidification potential	Embodied emissions of acidifying substances from energy consumption of the heating system.	*AP* ($kgSO_{2eq}$/year)	$AP = HC_{BHS}.APC$	*APC*: Acidification potential coefficient (Table A. 4)
Operation and maintenance cost	Annualised life cycle costs associated with labour, energy, services, and maintaining the heating system.	*OMC* (£/year)	$OMC = \sum_{t=1}^{N}\left(\frac{OC_t + MC_t}{(1+r)^t}\right) \times CRF(r,N)$	OC_t: Total operational cost (building energy model) MC_t: Total maintenance cost (Table A. 5) $CRF(r,N)$: Capital recovery factor [70] r: Real discount rate
Net present value	Value of capital cost plus all future operating costs over the entire life of the system discounted to the present.	*NPV* (£)	$NPV = UC + \sum_{t=1}^{N}\left(\frac{OC_t + MC_t}{(1+r)^t}\right) + \frac{C_{EoL}}{(1+r)^N}$	*UC*: Upfront cost C_{EoL}: End-of-life costs (Table A. 5)
Upfront cost	Costs related to the procurement, installation and commissioning.	*UC* (£)	$UC = HC_{BHS} \times TC$	*TC*: Technology unit cost per kW of heat capacity (Table A. 5)
Economic lifetime	Expected operational lifespan of the heating system before replacement is required.	*EL* (year)	Directly from database	Table A. 5
Health impacts	Public health costs associated with air pollution and particulate matter emissions during system operation.	*HI* (£)	$HI = \sum_{t=1}^{N}\frac{EC_{BHS}.{AC^E}_t + FC_{BHS}.{AC^F}_t}{(1+r')^t}$	AC^E: Activity cost of electricity (Table A. 6) AC^F: Activity cost of fuel (Table A. 6) r': Health discount rate [53]
Fuel poverty	Likelihood that the heating system will expose households to fuel poverty.	E_i (−)	$E_i = \frac{EEC_i}{ECT_{t_{(i)}}}$	EEC_i: Equivalised energy cost [37] $ECT_{t_{(i)}}$: Energy cost threshold [37]
Thermal comfort	Annual percentage of occupied hours during which the system maintains comfortable thermal conditions.	*TCI* (%)	$TCI = \frac{\sum_{t=1}^{8760}(fc,h_o)_t}{\sum_{t=1}^{8760}h_{ot}} \times 100$	(fc,h_o): Total comfort hours in a year (building energy model) h_o: Total occupied hours in a year
Safety	Total frequency of potential fatal accidents associated with the heating system.	*SI* (No./year)	$SII = \sum_S H_{GenS} \times FFR_S$	FFR_S: Fatality frequency rate for the heat source (Table A. 7)
Employment impact	Number of full-time equivalent (FTE) jobs created per unit of annual energy production.	*EI* (FTE/year)	$EI = \sum_S H_{GenS} \times EF_S$	EF_S: Employment factor for the heat source (Table A. 7)
Reliability	System's capacity to perform as designed under stated conditions for a specified duration.	*RI* (Likert scale)	Semi-quantitative metric	Table A. 8
Usability and functionality	Ease with which end-users can understand, operate, and adjust the system.	*UI* (Likert scale)	Semi-quantitative metric	Table A. 8
Social acceptance	Level of public preference and willingness to adopt the heating system.	*SA* (Likert scale)	Semi-quantitative metric	Table A. 8
Acoustic performance	Noise level of the heating system for surrounding residents.	*NL* (dB(A))	Directly from database	Table A. 8
Aesthetic aspects	Perceived visual impact of the heating system and its aesthetic compatibility with the surrounding environment.	*AI* (Likert scale)	Semi-quantitative metric	Table A. 8

Table A. 2
Fuel conversion factors and primary energy factors [71,72].

Energy source	Fuel conversion factor ($kgCO_{2eq}$/kWh)	Primary energy factor (kWh/kWh)
Electricity	0.2348	1.501
Natural gas	0.2026	1.130
Biomass wood pellets	0.0113	1.037

Table A. 3
Calculation elements for embodied carbon emissions [42].

Scale-up factor (f_s)	Buffer factor (f_b)	Annual leakage rate (LR)	Refrigerant end-of-life recovery rate (RR)
1.6	1.3	2%	99%

Table A. 4
Heating technology data for environmental indicators [56,73–77].

Heating technology	Water consumption coefficient (m^3/kW)	Land requirement coefficient (m^2/kW)	Acidification potential coefficient ($kgSO_{2eq}$/kW)
Gas condensing boiler	3.77	20	1.9
Biomass wood pellet boiler	7.43	400	8.69
Solar thermal heater	6.65	40	1.89
Direct electric radiator	17.50	20	5.23
Direct electric boiler	15.45	10	0.39
Air-water individual HP	3.24	50	14.10
Air-air individual HP	1.51	50	5.63
Ground source individual HP	15.5	60	5.11

Table A. 5
Heating systems data for economic indicators [31,78–80].

Heating system	Technology unit cost (£/kW)	Maintenance cost (£/year)	Replacement cost (£)	Typical lifetime (year)
Gas condensing boiler	207.6	160.7	1860	20
Biomass wood pellet boiler	400.9	319.6	2500	20
Solar thermal + gas boiler	537.4	55.6	2150	25
Direct electric + electric boiler	312.5	21.2	500	25
Air-water individual HP	1235.7	244.6	3000	16
Air-air individual HP + electric boiler	630.1	132.4	3000	13
Ground source individual HP	1648.7	242.8	3500	20
Gas hybrid HP	1557.1	316.1	2500	18

Table A. 6
Air quality activity costs for energy sources [53].

Energy carrier	Activity cost (p/kWh)
Electricity	0.14
Natural gas	0.15
Biomass	3.50

Table A. 7
Heating technology data for safety and employment indicators [81–85].

Heating technology	Fatality frequency rate (no./GWh.year)	Employment factor (FTE/GWh.year)
Gas condensing boiler	0.06790	0.11
Biomass wood pellet boiler	0.01490	0.21
Solar thermal heater	0.00025	0.23
Direct electric radiator	0.00050	0.05
Direct electric boiler	0.00020	0.05
Air-water individual HP	0.00100	0.49
Air-air individual HP	0.00100	0.49
Ground source individual HP	0.00174	0.25

Table A. 8
Heating technology data for other social indicators [56,64,73,76,77,83,86–90].

Heating system	Reliability indicator	Usability indicator	Acceptability indicator	Noise level (dB(A))	Aesthetic indicator
Gas condensing boiler	4	4	5	50	4
Biomass wood pellet boiler	2	2	3	55	2
Solar thermal + gas boiler	4	4	1	55	3
Direct electric + electric boiler	4	5	4	31	5
Air-water individual HP	2	4	2	54	3
Air-air individual HP + electric boiler	3	4	2	37	3
Ground source individual HP	3	3	3	46	3
Gas hybrid HP	3	3	3	60	3

B. Case study and heating systems

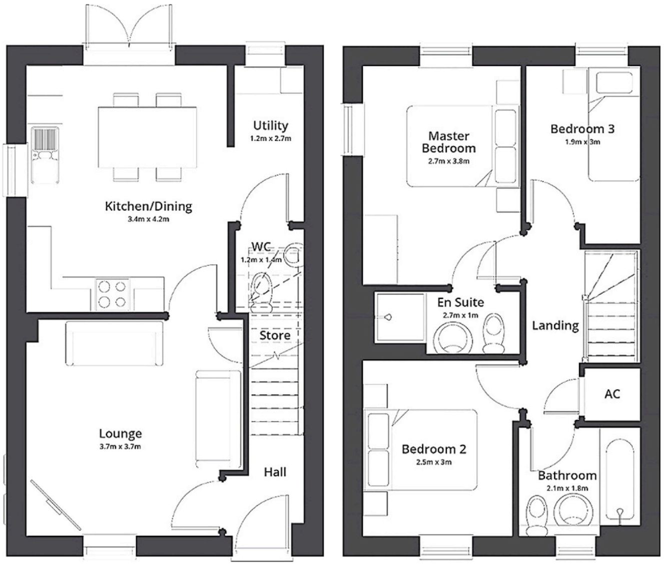


Fig. B. 1. Floor plans of the case study building

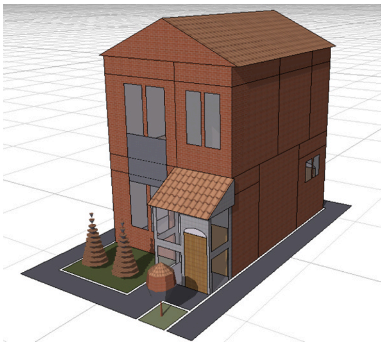


Fig. B. 2. Case study building model in IES-VE

Table B. 1
Thermal and physical properties of the case study building

Item	U value (W/m^2·K)	Thickness (mm)	Area (m^2)
Internal floor/ceiling	0.929	92	59.84
External door	1.897	45	5.38
External windows	1.106	28	28.71
Ground/Exposed floor	0.117	300	59.84
Internal partition/wall	1.594	105	91.45
External roof	0.117	202	70.83
External wall	0.155	286	215.97

Table B. 2
Material composition of the building heating systems [42,47,58,73,91–96].

Material (kg/kW)	Embodied carbon coefficient (kgCO$_{2eq}$/kg)	Heating source technologies						
		Gas condensing boiler	Biomass wood pellet boiler	Solar thermal heater	Direct electric radiator	Direct electric boiler	Air source individual HP	Ground source individual HP
ABS	3.76	-	-	-	-	0.06	-	-
Aluminium	13.10	0.75	-	1.1	0.13	-	5.5	3.2
Brass	4.80	0.05	-	-	-	0.06	-	-
Copper	3.81	0.3	0.2	3	0.18	0.7	1.25	2.2
Expanded polystyrene	3.43	-	0.72	-	-	0.13	-	-

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Table B. 2 (*continued*)

Material (kg/kW)	Embodied carbon coefficient ($kgCO_{2eq}$/kg)	Heating source technologies						
		Gas condensing boiler	Biomass wood pellet boiler	Solar thermal heater	Direct electric radiator	Direct electric boiler	Air source individual HP	Ground source individual HP
Glass	1.44	-	-	0.8	-	-	-	-
Insulation (elastomere, etc)	1.86	0.89	-	1.31	-	-	1	4
Polyethylene (PE)	2.54	-	0.22	-	0.27	0.47	1	5
Polyurethane foam	4.55	-	-	-	-	1.7	-	-
Polyvinylchloride (PVC)	3.10	-	-	4.7	-	-	-	0.1
Stainless steel	4.40	0.5	1.2	1.15	2.36	0.66	3.6	4
Steel (low-alloyed or galvanised)	2.97	11.5	19.72	4.75	4.36	6.4	10.1	7.5
Electronic components	49.00	0.15	0.18	0.2	0.5	0.5	1	1
Refrigerant (R-134a)	-	-	-	-	-	-	0.192	0.205

C. Energy simulation results

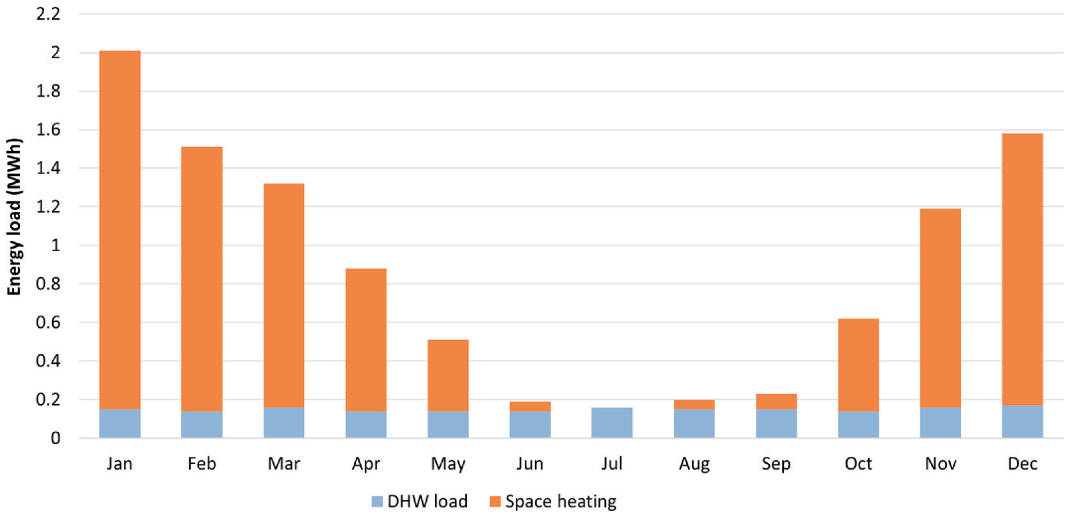

Fig. C. 1. Monthly energy consumption for space heating and DHW

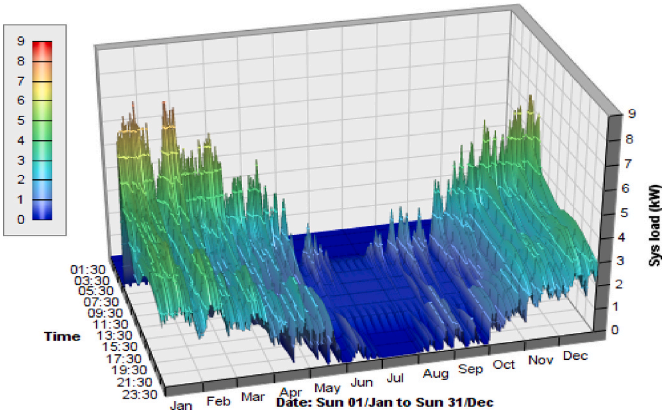

Fig. C. 2. Hourly heating load of the case study

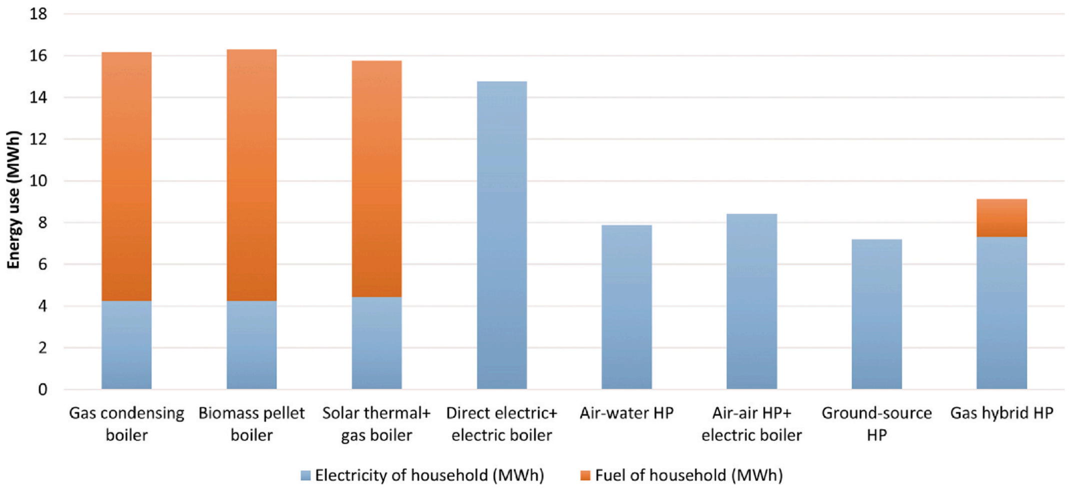

Fig. C. 3. Annual energy consumption of BHSs by the source of energy

D. Sustainability assessment results

Table D. 1
Initial values of the sustainability indicators

Sustainability indicators		Unit	Building heating systems							
			Gas condensing boiler	Biomass pellet boiler	Solar thermal + gas boiler	Direct electric + electric boiler	Air-water HP	Air-air HP + electric boiler	Ground-source HP	Gas hybrid HP
Environmental	Operational carbon emissions	$kgCO_{2eq}$/year	2700.93	730.53	2576.70	3146.81	1099.32	1243.56	920.24	1343.51
	Primary energy consumption	kWh/year	16385.36	13384.97	15611.97	18062.58	6310.05	7138.01	5282.17	7845.33
	Embodied carbon emissions	$kgCO_{2eq}$	1792.71	2449.57	2202.60	1622.10	5357.42	3505.55	4427.69	3679.56
	Share of renewable energy	-	0.02	0.97	0.18	0.43	0.43	0.43	0.43	0.29
	Energy efficiency	-	0.87	0.86	0.87	0.95	2.58	2.20	3.09	1.99
	Water consumption	m^3	52.22	104.04	109.19	234.38	14.82	30.66	57.89	16.09
	Land requirement	m^2	277.02	5601.00	480.20	253.05	228.75	156.93	224.10	182.18
	Acidification potential score	$kgSO_{2eq}$/year	26.32	121.68	22.51	61.87	64.51	16.41	19.09	44.90
Economic	O&M cost	£/year	1764.05	4283.00	1639.98	4739.61	1892.95	1997.03	1622.64	1960.05
	Net present value	£	−32736.81	−77261.77	−35248.89	−82583.84	−38121.44	−37023.72	−34382.46	−40654.30
	Upfront cost	£	2875.47	5613.60	7309.71	4256.25	5653.33	2840.18	6157.89	7291.90
	Economic lifetime	year	20.00	20.00	25.00	25.00	16.00	13.00	20.00	18.00
Social	Health impacts	£	387.71	8764.00	367.91	349.07	121.94	137.94	102.08	162.38
	Fuel poverty	-	2.45	4.36	2.44	4.67	2.49	2.66	2.27	2.48
	Thermal comfort	%	84.90	83.50	85.70	83.90	75.90	78.80	75.50	79.50
	Safety	No./year	7.37E-04	1.62E-04	2.98E-06	2.78E-06	1.09E-05	8.49E-06	1.89E-05	2.80E-04
	Employment impact	FTE/year	1.19E-03	2.28E-03	2.08E-03	5.72E-04	5.32E-03	3.38E-03	2.71E-03	3.79E-03
	Reliability	Likert scale	4.00	2.00	4.00	4.00	2.00	3.00	3.00	3.00
	Usability and functionality	Likert scale	4.00	2.00	4.00	5.00	4.00	4.00	3.00	3.00
	Social acceptance	Likert scale	5.00	3.00	1.00	4.00	2.00	2.00	3.00	3.00

(*continued on next page*)

Table D. 1 (*continued*)

Sustainability indicators		Unit	Building heating systems							
			Gas condensing boiler	Biomass pellet boiler	Solar thermal + gas boiler	Direct electric + electric boiler	Air-water HP	Air-air HP + electric boiler	Ground-source HP	Gas hybrid HP
	Acoustic performance	dB(A)	50.00	55.00	35.00	31.00	54.00	37.00	46.00	60.00
	Aesthetic aspects	Likert scale	4.00	2.00	3.00	5.00	3.00	3.00	3.00	3.00

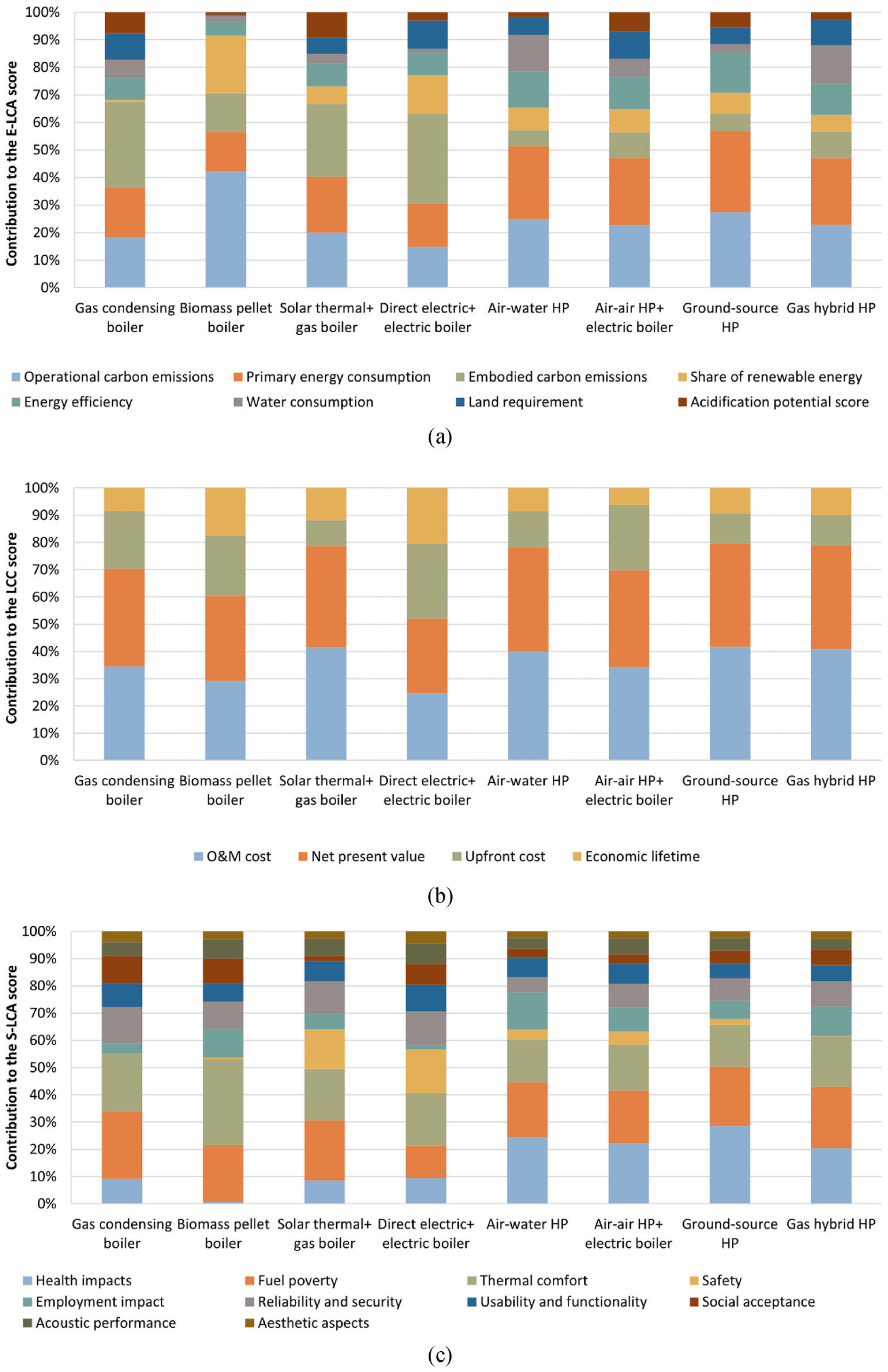

Fig. D. 1. Normalised weighted scores of indicators of (a) Environmental; (b) Economic; and (c) Social sustainability

Data availability

Data will be made available on request.

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