Phasing out fossil fuel heating in UK homes: A multi-dimensional framework for sustainability assessment of alternatives and their lifecycle implications

Mohammad Hosein Abbasi

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Abstract

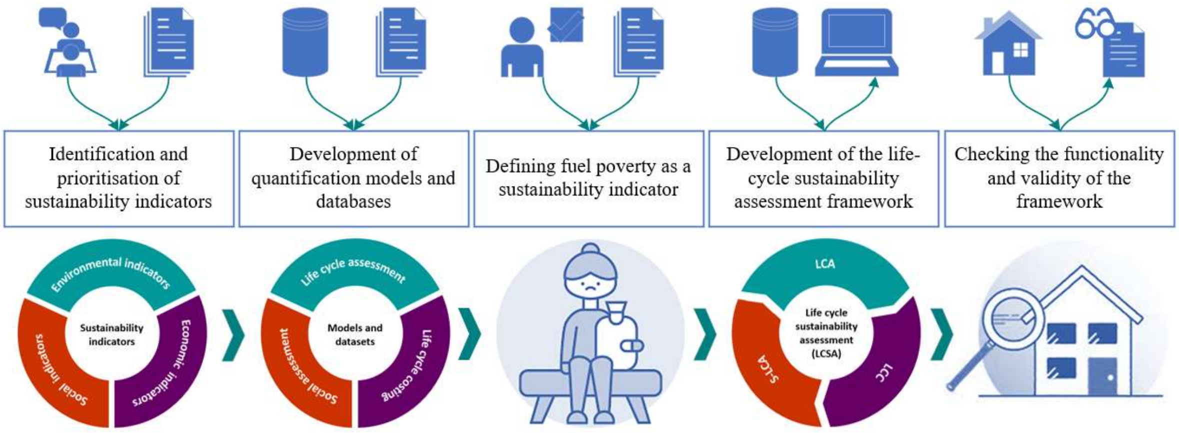
Space and water heating in the UK building sector, accounting for nearly a quarter of energy consumption and carbon emissions, is still dominated by fossil fuels. This has led to growing concerns regarding the decarbonisation of heating sources, supply chains, and operations in the built environment. The UK government aims to accelerate heat decarbonisation by mass deployment of low-carbon building heating systems (BHSs). However, heat transition involves more than shifting to less carbon-intensive technologies. It is tightly interlinked with end-user livelihood and could have invasive spatial, social, and financial impacts on households and living spaces. Furthermore, substantial upgrades in building stock, infrastructure, energy market, and legislative frameworks are needed alongside the rollout of low-carbon alternatives. The multi-faceted origins and complexity of the issue make it challenging to evaluate the potential of BHSs for serving a just and sustainable transition.

This study proposes a life cycle sustainability assessment (LCSA) to evaluate the environmental, social, and economic impacts of alternatives, informing decision-making for more informed, effective, and accurately targeted interventions. Therefore, an integrated and purpose-built LCSA framework is developed to evaluate BHSs' performance and lifetime implications at early project stages. This framework provides a sustainability-oriented decision support tool that expands current decision-making by proportional representation of all facets of sustainability and reflection of the stakeholders’ priorities.

A mixed-method approach is utilised to identify 22 pivotal sustainability indicators (SIs) which can effectively represent the dynamic and complexity of BHSs. This is followed by developing consistent measurement methods and datasets to quantify the SIs. A new method accounts for fuel poverty as an SI is also developed, bringing this critical factor into pre-intervention decision-making. The sustainability assessment principles are then integrated with multi-criteria decision analysis (MCDA) techniques to build a practical LCSA tool which is applied to common individual BHSs for single-family UK houses, as a case study. Ultimately, results are validated through sensitivity analysis that explores the LCSA uncertainties and interdependencies between the SIs.

The research argues that with climate change, economic uncertainty, and social inequity challenges, the need for holistic sustainability analysis of heating interventions is more evident than ever. A renewed focus on social sustainability is also needed as heating directly impacts households' health, comfort, and well-being. In this context, environmental sustainability was found to be the most critical element (39.5% of the overall sustainability weight), followed by the economic (33.2%) and social (27.3%) dimensions. The case study shows that no single BHS emerges as superior across all SIs. However, heat pumps (HPs) were the prominent technology in overall sustainability, with the ground-source form as the most promising option, followed by air-air and air-water HPs. The long-term benefits of HPs are highly reliant on the electricity:gas price ratio and the grid decarbonisation. Despite their increasing deployment, biomass boilers and direct electric systems were the least attractive options. The findings foster a better understanding of the sustainability challenges of heat transition, contributing to energy research, applied practices, and policy-making, towards a more sustainable future.

Graphical Abstract



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Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Acknowledgements

The work presented in this thesis marks the culmination of my academic journey as a doctoral student. I could never have reached this point without the support, guidance, and inspiration of so many individuals.

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Last but foremost, to my parents and sister for their unwavering love and support throughout this journey, I owe a debt of gratitude. To my partner, your understanding, patience, and belief kept me grounded and sustained me during the highs and lows of this period.

The scientific journey that has been condensed in this thesis has also been facilitated by many other individuals. To each contributor, big and small, thanks for being a part of this sustainability effort.

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Glossary of Terms

AHP	Analytic hierarchy process
AIP	Aggregation of individual priorities
ASHP	Air-source heat pump
BEIS	Department for business, energy & industrial strategy
BHS	Building heating system
BRE	Building research establishment
CCUS	Carbon capture utilisation and storage
CIBSE	Chartered institution of building services engineers
CIPHE	Chartered institute of plumbing and heating engineering
CSI	Composite sustainability index
Defra	Department for environment, food and rural affairs
DH	District heating
EC	Embodied carbon
ECE	Embodied carbon emission
EEF	Electricity emission factor
E-LCA	Environmental life cycle assessment
EPD	Environmental product declaration
FEF	Fuel emission factor
GDP	Gross domestic product
GHG	Greenhouse gas emissions
GSHP	Ground-source heat pump
GWP	Global warming potential
HEP	Hidden energy poverty
HFC	Hydrofluorocarbon
HP	Heat pump
HRE	Heat roadmap Europe
HVAC	Heating, ventilation and air conditioning
IES	Integrated environmental solutions
IPA	Impact pathways approach
IRR	Internal rate of return
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impacts assessment
LCSA	Life cycle sustainability assessment
LIHC	Low-income high costs
LILEE	Low-income low-energy efficiency
MAE	Mean absolute error
MAPE	Mean absolute percentage error

MCDA	Multi-criteria decision analysis
MEP	Mechanical, electrical and plumbing
MEPI	Multi-dimensional energy poverty index
NIA	Net internal area
NIMBY	Not in my back yard
NPV	Net present value
O&M	Operating and maintenance
ODP	Ozone depletion potential
ONS	Office for national statistics
PCM	Phase change materials
PFPI	Potential fuel poverty index
PM	Particulate matter
PMV	Predicted mean vote
PPD	Percentage of people dissatisfied
PtG	Power-to-gas
RES	Renewable energy sources
RGMM	Row geometric mean method
RO	Research objective
RQ	Research question
SCOT	Social construction of technology
SDG	Sustainable development goal
SI	Sustainability indicator
S-LCA	Social life cycle assessment
TBL	Triple bottom line
TOPSIS	Technique for order preference by similarity to ideal solution
VE	Virtual environment
VOC	Volatile organic compound
WAMM	Weighted arithmetic mean method
WGMM	Weighted geometric mean method
WLC	Whole life carbon
WSHP	Water-source heat pump
WSM	Weighted sum method
WTT	Well to tank

List of Symbols and Notations

AP	Acidification potential
APC	Acidification potential coefficient
AC^E	Activity cost
AI	Aesthetic indicator
EC_{BHS}	Annual electricity consumption
FC_{BHS}	Annual fuel consumption
LR	Annual leakage rate
f_b	Buffer factor
$CRF(r, N)$	Capital recovery factor
CD_i	Closeness degree
(fc, h_o)	Comfort hours
CSI_i^{OA}	Composite sustainability index
CI	Consistency index
CR	Consistency ratio
S_i	Distance from the ideal solution
ECC_j	Embodied carbon coefficient
ECE	Embodied carbon emission
EF_S	Employment factor
EI	Employment impact
C_{EoL}	End-of-life costs
E_i	Energy cost dimension
ECT	Energy cost threshold
UC^E	Energy unit cost
EDI	Equivalised disposable income
EEC	Equivalised energy cost
CF	GHG conversion factor
GWP_R	Global warming potential of the refrigerant
HI	Health impacts
r'	Health discount rate
F_i	Income dimension
w_k	Individual weight vector
LRC	Land requirement coefficient
LR	Lifecycle land requirement
FWC	Lifecycle freshwater consumption
MC	Maintenance cost
PT	Monetary poverty threshold
A^-	Negative ideal solution
NPV	Net present value
NL	Noise level

$P(A_i)$	Normalised collective weight vector
FFR_S	Normalised fatality frequency rate
h_o	Occupied hours
OMC	Operation and maintenance costs
OC	Operation cost
OCE	Operational carbon emission
OE	Operational efficiency
CF_{Ovr}	Overall conversion factor
A^+	Positive ideal solution
$PFPI$	Potential fuel poverty index
PEC	Primary energy consumption
PEF	Primary energy factor
N	Product service life
RI	Random index
r	Real discount rate
RC	Refrigerant charge
RR	Refrigerant end-of-life recovery rate
RI	Reliability indicator
r_g	Renewable energy ratio of the national grid
SII	Safety issue indicator
f_s	Scale-up factor
SPT	Severe poverty threshold
SOR	Share of renewables
SAI	Social acceptance indicator
HC_{BHS}	System heating capacity
TC	Technology unit cost
TCI	Thermal comfort indicator
E_{Tot}	Total energy consumption
E_{bio}	Total energy generation from biofuels
E_{geo}	Total energy generation from geothermal
E_{sol}	Total energy generation from solar
H_{Gen}	Total heat generated
UC	Upfront cost
UI	Usability indicator
WCC	Water consumption coefficient
M_j	Weight of material
WTT	Well-to-tank emissions factor

Chapter 1 Introduction and Background

1.1 Research context

1.1.1 Why heat matters

Space heating and hot water supply make up almost 80% of the final energy consumed by households. This represents over 25% of the UK's total energy demand, making heating the largest single energy consumer in the country (Heptonstall and Winskel, 2023). Most of the heat demand is met by natural gas that flows from North Sea production centres or import pipelines through a nationwide distribution system directly into end-user dwellings. This makes almost 85% of British households reliant mainly on gas to supply their heat and hot water (House of Commons, 2022). Meanwhile, less than 10% of the total gross energy used for heating is supplied by renewable energy sources (RES) and low-carbon technologies (BEIS, 2022e). The share of low-carbon heating which is expected to be provided mostly through the development of HPs, district heating, and biomass, is steadily increasing in the domestic sector, but the progress is certainly not yet sufficient.

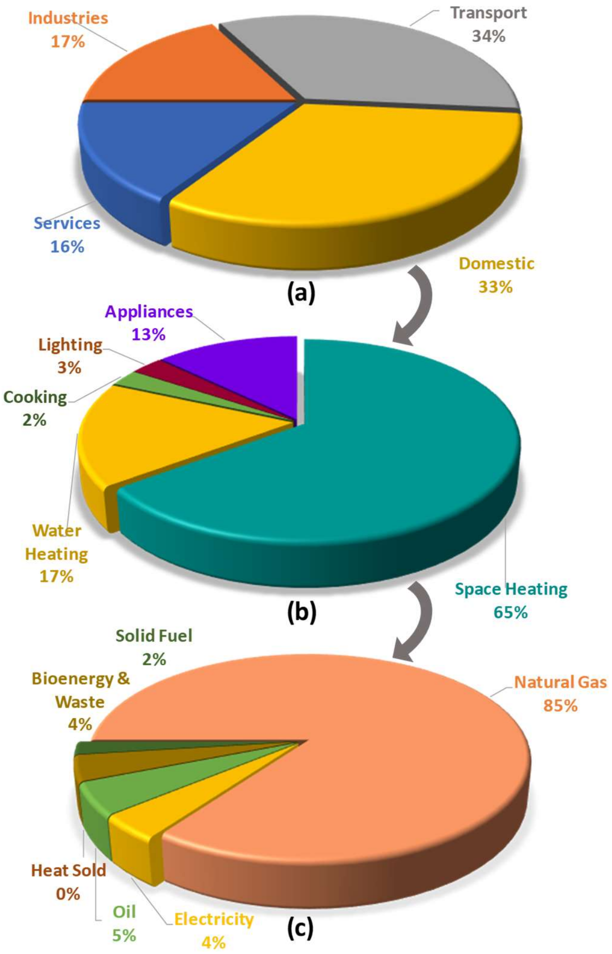


Figure 1-1 (a) UK final energy consumption by sector; (b) UK households energy consumption breakdown; (c) UK domestic heating and hot water consumption by source of energy (BEIS, 2022e; Heptonstall and Winskel, 2023)

Domestic heating and hot water provision also account for around 17% of carbon dioxide equivalent emissions which is due to the dominance of gas-fired heating systems in UK homes (Heptonstall and Winskel, 2023). This raises not only an environmental issue but also an energy security issue which needs to be addressed by reducing the reliance on fossil fuels. Therefore, reducing the carbon footprint of the building heating sector is a priority in the context of the climate emergency. However, unlike the significant drop in emissions from the electricity generation sector over the last decade, the progress in decarbonising the heat has been very slow. This can clearly be seen by comparing a 67% reduction in emissions from the electricity sector from 2010 to 2018 with an almost negligible reduction from the residential heat sector over the same period (Qadrdan et al., 2020). Figure 1-2 shows some of the key figures about the housing heating sector and why it needs to be decarbonised more rapidly.

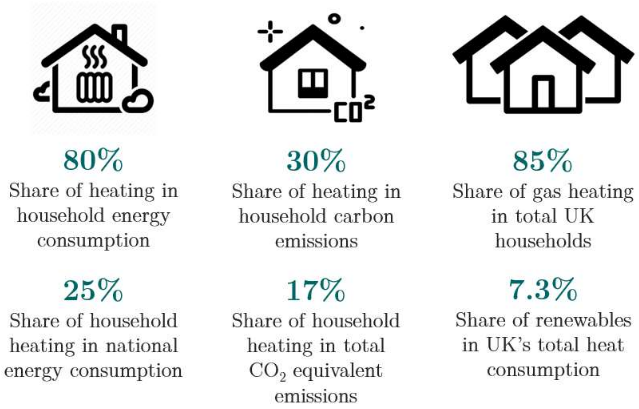


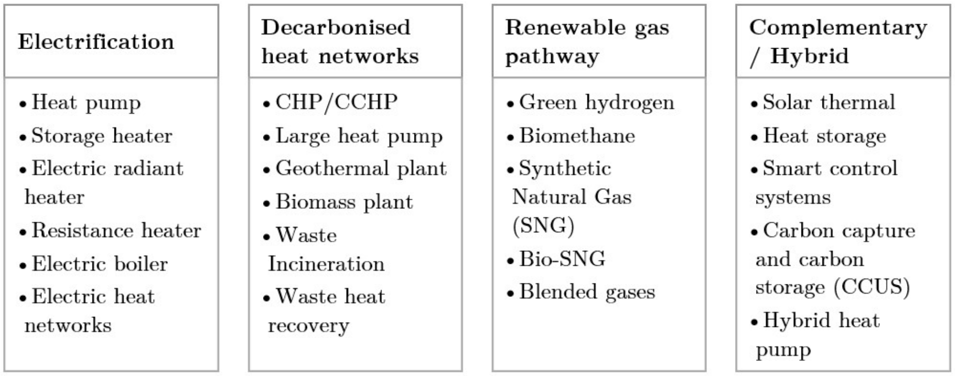
Figure 1-2 A snapshot of key facts and figures about heating in the UK's domestic sector

1.1.2 Heat decarbonisation targets

The UK is one of the first countries that recognised the growing threats of climate change and committed to act on it, announcing its ambitious net-zero targets. The UK government has commited to achieveing net zero levels of carbon emissions by 2050, with an interim milestone of a 78% reduction by 2035, relative to a 1990 baseline (Heptonstall and Winskel, 2023). Meeting these targets is not achievable without a rapid energy transition in buildings. The British government aims to fully decarbonise the building industry by 2050 under the Climate Change Act 2008, surpassing the EU's corresponding targets (Abbasi et al., 2022b). Decarbonising heat in the building stock, involving more than 26 million homes, is central to this challenge which is significantly off-track from its targets and needs to be further accelerated.

The journey to a decarbonised housing sector starts with improving energy efficiency and upgrading building fabric. Today, enhanced construction and retrofitting standards are ensuring that buildings are increasingly becoming energy efficient, lowering the energy demand in this sector. Buildings' energy performance is especially critical in the UK, where around 57% of homes were built before 1965, making it one of the countries with the least energy-efficient housing stock in Europe (Abbasi et al., 2022b). It is estimated that more than 90% of the UK's existing housing, 23 to 25 million homes, will still be in use in 2050 and require retrofitting before making changes to their energy system (Douglas, 2015). Therefore, the UK is pushing improvements to poorer performing buildings to upgrade as many homes as possible to EPC band C by 2035, where practical and cost-effective (BEIS, 2021a).

However, managing the demand side alone is not enough to fulfil the government's net-zero ambitions. Rather, it is the stepping stone to enabling a cost-effective and resilient transition towards low-carbon heating technologies. The overwhelming majority of UK homes will need to take up low-carbon solutions which currently only account for 5% of the total heating supply (Heptonstall and Winskel, 2023). Low-carbon domestic heat could be provided through a range of technologies, which can be categorised as in Figure 1-3 (elaborated in Chapter 2) (Abbasi et al., 2021). While none of these technologies can serve as the sole solution, some solid strategies are required to determine the role of each technology on the path to Net Zero.



Electrification	**Decarbonised heat networks**	**Renewable gas pathway**	**Complementary / Hybrid**
• Heat pump • Storage heater • Electric radiant heater • Resistance heater • Electric boiler • Electric heat networks	• CHP/CCHP • Large heat pump • Geothermal plant • Biomass plant • Waste Incineration • Waste heat recovery	• Green hydrogen • Biomethane • Synthetic Natural Gas (SNG) • Bio-SNG • Blended gases	• Solar thermal • Heat storage • Smart control systems • Carbon capture and carbon storage (CCUS) • Hybrid heat pump

Figure 1-3 Main categories of technologies for heat decarbonisation in the built environment (Abbasi et al., 2021)

1.1.3 National heat strategies

The UK Government has launched several strategies to set out its immediate actions and long-term plans to deliver a net zero transition in the building sector. Decarbonising heating, however, has become an increasingly important concern only in recent years. This was begun in 2017 when the 'Clean Growth Strategy' (BEIS, 2017) published high-level plans for meeting carbon budgets and recognised the particular challenge posed by heating. This strategy set out a range of programmes to promote energy retrofitting in buildings and low-carbon heat through programmes such as the 'Renewable Heat Incentive' and the 'Heat Networks Investment Project'.

In 2018, 'Clean Growth: Transforming Heating' (BEIS, 2018) was published, reviewing the evidence and options available for heat decarbonisation. The document concluded that it is unlikely that there will be a one-size-fits-all solution and a combination of various technologies will form the future of heat infrastructure. This was followed by the 'Future Homes Standard' (Government;, 2019), revealed in 2019, which focused on achieving high levels of energy efficiency in new-build homes, ensuring they are future-proofed with low-carbon heating. The standard also proposed the ambitious target of mandating the end of fossil fuel heating systems in all new homes from 2025.

This proposal was revised in the ‘Heat and Buildings Strategy’ (BEIS, 2021a) to phase out the fossil fuel heating systems in off-gas-grid homes from 2026 and in on-gas-grid properties from 2035. This strategy, launched in 2021, was the first UK government policy primarily focused on reducing emissions from domestic heating. The document was produced after advice from the Committee on Climate Change (CCC) which warned that the UK’s climate change targets will not be met without immediate reduction of fossil fuels from buildings’ energy chain. A timeline of the UK’s standards and regulations within this context is illustrated in Figure 1-4.

In the ‘Heat and Buildings Strategy’, the electrification of heat is proposed as a key action in reducing emissions from homes. The government has set a target for at least 600,000 air source heat pump (ASHP) installations per year by 2028. It is also noted that meeting this target is contingent on reduced upfront costs. Therefore, industries are pushed to reduce the costs of installing an HP by at least 25-50% by 2025 and to ensure that HPs are no more expensive than gas boilers by 2030. The strategy also expands its roadmap by setting out to deliver around 400,000 retrofits per year by 2028, as well as offering the Boiler Upgrade Scheme which provides households grants of up to £5,000 for ASHPs and £6000 for Ground Source Heat Pumps (GSHPs).

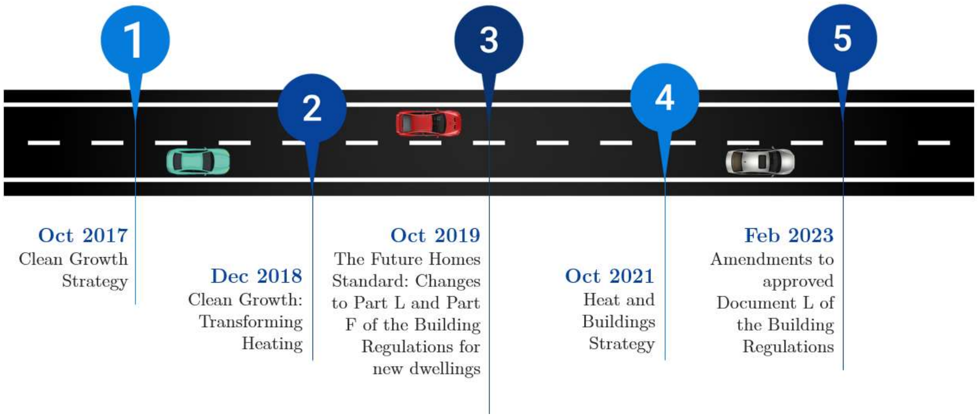


Figure 1-4 Timeline of the UK regulatory transition

1.2 Emerging needs and problems

Heating is one of the most difficult sectors to decarbonise in the energy system. Heat transition requires a radical uptake of low-carbon heating technologies ahead of fossil fuel phase-out. Regardless of what mix of technologies is taken forward, substantial upgrades in energy networks, the energy market, and the legislative framework are also needed alongside the installation of new systems. Therefore, the heat transition process involves more than a simple shift to less carbon-intensive technologies; it is tied up with a wide range of social, economic, and environmental factors that need to be considered before implementing transition measures. Many Brits still remember the consequences of the transition from burning coal or wood to central or district heating on the wider economy and society, but efforts to learn lessons from this to ensure a fairer and smoother transition in the future have been very limited (Mccarthy et al., 2023).

One of the unique challenges of domestic heat decarbonisation compared to transitions in other sectors is its tight interlinkages with societal regimes, because heating sources could affect households' health, comfort and well-being, triggering deeper changes to societies, economies and cultures. Understanding these social ties and how their impacts are distributed among the wider community is key to delivering a just and sustainable transition. These factors are often investigated under the theme of 'social sustainability' in academic and policy discourses. However, despite the well-established frameworks for economic and environmental assessments, social sustainability is less often discussed and, consequently, less addressed in the design and planning stages (Abbasi et al., 2022a).

Fuel poverty is one of the main social aspects in this context which is often overlooked as an important factor associated with building heating interventions. Fuel poverty is primarily a social issue which is tied up with heating effectiveness and affordability. Today in the UK, more than 10 per cent (25 per cent in Scotland) of households live in fuel poverty, exposed to a series of effects on illness and mental health (Stewart et al., 2022). However previous research that has shown that the transition to low-carbon systems could increase energy costs and introduce further pressure to vulnerable groups, putting additional households into fuel poverty (Green et al., 2020; Stewart et al., 2022). In this context, a key consideration emerging for the heat transition is how moving to low-carbon alternatives can be improved in such a way that, alongside the replacement of conventional systems, it would deliver reductions in energy bills and mitigate future price pressures.

Heat transition imposes many more challenges in a wider economic, logistic, and technological landscape. Bear in mind that, unlike electricity and gas, the transport of heat over long distances is not feasible; heat needs to be produced locally and therefore heat decarbonisation measures must be planned and investigated through detailed consideration of local circumstances (Qadrdan et al., 2020). Another emerging need is the development of manufacturing capacity and a skilled workforce. Constraints in the availability of technologies and skilled labour could give rise to prices across the sector, leading to a loss of competitiveness in the economy and aggravating distributional and 'just transition' conflicts (Stewart et al., 2022). A further challenge is how to coordinate the stakeholders' needs and interests. Multiple individuals, organisations, and regulations are involved in this process and need to be harmonised with continuing technological changes (Nava Guerrero et al., 2019). Finally, the transition to low-carbon heat will not happen in isolation, and many elements of the wider energy system and other sectors will influence and be impacted by how we decarbonise heat. For instance, decarbonisation of the electricity grid and upgrading the buildings' fabric are critical prerequisites that need to take place in parallel (Abbasi et al., 2021).

These challenges suggest the need for more holistic approaches which can account for economic viability, environmental protection, and social equity. These aspects could be bridged and studied under the heading of sustainability in an integrative and inclusive way. The term 'sustainability' is used to underline the necessity of attending to environmental, social, and economic factors in a balanced way. Using sustainability assessment methods, all these factors can be embedded in one multi-criteria analysis framework which can assist in comparing and contrasting the current and future scenarios (Figure 1-5). The consideration of sustainability is gaining greater prominence in research and practices, albeit not yet enough to guarantee a sustainable and equitable heat transition.

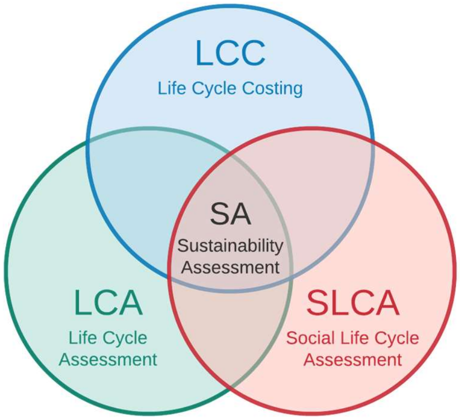


Figure 1-5 The overlap between the three dimensions of sustainability resulting in life cycle sustainability assessment

1.3 Research questions and hypotheses

The needs and challenges discussed above raise many uncertainties and unanswered questions regarding heating decarbonisation strategies, their long-term impacts, fairness, and potential to be widely rolled out across the country. The intersection between these uncertainties and the research goal and scope gives shape to the following questions that this study seeks to address. Each of these research questions is unpacked in one chapter of the thesis, which is structured to guarantee a consistent narrative that goes from the characterisation of needs and challenges to suggesting alternative solutions.

a) What does sustainability entail in this context and what factors contribute to it?
b) How can life cycle sustainability of building heating systems (BHSs) can be modelled and quantified at the early stages of the project?
c) How can social impacts of the heating transition, such as fuel poverty, be quantified and included in the decision-making process?
d) Can these quantification methods be integrated to facilitate a multi-criteria sustainability assessment of heating alternatives?
e) How will the low-carbon alternatives be compared and rated with respect to life cycle sustainability performance?

The research questions then lead to the development of hypotheses that are formulated in a way that reflects some of the core controversies surrounding the heat decarbonisation process in the UK. Thus, the following hypotheses are suggested for this thesis. Upon analysis of the findings, these hypotheses are supported throughout the research.

a) A wide range of parameters, apart from the cost and emission factors, are involved in the heating transition, which could affect the long-term sustainability of the building sector.
b) The UK's current roadmap to decarbonise heating in the built environment will not necessarily lead to the most sustainable outcome in practice.
c) Whilst supporting economic growth and environmental protection, heat decarbonisation has the potential to negatively impact the well-being of households and communities, reinforcing existing inequalities and vulnerabilities within society.
d) Some of the implications of energy transitions can be addressed through a predictive approach to tackle issues before they arise.

1.4 Research aim

To address the research questions and hypotheses, this study aims to demonstrate how life cycle thinking and sustainability assessment can be combined and integrated into the early stages of design and decision-making to improve the sustainability performance of heat decarbonisation practices. To do so, an inclusive and purpose-built life cycle sustainability assessment (LCSA) framework is developed to evaluate BHSs and provide the earliest possible feedback on the sustainability implications of different heat decarbonisation solutions. The developed framework encompasses the triple-bottom-line (TBL) dimensions of sustainability, including environmental, social, and economic aspects, acknowledging their interconnectivity and interdependence. This framework provides a sustainability-oriented decision support tool which enables trade-offs between multidisciplinary costs and benefits of the BHSs, assisting decision-makers in achieving more targeted, just, and sustainable heating solutions.

It is not intended in this study to find a common solution for heat decarbonisation in the domestic sector but to provide an assessment tool for the evaluation of available heating alternatives for each case study. Therefore, the functionality of the developed LCSA framework is demonstrated and verified through its application to the case of a single-family house in the UK. Focusing on the government's 'Heat and buildings strategy', the most potential low-carbon heating technologies in the UK's future market are evaluated and prioritised with respect to their life cycle impact on the environment, economy, and society. The study, overall, can serve as a guideline to select and promote the most sustainable heating solutions for the built environment and accelerate their adoption in this sector.

1.5 Research objectives

In order to achieve the research aims, five research objectives are proposed, outlining the specific tasks and targets that need to be accomplished. These research objectives are designed in such a way that cover all the essential aspects of the research questions. Therefore, the following objectives are formulated to be pursued in this thesis. Figure 1-6 shows the research objectives and their interrelations, as well as their correspondence with the research questions.

a) Identify sustainability indicators and their relative weight in proportion to their importance with respect to building heating systems
b) Establish the quantification methods and datasets required to measure and analyse the identified indicators
c) Evaluate the critical issue of fuel poverty and how it can be analysed and integrated into the sustainability assessment process
d) Develop a holistic and practical life cycle sustainability assessment framework
e) Demonstrate and validate the functionality of the developed framework as a tool to guide sustainability-oriented research, development, and deployment of heating technologies

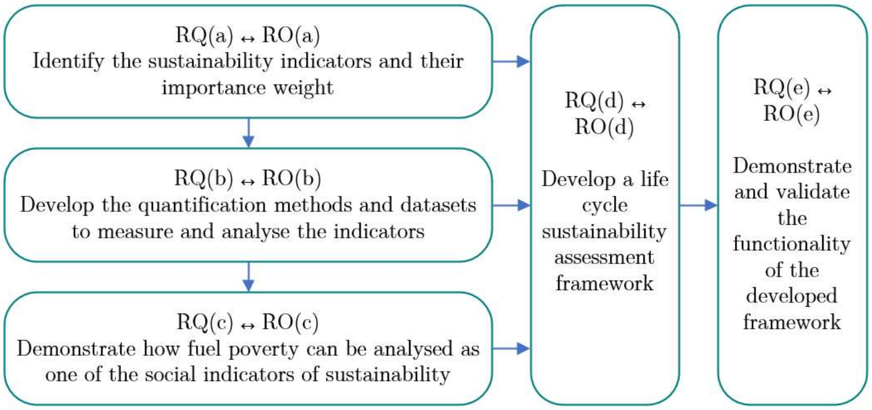


Figure 1-6 Interrelations between research questions (RQs) and research objectives (ROs)

1.6 Research scope and boundaries

The scope of the research and the system boundaries are set according to the aims and objectives. Therefore, the life cycle scope of the sustainability assessment includes allof the life-cycle stages of the BHSs, known as cradle-to-grave analysis. The cradle-to-grave analysis encompasses the entire material and energy supply chain from “raw material acquisition through production, use, end-of-life treatment, recycling and final disposal” as per ISO 14044 procedures (International Standard Organization, 2006). Cradle-to-grave is the most consistent assessment boundary for this study, rather than cradle-to-gate and cradle-to-cradle, as it covers the lifecycle of the systems with an acceptable level of reliability.

The life cycle assessment boundaries are illustrated in Figure 1-7, in which the life cycle of a built asset or building component is broken down into different stages and modules, as defined by BS EN 15978:2011 (European standard, 2012). These terms are used throughout this thesis to explain which part of the life cycle the calculations are referring to. Phase D (beyond the life cycle) of the lifecycle information is, therefore, outside the scope of this research as it is still subject to a high degree of scepticism and uncertainty (Bjørn and Hauschild, 2011); lack of information about the reuse and recycling of heating systems after their service life causes a high level of ambiguity in cradle-to-cradle assessments.

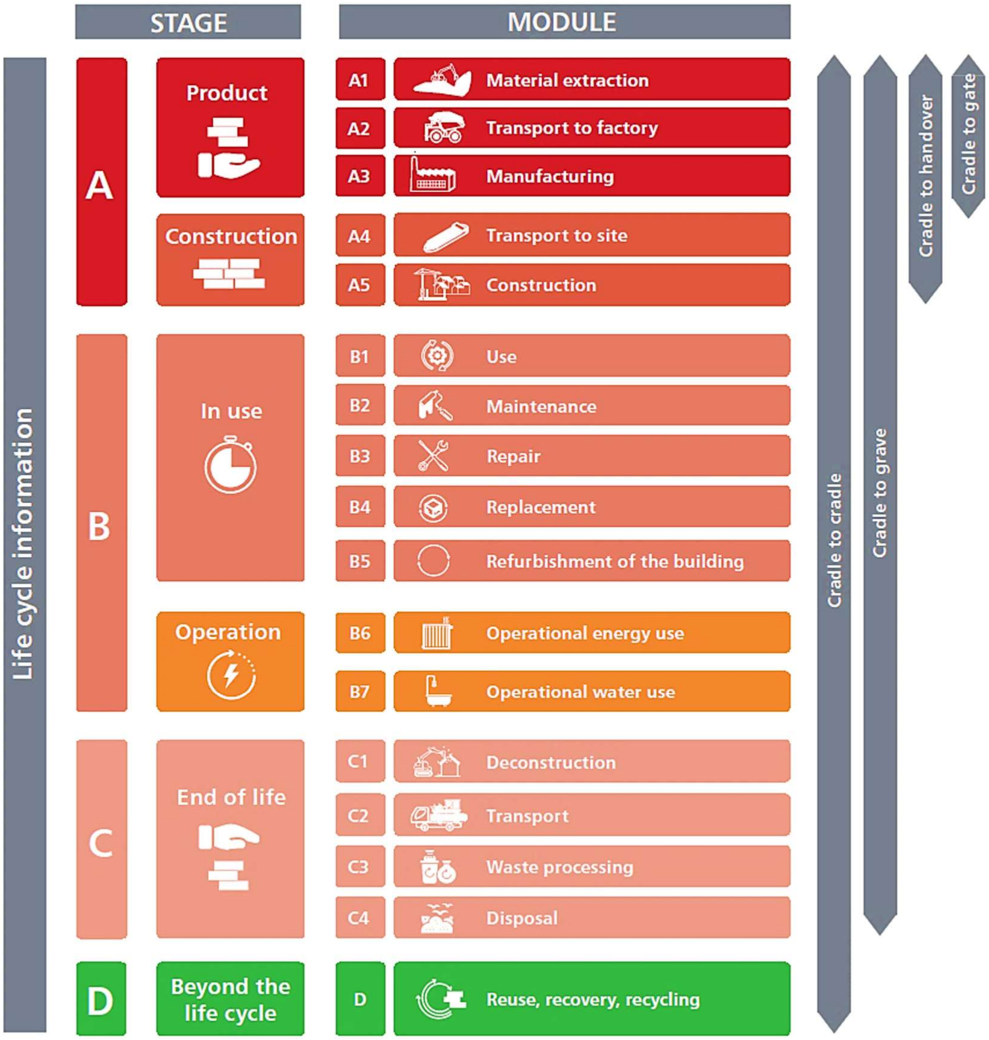


Figure 1-7 Building life cycle stages and assessment boundaries as defined by BS EN 15978:2011 (European standard, 2012)

Moreover, system boundaries need to be set which are subjective boundaries that determine what is included within the system under analysis and what is external to the system and should not be considered in assessments. Here, the challenge lies in selecting system boundaries that are consistent with the assessment scope and the sustainability indicators (SIs). Depending on the level at which the heating system is being examined, boundaries may vary in determining which stages or modules of life cycle information should be included in the LCSA. For this thesis, the boundry is set to assess the life cycle sustainability of BHSs at the product level, rather than at the system or building level. Accordingly, system boundaries are set around the BHS, as distinct from the building it serves. Therefore, LCSA does not include impacts associated with the B4 (replacement) and B5 (refurbishment) modules.

Furthermore, the aim of the research specifies that the framework should be functional at the early stages of selecting BHSs for buildings. Therefore, the boundaries also need to be restricted on the grounds of practicality and data availability at the early stages of the projects. In this respect, the applicability of the framework in terms of the project stage is set to the concept design, which is stage three of the RIBA Plan of Work (see Figure A-1 in Appendix) (RIBA, 2021). In other words, the developed LCSA framework can be utilised relying on the outcomes of stage two of the RIBA plan of work, eliminating the need for detailed technical designs and post-construction assessments such as building monitoring and household surveys. The RIBA Plan of Work describes the inputs and outputs required at key stages of construction projects.

1.7 Novel areas

The significance of this study lies in the development of an integrated evaluation tool for assessing the life cycle sustainability of heating systems in the built environment. The novelty of this framework and its unique contributions to the literature can be pinpointed as follows:

a) A purpose-built sustainability assessment tool

Unlike existing building sustainability tools and studies, which often exclude or underrepresent heating systems, the LCSA framework developed in this study specifically portrays the sustainability of BHSs. This framework provides a sharper focus on heating solutions, their life cycle impacts, and their role in the decarbonisation of the built environment. Using this tool, researchers and decision-makers can compare and contrast the whole package of heating systems, comprised of primary and auxiliary heating technologies, piping, storage, etc, through an independent and consistent process. This enables a simplified sustainability assessment at early stages of design and decision-making which does not need post-occupancy building monitoring and household surveys.

b) Adoption of life cycle perspective

This study embraces a life cycle perspective which extends the reference design time frame to the entire life cycle of the heating technologies. This has resulted in the creation of a holistic and lifecycle-based evaluation methodology that could facilitate the design and decision-making processes. The proposed methodology provides a more comprehensive evaluation compared to current decision-making support tools which are driven primarily by minimizing direct costs and emissions. It takes the embodied carbon and refrigerant impacts into consideration which account for a large proportion of the building's life cycle footprint, but just recently has come into sharper focus. Doing so, it sought to address the research gaps surrounding the whole-life carbon (WLC) assessment of the BHSs.

c) A multi-faceted and integrated evaluation approach

This study goes beyond previous research by positively integrating the social, environmental, and economic dimensions into a unified framework, engendering a more holistic sustainability evaluation. By combining life-cycle thinking with multi-criteria decision analysis (MCDA) methods, the developed framework enables trade-offs between the critical indicators from three facets of TBL sustainability. These sustainability indicators (SIs) are identified through a series of quantitative and qualitative methods to ensure a proportional representation of all facets of sustainability and reflection of the stakeholders' priorities. Therefore, this study could be a starting point to uncover the nuances of heat decarbonisation and its multidisciplinary impacts on the environment, economy, and society.

d) Renewed focus on social sustainability

Social sustainability has not been addressed proportionally to its importance. However, as it is a critical consideration for the sustainability of the heating sector, this research sets out to incorporate it into the LCSA framework to provide a better understanding of the dynamics between the BHSs, households, and the community. This makes the connection between social aspects and heat decarbonisation visible and demonstrates their significance in sustainability-oriented decision analyses. The proposed method also allows complex social sustainability information to be communicated quantitively, which, to the best of the author's knowledge, has not been explored previously. Doing so, the aim is to re-connect the notion of social sustainability to design and decision-making practices.

e) Incorporating fuel poverty in decision analysis

Based on the literature (reviewed in Chapter 2), some limitations have been identified in fuel poverty studies such as the exclusion of this factor from multi-criteria analyses, detachment from its engineering context, and a predominatly remedial approaches. This is where this thesis intends to contribute by devising a new indicator for fuel poverty. The Potential Fuel Poverty Index

(PFPI) is developed in Chapter 6 to evaluate the risk of fuel poverty under the circumstances of future heating scenarios. The PFPI method contributes to the field in the following ways:

- The developed method can complement current multi-criteria analyses by incorporating fuel poverty as an SI into the LCSA framework. Using the PFPI, fuel poverty can be included in design and decision-making processes in conjunction with other economic and environmental factors. By shedding light on the potential impacts of future BHSs on fuel poverty, the PFPI enables the shift from a remedial to a preventive approach. This will bring fuel poverty forward from post-transition to the early stages of the project, aiding decision-makers in tackling this social disparity before it arises.
- This method offers an important advantage in recognising the socio-spatial characterisation of households. Households are categorised into four demographic types across twelve standard UK regions so that they are not treated as a homogeneous group. This provides a more realistic estimate of household demands and resources, leading to a more meaningful prediction of fuel poverty and ultimately more targeted measures.
- The PFPI uses simulated energy demand instead of actual energy use to account for building, household, and geographical specifics that are often not represented in the common income/expenditure-based indicators. As a result, it can reflect the underconsumption of heating due to a lack of monetary resources or the overconsumption of households with special requirements, known as hidden energy poverty (HEP).

1.8 Thesis structure

The present manuscript is structured in the following sections consistent with the research objectives. The current chapter laid the groundwork by presenting the basic elements of this research study, including its background, a problem statement, and research aims, objectives, and scope. This is followed by Chapter 2 which reviews the state of the art and limitations of the literature. Next, in Chapter 3, a methodology is proposed and elaborated to address the research objectives. The original research work starts from Chapter 4, where a process is described for selecting and prioritising the critical SIs. This leads to the development of a series of quantification methods and datasets in Chapter 5 to analyse and communicate the selected SIs. The same process is conducted in Chapter 6, but specifically for fuel poverty, to which a separate chapter is devoted due to the importance of this factor within the context. All the derived data and methods are then integrated into an LCSA framework in Chapter 7 to develop a systematic LCSA framework. Chapter 8 presents and discusses the results of applying the developed framework to the selected case study. Finally, the main findings and conclusions that can be drawn from this research are summarised in Chapter 9, together with comments on its limitations.

Chapter 2 Literature Review

This chapter reviews the state of the art of heat decarbonisation pathways and sustainability studies in the field. It also identifies major limitations in the research and practice that could hinder or divert decarbonisation interventions[1].

2.1 Heat transition in the built environment

Energy is critical to economic development and human well-being, but also intricately linked to the challenges of sustainability. With growing concerns about energy security and climate change, the imperative for sustainable energy transitions has taken centre stage globally (Chen et al., 2019). The 'term energy' transition, in general, describes "the change in the composition/structure of primary energy supply, the gradual shift from a specific pattern of energy provision to a new state of an energy system" (Smil, 2010). One of the most critical elements of the energy transition is the decarbonisation of heating in the built environment. Heat decarbonisation/transition refers to the shift from heating systems that are dominated by carbon-intensive fossil fuels towards low-carbon, renewable and efficient alternatives. However, heat transition has lagged far behind the rapid growth of renewable electricity. More than 75% of new heating technology sales globally are either fossil fuel-based systems that produce emissions directly from combustion, or conventional electric systems that cause emissions indirectly through the power sector (Victor et al., 2019). The situation is no better in the UK, where over 85% of households still use gas boilers to heat their home (BEIS, 2022b).

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[1] This chapter is built upon two peer-reviewed and published works:

- Abbasi, M.H., Abdullah, B., Ahmad, M.W., Rostami, A. and Cullen, J., 2021. *Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology.* Sustainable Energy Technologies and Assessments, 48, p.101630.
- Abbasi, M.H., Abdullah, B., Ahmad, M.W., Rostami, A. and Cullen, J., 2022. *Bringing fuel poverty forward from post-intervention evaluations to design and decision-making stages.* People, Place and Policy Online, pp.1-9.

Heat decarbonisation research and policy has rapidly expanded since the early 2010s in the UK. Key focuses include assessment of scenarios and pathways (Quiggin and Buswell, 2016; Barton et al., 2018), heat demand reductions (Barrett et al., 2021; Alabid et al., 2022), market policies and adoption incentives (Curtin et al., 2017; Calver et al., 2022), and pilot projects to test real-world performance (Cowell and Webb, 2021; Reigstad et al., 2022). Multiple research centres have also focused on heat transition, e.g., the UKERC's 'Decarbonisation of heat' project (UKERC, 2022a), 'Leeds Heat Planning Tool' project at the University of Leeds (University of Leeds, 2014), and the 'Just heat' project at Sheffield Hallam University (Sheffield Hallam University, 2022). Furthermore, several studies have assessed the techno-economic feasibility and environmental impacts of various low-carbon heating technologies for buildings that are reviewed in the following section.

2.2 Heat decarbonisation pathways and solutions

Understanding the possible transition pathways of the heating system has attracted worldwide concerns. In the UK, many research projects have been designed to explore low-carbon heating options for national transition, as well as those with regional deployment potential. In a report developed by the 'Net-Zero Infrastructure Industry Coalition' (Net-Zero Infrastructure Industry Coalition, 2020), a comprehensive literature review was carried out to explore the range of potential pathways for heat decarbonisation in the UK. This study identified 87 relevant pathways that have already been proposed by industry, academia and other organisations. Each of these pathways involves a combination of low-carbon supply technologies, demand management strategies, and energy efficiency measures. Figure 2-1 shows a Venn diagram of the identified heating technologies which are proposed across the literature, with HPs, heat networks, Hybrid HPs, biomass and hydrogen at the top of the list.

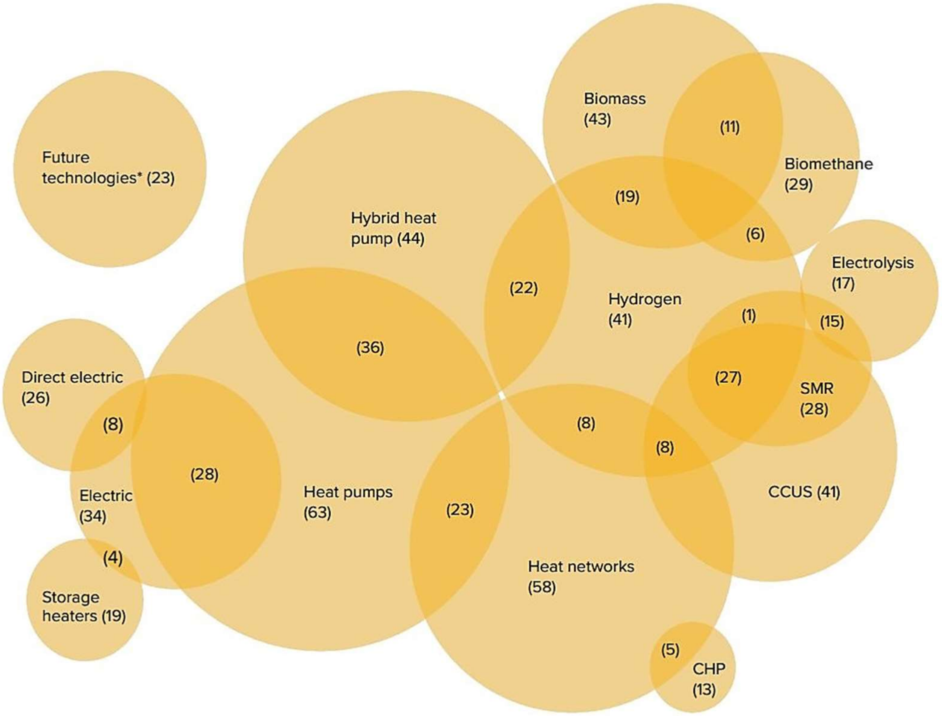
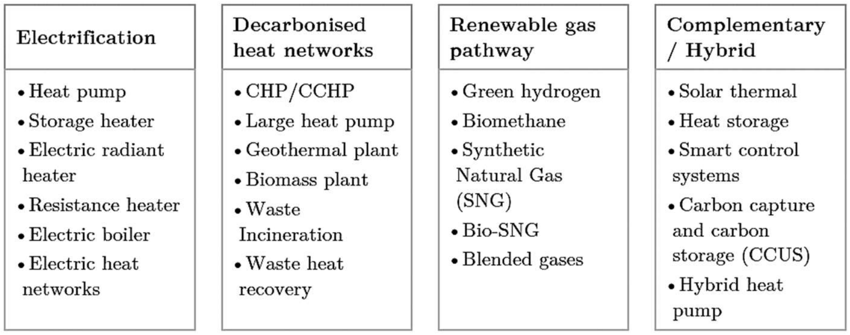


Figure 2-1 Presentation of the technologies and their number of appearances in heat decarbonisation pathways (Net-Zero Infrastructure Industry Coalition, 2020)

None of these technologies can stand alone in the future energy system and a range of options need to be developed in parallel to be able to offer a successful transition. The main technology options can be broadly categorised into four groups as shown in Figure 2-2. The first three categories are the key vectors of heat transition, complemented by a fourth category which includes secondary and transitional technologies.



Electrification	Decarbonised heat networks	Renewable gas pathway	Complementary / Hybrid
• Heat pump • Storage heater • Electric radiant heater • Resistance heater • Electric boiler • Electric heat networks	• CHP/CCHP • Large heat pump • Geothermal plant • Biomass plant • Waste Incineration • Waste heat recovery	• Green hydrogen • Biomethane • Synthetic Natural Gas (SNG) • Bio-SNG • Blended gases	• Solar thermal • Heat storage • Smart control systems • Carbon capture and carbon storage (CCUS) • Hybrid heat pump

Figure 2-2 Categorisation of the main technologies of heat decarbonisation in the built environment (Abbasi et al., 2021)

2.2.1 Electrification

The concept of electrification or power-to-heat refers to converting electricity into heat to meet the energy demand for heating, cooling, and transport (Abbasi et al., 2021). Electrification of heating has emerged as a leading decarbonisation pathway on the global scale. The European Commission recognised in Energy Roadmap 2050 that electric heating can reach a share of 40% contribution to the heat supply by 2050 (Honoré, 2018). Several electric heating technologies are commercially available. However, heat pumps (HPs) are the most appealing technology due to their zero on-site emissions, as well as their higher efficiencies versus direct electric heating systems. A review of technologies, modelling approaches, and potentials of power-to-heat technologies can be found in (Bloess et al., 2018; Abbasi et al., 2021)

Air-source heat pumps (ASHPs) are currently the most widespread HPs in the world. Although ASHPs still have the limitation of reduced efficiency during the heating season, they have made significant advances in recent years, as reviewed in (Guo and Goumba, 2018; Wang et al., 2020). For large-scale applications, water-source heat pumps (WSHPs) with sewage water as the heat source are the most installed systems, representing 56% of the total capacity of large HPs across the EU (David et al., 2017). Nevertheless, WSHPs also lose efficiency as the temperature goes down and this is in addition to some other constraints that are explored by Zhang et al. (2019b). In turn, ground-source heat pumps (GSHPs) take advantage of a heat source with a much lower variation in temperature. There has been increasing demand for GSHPs in residential and commercial buildings over the last decade (Lucia et al., 2017). HPs could also operate with other sources, such as wastewater, industrial exhaust gas, and cooling systems, to enhance their overall energy efficiency. Considerable efforts have been made to explore the combination of these heat sources and these can be reviewed in (Jouhara et al., 2018; Lazzarin, 2020).

The potential of HPs for wide-scale electrification of building heat in the UK has been highlighted in multiple UK modelling scenarios and feasibility assessments (National Infrastructure Commission, 2018; Carbon Trust, 2020). However, adoption remains limited to date, accounting for only 1-2% of UK heating systems as of 2020 (Carbon Trust, 2020). The main barrier has probably been the impact of mass HP uptake on the total and peak electricity demand (Net-Zero Infrastructure Industry Coalition, 2020); a study shows that the replacement of all gas heaters in the UK with HPs would result in a 25% increase in national electricity demand, and a 65% rise in peak demand (Fawcett et al., 2014). Other barriers include upfront costs, consumer awareness, skill shortages, and policy limitations (Lowes et al., 2020). Therefore, infrastructure upgrades and policy interventions are both essential to tackling these challenges and successfully electrifying heat in British buildings.

2.2.2 Decarbonised heat networks

District heating (DH), also known as heat networks, refers to the distribution of heating and hot water to multiple buildings from a centralised production source via insulated pipes (Rezaie and Rosen, 2012). Provided that the fuel for the DH is low carbon, e.g., geothermal, solar thermal, waste heat, and HPs, the heat network itself will also be low carbon. DHs are highlighted as a key potential low-carbon solution for dense urban areas in many heat decarbonisation studies (Abbasi et al., 2021). According to the Heat Roadmap Europe (HRE), the contribution of DH for space heating and hot water supply in the EU accounts for 12%, 70% of which was driven by fossil fuels in 2017 (Mathiesen et al., 2019). The HRE studies estimate expanding this capacity to supply around 50% of the EU's heat demand by 2050 (David et al., 2017). Recent advances in DH systems, integration of renewables and design innovations are reviewed in (Mathiesen et al., 2019; Lund et al., 2021).

DH potentials are underexploited in the UK where heat networks currently account for 2% of national heat demand, only 7% of which comes from low-carbon primary fuel sources (Holmes et al., 2019). Key barriers to wider adoption include high upfront costs, policy uncertainty, and commercialisation challenges between suppliers and end-users (Energy Systems Catapult, 2018). The CCC, however, suggest that around 19% of heating will need to be supplied by DH by 2050 if the UK is to meet net-zero targets ina cost-effective way (BEIS, 2022b). The government has introduced some policies to support heat network development, including regulation, public investment and heat network zones. The challenges ahead of the growth of low-carbon heat networks in the UK are analysed in (Heggy et al., 2023; Hepple et al., 2023).

2.2.3 Renewable gas pathway

The renewable gas pathway offers another valuable solution for decarbonising the building heating sector. Renewable gas, often produced through a process called Power-to-Gas (PtG), involves converting renewable electricity into gaseous fuels (Wulf et al., 2018). This can be accomplished through electrolysis or various chemical processes. The primary advantage of renewable gas is the continued use of existing gas infrastructure and its ability to store excess renewable energy. The clean gases can be injected into the existing natural gas grid or used directly for heating purposes in buildings. Biomethane grid injection is reported as a short-term, low-regret measure, but its potential is limited to around 5% of gas consumption (Joffe et al., 2018).

The implementation of renewable gases as a long-term solution depends on a few alternatives including biogas, biomethane, and green hydrogen. However, hydrogen, known as the missing link in the energy transition, is the only option for full decarbonisation at-scale if produced via electrolysis powered by renewables (Van Hulst, 2018). Projections estimate a potential of €820 billion market size for the hydrogen industry and equipment, representing approximately 24% of the EU's total energy demand in 2050 (FCHJU, 2019). A review and evaluation of recent developments in power-to-gas projects can be found in (Wulf et al., 2018; Hu et al., 2020). In the UK, there is no straightforward route for hydrogen development under consideration as it will require the installation of national-scale pipeline infrastructure for transportation of both hydrogen and CO_2 (Baldino et al., 2020; Aunedi et al., 2022).

2.2.4 Complementary/Hybrid systems

Additional technologies like Hybrid HPs, solar thermal, carbon capture utilisation and storage (CCUS), and thermal energy storage, which are mostly used as auxiliary systems or in combination with other technologies can provide unique benefits over single technology pathways. This can enhance the pace and efficiency of heat decarbonisation or leverage existing gas or electric grids before full transformation to new energy systems. These technologies enable synergies between systems by managing, covering, or shifting the peak periods when insufficient heat is supplied by the primary heat generation system (Abbasi et al., 2021). However, they face unique challenges around integration, control optimisation and user behaviour modification which need more demonstration projects and incentives to scale up their implementation as part of a diversified heat strategy.

Hybrid HPs utilise gas only during peak periods when heat demand exceeds their capacity, demonstrating gas savings of up to 73% while avoiding the cost of full electrification (Sevindik et al., 2021). Studies show that hybrid HPs can cost-effectively contribute a significant share of the UK's heat decarbonisation with a potential to reach 10 million installations by 2035 (Sevindik et al., 2021). Solar thermal systems have seen renewed interest for DHW and heating and are currently growing more than 2.5 times as fast as in 2021 (IEA, 2022). Combining solar thermal with HPs can provide 23-35% of UK household heat demand (McDowall et al., 2014). Thermal storage can overcome the challenge of seasonal mismatch that hampers solar systems; thermal storage using phase change materials (PCM) or water tanks improves the flexibility of hybrid systems to better match the supply and demand sides (Pinamonti and Baggio, 2020). CCUS is another decarbonisation mechanism that can achieve up to 97% carbon reductions, though this technology has not yet been proven at scale (NGT, 2016).

2.2.5 Trends and projections

Several studies have been conducted on heat decarbonisation strategies to project the future structure of the heating sector. The 'Heat Roadmap Europe 4′ and 'Hotmaps' are two major European projects studying the transition scenarios and solutions from the industry point of view. These studies agree upon the 25–40% reduction in the total heat demand in residential and commercial buildings by 2050 through efficiency improvements in the buildings, offset by the rise in the number of buildings. Both studies argue that despite the significant reduction in the contribution of natural gas, it will still cover the largest proportion of heat demand until 2050. Likewise, the share of renewables, made up mainly of biomass boilers, HPs and solar thermal systems, will rise to 30–37% based on the baseline scenario of both models. HPs and electric heaters are projected to supply 200–300 and 400–500 TWh/year, respectively. On the other hand, some considerable inconsistencies can be found in the speculations of these projects. For instance, in the Hotmaps project, the demand for natural gas in 2050, based on the business-as-usual scenario, would be around 819 TWh, while the baseline scenario of the Heat Roadmap predicts 54% more gas demand (1268 TWh) in the same year (Nijs et al., 2017; Kranzl et al., 2018). Figure 2-3 illustrates how these two projects estimate the composition of the heating supply by 2050.

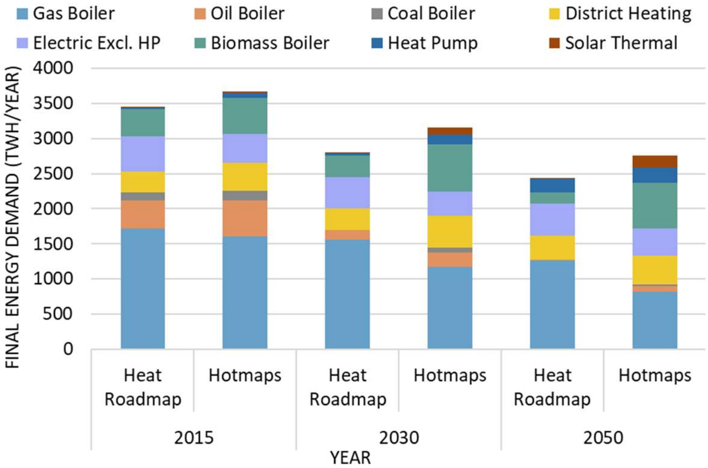


Figure 2-3 Total heat demand of EU buildings by technology, based on the business-as-usual scenario estimations by 'Heat Roadmap Europe 4' and 'Hotmaps' projects, 2015–2050 (Nijs et al., 2017; Kranzl et al., 2018)

In the academic literature, however, the trends are not quite consistent with these projections. Figure 2-4 illustrates the number of academic articles published between 2000 and 2022 on the main technologies of low-carbon heating. The data is extracted from the Scopus database and includes all the peer-reviewed publications in this period. For each technology, the name of that technology is searched for, along with 'heating' and 'building' as supplementary keywords to refine the search results in accordance with the study's scope. Overall, an upward trend can be seen in the academic interest in low-carbon systems, with HPs standing out from 2006 onward. Heat storage has also been an increasingly hot topic over the last decade, due to its wide applications and adaptability with various systems. This has been closely followed by DH systems as the third most attended technology.

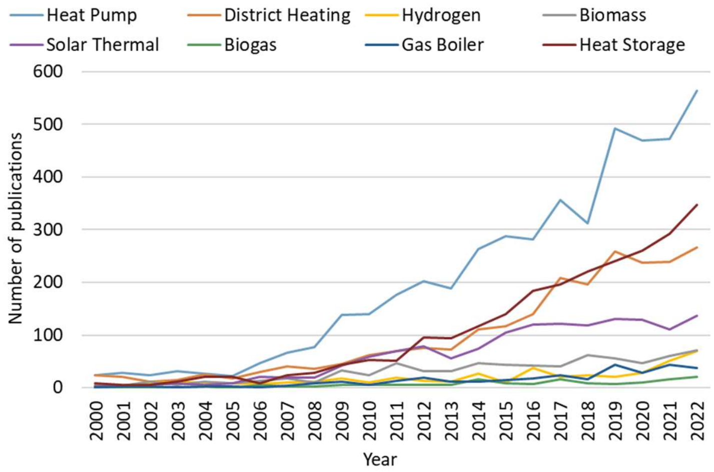


Figure 2-4 The number of indexed documents in the Scopus database, 2000 to 2022

2.3 Sustainability of heating systems

Heat transition is tied up with a wide diversity of social, economic, and environmental factors that need to be considered before implementing transition measures and policies. These factors could be bridged and studied under the term of Triple Bottom Line (TBL) sustainability in an integrative and inclusive way in order to plan and deliver a sustainable and equitable transition. First coined by Elkington (1997), TBL sustainability is a tri-dimensional concept that incorporates social, environmental, and economic dimensions to examine sustainability performance. These dimensions each have a life of their own, but they are also closely intertwined and can trigger transformations in each other (Al Sarrah et al., 2021).

Based on the TBL concept, environmental sustainability measures various types of pollution and implications that result in environmental impacts from a local to a global scale. The environmental sustainability of the energy systems is often affected by air and water emissions, land degradation, freshwater exploitation, depletion of non-renewable resources and changes in wildlife. Economic sustainability contributes to the progress of society toward achieving its economic objectives. Clune and Zehnder (2018) argue that economic objectives include wealth, employment, income, welfare and high productivity. Finally, social sustainability usually deals with the impacts on human health, equity, community liveability, historic and cultural heritage, and aesthetics (Ajmal et al., 2018).

2.3.1 Assessment methods

There are many attempts to assess the sustainability of energy systems in the literature. At the technology level, life cycle sustainability assessment (LCSA) has been the most common approach to promoting sustainable thinking throughout the whole life cycle of the system (Haase et al., 2022). Numerous evaluation methods and calculation tools have been used in LCSA studies which are reviewed in (Costa et al., 2019; Wulf et al., 2019). The variety of these methodologies has caused a lack of harmonisation in the sustainability assessment of energy technologies and their outcomes. However, what appears consistently among these studies is the definition of LCSA based on the following equation:

$$LCSA = E\_LCA + LCC + S\_LCA \tag{2-1}$$

Based on this equation, LCSA is the combination of environmental life cycle assessment (E-LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) in an integrated MCDA framework. Despite the growing LCSA of energy systems, there is a lack of studies dealing with the sustainability assessment of the heating sector. Focusing on these limited resources, it can be seen that no standard methodology or the TBL principles of sustainability are followed strictly. For instance, Hehenberger-Risse et al. (2019) developed a sustainability framework in which all impacts are presented under the collective term “environmental impacts”. However, they have rated the systems based on a dimensionless scaling between −1 and 1 that is not easy to follow in complex cases and is not developed in any other research. Likewise, Hobley (2019) examined scenarios for decarbonising the UK heating sector, taking into account the security of energy supply, sustainability objectives, affordability, and technical viability. In this study, sustainability in the heating sector is simplified to environmental impact and is determined by CO_2 emissions.

On the other hand, those studies sticking to the TBL concept of sustainability as the base, have been incompatible in other terms. For instance, Vasić (2018) and Zhang et al. (2019a) both assessed household-scale heating generation technologies in light of environmental, economic, and social factors. The former study considered only six criteria, three of which are qualitative elements which are determined based on the authors' perception. They then used the PROMETHEE method to rank the alternatives. The latter study, however, focused more on the

MCDA side and combined the TOPSIS, EDAS, and WASPAS methods to provide a robust ranking system, while it used a simplistic subjective method for rating the sustainability criteria. In another study (Herrera et al., 2020), only one technology, a hybrid solar/biomass micro-cogeneration, is assessed in terms of environmental and socioeconomic impacts. In this case, no MCDA was used and results are only compared to the existing fossil fuel alternative.

It can also be seen in some other studies that assessments do not correspond to the traditional three-dimensional definition of sustainability. Chen et al. (2020) constructed a model to evaluate the composite sustainability of a single solar-geothermal DH system under four different scenarios. They distinguished indicators related to energy consumption into a separate category named Energy Indicators. Similarly, technical factors of the heating systems are assessed in a separate category in several papers; namely, Yang et al. (2018), Pinto et al. (2019), and Kirppu et al. (2018) all evaluated heating technologies under the framework of cost, technical, and environmental dimensions. These studies, however, are not compatible in terms of indicators of each dimension, assessment boundaries, and analysis methods.

Looking at these studies, it is evident that while multi-criteria approaches have facilitated the study of sustainability in a holistic and integrative way, there is still no consistency in assessed criteria, analysis methods, and outcomes. That is why it is argued in this thesis that a renewed focus on indicators of sustainability is essential prior to any multi-criteria analysis.

2.3.2 Indicators of sustainability

Dimensions of sustainability are measured and communicated by reference to sustainability indicators (SIs). SIs reflect the level of sustainability and provide means for monitoring and signalling the progress towards sustainability (Moldan and Dahl, 2007). SIs emerge from the fact that sustainability is affected and depends on a long list of factors (Kylili et al., 2016). To evaluate the sustainability of any technology, it is essential to selecting an effective set of SIs that can fulfil the SI requirements and comply with the relevant standards and literature.

According to (Vidal et al., 2011; Siksnelyte-Butkiene et al., 2021a), the SIs utilised in multi-criteria analyses are required to have certain qualities that reflect sustainability and its roots within a system. They have to be: (1) representative to holistically reflect the essential characteristics of the system; (2) sensitive and operational in addressing the changes in the system to accurately portray the differentiation between system elements and comparisons among them; (3) independently measurable and verifiable using methodologically-based and repeatable methods, as well as accessible and transparent data; and (4) concise and few in number to avoid repetition and overlapping between them and minimise the complexity and indeterministic nature (plurality) of the problem.

Extensive literature is available regarding the identification of the SIs associated with energy systems in the built environment. Focusing on the heating technologies, Table 2-1 provides a list of recent studies dealing with the sustainability of these systems.

Table 2-1 Indicators used for sustainability assessment of heating systems and interventions in buildings

	Application (Case study location)	**Indicators**				**Gaps/Limitations**
		Economic	**Environmental**	**Technical**	**Social**	
(Vasić, 2018)	Space and water heating in households (Serbia)	Investment cost, Operating expenses, Economic development, Commercial maturity	CO_2 emissions	-	Comfort	Limited scope for environmental and social assessment; Simplistic (close to equal) weighting method
(Rutz et al., 2019)	Renewable district heating and cooling systems for communities (Southeast European countries)	Investment, fuel costs	CO_2 emissions, SO_2 emissions, NO_x emissions, PM emissions	-	Increase in employment, Local income generation, Region development	Non-participatory method for SI selection; Weighting factors are given by authors
(Hehenberger-Risse et al., 2019)	Local heat supply systems based on renewable energies (Germany)	Regional added value	Renewable energy, Non-renewable energy, Area, Heat price, CO_2 emissions, SO_2 emissions, Wastewater, Overall efficiency, Avoided environmental impacts	-	-	Non-participatory method for SI selection; Social dimension is not included
(Kuznecova et al., 2017)	Household heat generation systems (-)	Energy costs for one household member, Share of costs from income, Share of low-income households, Gross domestic product (GDP)	Heating consumption in household, Share of RES, Share of fossil fuels, CO_2 emissions, PM emissions	-	Number of house rooms, Number of rooms per inhabitant, Size of dwelling, Environmental problems, Expenditure problems	SIs and weighting are location-specific; Same weighing factor is applied to all SIs of each group

(Zhang et al., 2019a)	Micro-generation heat and electricity technologies in households (Lithuania)	Technology cost, O&M costs, Payback period	CO_2 emissions, Land use	Noise, Technology maturity, Technological improvement	Distortion of the landscape, Society appreciation, Job generation, Impact on the social progress, Market stability, Local & global market	Non-participatory weighting method; National-level indicators
(Yang et al., 2018)	Household-level renewable heating technologies (Denmark)	Energy bill, Energy expenses reduction, Initial investment, Payback period, Subsidy	GHG emissions, Use of RES	Performance, Needed reparations, Reliability, Ease-of-use	-	Non-participatory method for SIs; Social dimension is not included, Focused on a specific region
(Ren et al., 2009)	Distributed heat and electricity generation systems for residential buildings (Japan)	Investment cost, Running cost	CO_2 emissions, Primary energy consumption	-	-	Non-participatory method for SIs and weighting; Social dimension is not included
(Russo et al., 2014)	Geothermal heat pump and LPG greenhouse heating systems (Italy)	Energy payback time, Emissions payback time	Depletion of abiotic resources, Depletion of fossil resources, Acidification, Eutrophication, Global warming potential, Reduction of the ozone layer in the troposphere, Formation of photochemical smog, Primary energy demand	-	-	Non-participatory method for SIs; Social dimension is not included, Equal weighing
(Poppi et al., 2018)	Solar heat pump systems for residential heating applications (-)	Payback time	-	Seasonal performance factor	-	Social and environmental dimensions are not included; No life

						cycle impact is considered
(Ekholm et al., 2014)	Household-level heating technologies (Finland)	-	Acidification potential, Climate impact	-	Health impact	Limited and non-participatory SI selection; Economic dimension is not included
(Siksnelyte-Butkiene et al., 2021a)	Country-level heating sector analysis (North European countries)	Household gas price, Non-household gas price, Availability of financial measures	Heat generation from RES, Heat generation from waste, GHG emissions	-	Arrears on utility bills, Population in fuel poverty, Population in leaky homes	National scale metrics; Non-participatory method for SIs and weighting
(Chen et al., 2020)	DH systems coupled to geothermal and solar resources (China)	Annual investment cost, Annual cost-saving	CO_2 emissions, SO_2 emissions, NO_x emissions, PM emissions	-	Employment opportunities	Non-participatory method for SIs and weighting

Overall, above studies fail to provide a uniform set of SIs due to limitations that are discussed here. Firstly, most of these studies established the SIs based on the conditions and requirements of a specific country. Therefore, they cannot be applied universally to different locations to track the sustainability of heating systems or transition plans. Additionally, depending on whether the technology or the whole sector is assessed, the selected indicators vary widely in terms of the scale of their application (Siksnelyte-Butkiene et al., 2021a). The reviewed indicator sets are primarily produced based on the top-down approach and are often aimed at national or local scales. Thus, the effectiveness of these methods in assessing sustainability at finer spatial scales could be problematic (Graymore et al., 2008).

Another important limitation is that many studies do not involve stakeholders in the decision-making process in a systematic and participatory way. They often attempt to mitigate stakeholders' preferences instead of directly including them in the decision-making process. This is while the literature increasingly supports the implementation of socio-technological analytical approaches such as the social construction of technology (SCOT) to further understand the relevant social groups and stakeholders and their concerns in developing technologies (Elle et al., 2010). Furthermore, indicator developers have rarely attempted to validate the credibility of the SI selection, alternatively relying on the long-term acceptance of indicators by other users (Grafakos et al., 2017).

Finally, the existing literature has not equitably considered the three dimensions of TBL sustainability. Reviewing the articles in Table 2-1, what is often found to be underrated or not included at all is the social dimension of sustainability. In a broader sense, the lack of consideration of social factors in research and practices is noted by several scholars and is discussed in the following section.

2.3.3 The issue of social sustainability

Energy systems and interventions are often intertwined with several social factors that could potentially impact the well-being of people and communities (Avanzini et al., 2022). These factors are often investigated under the theme of “social sustainability” in academic and policy discourses (Stender and Walter, 2019). However, despite the well-established frameworks for economic and environmental assessments, social sustainability is less often discussed and, consequently, less addressed in building and energy system assessments (Vilches et al., 2017). A consistent understanding of how to specify and measure social sustainability is still lacking.

Different perspectives on social sustainability have resulted in many variations in its definitions (Afshari et al., 2022). However, the core idea of social sustainability among its different definitions in the literature targets the interactions of a process with the health, safety, well-being, and equal opportunities of current and future generations (Jafari et al., 2019). In the energy sector, social sustainability is intrinsically linked with the concepts of just transition, environmental justice, energy poverty, public engagement and inclusivity, emphasising the equitable distribution of benefits and burdens across society. For an energy transition to be considered socially sustainable, it must be aligned with the concerns, needs, and preferences of a large majority of the population (Setton, 2020).

The second gap in the literature is that there is no agreement about which indicators are to be used to measure and assess the state of social sustainability in a given context. In the building assessments, a recent review by Hashempour et al. (2020) shows that only 22% of studies considered social sustainability in analysing energy retrofits in buildings. Gathering 51 academic publications, they concluded that social sustainability was considerably understudied compared to economic and environmental impacts. Figure 2-5 shows the balance of sustainability factors in the studies investigated by Hashempour et al. (2020). Similarly, Pombo et al. (2016b) found that only three out of the 42 reviewed studies incorporated social issues in the multi-criteria assessment of building renovations. Where social sustainability is included, the focus has been mostly on indoor air quality, functionality, employment, thermal comfort, and cultural aspects, leaving aside some important issues like fuel poverty and health impacts (Antunes and Henriques, 2016).

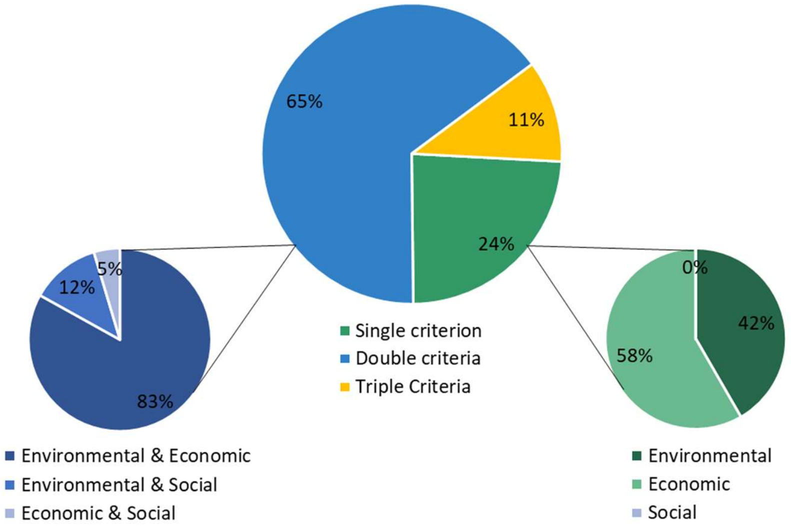


Figure 2-5 Percentage of building energy assessments with single, double and triple criteria and share of sustainability dimensions in these studies (Hashempour et al., 2020)

Likewise, a similar lack can be found in the scholarship of energy systems. Zanghelini et al. (2018) showed that social sustainability in energy systems can be often found in general propositions, usually integrated with environmental or technical aspects. This gap is noticed by other scholars, generally stating that most sustainability studies focus on environmental and technical aspects of energy systems (Grafakos et al., 2017). Afshari et al. (2022) noted that the lack of a compelling set of social criteria and their subjectivity often make the implementation of social sustainability difficult. The role of social factors, however, is increasingly considered in technology assessments (Mainali and Silveira, 2015). For this reason, this thesis renews the focus on social sustainability and its potential role in LCSAs.

2.4 Fuel poverty: a missing factor in sustainability analyses

Fuel poverty is a key component of social sustainability that is often overlooked as a criterion associated with building energy interventions (Siksnelyte-Butkiene et al., 2021a). The existing frameworks for multi-criteria sustainability assessment do not usually take into account the risk of fuel poverty that may be encountered as a result of implementing interventions. Understanding the linkage between fuel poverty and these scenarios is of vital importance for designing effective, fair, and sustainable solutions.

2.4.1 Definition and drivers of fuel poverty

Bouzarovski and Petrova (2015) have provided a general definition that underpins all different forms of energy and fuel poverty: “The inability to attain a socially and materially necessitated level of domestic energy services”. This is more often referred to as fuel poverty in the UK, where it has a long history in academic and policy discourses (Bouzarovski and Petrova, 2015). Fuel poverty is recognised as a global concern and a rapidly growing agenda for policymakers and practitioners (Longhurst and Hargreaves, 2019). Based on an EU-wide survey in 2020, around 8% of the EU population was unable to access or afford adequate indoor thermal comfort in their homes (Widuto, 2022). This problem is more striking in the UK, where about 4 million UK households (15 % of all households) were estimated to live in fuel poverty in the same year (NEA, 2021).

Fuel poverty is typically driven by energy-inefficient buildings, high energy prices, and low income, resulting in either cold indoor temperatures or sacrificing other essentials, such as food and health services, to afford adequate warmth (Longhurst and Hargreaves, 2019). This can cause several detrimental effects on households and society. Perhaps the most significant effect is on physical health, with a close correlation between fuel poverty and excess winter deaths, cardiovascular disease, and respiratory problems (Koh et al., 2012). Fuel poverty has also been closely linked to mental health issues and social isolation, more severely in children and the elderly (Thomson et al., 2017). Social health is another affected factor, as fuel poverty alleviation could reduce anti-social behaviour and dysfunction within families (Koh et al., 2012).

2.4.2 Indicators of fuel poverty

Since the concept of fuel poverty originated in the UK in the 1970s (Lewis, 1982), various indicators have been developed to identify and quantify this issue. These indicators are often categorised as subjective (also known as consensual or self-reported approaches; based on households' perception) and objective (based on measurements) indicators and are reviewed by (Robinson et al.) and (Siksnelyte-Butkiene et al.).

The most established objective indicator is the 10% measure, first proposed by Boardman (1991). It defines households as fuel-poor if they need to spend over 10% of their income on fuel costs to maintain satisfactory heating. However, it has been critiqued for not accounting for energy efficiency and targeting households with high fuel requirements rather than just low incomes (Hills, 2011). In response, the Low-Income High Costs (LIHC) indicator was introduced in 2012, based on which, a household is considered fuel-poor if their required fuel costs are above the national median and their residual income after fuel costs is below the poverty line (BEIS, 2020a). By accounting for both income and costs, LIHC provided a more sophisticated measurement which was used as an official fuel poverty measure in the UK until 2021, when it was replaced by the Low-Income Low-Energy Efficiency (LILEE) indicator. The LILEE uses an absolute measure of energy efficiency rating instead of energy costs in the LIHC (DESNZ, 2023). More recently, there have been calls for dynamic indicators that can track fuel poverty in real time using smart meter data.

Subjective self-reported indicators complement these by capturing perceived fuel poverty. These include surveys asking if households can afford adequate warmth or if they have difficulty paying bills (Bouzarovski and Petrova, 2015). While able to incorporate household experiences, subjective indicators have been critiqued for capturing broader financial stress beyond just fuel poverty (Middlemiss and Gillard, 2015). The diversity of fuel poverty indicators reflects its multi-faceted nature that requires hybrid ‘assemblages’ comprised of different inputs from building, energy usage, household, and society, to provide a more comprehensive understanding of the issue (Bouzarovski and Petrova, 2015).

2.4.3 Fuel poverty in sustainability studies

Integration of fuel poverty into sustainability discourses has been linked to United Nations sustainability goals, particularly Sustainable Development Goal 7 (SDG7) which calls for universal access to affordable, reliable, and clean energy services (IPCC, 2022). This was followed by the evolution of fuel poverty indicators, demonstrating a shift from a narrow financial lens to situating fuel poverty as a key component of social sustainability. However, fuel poverty is not often explicitly considered in sustainability assessments. Even commercial building assessment methods like BREEAM and LEED have been mainly focused on environmental criteria like energy and carbon reductions (Sharifi and Murayama, 2013).

Previous research has suggested that sustainable energy transitions are one of the most effective ways to alleviate fuel poverty (Grey et al., 2017). However, untangling the synergies between fuel poverty and these interventions requires more holistic approaches to better understand their potential interferences (Ürge-Vorsatz and Herrero, 2012). To date, no specific mechanism has been established to explore the risk of fuel poverty under the wider sustainability framework in conjunction with other sustainability criteria. Referring back to the collected studies in Table 2-1, it can be seen that none of these studies has considered fuel poverty as one of the important criteria concerning energy systems and building interventions. This gap has consequently led to limited attention being given to fuel poverty as a design or decision factor in engineering processes; the gap can be attributed to several reasons (Bouzarovski et al., 2014).

The first possible reason can be found by looking at the technical drivers of fuel poverty, namely building efficiency and energy systems, which are always highlighted along with the demographic parameters (Castaño-Rosa et al., 2020c). The factor of building efficiency has received increasing attention as a crucial factor for identifying fuel poverty and, consequently, is gradually emerging in fuel poverty indicators, e.g., in the new LILEE indicator. However, the role of building energy systems is still marginalised in fuel poverty studies and indicators (Bouzarovski and Petrova, 2015). This is a gap in the literature where not all of the driving forces of fuel poverty are equally represented in the existing indicators. This is also recognised in earlier studies, acknowledging the division between trajectories of recognition of fuel poverty and its driving forces, as well as highlighting the key role of technological factors in mitigating fuel poverty (Bouzarovski and Petrova, 2015; Sovacool et al., 2019).

Secondly, fuel poverty is widely recognised as a complex societal challenge in the existing body of research, primarily falling under the remit of economists and social scientists (Bouzarovski and Petrova, 2015). Researchers have often investigated this issue with a diagnostic approach in post-intervention phases (Sovacool et al., 2019). Abbasi et al. (2022b) elaborated on this gap, signifying that pre-intervention assessments are less sensitive to social factors, namely fuel poverty, as they are primarily aimed at minimising the cost and emission factors. Reflecting on the aforementioned gaps, this thesis argues that fuel poverty should be brought forward from post-intervention evaluations to early-stage sustainability studies. This exposes an opportunity to account for fuel poverty as a design/decision factor, resulting in more informed, effective, and accurately targeted interventions. This exposes an opportunity to tackle fuel poverty through a predictive approach rather than the remedial approach which is taken in most instances to treat the present situation.

2.5 Literature gaps and research motivations

Despite the extensive research history in addressing the emerging challenges of heat decarbonisation, there are still some outstanding gaps in understanding the long-term implications of the potential pathways. This section highlights major gaps in the research and practice that could hinder or divert decarbonisation actions. Five gaps are identified through an extensive literature review, all of which this study seeks to address. These lacking areas have been the foundation for developing the research objectives and respectively correspond to the research novel areas covered in Section 1.7.

a) The underrated role of heating services in building assessments

Although it is now well-recognised that low-carbon heating in households is a major contributor to the national net-zero targets, there is still little published research focused on these technologies. Most sustainability studies tend to limit their assessment boundaries to building physics and construction materials, leaving to one side the heating, cooling and other energy services (Hoxha and Jusselme, 2017). These energy uses are often excluded from analyses due to their complexity in design and operation, as well as their overall share of the building's impact, which was estimated to be small. However, over the last decade and after realising the significant life cycle footprint of building energy services, scholars learnt that omitting these systems would constitute a serious oversight in their analyses (Rodriguez, 2019). Nonetheless, the current growing literature still struggles to portray a detailed and comprehensive evaluation of heating systems in the built environment.

b) Limited use and understanding of the life cycle approach

Current literature has been very limited in determining the life cycle impacts of building heating services. The design and assessment of these systems have exclusively been focused on the operational phase, assessing in-use energy, costs, and emissions (Mohammadpourkarbasi and Sharples, 2022). For instance, environmental assessment of HVAC systems has been dominated by operational carbon analysis, ignoring the embodied carbon emissions and high global warming potential (GWP) of the commonly used refrigerants. At the same time, recent studies show that building services account for 40-70% of total building embodied carbon emissions, representing an average of 11% of the building's total life cycle emissions (George et al., 2019). Although LCA and whole life carbon (WLC) approaches have gained attention in the building research and industry over the last two decades, the life cycle impacts of heating systems have remained underexamined.

c) Lack of inclusive multi-faceted sustainability assessments

The current literature also reveals a considerable limitation concerning the multi-dimensional sustainability analysis of energy services in the built environment. The existing studies often have not equitably considered the three facets of TBL sustainability in their evaluations. To date, analysis of the social dimension of sustainability has been largely overlooked in favour of environmental and economic impacts. The predominance of environmental factors, in particular, is underlined by several scholars in studies on both buildings (Hashempour et al., 2020) and energy technologies (Zanghelini et al., 2018). It is essential, however, to encompass all economic, environmental, and social aspects, in order to properly address the sustainability issue in the heat transition. Therefore, a renewed focus on the TBL notion of sustainability is required to engender a comprehensive sustainability assessment of alternative technologies and their wider impacts.

d) The vague and overlooked aspect of social sustainability

The underrepresentation of social sustainability leads us to the next critical gap, which is the lack of a consistent understanding of this concept in the scholarship. Social sustainability has a critical role within the context of heat transition. However, social aspects of this transition are often addressed only in general propositions or implicitly studied under environmental or technical terms. Some other studies have qualitatively analysed these factors from the social science point of view. As a result, there is still no consensus on how to define, measure and evaluate social sustainability in this sector (Afshari et al., 2022). This could be due to the challenging nature of implementing and measuring social aspects, as well as the subjectivity of the social indicators. This observation makes it necessary to revisit the notion of social sustainability to alleviate the social risks of transition pathways, which is a key requirement of a just and sustainable transition.

e) Exclusion of fuel poverty from design and decision-making processes

The transition towards low-carbon heating could potentially expose more households to the risk of fuel poverty, whereas fuel poverty is often overlooked in evaluating low-carbon alternatives and transition strategies. Researchers have often investigated this issue with a diagnostic approach in post-intervention phases with little attention to alleviating the risk of fuel poverty through the design and decision-making processes. Furthermore, fuel poverty is widely recognised as a complex societal challenge in the existing body of research, primarily studied by economists or social scientists. The extensive research in this area has made significant advances in understanding the socio-economic context of fuel poverty. However, the role of heating systems is still underexplored in fuel poverty studies and indicators. These technical nuances of fuel poverty cannot be precisely uncovered in solely social terms, but more holistic approaches are required, expanding the traditional boundaries of fuel poverty scholarship (Abbasi et al., 2022b).

Addressing the gaps discussed above, this study contributes to the understanding of sustainability in heat decarbonisation, its indicators, triggers, and life cycle impacts by developing an integrated sustainability assessment framework following the methodological stages described in the next chapter.

Chapter 3 Methodology

This chapter explains the methodological approach of this study, which was developed after extended research across the relevant literature, as reviewed in the previous chapter. The methodology is based on similar LCSA frameworks but extends their understanding and methods to address the identified gaps. The proposed methodology merges the principles of the exploratory mixed method approach and life cycle assessment (LCA) to establish its sequential stages, corresponding to the research objectives. The chapter begins by providing a background to the proposed approach and its principles, followed by elaborating the design of the methodology stages and anticipating potential limitations.

3.1 Methodology foundations

The general theoretical base of the methodology is founded on the exploratory sequential mixed method approach. This method is useful for exploring phenomena when "measures or instruments are not available, the variables are unknown, or there is no guiding framework or theory" (Creswell and Clark, 2017). Thus, this method can address the first gap in the literature which identified the lack of a solid understanding and a standard tool to assess the sustainability of BHSs. For this particular area, the exploratory mixed method allows us to qualitatively explore the concept of sustainability and its dimensions in building services, and then develop an instrument for quantifying them for different case studies. This approach is initiated by a qualitative phase of data collection and analysis, followed by a phase of quantitative data collection and analysis, and eventually integration and interpretation of the results (Wunderlich et al., 2019). In the exploratory sequences, the qualitative and quantitative phases link together, with the results of the qualitative analysis in the first phase forming the basis of data collection and quantitative analysis in the second phase. Likewise, in this thesis, the proposed LCSA framework and the case study analysis are based on the sustainability propositions and indicators that are identified through the qualitative survey at the first stage. The sequence of qualitative and quantitative research in this method, as demonstrated in Figure 3-1, provides a better comprehension of the problem and initial confirmatory evidence in support of the validity of the constructed tool (Castro et al., 2010).

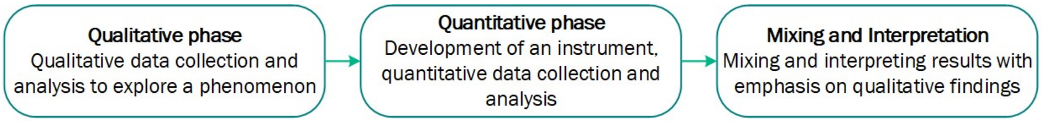


Figure 3-1 Stages of the exploratory sequential mixed method (Creswell and Clark, 2017)

Founded on the fundamentals of the exploratory method, sequential stages of the methodology are also designed following the standard life cycle assessment (LCA) framework. The LCA framework is standardised in ISO 14040 (ISO, 2006) and elaborated in detail in ISO 14044 (ISO, 2006) and is widely recognised and adopted to analyse the environmental impacts of products and services. ISO 14040 and 14044 establish the principles of LCA in four stages including goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results, as presented in Figure 3-2. However, the ISO-standardised LCA is unable to achieve a comprehensive evaluation of sustainability on its own, since its default structure only provides the reference framework for environmental analysis. A standard extension of the ISO 14040 which can be applied to environmental, social and economic assessments, has not yet been created (Campos-Guzmán et al., 2019). This corresponds to the second and third literature gaps, which identified the lack of a multi-dimensional life cycle sustainability assessment in the field. Thus, the proposed methodological approach encompasses the LCA steps in an expanded manner to apply to a broader scope of sustainability assessment.

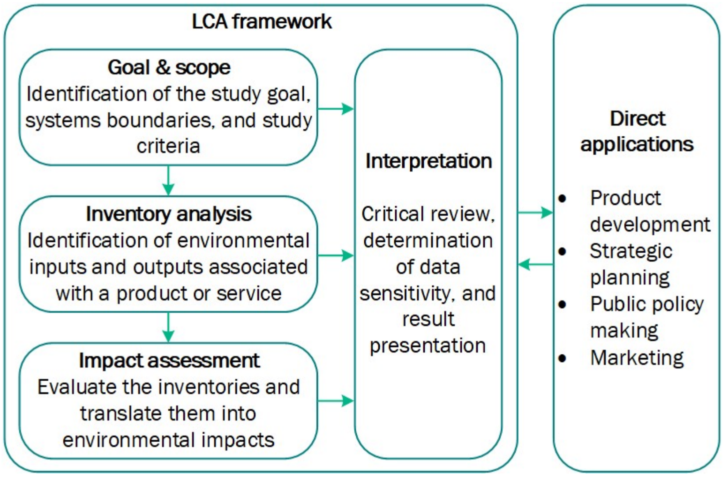


Figure 3-2 Stages of LCA framework and its applications established in ISO 14040 (ISO, 2006)

The foundations of the methodology having been laid in this section, the next section establishes the methodological stages specifically designed for this research.

3.2 Methodology stages

Built on the principles of exploratory mixed method and ISO guidelines for LCA, a four-stage methodological framework is designed for this study, as depicted in Figure 3-3. In this framework, the first stage is to determine the sustainability issues and indicators through a qualitative survey. The next stage is the quantitative modelling phase, where the required datasets and mathematical models for measuring the identified indicators are established. This is followed by stage three of the methodology, where all the collected data and models are integrated into an MCDA model to develop an LCSA framework. Subsequently, the developed framework is applied to a case study where its functionality and validity are checked and discussed. These stages are briefly explained in this section but are thoroughly covered in their corresponding chapter.

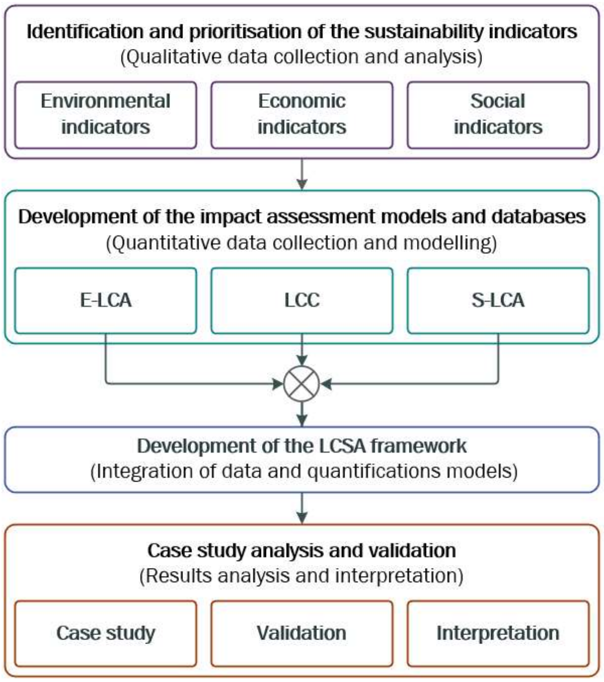


Figure 3-3 Methodology stages designed for the present research

The developed methodological stages inherit the sequential nature of the exploratory method and the LCA method and correlate with their frameworks. The designed stages are also consistent with the research objectives. Figure 3-4 illustrates the correlations between the exploratory method, LCA framework, research objectives, and methodology stages. It also presents the chapters associated with each of the stages. Some of the stages from each column appear to overlap with other items in other columns. For instance, the second methodology stage is associated with the research objectives (b) and (c), meaning that both objectives are covered under and concur with the methodology stage 2, the development of the impact assessment models and databases.

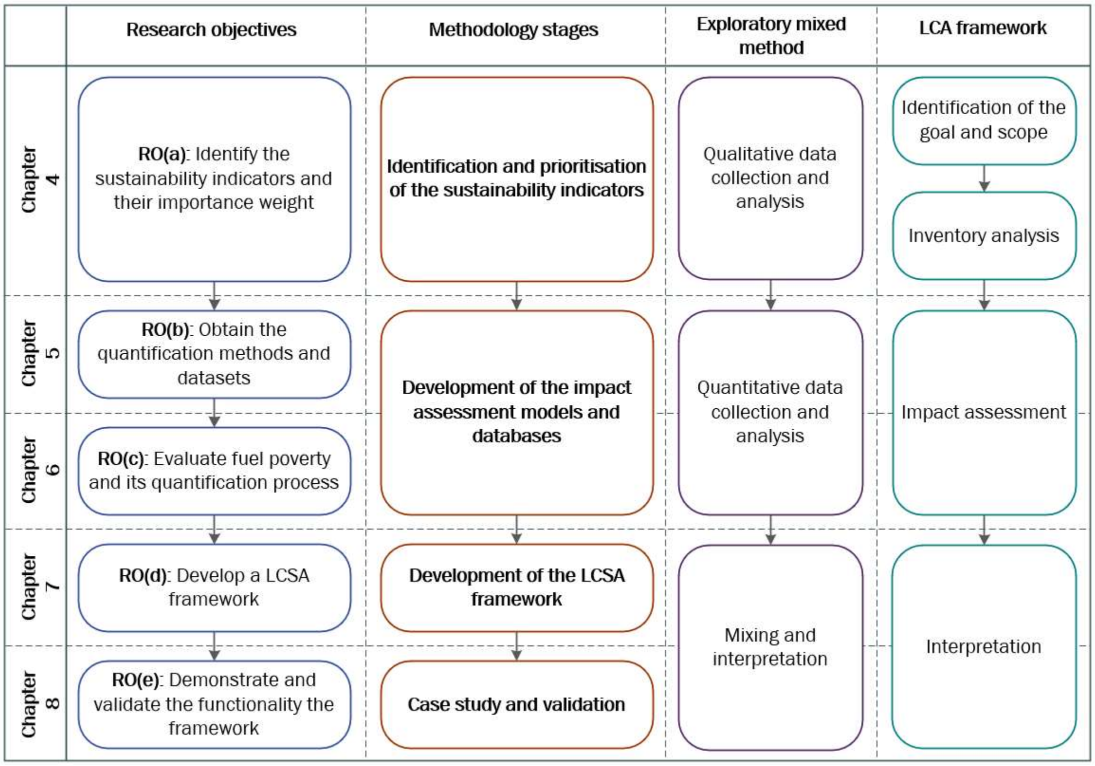


Figure 3-4 Thesis chapters and their correlations with the research objectives, methodology stages, and methodology foundations

3.2.1 Stage 1: Identification and prioritisation of the sustainability indicators

A crucial early step in the LCSA is to identify all the factors that impact on the sustainability of a product or service, known as sustainability indicators (SIs). This stage starts off the research process through qualitative data collection and analysis. This stage is also correlated with the goal and scope identification and inventory analysis in the LCA process, where everything involved in the system with environmental impacts is identified. SIs are quantified measures of issues that are recognised to influence the sustainability of products or systems. These indicators reflect the level of sustainability and can be used as decision-support tools. Determining a set of truly effective indicators can represent the dynamic and complexity of the systems in assessments and decision-making. Depending on the research area, scope, technologies and case studies, a wide variety of indicators can be used in E-LCA, LCC, and S-LCA studies.

For this stage of the methodology, a series of methods are utilised in a workflow framework to obtain the required set of SIs through three phases, comprised of six steps, which are illustrated in Figure 3-5. The process begins with the identification stage in which a preliminary list of indicators that have been applied in building and energy studies are gathered. Collecting SIs from the previous research through the literature review is a prevalent starting point for this process and a foundation for the development of an effective sustainability assessment model (Rigo et al., 2020; Daugavietis et al., 2022). Therefore, at this stage, a wide range of relevant SIs are obtained through a systematic review of the peer-reviewed literature, which reflects sustainability issues in energy systems and building energy interventions.

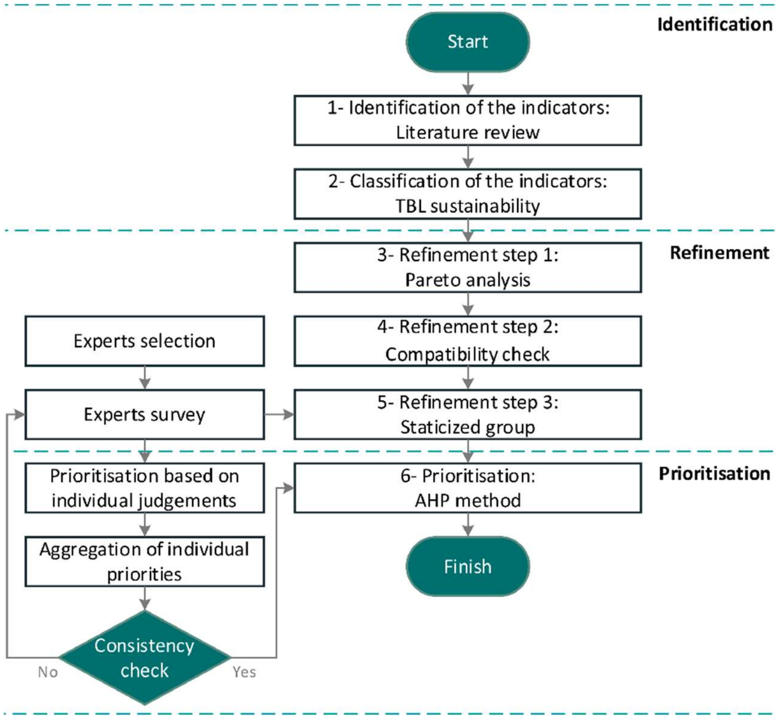


Figure 3-5 The flowchart of the developed framework for identification and prioritisation of the sustainability indicators

The long list of identified indicators needs to be reviewed and clustered to shape the categories required for sustainability assessment. Therefore, in the second stage, the collected indicators are classified to comply with the principles of TBL sustainability, which defines sustainability upon the three pillars of the economy, society, and environment. The SIs are re-categorised into economic, social, and environmental indicators based on the area of their ultimate impact.

The abundance of SIs, however, is problematic as it complicates the data collection and processing. Furthermore, developing a concise set of indicators (according to the literature reviewed in Section 2.3.2) is fundamental to the reliability and maturity of sustainability assessments. Therefore, the refinement phase, consisting of three stages, is designed to eliminate indicators that are not vital and alternatively select those which reflect the most important aspects of sustainability.

The first step of refinement is performed using the Pareto analysis method (Craft and Leake, 2002) to identify the most frequently used indicators in the relevant literature. Using this method, the essential SIs under each dimension of sustainability are determined and trivial indicators are screened out. The shortlisted indicators sometimes have overlaps in functionality or are not applicable or relevant to BHSs as they were initially collected from a broader literature context. These indicators need to be eliminated or merged at the second stage of refinement, referred to as a compatibility check, to ensure a concise and representative selection of SIs. This is followed by the last stage of refinement, based on the Staticized group technique (Hallowell and Gambatese, 2010) to validate and improve the selected SIs using experts' opinions.

To ensure the reliability of the expert judgments and minimise biased decisions, a group of certified professionals in design, planning, and policymaking from a wide spectrum of backgrounds and affiliations are selected. The same group of experts are also asked to prioritise the SIs based on their importance and impact on the sustainability performance of BHSs. The level of importance can be quantitatively expressed by the indicator's priority weight in MCDA frameworks. Hence, the last step of this section deals with assigning priority weights to the indicators based on the expert judgments and using the Analytic Hierarchy Process (AHP) (Saaty, 1987). Aggregation of the individual judgments and consistency checks are critical steps of prioritisation which are also addressed at this stage. The entire process related to designing, publishing, and distributing the questionnaire to experts, as well as the methods for analysing their responses and drawing results, is thoroughly explained in Chapter 4.

3.2.2 Stage 2: Development of impact assessment models and database

Once the indicators of sustainability are identified, it is necessary to obtain calculation models and datasets to enable their measurement, monitoring, and trade-offs in the MCDA process. This stage of the research, therefore, involves quantitative data collection and modelling for conducting E-LCA, LCC, and S-LCA. This stage correlates with the impact assessment in the LCA process, where the potential impacts of inventory data is assessed. Chapters 5 and 6 are associated with this methodology stage, where appropriate datasets and calculation methods for measuring each indicator are developed and thoroughly discussed.

Quantification methods are mathematical models by which SIs over the life cycle of a product can be measured and analysed (Bragança et al., 2010). The quantification methods are mostly obtained from the literature and LCA standards and modified to fit the case of BHSs. However, quantification of some of the qualitative indicators such as social SIs is not straightforward as it requires historical data, surveys, or subjective judgments (Saad et al., 2019). For some social SIs, such as fuel poverty, a new quantification method is needed to be able to incorporate this factor into multi-criteria analysis. The development of the fuel poverty quantification method is separately elaborated in Chapter 6.

Furthermore, a wide variety of data need to be aggregated at this stage to serve as input data to the quantification stage. Data collection in this study involved different types of data including technology-specific data, such as systems' efficiency and material composition, environmental factors such as energy and material emission factors, economic factors such as technology prices and energy tariffs, and demographic data such as household income levels and fuel poverty gap. The required input data were collected from a wide variety of secondary data resources, including the existing literature, LCA databases, national and regional stored data, and manufacturers' datasheets. The research team searched for best-fit data for the goal and scope of the study, prioritising UK building-specific resources, followed by European resources where no UK-based alternative was available.

Given the complexity of heating equipment and their supply chains, very few studies and databases can be found with detailed and reliable data regarding these systems. Therefore, a database was created for this research, containing the required LCSA data from a variety of sources. Technical and environmental data associated with heating technologies are mainly taken from two important European LCA data sources, the ÖKOBAUDAT database (ÖKOBAUDAT, 2023) and the PEP Ecopassport database (P.E.P. Association, 2023). These databases provide transparent and verified information about the environmental performance of a product throughout its life cycle stages. Economic data and cost factors are mostly derived from Spon's Mechanical and Electrical Services Price Book (AECOM, 2022) and Danish Energy Agency technology data (Danish Energy Agency, 2021). Demographic and econometric data are based on the guidelines and documents provided by the UK government. Other resources, such as the BCIS database (BCIS, 2022) and household finances data of the Office for National Statistics (ONS) (ONS, 2021) are also used to complement the database.

The required data at this stage are collected from a variety of primary and secondary sources. The secondary sources of data are the most used in LCSAs and are considered the exclusive source in most of these studies (Costa et al., 2019). Using secondary data for sustainability assessment in this project, although it was done of necessity, comes with some advantages (Wu and Wang, 2022):

- The project requires a large range of data from all the pillars of sustainability. Obtaining these data using primary data collection methods would need an immense amount of time and resources which is not feasible in a practical instance.
- Appropriate documentation and homogeneity of secondary data serve as the basis for developing a reliable and consistent LCSA framework. Commercial databases allow this consistency to be achieved by observing the appropriate selection and collection of the data.
- Some of the required data are only available through access to historical data sets and analysis meta-data. These parameters, including geometrical and weather data, econometrics, material emission factors, etc., are usually generated by international organisations and research institutes who make them available for use by researchers.
- Some data need to be collected by professional teams and under specialised standards. Using secondary sources ensures that only standard and professionally documented data are being used.

The outcome of this stage is a comprehensive set of quantification methods and datasets which will feed the next stage to build up the LCSA framework.

3.2.3 Stage 3: Development of LCSA framework

An LCSA framework carries out E-LCA, LCC, and S-LCA in a uniform format, followed by a decision-making process to compare and contrast the decision factors and finally rank the alternatives accordingly (Ciroth et al., 2011). Therefore, this stage is designed to mix all the data and quantification models that were developed in previous stages and integrate them into an

MCDA framework. This stage follows the four phases of data collection, data processing, framework development, and determining the validation methods, as shown in Figure 3-6. The outcome is a practical tool tailored specifically for the evaluation of BHSs, to make informed choices that align with sustainability goals and stakeholder priorities. The framework is developed in the Microsoft Excel platform to create a user-friendly, flexible, and simplified tool.

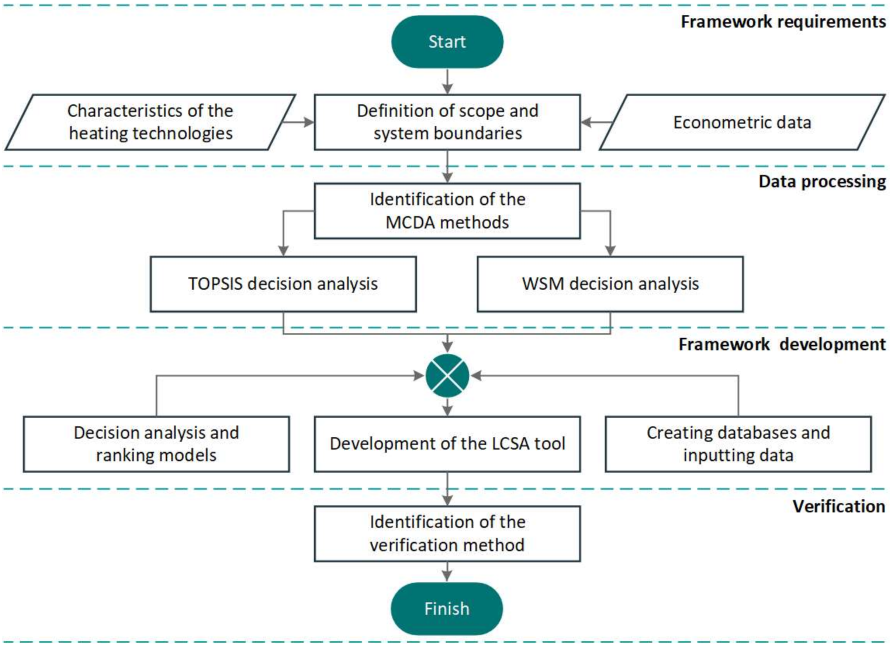


Figure 3-6 Flowchart of the development steps of the LCSA framework

The above workflow that is followed at this stage starts with collecting the further inventory data, including BHS technical data and econometrics, which are required to complement the LCSA database. Using these data, the E-LCA, LCC, and S-LCA analyses can be performed. The results of these analyses then need to be normalised and weighted before proceeding to the final step of the workflow to perform MCDA. MCDA methods facilitate decision-making where there is a wide range of decision variables and objectives with the complexity of interconnections. MCDA helps to integrate these factors into a unified framework to achieve a single index to aid decision-making (Raghoo et al., 2018). The decision models then need to be verified to ensure the robustness of the whole MCDA process.

Chapter 7 is devoted to the development of the LCSA framework and explains the details of the process in Figure 3-6. It also presents the rationale behind the use of the Weighted Sum Method (WSM) (Zadeh, 1963) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981) for performing multi-criteria analysis. Different validation methods are also discussed in this chapter and sensitivity analysis is found to be a robust and consistent technique. While other validation approaches are deemed not feasible for this study, sensitivity analysis is an available method that can theoretically unveil critical uncertainties surrounding the model. Three types of sensitivity analysis, i.e., dynamic analysis, performance analysis, and using different MCDA methods, are employed in this framework. At this stage, all the data processing methods are discussed, justified, and programmed in the Excel-based framework. However, the functionality of the framework using case studies is assessed in the following stage.

3.2.4 Stage 4: Case Study and validation

The final stage of the methodology is to apply the developed framework to a case study to demonstrate its functionality, evaluate and interpret the results, and validate the robustness of the process. The basis of the case study application is to serve as a detailed example of the way that the developed LCSA tool can be utilised for different BHS assessments. The case study assessment, addressed in Chapter 8, unfolds the capabilities and potential limitations of the framework. Furthermore, this chapter can serve as a stand-alone LCSA of the most common low-carbon BHSs in the UK. Therefore, the outcomes of the case study evaluation are thoughtfully analysed, discussed, and interpreted. The results are compared with relevant studies and prevailing perceptions over the sustainability of BHSs and decarbonisation strategies.

For this study, a 2-storey, 3-bedroom, semi-detached house in Liverpool with a 102 m^2 floor area is selected as the case study and will be equipped with eight different heating systems. This represents a typical single-family house in the UK, where about half of all properties are of similar size and structure (LABC, 2018). The building material and construction characteristics are based on the minimum requirements of the Building Regulations Part L1A (HM Government, 2023) to meet compliance with 2025 notional standards. The benchmark building is simulated in IES-VE software equipped with eight different BHS but with identical indoor conditions, electrical equipment, and occupancy patterns. The IES-VE simulation provides hourly heating and electricity loads of the building throughout a year, validated against data from real-world cases and the UK average figures.

The heating systems to be assessed in this thesis were selected by observing the UK's heat decarbonisation pathways (covered in Section 2.2) and is consistent with the goal and scope of the study. The aim is not to provide a comprehensive assessment of all low-carbon alternatives; the presented BHSs are only selected to demonstrate the applicability of the LCSA framework. Therefore, with the gas-fired BHS as the reference system, seven renewable-powered or hybrid-fuelled systems are modelled and analysed in this study. Heat is generated through eight different technologies and delivered to the home spaces through water-based convector radiators or local modules. Buildings are not equipped with a cooling system, except mechanical ventilation units which serve single areas. The system settings and configurations of the BHSs are outlined in Table 3-1.

Table 3-1 Configuration of the selected heating systems for the case study

Heating system	Space heating Source	Distribution mechanism	Hot water Source	Cooking source
Individual gas condensing boiler	Low-temperature hot water gas boiler	Central heating using convector radiators	Gas boiler	Gas
Biomass wood pellet boiler	Low-temperature hot water boiler	Central heating using convector radiators	Biomass boiler	Electricity
Solar thermal + gas boiler	Solar thermal collector + gas boiler	Central heating using convector radiators	Solar thermal collector + gas boiler	Electricity
Direct electric heating + electric boiler	Electric radiator panels	Local unfanned electric panels	Electric boiler	Electricity
Air-water individual HP	Air-water HP	Central heating using convector radiators	Air-water HP	Electricity
Air-air split HP + electric boiler	Air-air HP	Local fanned split systems	Electric boiler	Electricity
Ground-source individual HP	Ground-source water-based HP	Central heating using convector radiators	Ground-source HP	Electricity
Gas hybrid HP	Air-water HP	Central heating using convector radiators	Gas boiler	Electricity

The selected BHSs were modelled in IES-VE and their performance was simulated to obtain their hourly energy consumption and carbon emissions, along with other data required for the LCSA, e.g., peak loads, thermal comfort, and share of renewables. Technical details of the heating systems, such as efficiency rating and material composition were obtained from the manufacturers' datasheets, and verified with the data from peer-reviewed articles. To provide a fair comparison between BHSs, LCSA calculations for each scenario were performed over 25 years, equal to the lifetime of the BHS with the longest expected service life, so that at least one instance of system replacement was considered for all the selected systems.

Compliant with both ISO 14040 guidelines and exploratory mixed method structure, the research process will be accomplished by the interpretation step, where all results are discussed and verified. On the basis of these results, several conclusions and policy recommendations are developed. Sensitivity analysis, found to be the most appropriate validation method for this study in the previous stage, is carried out to validate the results and analyse the uncertainties in LCSA outcomes. Using eight sensitivity analysis scenarios, interactions and interdependencies between the SIs are analysed and those with significant impacts and burdens are identified. Sensitivity analysis scenarios are defined in light of the inherent uncertainties of the utilised methods and assumptions, such as SIs priority weights, future energy tariffs, and the MCDA process.

3.3 Potential methodology limitations

Some limitations associated with the proposed methodology can be anticipated and are discussed below, along with modifications that are considered to mitigate them:

Sustainability indicators: Each system encompasses a variety of sustainability issues and indicators with different levels of impact. The proposed methodology will identify the most important SIs with reference to existing literature, LCA tools, and experts' intuition. However, the number of selected SIs has been kept limited to minimise the complexity of judgments and analyses. Hence, the models may not be able to capture all the nuances of sustainability in BHSs. It is important to recognise that a different set of SIs might be selected in other study circumstances or by other stakeholders.

Data collection: Many economic, environmental, and social data are required to measure the SIs along with additional technical data for the final decision-making process. These data are selectively collected from a variety of secondary sources to create a comprehensive database for this thesis. Credible but diverse sources, including existing LCA databases, product datasheets, governmental documents, and academic literature are used in this methodology, which might not always be compatible in terms of measurement methods or scope. Such uncertainties could influence the outcomes of the LCSA framework.

Heating alternatives: The research focuses on domestic sector heat provision only. It evaluates the selected set of technologies for space heating and hot water generation. However, some emerging technologies like hydrogen boilers are not studied in this research. Apart from the lack of availability and reliability of data and references concerning these technologies, these systems cannot even be simulated in energy modelling software like IES-VE.

Lifecycle uncertainties: Despite being standardised in ISO 14040 and 14044, the LCA process inherently comes with some uncertainties in the methodology that are widely recognised in the literature (Zamagni et al., 2008). Each LCA study is an individual analysis based on a variety of uncertainties, approximations, simplifications, and analyst judgments (Rønning and Brekke, 2014). These limitations could also apply to the LCSA study developed in this thesis.

Micro-level decisions: The LCSA framework developed in this study supports micro-level decision-making, assessing BHSs at the scale of single-family houses. Micro-level life cycle models, in general, are used for predicting how individuals across diverse populations adopt technology, making them ideal for studying technology implementations and market adoptions (Sharp and Miller, 2016). These studies necessitate data and simulations with high levels of detail, which are not always straightforward. For supporting national-scale policymaking, however, the LCSA framework should be adjusted with macro-level data and SIs.

Chapter 4 Identification and Prioritisation of the Sustainability Indicators

Selecting an effective set of SIs, encompassing all economic, environmental, and social aspects of the systems, is essential before any multi-criteria analysis. Both the building industry and the energy sector have a relatively long tradition of developing and using SIs for tracking sustainability (Liu, 2014; Lynch and Mosbah, 2017). However, the existing SI sets, as discussed in Chapter 2, often present considerable limitations, such as the subjectivity of the SIs, lack of stakeholders' participation, predominance of environmental criteria, and dissimilarity of the indicator sets. This highlights the need to revisit traditional sustainability assessments and renew the focus on the TBL notion of sustainability.

To bridge these gaps, this chapter seeks to answer the first research question and find out which elements could accurately portray the sustainability of BHSs, while ensuring proportional representation of all facets of sustainability and reflecting the stakeholders' priorities. Therefore, a generic workflow framework is established, aimed at identifying, selecting, and prioritising a representative set of SIs in various fields [1]. The developed framework is comprised of six stages that are grouped under three phases (identification, refinement, and prioritisation), as illustrated in Figure 4-1. This process is then elaborated and applied to the case of BHSs to form the foundation for the LCSA of these systems. This chapter is correlated with the inventory analysis of the LCA standards and the qualitative data collection of the exploratory mixed methods approach.

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[1] This chapter is peer-reviewed and published as:
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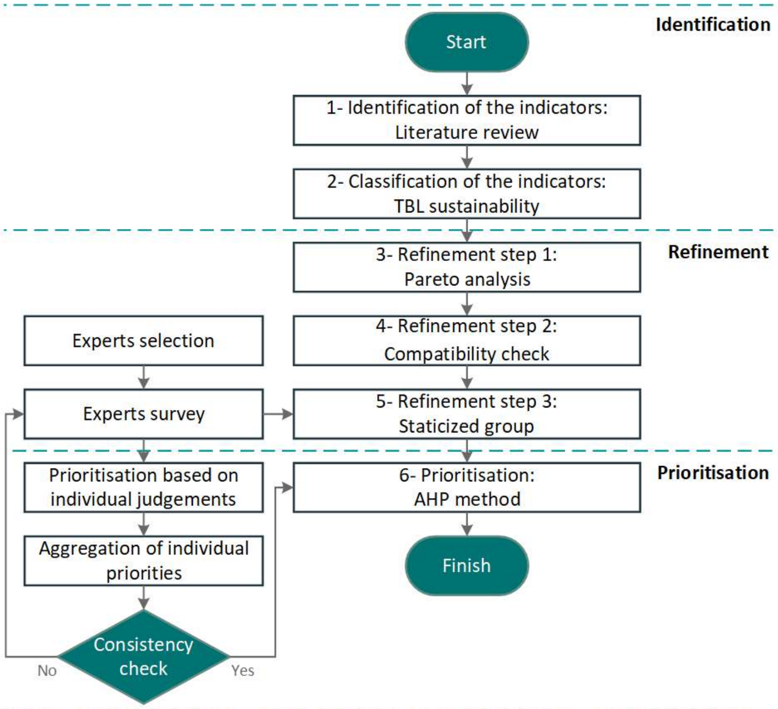


Figure 4-1 The flowchart of the methodological stages for identification and prioritisation of the SIs

4.1 Identification

This stage aims to identify a preliminary list of SIs that can potentially be used for this study. A long history of SIs can be tracked in both the building industry and energy systems. On this occasion, the process of searching started with a focus on the overlap of these two sections, i.e., the building energy technologies. However, to provide a more comprehensive list of SIs, the search domain was extended, covering a broader area of building energy interventions and distributed energy systems, using keywords such as ‘sustainability indicators’, ‘multi-criteria decision analysis’, ‘building heating technologies’, ‘energy renovations’, and ‘renewable energy technologies’.

The focus of this research was the sustainability of energy systems at the product level, rather than at the building level or larger spatial scales such as the local or national level. From the initial list of articles that were found through extensive searching, those not addressing the sustainability of energy systems or building energy interventions are excluded. Finally, a set of 66 articles published between 2010 and 2023 were reviewed. A total of 156 SIs were identified from these articles as the preliminary list of indicators that could potentially be used for BHS studies. Table 1 in Appendix B presents an initial list of indicators and a few references for them.

4.2 Classification

The long list of collected SIs in the previous section needs to be re-categorised into the TBL sustainability dimensions which are the basis of this research. The TBL model has been the model for many studies, while in many other studies, the SIs and their classification do not exactly correspond to the TBL definition of sustainability. In such cases, indicators have to be re-categorised under one of the TBL dimensions of sustainability based on the area of their ultimate impact. For instance, indicators such as job creation and indoor air quality which are both categorised under social sustainability in this study, are sometimes considered economic and environmental indicators in other studies.

Furthermore, the identified SIs are reviewed to avoid any repetition of the indicators. Despite the broad differences in indicator sets, there are some commonalities, such as upfront costs, carbon emissions, and land use are referred to by different terms in the studies (Ahmad and Thaheem, 2017). Therefore, the initial SIs were reviewed and those with the same meaning and functionality were merged to avoid duplication of SIs. Upon this filtration, the initial collection of 156 indicators was screened down to 118 indicators, 47 of which were grouped under the environmental dimension, 39 under social, and 32 under economic, as demonstrated in Table B-1 in Appendix B.

4.3 Refinement step 1: Pareto analysis

The first refinement step aims to identify the critical indicators that are frequently used by researchers using the Pareto analysis. Also called the 80/20 rule, the Pareto Analysis is a statistical technique of decision-making, primarily presented by Vilfredo Pareto (Craft and Leake, 2002). The Pareto principle is used in various areas, helping to identify a limited number of vital factors among a large number of factors that produce a significant overall effect. The Pareto principle states that 80% of consequences in many problems come from 20% of causes (Fernández-Sánchez and Rodríguez-López, 2010). Accordingly, it can be argued that 80% of sustainability can be achieved through 20% of the most important indicators (Fernández-Sánchez and

Rodríguez-López, 2010). This principle is widely used in sustainability studies, assisting in distinguishing the “vital few” from the “trivial many” decision factors (Fernández-Sánchez and Rodríguez-López, 2010; Gani et al., 2021; Lazar and Chithra, 2021).

The Pareto analysis process can be demonstrated with the aid of a Pareto chart, in which the frequency of SIs is presented in descending order and their cumulative percentage is presented on the secondary axis. Where the frequency graph cuts an 80% cumulative percentage, the SIs can be divided into the vital few indicators and the trivial many (Gani et al., 2021). In this study, the Pareto analysis is separately performed for each category of SIs, depicted in Figure 4-2 to Figure 4-4. The vital indicators which make up 80% of the cumulative frequency are separated via the red line. In this way, the initial 48 environmental SIs are narrowed down to 15 critical SIs. Regarding the economic indicators, the initial list of 32 SIs is screened down to 8. Also, social SIs are reduced from 39 indicators to 11 critical items after the Pareto analysis.

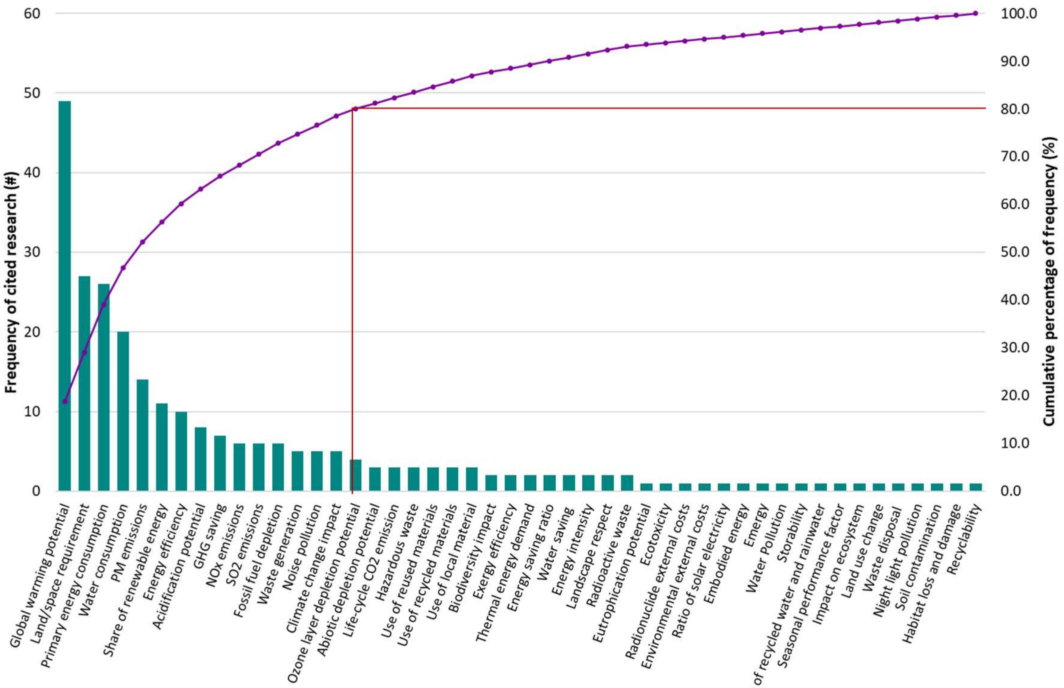


Figure 4-2 Pareto chart for environmental sustainability indicators

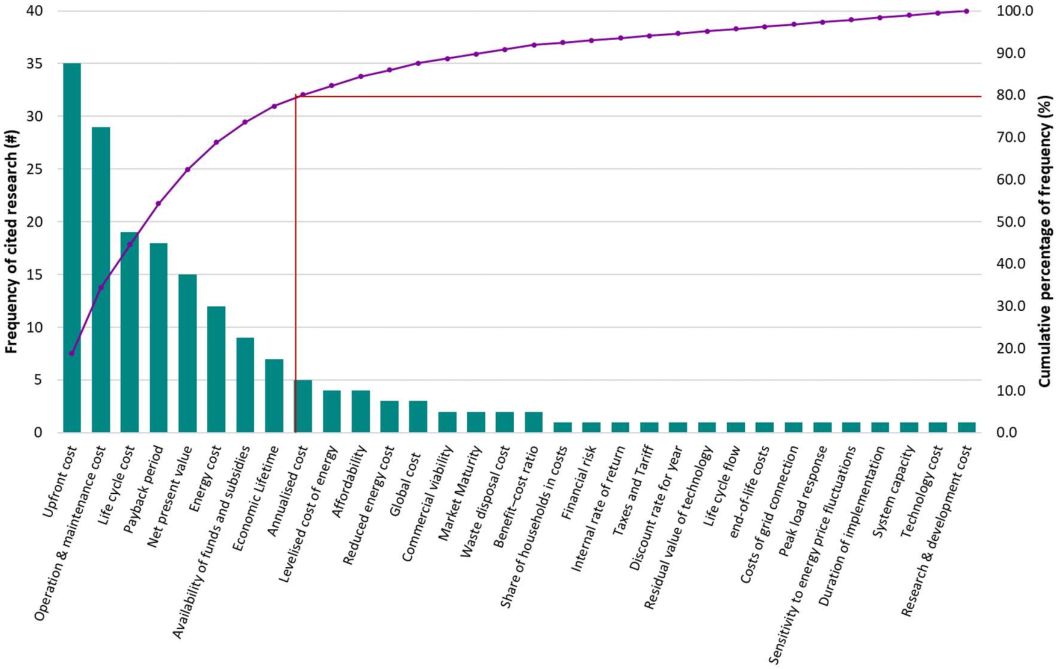


Figure 4-3 Pareto chart for economic sustainability indicators

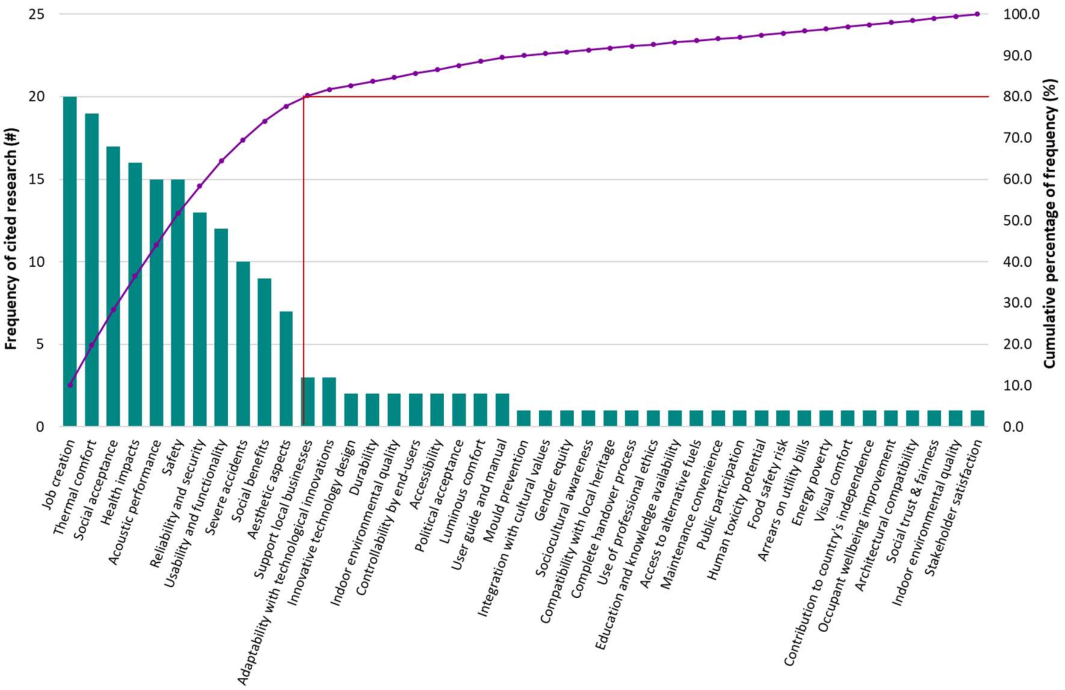


Figure 4-4 Pareto chart for social sustainability indicators

4.4 Refinement step 2: Compatibility check

The indicators obtained from the Pareto analysis have not yet been evaluated against the range of SI qualities which were reviewed in Section 2.3.2, including representativeness, independency and applicability. Furthermore, there is a risk of overlap among the indicators that undermine their independence and objectivity in assessments. The number of selected SIs is also still quite considerable, making them technically and practically impossible to implement in real-world projects. It is highlighted in the literature that having a reasonable number of indicators is beneficial to the sustainability assessment (Fernández-Sánchez and Rodríguez-López, 2010). Experiments show that most individuals cannot accurately make pairwise comparisons between more than seven two criteria (Bagočius et al., 2014).

Therefore, the second round of refinement is required to filter out the indicators which do not meet the SI qualities, as well as merge those with overlap or correlation in functionality. This refinement step, called a compatibility check in this study, also further reduces the number of indicators, making the judgements and comparisons more consistent (Asadabadi et al., 2019). Therefore, the following modifications are made concerning the environmental indicators:

- NO_x and SO_2 emission factors are eliminated because these compounds are already included and addressed in the 'Acidification potential'.
- The indicators of 'Global warming potential', 'GHG saving', and 'Climate change impact' have a clear overlap in addressing the same issue of GHG emissions. Thus, the 'GHG saving', and the 'Climate change impact' indicators are removed to avoid repetition.
- Likewise, indicators of 'Fossil fuel depletion' and 'Primary energy consumption' overlap in capturing relevant aspects associated with resource depletion. 'Fossil fuel depletion' is thereby eliminated.
- The acoustic performance and noise level of the system are studied under social sustainability in this research. Therefore, the indicator of 'Noise pollution' is eliminated from the environmental SIs.
- Fine particles are one of the biggest contributors to human health problems. Therefore, the PM emission factors are studied under the social indicator of 'Health impacts' and then 'PM emissions' is removed from environmental SIs.
- The indicator of 'Waste generation' is also removed because, concerning the case of buildings without solid fuel heating, the level of waste production and disposal is negligible (Lebersorger and Beigl, 2011).

Likewise, regarding the economic indicators:

- Energy cost constitutes a sizeable share of O&M costs of a heating system, and it is taken into account in this indicator. It is, thereby, the 'Energy cost' indicator is eliminated to avoid double-counting.
- Net Present Value (NPV) and the Payback time are two different approaches to performing the life cycle cost (LCC) analysis. While the payback method is found to be the most used indicator, LCC based on NPV is more accurate and efficient as it uses cash flow instead of earnings (Jensen et al., 2018b). Therefore, 'Net present value' is used in this study, and indicators of 'Payback period' and 'Life cycle cost' are removed from the list.

And finally concerning social indicators:

- The indicator of 'Safety' represents all the injuries, accidents, and mortality over the life cycle of the systems. Thus, 'Severe accidents' is eliminated from the SI list to avoid duplication.

- The indicator of 'Social benefits' refers to the positive impact that an energy system has on the social progress of the community at the regional or national level (Saraswat and Digalwar, 2021). The crucial social impacts associated with household-level energy systems are covered in the other social SIs. Thus, this indicator is deemed irrelevant to the scope of the study and is removed from further consideration.

Taking the above considerations into account, from the list of 34 SIs, 21 remain as the modified set of indicators. The outcome of the second refinement step is presented in Table 4-1.

Table 4-1 List of critical indicators at the end of the second step of refinement

Objective	Sustainability dimensions	Sustainability indicators
Sustainability of building heating systems	Environmental	Global warming potential
		Land requirement
		Primary energy consumption
		Water consumption
		Share of renewable energy
		Energy efficiency
		Acidification potential
	Economic	Upfront cost
		O&M cost
		Net present value
		Availability of funds and subsidies
		Economic Lifetime
	Social	Job creation
		Thermal comfort
		Social acceptance
		Health impacts
		Acoustic performance
		Safety
		Reliability and security
		Usability and functionality
		Aesthetic aspects

4.5 Refinement step 3: Staticized group technique

In most of the previous studies, the selection or validation of SIs is undertaken exclusively by the researchers without involving the stakeholders. However, compared to individual decisions, group decision-making provides the advantages of a broader perspective and more experience and knowledge, while reducing the harms of individuals' cognitive restrictions and mistaken evaluations (Ossadnik et al., 2016). Including stakeholders in the initial stages of the process also ensures the effectiveness and applicability of the framework and facilitates long-term commitment and cooperation in implementing the results (Grafakos et al., 2017). Thus, the current study engages stakeholders in the process of identification of SIs, ensuring that experts' perspectives are reflected in the assessments. This approach is similarly used in (Gani et al., 2021; Lazar and Chithra, 2021) to distinguish the critical SIs in different fields. This stage of the process seeks to:

a) Validate the set of SIs selected in the previous steps

b) Identify the potential missing indicators

c) Find out if any amendments for clarity purposes are required

Several participatory techniques exist to incorporate judgments from a group of experts. Traditionally, interviews and group brainstorming techniques, which involved substantial bias and uncertainties, were often used to collect subjective data from experts in engineering areas (Hallowell and Gambatese, 2010). However, alternative methods that could control the bias and ensure the qualification of the respondents are increasingly employed to collect data in these fields. Methods such as the Delphi technique, Staticized groups, Dialectic procedure, and Nominal group technique allow researchers to maintain a greater level of control over bias in well-established, rigorous processes (Hallowell and Gambatese, 2010).

The Staticized groups technique is one of these methods that has been useful for finding the key sustainability criteria. This technique is identical to the Delphi method but excludes the feedback and iteration stages (Hallowell and Gambatese, 2010); it has been described as the Delphi method with one round of analysis (Deniz, 2017). Therefore, there is no interaction between experts, avoiding the need for conformity among individuals and reducing bias in judgments. The main reason for preferring the Staticized group over the Delphi method is to avoid leading the experts to conform to a value which is not necessarily correct, but it is also useful when there is limited access to experts (López-Arquillos et al., 2015). In other words, this method avoids the inaccuracy of consensus results which tends to arise after many iterations in the Delphi method. Therefore, the Staticized groups method is used in this study to conduct the refinement step three.

4.5.1 Qualification and selection of experts

Selecting a group of competent experts is a fundamental step in group decision-making techniques and this is itself a matter of judgment (Zio, 1996). To date, there are no universally agreed instructions or criteria for selecting the experts (Hallowell and Gambatese, 2010). In general, an expert is defined as someone possessing a special or high-level education qualification, or someone with distinct skills or knowledge evident through their track record in professional organisations or academia (Ahmad and Wong, 2019). They also need to have the willingness, adequate time, and ability to participate in the exercise (Rådestad et al., 2013). Furthermore, the experts chosen should represent a diverse spectrum of backgrounds to provide a realistic assessment of the given issue, as well as being independent and having no conflict of interest with the study to minimise motivational biases (Zio, 1996).

To meet the criteria specified above, the candidates in this study were selected from the following groups to ensure a wide range of perspectives and a high level of expertise:

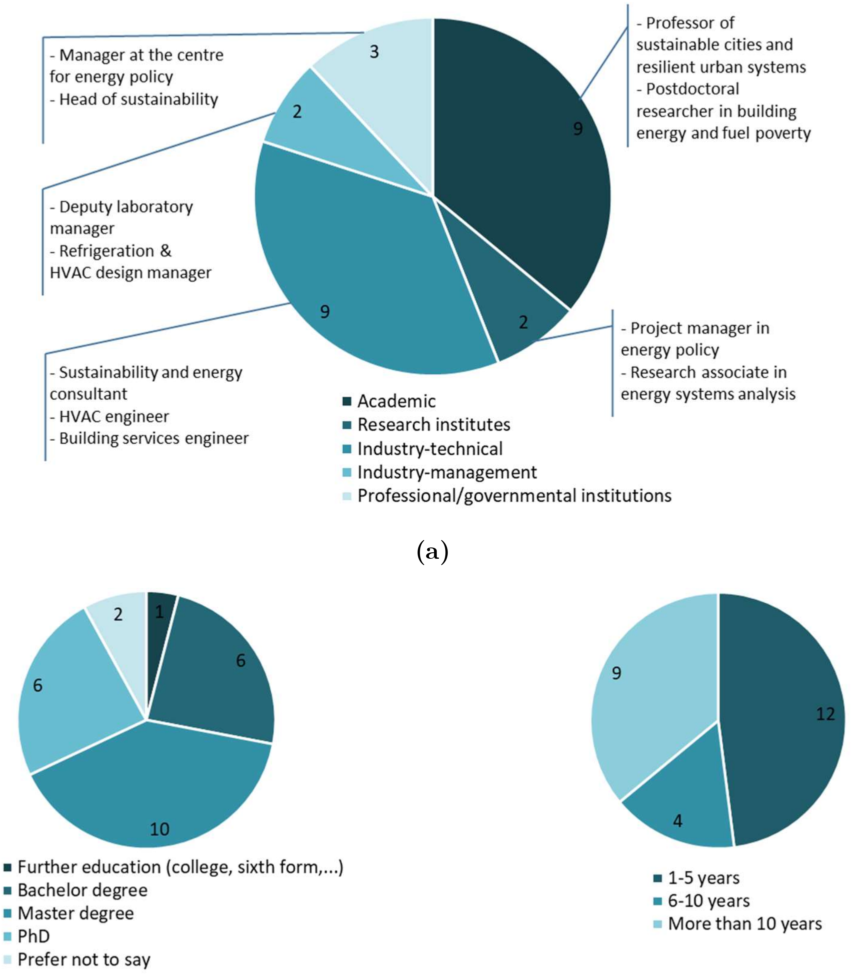
- Academia and research institutes: Researchers and academics with an advanced degree and a record of publications in the related field
- Industry (technical and management): Experts with a history of professional experience or holding a management position
- Professional or governmental organisations: Members of national committees and professional bodies with a demonstrated history of expertise in the field

The Scopus database was used to explore relevant research and to find qualified academics based in the UK. For industry experts, professionals accredited by UK professional bodies such as CIBSE (Chartered Institution of Building Services Engineers), CIPHE (Chartered Institute of Plumbing and Heating Engineering) and the Energy Institute were considered. Experts from governmental bodies and research institutions were also contacted on the basis of their credibility, reputation, and authority in the respective fields.

The number of participants is another important factor in determining the quality of group decision-making (López-Arquillos and Rubio-Romero, 2015). According to the literature, a minimum number of eight experts for homogeneous groups (experts in the same field) and a range from 20 to 60 participants for heterogeneous groups (experts from different social or professional groups) are deemed appropriate (López-Arquillos and Rubio-Romero, 2015; Ahmad and Wong, 2019). Particularly concerning sustainability, a range of 3 to 19 experts is often considered in the research studies (Ahmad and Wong, 2019). This study aimed at 25 expert responses, higher than the reviewed articles, to get stronger outcomes. To get to that point, the survey was emailed to 180 qualified experts, and the invitation was open for five months, from

September 2021 to January 2022. The response rate was 13.8% which is acceptable for an online survey, with an average response rate of 10-15% in the literature (Xu et al., 2012; Fellows and Liu, 2021).

The analysis of the respondents shows that a variety of experienced professionals from different stakeholders participated in the survey. Figure 4-5 illustrates the range of participants. In terms of participants' affiliation, those from academia and industry-technical form the biggest (36%), followed by respondents from professional/governmental bodies (12%). Also, 64% of the members were postgraduates, having a Master’s degree (10 members) or a PhD (6 members) in a relevant field. Detailed characteristics of participants are presented in Table B-2 Appendix B.



(a)

(b) (c)

Figure 4-5 Proportion of the participants based on their (a) Affiliation and job role; (b) Academic education; (c) Professional experience

The questionnaire included questions to analyse the level of knowledge and expertise of the panel concerning the research focus points, i.e., building energy systems, building energy performance, and sustainability of energy systems. On a Likert scale, participants were asked to indicate their level of knowledge/experience of these themes. As shown in Figure 4-6, experts who either agree or strongly agree that they have an advanced level of knowledge/experience in each field constitute a range of 70 to 88% of respondents, with no one strongly opposing these statements.

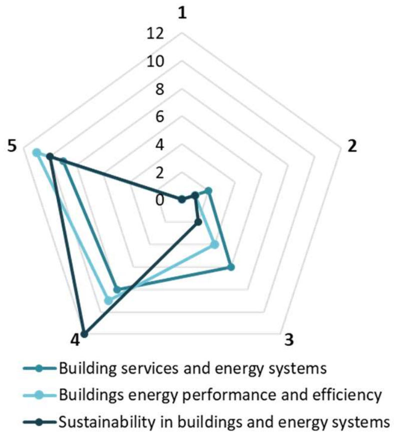


Figure 4-6 Level of knowledge/experience of participants in the research

4.5.2 Survey design and results

A questionnaire survey (Table B-3 Appendix) was developed in three separate parts to collect all required data in one survey round. In the first part, some questions were asked regarding the participants' background, as discussed in the previous section. Next, experts were asked to rate the given list of SIs which is discussed in Section 4.6. This was followed by some questions designed to collect qualitative data regarding the effectiveness, inclusivity, and conciseness of the selected SIs. Thus, using open-ended questions regarding each dimension of SIs, the experts were asked to validate the provided list of indicators or suggest any additional indicators which were not being considered. They could also eliminate any indicators that they deemed to be irrelevant or not applicable to the research area, as well as suggest any modifications to enhance the clarity and functionality of the indicators.

Twenty-one SIs shortlisted in the second round of refinement, were put under the lens of the experts to be analysed at this stage. Indicators which were deemed incompatible or inapplicable by at least two experts were excluded from the analysis. On the flip side, additional indicators suggested by at least two experts were considered to be added to the final list. On the basis of the collected responses, two indicators were added to the final list of SIs as follows:

- The importance of embodied carbon emissions as part of a whole-life carbon assessment was highlighted by three experts, one of whom commented:

  "*The embodied carbon is critical to the efficient specification of the equipment. But it matters nought once the client has possession of the system.*"

  Recent studies show that embodied carbon associated with building services accounts for a considerable proportion of the life cycle footprint, large enough to be independently taken into account in the design and decision-making stages (Rodriguez et al., 2020). Thus, the factor 'Global warming potential' is split into two separate indicators of 'Operational carbon emissions' and 'Embodied carbon emissions' to differentiate the direct and embodied footprint.
- Concerning social indicators, `fuel poverty` is added to the list of indicators as the households' struggle to pay the bills was brought up by three respondents:

  "*Selection of heating systems is usually a factor of who pays the bills when it is designed. Many options are pricy to install and operate, so not an option for many.*"

  This chimes with the findings from the literature review where it was argued that fuel poverty is an essential, but often overlooked, consideration for designing effective, just, and targeted energy interventions in the built environment. Therefore, an indicator for fuel poverty is required to facilitate the inclusion of this factor into design and decision-making processes.

Survey analysis also resulted in the exclusion of one indicator from the initial list:

- The survey was designed to achieve a new understanding of the sustainability of heat transitions that may lead to some modifications in existing policies and incentives. Thus, the experts were asked to respond based on their specialist perspectives. However, two respondents raised an issue that they were unsure of what approach to take when completing the questionnaire, noting 'Availability of funds and subsidies' as one of the confusing reasons:

  "*I generally feel that the answers to these questions will depend on the perception taken. Are these to be responded from a policy maker point of view as it is stated? Or low-income* *households? I wasn't sure how best to answer in some cases like the availability of public funds.*"

The authors agree that the existing funds and support should not be a matter of concern in this study as it contradicts the purpose of the research and its critical eye on the current policies. Therefore, this indicator was eliminated from the list of SIs.

In addition, some minor amendments were made to the SIs to improve their presentation. For instance, the term 'job creation' was changed to 'employment impact' to expand its indication from the number of created jobs to include job losses. Overall, 22 SIs were finalised, comprised of 4 economic, 8 environmental and 10 social indicators, which form the basis of the sustainability assessment of BHSs. The final SI set and the direction of impact of each indicator are given in Table 4-2. A positive (+) or negative (–) sign is assigned to the indicators based on the direction of their impact on sustainability; in other words, if increasing the score of an indicator positively contributes to sustainability, its sign is positive; otherwise, it is negative.

Table 4-2 Final list of sustainability indicators for building heating systems

Main criteria: Sustainability dimensions	Sub-criteria: Sustainability indicators	Unit	Impact on sustainability
Environmental	Operational carbon emissions	$kgCO_2eq/y$	-
	Primary energy consumption	kWh/y	-
	Embodied carbon emissions	$kgCO_2eq$	-
	Share of renewable energy	%	+
	Energy efficiency	%	+
	Water consumption	m^3	-
	Land requirement	m^2	-
	Acidification potential	$kgSO_2eq/y$	-
Economic	O&M cost	£/y	-
	Net present value	£	-
	Upfront cost	£	-
	Economic lifetime	y	+
Social	Health impacts	£	-
	Fuel poverty	%	-
	Thermal comfort	%	+
	Safety	No./y	-
	Employment impact	FTE/y	+
	Reliability	Qualitative	-
	Usability and functionality	Qualitative	+
	Social acceptance	Qualitative	+
	Acoustic performance	dB(A)	-
	Aesthetic aspects	Qualitative	+

4.6 Prioritisation: AHP weighting method

Several weighting methods for multi-criteria analyses are used in the literature and these can generally be divided into three groups as follows (Jahan et al., 2016):

- Subjective methods in which priority weights are assigned based on the judgment of decision-makers, not on the measured data or analysis, i.e., AHP, SIMOS, Pair-wise comparison, TRADEOFF, Delphi method, SMART, SWING, Best-worst method, etc.
- Objective methods in which mathematical models based on the analysis of initial data or measured data are used for determining the importance of the indicators, i.e., entropy method, TOPSIS, Least mean squares method, Mean Weighting, etc.
- Combined weighting methods that integrate the two previous groups to strengthen the existing methods, i.e., multiplication synthesis, additive synthesis, game theory, etc.

Within the context of sustainability, subjective methods have been widely used since they can accurately reflect the preferences of different stakeholders (Ren and Toniolo, 2020). The AHP, in particular, has been the most popular weighting technique for energy systems analyses (Wang et al., 2009; Ren and Toniolo, 2020). The AHP weighting method, first developed by Saati (1987), relies on pairwise comparisons to obtain the relative importance of decision criteria. This study used the AHP method to assign priority weights for the selected SIs. The third part of the survey recorded the participants' views on the level of importance of each indicator. Once the required data was collected, the AHP process could be followed through the steps below (Kamaruzzaman et al., 2018):

1. Build a hierarchical model
2. Prioritise based on individual judgement matrices
3. Aggregate individual priorities to obtain the overall weights
4. Check consistency

The first step structures the problem into its constituent parts by building a hierarchical model to identify the goal of the process, criteria, sub-criteria, and alternatives (Kamaruzzaman et al., 2018). The hierarchical structure of the current study is presented in Figure 4-7. The consecutive steps of the AHP process are separately discussed in the following sections.

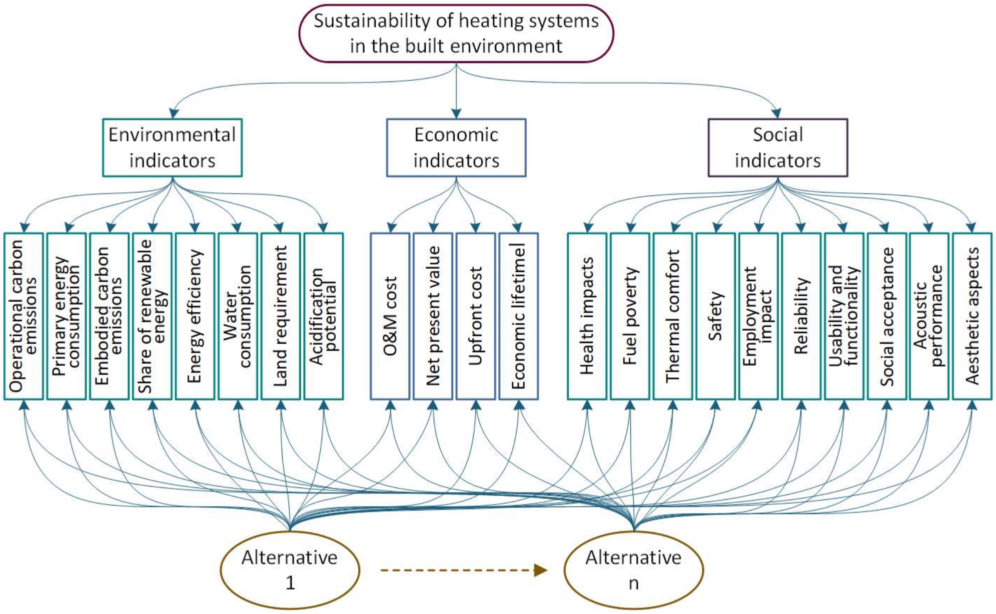


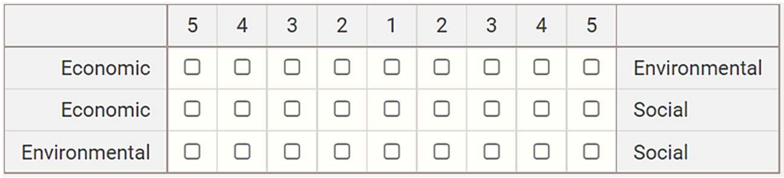
Figure 4-7 Analytical hierarchy model of the system

4.6.1 Prioritisation based on individual judgements

This step was founded on the pairwise comparisons collected from the survey. Experts evaluated the SIs by comparing them to each other concerning their impact on the above element in the hierarchy structure. Comparisons were made by pairing two SIs based on the five-point Likert scale, as defined in Table 4-3. For n factors, total number of $n(n-1)/2$ comparisons should be made to establish the comparison matrix (Song and Kang, 2016). Figure 4-8 shows an example of pairwise comparisons needed to find the relative importance of the three dimensions of sustainability.

Table 4-3 The five-point Likert scale for AHP preferences

Likert scale rating	Definition	Explanation
1	Equal importance	Two SIs contribute equally to the objective
2	Moderately important	Judgments slightly favour one SI over the other
3	Strongly important	Judgments strongly favour one SI over the other
4	Very strongly important	One SI is strongly favoured and its dominance is demonstrated in practice
5	Extremely important	The evidence favouring one SI over another is of the highest possible validity



	5	4	3	2	1	2	3	4	5	
Economic	☐	☐	☐	☐	☐	☐	☐	☐	☐	Environmental
Economic	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social
Environmental	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social

Figure 4-8 A pairwise comparison example concerning the main dimensions of sustainability

The resulting output of this procedure is the comparison (judgment) matrix. Pairwise comparisons are converted into ratios to build comparison matrices. The comparison matrix $A_{n\times n}$, based on each expert's judgment is then constructed as follows:

$$A = (a_{ij})_{n\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad \textbf{4-1}$$

where a_{ij} is the relative importance weight of indicator *i* compared to indicator *j*. In fact, a_{ij} indicates experts' opinion on how much more important the *i*th factor is than the *j*th factor for achieving the AHP goal, meeting the following conditions:

$$a_{ij} = \begin{cases} a_{ij} > 0\,, (i, j = 1,2, \dots, n) \\ a_{ii} = 1\,, (i, j = 1,2, \dots, n) \\ a_{ij} = 1/a_{ji}\ , (i, j = 1,2, \dots, n) \end{cases} \qquad \textbf{4-2}$$

Once the comparison matrix is built, the weightage of indicators can be computed by prioritisation. Prioritisation refers to the process of deriving the weight vector $w_i(A) = [w_i]^T = (w_1, \dots, w_n)$ from the comparison matrix $A_{n\times n}$. The row geometric mean method (RGMM) is one of the most preferred methods in the prioritisation step (Dong et al., 2010). The unique weight vector ($w_i(A)$) using the RGMM can be found as follows:

$$w_i(A) = \frac{(\prod_{j=1}^{n} a_{ij})^{1/n}}{\sum_{i=1}^{n}(\prod_{j=1}^{n} a_{ij})^{1/n}} \qquad \textbf{4-3}$$

where $w_i \geq 0$ and the $w_i(A)$ satisfies the normalisation function as $\sum_{i=1}^{n} w_i = 1$. The comparison matrix and the weight vector were generated for all 25 respondents. Figure 4-9 (a) shows an example comparison matrix that is arrayed by the random expert *A* after making 28 comparisons concerning environmental indicators. The weight vector corresponding to this comparison matrix is presented in Figure 4-9 (b), where $W(A)^{Env}$ represents the weight factor of each environmental SI based on expert *A*'s point of view.

$$\begin{array}{lcccccccc}
 & \text{Env1} & \text{Env2} & \text{Env3} & \text{Env4} & \text{Env5} & \text{Env6} & \text{Env7} & \text{Env8} \\
\text{Operational carbon emissions (Env1)} & 1 & 1/2 & 2 & 1 & 2 & 2 & 4 & 5 \\
\text{Primary energy consumption (Env2)} & 2 & 1 & 3 & 2 & 2 & 3 & 4 & 2 \\
\text{Embodied carbon emissions (Env3)} & 1/2 & 1/3 & 1 & 1 & 1 & 1 & 2 & 2 \\
\text{Share of renewable energy (Env4)} & 1 & 1/2 & 1 & 1 & 4 & 2 & 4 & 2 \\
\text{Energy efficiency (Env5)} & 1/2 & 1/2 & 1 & 1/4 & 1 & 1 & 2 & 2 \\
\text{Water consumption (Env6)} & 1/2 & 1/3 & 1 & 1/2 & 1 & 1 & 4 & 1 \\
\text{Land requirement (Env7)} & 1/4 & 1/4 & 1/2 & 1/4 & 1/2 & 1/4 & 1 & 1/3 \\
\text{Acidification potential (Env8)} & 1/5 & 1/2 & 1/2 & 1/2 & 1/2 & 1 & 3 & 1
\end{array}$$

(a)

$$\begin{array}{lcccccccc}
 & \text{Env1} & \text{Env2} & \text{Env3} & \text{Env4} & \text{Env5} & \text{Env6} & \text{Env7} & \text{Env8} \\
W(A)^{Env} = & [0.19 & 0.24 & 0.10 & 0.17 & 0.09 & 0.09 & 0.04 & 0.07\,]
\end{array}$$

(b)

Figure 4-9 Comparison matrix (a) and the corresponding weight vector based on judgments by Expert A regarding the environmental SIs

The variations of the weight factors obtained from the individuals' judgments are displayed via the box-whisker plot in Figure 4-10. A comparatively lower spread of weighting was observed in the case of social sustainability as compared to significant variations in environmental and economic factors. The NPV stands out as the indicator with the highest mean and median values. However, it is discussed in the next section that using the mean or median value is not the best method to represent the collective value of individual judgments.

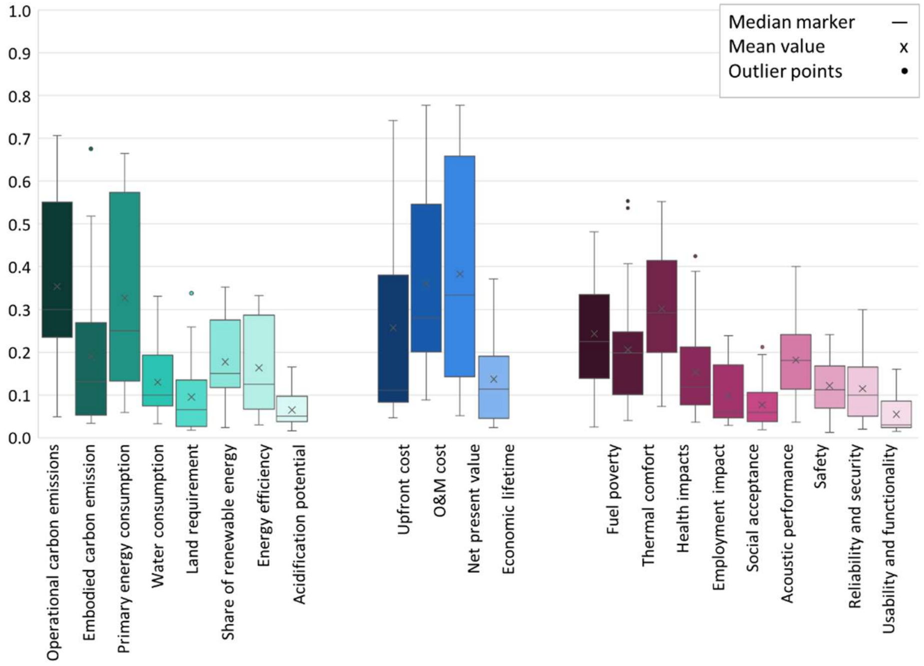


Figure 4-10 Variations in the indicator weights based on the judgements of individuals

4.6.2 Aggregation of individual priorities

The AHP weighting process is followed by the aggregation (consensus) step, in which different individual preferences are aggregated to obtain a single collective weight vector. Since full agreement among all decision-makers is not always achievable in real-life problems, aggregation methods are utilised to synthesise all the judgments and obtain the overall priority of the elements. The method used in this study was the Aggregation of Individual Priorities (AIP), also called the weight aggregation technique (Ossadnik et al., 2016). The AIP is recommended in specialist assessment processes where the decision-makers are experts with individual viewpoints, no supra-decision-maker dominates the others, and they do not want to compromise their judgments (de FSM Russo and Camanho, 2015). The AIP is also the only method that does not require agreement on a common decision model (Ossadnik et al., 2016).

Under the AIP approach, two calculation techniques, the Weighted Geometric Mean Method (WGMM) and the Weighted Arithmetic Mean Method (WAMM), can be used to obtain the aggregated weights (Forman and Peniwati, 1998). The WGMM, however, is favoured by several researchers (Forman and Peniwati, 1998; Ossadnik et al., 2016) and, therefore, is utilised in this study. Within this process, let $w_k(A_i) = [w_k] = (w_1, \dots, w_m)$ be the individual weight vector derived from the individual comparison matrix A_i, made by the decision-maker k, and $\lambda^k =$

$(\lambda^1, \dots, \lambda^m)$ be the weight of the decision-maker k where $\lambda^k \geq 0$ and $\sum_{k=1}^{m} \lambda^k = 1$. Then the normalised collective weight vector, $P(A_i)$, using the WGMM method (Ossadnik et al., 2016) can be obtained by:

$$P^{WGMM}(A_i) = \frac{\left(\prod_{k=1}^{m} (w_k(A_i))^{\lambda^k}\right)^{1/m}}{\sum_{i=1}^{n} \left(\prod_{k=1}^{m} (w_k(A_i))^{\lambda^k}\right)^{1/m}} \qquad \textbf{4-4}$$

Applying this method to each group of SIs, the collective local weights can be obtained, as presented in Table 4-4. ‘Local weights’ refers to weights of the indicators with respect to the element above them in the hierarchy tree; that is, their importance to their parent criterion, whereas ‘global weight’ is the result of multiplying the local weight of the SI by its dimension, representing the contribution of the SI to the overall goal of sustainability (Chatzimouratidis and Pilavachi, 2009).

Table 4-4 Aggregated priority weights of the sustainability dimensions and indicators

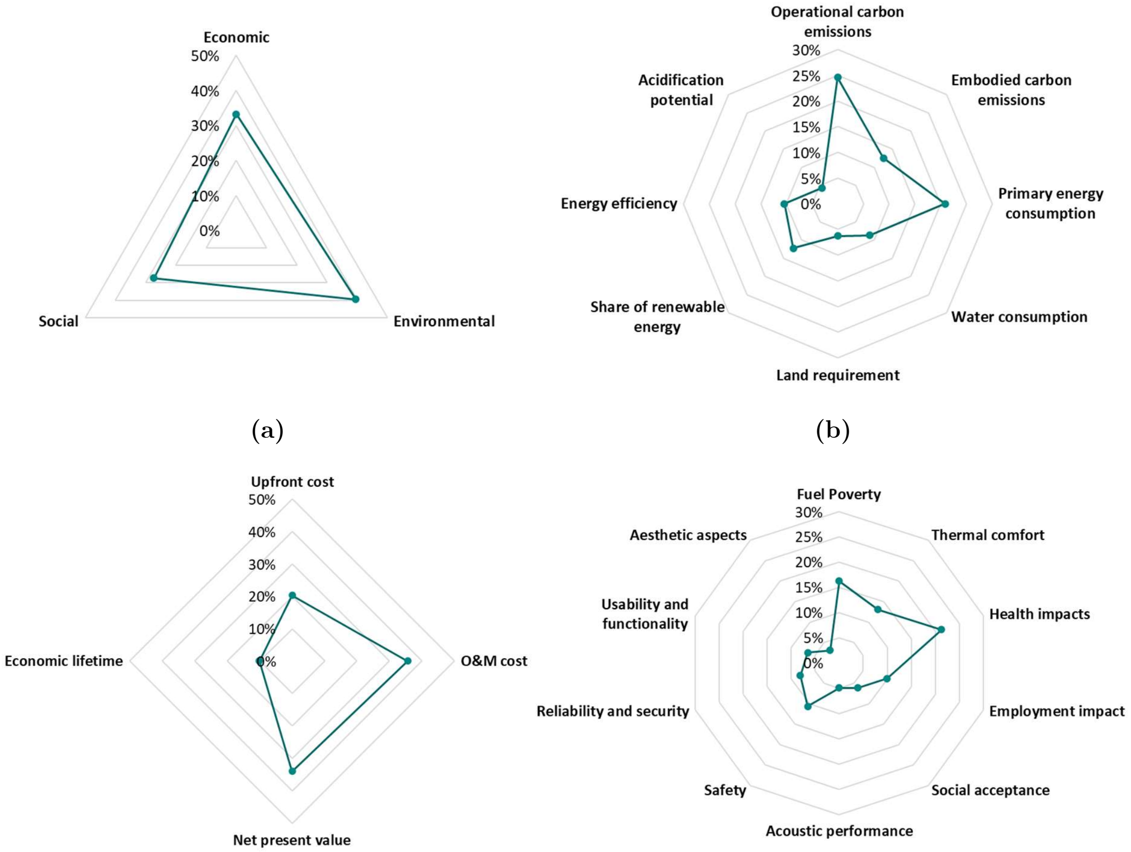
Main criteria				Sub-criteria				
Sustainability dimensions	Local weight	Global weight	Rank	Sustainability indicators	Local weight	Global weight	Local rank	Global rank
Environmental	0.395	0.395	1	Operational carbon emissions	0.246	0.097	1	3
				Primary energy consumption	0.209	0.082	2	4
				Embodied carbon emissions	0.125	0.049	3	7
				Share of renewable energy	0.123	0.049	4	8
				Energy efficiency	0.104	0.041	5	10
				Water consumption	0.087	0.034	6	12
				Land requirement	0.063	0.025	7	16
				Acidification potential	0.044	0.017	8	19
Economic	0.332	0.332	2	O&M cost	0.356	0.118	1	1
				Net present value	0.340	0.113	2	2
				Upfront cost	0.203	0.067	3	5
				Economic lifetime	0.101	0.034	4	13
Social	0.273	0.273	3	Health impacts	0.213	0.058	1	6
				Fuel poverty	0.162	0.044	2	9
				Thermal comfort	0.130	0.036	3	11
				Safety	0.107	0.029	4	14
				Employment impact	0.100	0.027	5	15
				Reliability	0.081	0.022	6	17
				Usability and functionality	0.065	0.018	7	18
				Social acceptance	0.062	0.017	8	20
				Acoustic performance	0.050	0.014	9	21
				Aesthetic aspects	0.031	0.008	10	22

In this study, the weights of the main criteria were separately obtained based on expert judgments. Unequal weighting for sustainability dimensions is employed in the literature to analyse the sensitivity of parameters under different scenarios (Ghenai et al., 2020). According to Table 4-4 and Figure 4-11 (a), the environmental dimension has received the highest weight, followed by the economic and social dimensions. This could be explained by the fact that sustainability is traditionally perceived exclusively in environmental terms (Redclift, 2000). Furthermore, the social dimension is less prominent in the energy and building industry discourses and perhaps harder to pinpoint.

Under the environmental dimension, operational carbon proved the most crucial indicator in this group, with a weight reaching 0.246. Primary energy consumption also attracted considerable attention and accounts for almost 21% of the overall environmental score, while the two SIs at the bottom of the list, land requirement and acidification potential, collectively contribute less than 11% to this element. The embodied carbon emissions and share of renewable energy, as the third and fourth environmental SIs weigh about half of the first indicator. The contribution of SIs to overall environmental sustainability is illustrated in Figure 4-11 (b).

In terms of economic sustainability, a relatively high weight was given to the selected SIs because all stakeholders, regardless of their knowledge, felt directly connected to at least one of the economic SIs. For instance, building occupants are often cautious about operational costs, while developers care more about upfront costs. Overall, the O&M costs dominated the economic category, probably because it has a direct impact on the cost of living. Among the four economic indicators, only one indicator represented the profit (i.e., savings compared to the basic scenario), and this obtained the second rank in the indicators list, as shown in Figure 4-11 (c).

Regarding social sustainability, although this dimension received a lower weight, it has the highest number of indicators. This could be explained by the fact that heating systems have a wider domain of impact on end-users and societies than other energy systems, and this must be explored. The ‘health impacts’ factor has also been given a high score because of the prevailing health problems and detriments that could be caused by poor indoor heat conditions. Fuel poverty, which was added to the list of SIs by experts, was rated the second prominent indicator. The least important SIs of this category were related to qualitative factors, such as social acceptance and aesthetic aspects, as illustrated in Figure 4-11 (d).



(a) (b)

(c) (d)

Figure 4-11 Contribution of the indicators to the priority weight of (a) Overall sustainability; (b) Environmental sustainability; (c) Economic sustainability; (d) Social sustainability

4.6.3 Consistency Check

The AHP method has the advantage that the consistency of judgments can be verified using consistency check methods. In group decision settings, the consistency check examines the homogeneity of the group judgments, as well as the misattributions of individuals. This can ensure the reliability of the outcomes and validate the first stage of the thesis methodology. In group decision-making, the aggregation process consolidates the consistent properties of the individual comparison matrices (Dong and Cooper, 2016). In other words, if the degree of consistency of each of the initial comparison matrices is satisfactory, then the aggregated priorities will be consistent. Therefore, the consistency of all the individual comparison matrices is calculated using the consistency ratio (*CR*) which can be obtained as follows (Saaty, 1987):

$$CR = \frac{CI}{RI} \tag{4-5}$$

$$CI = \frac{\lambda_{max} - k}{k - 1} \tag{4-6}$$

Where *CR* is the consistency ratio; *CI* is the consistency index; *k* is the number of criteria; and *RI* is the random index, whose value depends on the matrix's dimension and can be selected from Table 4-5:

Table 4-5 RI of random matrices (Saaty, 1987)

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

And λ_{max} is the largest eigenvalue of the judgment matrix and is defined by:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}(\sum_{j=1}^{n}\frac{a_{ij}.w_j}{w_i}) \tag{4-7}$$

The experts' judgment and its associated comparison matrix have acceptable inconsistency only when *CR* is smaller than 10%. When the ratio falls beyond this threshold, inconsistency becomes problematic, and the comparison matrix needs to be reassigned and modified by decision-makers. Typically, when the order of the comparison matrix grows, as a result of the increased number of pairwise judgments, the inconsistency issue appears and increases exponentially (Asadabadi et al., 2019). In this study, consistency ratios range from 0.028 to 0.097, implying that the analyses conducted are reliable. For example, the *CR* corresponding to the example comparison matrix given in Figure 4-9 is 0.092 (9.2%) which meets the consistency check requirements. This validates the results shown in Table 4-4. Figure 4-12 recaps the outcomes of this chapter in a pie chart.

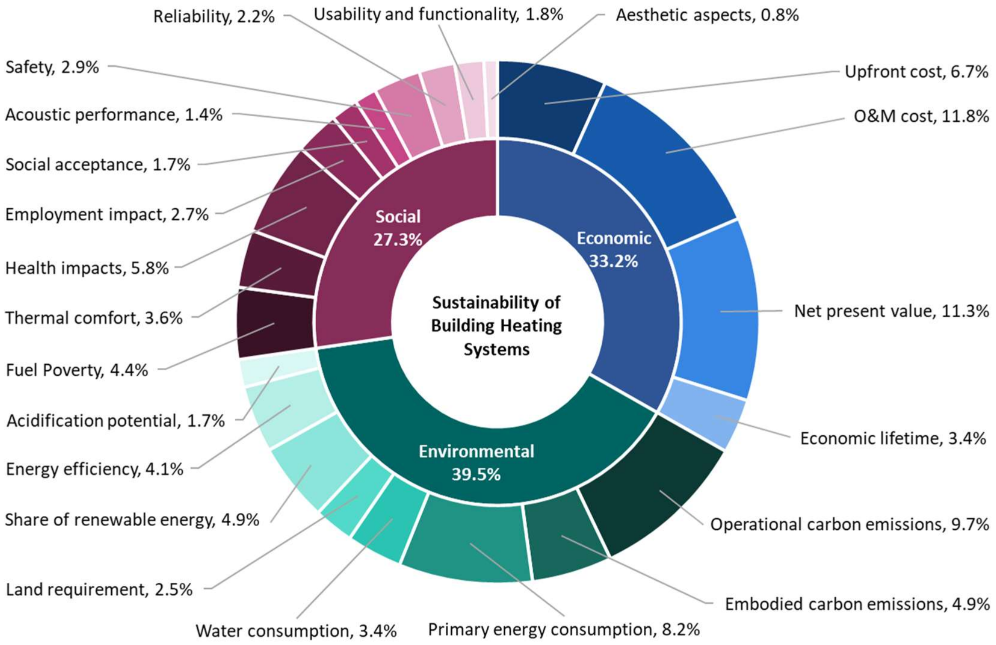
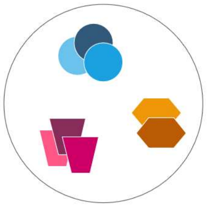
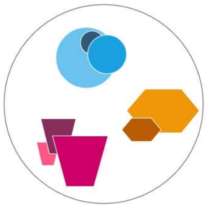


Figure 4-12 Final set of sustainability indicators and their global priority weight

4.7 Chapter summary

This chapter develops a framework for the identification and prioritisation of the set of SIs. The proposed framework utilises a series of quantitative and qualitative methods to ensure the reflection of the stakeholders' priorities and a balanced representation of all facets of sustainability. Using the developed framework, a representative set of SIs can be determined to quantify, analyse, and communicate complex sustainability information through consistent and transparent measures. This framework can be broadly applied to the routine determination and analysis of key sustainability factors in various fields. Applying these steps to the case of BHSs, a set of 22 SIs, consisting of 4 economic, 8 environmental, and 10 social indicators were selected. Table 4-6 presents a comprehensive recap of the chapter workflow.

Table 4-6 Recap of the Chapter steps, methods, and corresponding outputs

Framework stage	Schematic	Workflow step	Applied method	Number of output SIs	Notes
Identification		Identification	Literature scanning	156	Identified SIs from 66 studies
Classification		Classification	Authors' intuition	118	Categorised into sustainability dimensions and remove duplications
Refinement		Refinement step 1	Pareto analysis	34	Identify the vital SIs
		Refinement step 2	Compatibility check by authors	21	Dismiss the irrelevant and merge the overlapped SIs
		Refinement step 3	Staticized group technique	22	Input from experts to validate and amend the SIs
Prioritisation		Prioritisation	AHP weighting method	22	Prioritise based on experts' judgment

With the input of 25 experts from diverse stakeholder groups, the environmental dimension was found to be the most crucial element of sustainability (39.5% of the overall weight), followed by the economic dimension (33.2%). It was also found that the social dimension constitutes a considerable proportion (27.3%) of the overall sustainability weight. Concerning indicator weights, the O&M cost, NPV, and operational carbon emissions were the top three critical SIs. It is worth mentioning that the range of SIs considered, although verified by experts' input, is not exhaustive in all circumstances and could be augmented through a broader survey of households and key stakeholders. In the next step, appropriate measurement tools and methods need to be determined to be able to quantify the identified SIs for different BHSs.

Chapter 5 Development of quantification methods and datasets

Based on the Chapter 4 outcomes, 22 sustainability indicators (SIs) were identified. To utilise these SIs, a set of calculation models, measurement tools, and datasets are required, which are further referred to as ‘quantification’. Quantification is an essential step for analysing the SIs and comparing different solutions (Bragança et al., 2010). The quantification methods are tools and formulas by which SIs can be measured and analysed. While the research tradition on sustainability provides some theoretical groundwork, the lack of a consistent quantification standard leads to rather diverse theories and measurement methods for SIs. Especially concerning the social dimension of sustainability, further research is required to find suitable methods for quantification (Carrera and Mack, 2010).

Generally, SIs can be classified as *Quantitative* and *Qualitative indicators* (Saad et al., 2019). *Quantitative* SIs can be measured directly or obtained using mathematical models, simulation tools, or databases that provide an objective value for the indicators. *Qualitative indicators,* however, need to be transformed into quantitative indicators before they can be used in MCDA. The quantification of these indicators is not straightforward as it requires historical data, surveys or subjective judgments, which are usually based on end-user or decision-maker experiences. Thus, there is often less information in the literature than about quantitative SIs and it is not always possible to guarantee their certainty, accuracy, or reliability (Reed et al., 2006; Saad et al., 2019).

Therefore, this chapter seeks to determine the most suitable quantification methods and collect the required data for calculating values of the identifies SIs. These quantification methods are defined in such a way that they can be applied independently, using data that are accessible at the early stages of projects. The proposed methods should provide accurate measures in a scientifically rigorous way while remaining easy for users to employ and interpret. These methods and datasets are aggregated from different sources such as national standards, databases, literature, and expert opinions. This stage of the thesis correlates with the quantitative data collection and analysis part of the exploratory mixed methods approach and provides the required data for inventory analysis based on the ISO 14040 LCA process. In the following, each of the selected SIs is defined and then their quantification method is explained.

5.1 Environmental indicators

5.1.1 Operational carbon emissions (Env1)

5.1.1.1 Definition of indicator

'Operational carbon emissions' is an indicator that reflects the potential global warming impacts of buildings or energy systems caused by GHG emissions during the operational or in-use phase of a building over its life cycle. Regarding the BHSs in particular, this indicator refers to the GHGs emitted during the procurement, distribution, and consumption of fuels and electricity needed for generating the heat and hot water demand of the household and the building (Vares et al., 2019). This indicator is used in almost all studies on the environmental footprint of buildings and energy technologies (Martín-Gamboa et al., 2017; Campos-Guzmán et al., 2019; Hashempour et al., 2020; Siksnelyte-Butkiene et al., 2020)

It is worth noting that the term 'carbon' in this study denotes all GHG emissions, e.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), that are responsible for global warming. Values for the non-carbon dioxide GHGs are converted to carbon dioxide equivalent (CO_2eq) using their global warming potential (GWP) factors. Using the CO_2eq standard unit, the impact of each different GHG can be expressed in terms of the amount of CO_2 that would create the same amount of global warming impact (Amponsah et al., 2014). For instance, 1 kg of methane has the same effect as 25 kg of CO_2; thus, its GWP equals 25 kg CO_2eq (Chersoni et al., 2022). Therefore, the indicator of operational carbon emissions represents GHG emissions in kgCO_2eq/kWh (kg of equivalent CO_2 emissions per unit of energy delivered).

As shown in Figure 5-1, operational carbon emissions are associated with stages B6 and B7 of the life cycle stages of the heating equipment. The life cycle of a built asset (in the case of this thesis, a heating system) is categorised into different life cycle stages and broken into modules, defined by the BS EN 15978:2011 standard for sustainability assessment in the building industry (BSI, 2011). This means that the operational carbon indicator consists of all the GHG emissions as a result of energy and water consumption of the BHS, once complete, to supply heating and hot water.

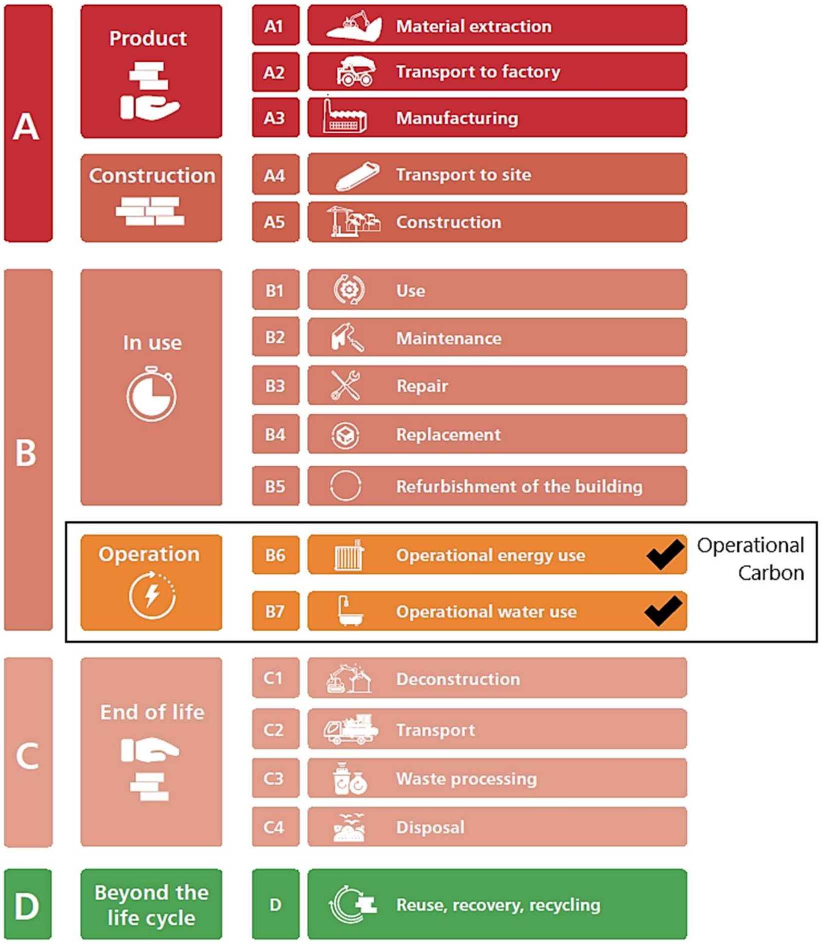


Figure 5-1 Boundary and modules included in operational carbon assessment over a system's lifecycle (CIBSE, 2021b)

5.1.1.2 Quantification method

Operational GHG emissions can be estimated according to the type and amount of energy resources and by applying the conversion factors. This is the most common method of estimating operational GHG emissions of different organisations or energy systems (Dones et al., 2004). The GHG conversion factors – also referred to as emission factors - are the weighted average of the GHG emissions for each energy source and usage and allow companies and individuals to calculate the contribution of their activities to global warming. This study follows the GHG environmental reporting guideline provided by the UK government (HM Government, 2019). Based on this method, emissions from a range of activities such as energy use, water consumption, waste disposal, and transport activities are categorised into three groups, known as scopes. Each activity is listed as either Scope 1, Scope 2, or Scope 3, based on which conversion factor can be assigned (BEIS, 2022c).

- Scope 1 covers direct emissions of activity from owned or controlled sources. Examples of Scope 1 emissions include emissions from combustion in boilers, furnaces and vehicles; and emissions from chemical production in controlled process equipment.
- Scope 2 includes indirect emissions that are associated with the input of electricity, heat, steam and cooling. These indirect emissions are a consequence of energy use but occur at sources that are not owned or controlled by the user.
- Scope 3 covers all other indirect emissions of activities that occur at sources that are not owned or controlled by the user. Examples of Scope 3 emissions are waste disposal and materials or fuel purchases. Scope 3 emissions can be from activities that are upstream or downstream of the system's energy use.

The UK government provides a dataset each year that includes the conversion factors for different fuels and sections, broken down by their scope. Table 5-1 shows the conversion factors for the common primary fuel sources.

Table 5-1 Energy carriers GHG conversion factors breakdown for the UK, 2022 (BEIS, 2022c)

Energy carrier	**Activity**	**Scope**	**Conversion factor ($kgCO_2eq/kWh$)**
Electricity	Electricity generation	Scope 2	0.1934
	Electricity T&D	Scope 3	0.0177
	WTT for generation	Scope 3	0.0462
	WTT for T&D	Scope 3	0.0042
Natural gas	Gross CV	Scope 1	0.1825
	WTT emissions	Scope 3	0.0311
Biomass	Wood chips production	Scope 1	0.0105
	WTT for wood chips	Scope 3	0.0079
	Wood pellets production	Scope 1	0.0105
	WTT for wood pellets	Scope 3	0.0374

Some of the terms that are used in Table 5-1 are defined below:

- Electricity generation: The average CO_2 emission associated with the UK national grid per kWh of electricity generated at a power station, classed as Scope 2 of the activities.

- T&D: Emissions associated with the transmission and distribution loss per kWh of the purchased power.
- WTT: Well-to-Tank emissions factor represents the upstream emissions of extraction, refining and transportation of raw fuel sources, before their combustion.

For this study and in line with the life cycle approach of the assessment, total direct and indirect GHG emissions that occur in the system's value chain are taken into account. Therefore, emission factor values of scopes 1 to 3, including emissions have to be added up to achieve the figures that reflect the 'cradle-to-grave' system boundary (CIBSE, 2021b). For electricity, for example, the overall conversion factor for electricity (CF_{Ovr}^{E}) comprises four items as follows:

$$CF_{Ovr}^{E} = CF_{Gen}^{E} + CF_{T\&D}^{E} + WTT_{Gen}^{E} + WTT_{T\&D}^{E} \qquad \textbf{5-1}$$

$$CF_{Ovr}^{E} = 0.1934 + 0.0177 + 0.0462 + 0.0042$$

$$CF_{Ovr}^{E} = 0.2615$$

Likewise, the final values of GHG conversion factors that are used in this research are calculated and listed in Table 5-2.

Table 5-2 Energy carriers' overall GHG conversion factors for the UK, 2021

Energy carrier	Overall conversion factor ($kgCO_2eq/kWh$)
Electricity	0.2615
Natural gas	0.2136
Biogas	0.0286
Biomass wood chips	0.0184
Biomass wood pellets	0.0479

Having the conversion factors for different fuels, the carbon emissions associated with operating and running the heating systems over their lifetime can be obtained. The operational carbon emission (OCE in $kgCO_2eq/kWh$) is calculated by converting the BHS's total energy consumption at the utility meters to CO_2 equivalent emissions, using the overall GHG conversion factors (CF_{Ovr}) according to Eq. **5-2** (Fumo et al., 2009).

$$OCE = EC_{BHS}.CF_{Ovr}^{E} + FC_{BHS}.CF_{Ovr}^{F} \qquad \textbf{5-2}$$

where EC_{BHS} is the annual electricity consumption of the heating system, FC_{BHS} is the annual fuel consumption of the BHS in non-fully electric systems, and CF_{Ovr} represents their respective conversion factors, which are considered to remain constant throughout the life cycle of the system. Ultimately, the annual electricity and fuel consumption of the BHSs can be obtained through the dynamic building energy simulation using IES VE.

5.1.2 Primary energy consumption (Env2)

5.1.2.1 Definition of indicator

Building accounts for some 40% of the total final energy consumption in the EU and nearly half of the UK's primary energy consumption (Karmellos et al., 2015; Johns, 2017). Hence, improving the energy performance of buildings is a key priority toward the sustainability targets. The energy performance in the built environment can be expressed by the indicator of primary energy consumption (*PEC*). Primary energy is described as "energy from renewable and non-renewable sources which has not undergone any conversion of the transformation process." (BRE Group, 2022). The PEC could also provide a meaningful measure of energy use in BHSs, taking into account upstream energy uses.

Using the dynamic simulations performed by the IES-VE software, it is possible to determine the BHS energy requirements, broken down by the type of energy carrier and then convert them to the *PEC* figures. Thus, apart from the necessary information for the building physics simulation, the model and configuration of the BHS are also required. More technical data associated with the BHS features and components, like fans, pumps, efficiency, and loss rate, should be included in the modelling phase. By modelling the performance of different heating technologies in the building, the *PEC* of these systems can be predicted.

5.1.2.2 Quantification method

The *PEC* (in kWh/(m^2.y)) can be obtained by converting the final electricity and fuel consumption of a dwelling or an energy technology to primary energy figures by using primary energy factors (*PEF*). The *PEF* indicates the kWh of primary energy sources, including fossil energy fuels, nuclear, and renewables, that are used to generate a kWh measure of usable energy output. Like the GHG conversion factors that connect energy use and carbon emissions, *PEFs* connect final energy use and primary energy sources. For instance, the *PEF* of 1.5 for electricity implies that each unit of electricity requires an input of 1.5 units of primary energy in today's UK grid. The PEFs for different energy carriers are calculated by the UK Standard Assessment

Procedure (SAP) for the energy rating of dwellings and are listed in Table 5-3 (BRE Group, 2022).

Table 5-3 Primary energy factors for energy carriers in the UK, 2022 (BRE Group, 2022)

Energy carrier	Primary energy factors (kWh/kWh)
Electricity	1.501
Natural gas	1.130
Biomass wood pellets	1.037

Once the *PEFs* and the total energy consumption of the system are identified, the *PEC* (kWh) can be calculated using Eq. **5-3**. The *PEC* represents the indicator Env2 in the assessments, based on which energy systems can be prioritised according to the minimum value.

$$PEC = EC_{BHS}.PEF^{E} + FC_{BHS}.PEF^{F} \qquad \textbf{5-3}$$

where EC_{BHS} and FC_{BHS} are the annual electricity consumption and fuel consumption of the heating system, respectively, and PEF represents their respective primary energy factor. Annual electricity and fuel consumption of the BHSs is obtained through the building energy simulation using IES-VE. The two limitations associated with the *OCE* methodology mentioned in Section 5.1.1 apply to *PEC* estimation as well.

5.1.3 Embodied carbon emissions (Env3)

5.1.3.1 Definition of indicator

The building industry has been predominantly focused on operational GHG emissions, paying less attention to footprints related to the other life cycle stages (Schmidt et al., 2020). To make well-informed decisions that will mitigate global warming, decision-makers need to embrace the whole life carbon (WLC) approach (CIBSE, 2021b). The WLC refers to both operational and embodied carbon emissions (ECE), from the extraction of raw materials through to the deconstruction and waste process. Experts suggest that only by adopting the WLC approach can we effectively decarbonise the building sector. Therefore, this study takes into account GHG emissions from the entire life cycle of the BHSs by assessing both operational and embodied impacts independently. ECE of BHSs includes the emissions arising from extracting, transporting, manufacturing, and installing the BHSs, as well as their end-of-life emissions.

Despite the extensive history of studies on the whole life carbon of buildings, there is a knowledge gap regarding the embodied impact of building services (Alwan and Jones, 2014).

However, the significance of ECE in building services has been recently recognised, as it has been reported that it could represent between 10% and 12% of the total embodied carbon of a building (Kiamili et al., 2020). This could be quite substantially higher in homes with modern heating technologies such as solar-assisted heat pumps, reaching up to 28.5% (Zhang and Wang, 2017). Focusing on heating systems only, these systems represent 1-25% of the home's total embodied carbon; that is excluding the impact of refrigerants in HPs (Hamot et al., 2021). Refrigerant losses through the in-use leakage and recovery at the end of life contribute significantly to climate change. HPs often use synthetic hydrofluorocarbon (HFC) refrigerants, which lead to substantial GHG emissions into the atmosphere (Moore et al., 2017).

Therefore, there is a need to take the WLC approach to be able to holistically assess the environmental footprint of BHSs, as was also remarked by the experts in the conducted survey (Chapter 4). Similar to the Env1 indicator, 'carbon emissions' refers to the GHG emissions responsible for global warming and is measured on a kgCO_2eq per kWh basis. According to the cradle-to-grave approach of this study, ECE can be defined as GHG emissions related to A1–A3 (product), A4–A5 (construction), B1–B3 (in-use) and C1–C4 (end-of-life), as illustrated in Figure 5-2. Emissions associated with B4 (replacement) and B5 (refurbishment) are excluded due to the assessment level at which products are studied and stage D (beyond the lifecycle) emissions are excluded due to the cradle-to-grave scope of the study, compliant with the TM65 calculations (CIBSE, 2021b).

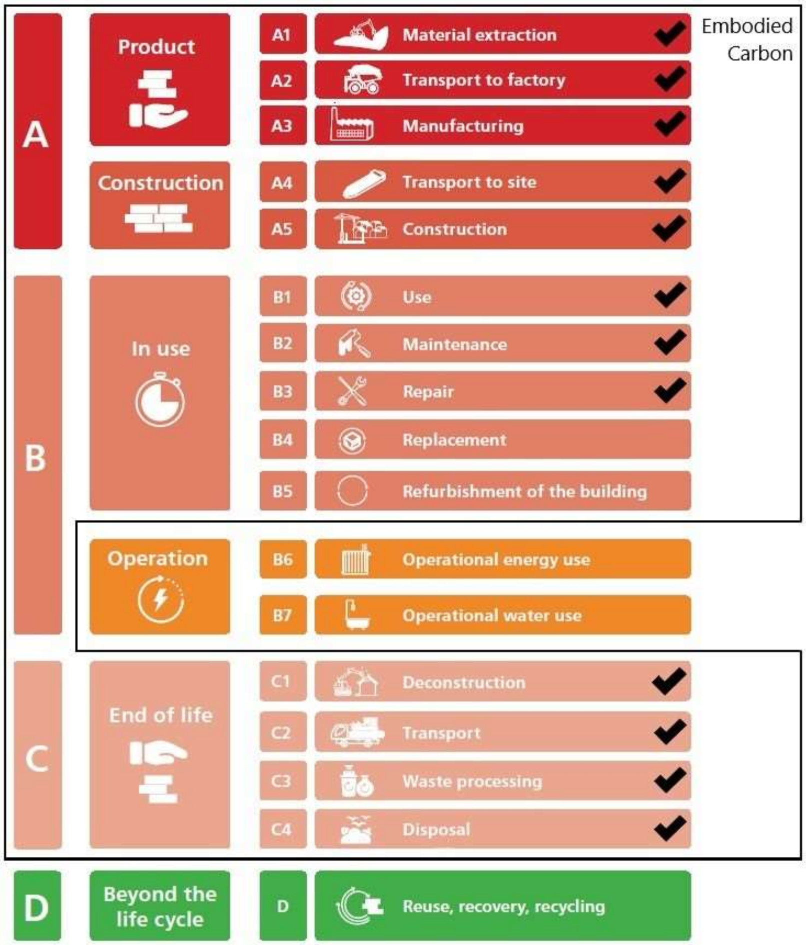


Figure 5-2 Embodied carbon boundary with ticked modules indicating the included stages in the product level assessments (CIBSE, 2021b)

5.1.3.2 Quantification method

Correct quantification of embodied carbon has been a challenge for building carbon assessments (Pomponi et al., 2018). It requires extensive knowledge of raw material types, quantities and sources, as well as valid carbon emission factors for the materials (Medas, 2019). Today, there are some specialised tools such as SimaPro, One Click LCA, and GaBi which can be used to conduct LCA analyses. However, these software tools were primarily developed to assess construction elements at the building level and are found to have considerable truncation errors due to the complexity of requirements (Finnegan et al., 2018). Therefore, these tools were not found suitable for analysing the ECE of BHSs at the product level.

For different products, Environmental Product Declaration (EPD) forms are considered the most reliable way of understanding the embodied impacts (CIBSE, 2021b). However, very few manufacturers provide EPDs for heating and cooling technologies, mainly due to the complexity of these products and their supply chains. To address this lack, CIBSE has published a new guideline, CIBSE TM65, to facilitate whole-life carbon assessment in building services, while waiting for EPDs to become widely available (CIBSE, 2021b). The TM65 basic calculation method is recommended for LCAs at the early stages of projects, up to level 3 of the RIBA plan of work, which is also compatible with the scope of this study. Therefore, this method is used in the present study to estimate the ECE of different BHSs.

Based on CIBSE TM65, the following information is required to obtain the ECE for heating, cooling, and electrical equipment.

- Product weight
- Material composition breakdown for at least 95% of the product weight
- Type and amount of refrigerant within product (refrigerant charge (RC))
- Product service life (n)

Once this information is collected either from EPDs or datasheets, the ECE of each heating technology can be calculated using Eq. **5-4** (CIBSE, 2021b):

$$ECE = \left[\left(\sum_j M_j.ECC_j + 0.1 \times \sum_j M_j.ECC_j\right) \times f_s \times f_b \times HC_{BHS}\right] + [RC \times GWP_R \times LR \times N] + [RC \times GWP_R \times (1 - RR)] \quad \textbf{5-4}$$

This equation comprises of the elements that are outlined below:

- #1: The embodied carbon associated with the extraction of the material of the components (A1) (see Fig. 5-2) is calculated by multiplying the weight of each material (M_j) in kg/kW by its embodied carbon coefficient (ECC_j) by the system's heating capacity (HC_{BHS}). The ECC_j of common materials can be found in Table 5-4. The information must be provided for at least 95% of the product weight and the remaining material is assumed to be steel.

Table 5-4 Embodied carbon coefficients of materials (CIBSE, 2021b)

Material	Embodied carbon coefficient ($kgCO_2eq/kg$)
ABS	3.76
Aluminium	13.10
Brass	4.80
Ceramic	0.70
Copper	3.81
Expanded polystyrene	3.43
Glass	1.44
Insulation	1.86
Iron	2.03
Lithium	5.30
Plastics	3.31
Polyethylene	2.54
Polyurethane foam	4.55
PVC	3.10
Stainless steel	4.40
Steel (general or galvanised)	2.97
Zinc	4.18
Cast iron	1.52
Electronic components	49.00

- #2: The embodied carbon associated with materials that are replaced within the product service life (B3) is calculated. It is assumed that 10% of the materials in the product are replaced during the service life (CIBSE, 2021b). Therefore, 10% of A1 is added to the result of #1.
- #3: A scale-up factor (f_s) is multiplied by the result of the above steps to account for the A2, A3, A4, B2, C2, C3, and C4 modules of the product life cycle. The values of f_s depends on the complexity of the product and can be found in Table 5-5.

Table 5-5 Scale-up factors based on the complexity of the products and supply chain (CIBSE, 2021b)

Product category	Examples	Scale-up factor
Category 1: Low complexity	Pipes, cables, ducts, valves, fire alarm devices, cable containment, electrical outlets	1.3
Category 2: Medium complexity	Pumps, luminaires, radiators, control panels, sensors, thermal store	1.4
Category 3: High complexity	Air handling units, HPs, boilers, heat interface units, chillers, generator, UPS	1.6

- #4: The result of #3 is multiplied by a buffer factor (f_b) to provide an adjustment for the simplicity of the approach. The TM65 considers 1.3 for the f_b in the basic calculation method.
- #5: Any emissions associated with refrigerant leakage are added to cover B1 by multiplying the annual leakage rate (LR) by the quantity of the refrigerant in the product (RC), the global warming potential of the refrigerant (GWP_R) and the service life of the system (N). The LR and GWP_R can be selected through Table 5-6 and Table 5-7, respectively.

Table 5-6 Refrigerant leakage scenarios [3] (CIBSE, 2021b)

Product category	Annual leakage rate	End-of-life recovery rate
Category 1: Package HP or chiller, where no refrigerant is managed on-site	2%	99%
Category 2: HP or chiller where some works to refrigerant pipework are carried out on-site	4%	98%
Category 3: VRF systems where a large amount of refrigerant pipework is installed and filled on-site	6%	97%

Table 5-7 Refrigerants' global warming potential over 100 years (CIBSE, 2021b)

Type	Refrigerant	Global warming potential ($kgCO_2eq/kg$)
CFC	R11	4750
HCFC	R22	1810
	R407c	1774
HFC	R410a	2088
	R134a	1430
	R32	677
HFO	R1234yf	<1
	R1234ze (E)	1
Hydrocarbon	R290 (propane)	4
Natural	R744 (CO2)	1
	R717 (ammonia)	0
	R718 (water)	0

- #6: The final item is the emissions related to the refrigerant leakage that occurs in decommissioning the system (C1). For this, the GWP_R of the refrigerant that is not

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[3] Leakage rates reported by CBSE TM65 are used in this study, although many higher leakage rates can be found in other research and real case studies, e.g. Johnson, E.P. (2011) Air-source heat pump carbon footprints: HFC impacts and comparison to other heat sources. *Energy Policy*, 39 (3), 1369-1381.

recovered is calculated using the refrigerant end-of-life recovery rate (RR) that can be found in Table 5-6.

Adding the results of the above items results in a figure which can be used as an estimate of the embodied carbon of the BHS. Figure 5-3 illustrates the outline this method. Further details of the estimation method can be found in (CIBSE, 2021b).

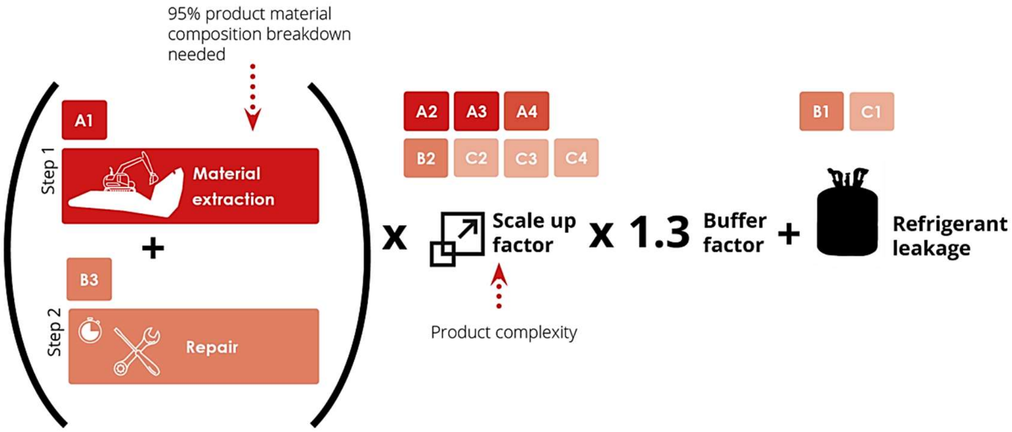

Figure 5-3 The CIBSE TM65 method for calculating the embodied carbon of building services (CIBSE, 2021b)

5.1.4 Share of renewable energy (Env4)

5.1.4.1 Definition of indicator

The share of renewable energy sources (RES) in heating and cooling is increasing but the progress is certainly not yet sufficient to meet the targets. The recently updated document, “Fit for 55”, as part of the European Green Deal has set a gradual, binding increase of 0.8% per year until 2026 and 1.1% from 2026 to 2030 (European Council, 2021). In the UK, less than 10% of the heating need is met by renewables, while 90% of the UK’s heating sector is reliant on natural gas (Siksnelyte-Butkiene et al., 2021a). This raises not only an environmental issue but also an energy security issue which can be addressed by moving towards RES. The RES share in the UK is expected to be achieved mostly through the development of HPs, district heating, and biomass in both domestic and commercial markets. Therefore, the share of RES is deemed an important indicator of environmental sustainability to be included in this study.

5.1.4.2 Quantification method

The share of renewables (SOR) in this study is calculated based on the building energy model. The SOR is estimated by dividing the amount of renewable energy consumed for heating (E_{RES})

divided by the total energy consumption (E_{Tot}) of the BHS. The RES represents those energy sources that can be used directly in individual systems and are not considered primary energy. The Env4 indicator can be calculated as follows (Chapman et al., 2016):

$$SOR = \frac{E_{RES}}{E_{Tot}} \tag{5-5}$$

$$E_{RES} = E_{sol} + E_{bio} + E_{geo} + (EC_{BHS}.r_g) \tag{5-6}$$

where E_{RES} is the renewable energy consumption for the given system, which can be obtained by multiplying the total electricity consumption (EC_{BHS}) by the renewable energy ratio of the national grid (r_g), summed with the total energy generation from solar (E_{sol}), geothermal (E_{bio}) and biofuels (E_{geo}), the main three forms of renewable sources of heat. All the energy figures used in equations **5-5** and **5-6** can be obtained from the building energy simulation, and the r_g for the UK national grid is taken as 43%, based on 2021 data (BEIS, 2022d). In cases where only fossil fuels are used, the value for SOR is 0, while if only RES is used the value is equal to 1.

5.1.5 Operational efficiency (Env5)

5.1.5.1 Definition of indicator

A sustainable local heating system is based on three main parameters: careful use of resources, renewable energy, and efficiency in technology (Hehenberger-Risse et al., 2019). The use of primary resources and use of renewables were addressed using the indicators Env2 and Env4, respectively. Efficiency is the third parameter that has to be studied as an essential in slowing growth of the energy demand by reducing system losses and using fuel with an appropriate heating value. Efficiency is also related to the reliability and economic benefits of the system. Efficiency, in general, refers to how much useful energy can be obtained from an energy source (Wang et al., 2009). Operational efficiency is the term to explain the ratio of generated energy to the input energy in energy systems.

Efficiency is the most frequently used technical criterion in evaluating energy systems (Şengül et al., 2015). In this study, the operational efficiency of BHSs is studied under the environmental dimension of sustainability to facilitate meaningful comparisons of the different alternatives. Efficient systems will typically have lower GHG emissions and operating costs, which directly influence the environment and human welfare. Employing these systems in the energy transition will enhance the efficiency of the whole energy system while maintaining energy security and increasing demand. Less efficient systems, however, may need more significant technological advancement and innovation to be viable options.

5.1.5.2 Quantification method

The fourth environmental indicator is defined as the ratio of produced heat to the input energy, and is expressed in percentages. Determining the operational efficiency of using technical data is not straightforward in many cases. The challenging aspect of this indicator is that each system is made up of a complex set of system functions and components that can influence the ultimate system efficiency. In this case, the whole system's operational efficiency (OE) can be obtained using the ratio of produced heat to the input energy, as in Eq. **5-7** (Chapman et al., 2016).

$$OE = \frac{H_{Gen}}{E_{Tot}} \qquad \textbf{5-7}$$

To calculate the OE as a percentage, the total heat generated (H_{Gen}) is divided by the total energy consumption (E_{Tot}) of the BHS. The operational efficiency rate calculated using this equation is different from the efficiency rates reported by the manufacturers.

5.1.6 Water consumption (Env6)

5.1.6.1 Definition of indicator

Water footprint, along with GHG emissions, energy consumption, and waste generation, has often been accounted as one of the ecological footprint indicators to measure the environmental sustainability of buildings and energy systems (Onat et al., 2014). Water consumption is especially important in arid climates, where water has always been a key factor in decision-making. Today, the transition to low-carbon technologies and the evolution of new alternatives with high water consumption and evaporation rates are not sustainable when water shortages are problematic in many parts of the globe.

Water consumption is, therefore, one of the important indicators of environmental sustainability considered in this study (Env6), measuring the impact of BHSs on water resources. Previous studies have often considered this factor in assessing the power sector, while water requirements of thermal technologies are usually sidelined in LCA studies (Evans et al., 2009). However, with an increasing share of electric heating, water consumption will become a more important factor in the heating sector, since electricity accounts for a large and growing share of water demand (Sharma and Balachandra, 2015).

5.1.6.2 Quantification method

Obtaining the correct value of water consumption is not straightforward, especially for renewable energy resources. It is usually difficult to distinguish between water withdrawal, which is water taken from resources and circulated in the unit, and water consumption, which is water used in the unit and removed from circulation (Evans et al., 2009). Furthermore, in some energy technologies, like ground-source HPs, a major part of water consumption takes place during their service life, while most of the water used in solar systems is associated with the production of solar collectors and little water is used during operation and maintenance (Evans et al., 2009). This study uses freshwater consumption during the overall life cycle of the heating systems to represent the indicator of water footprint.

The life cycle freshwater consumption (FWC) of the selected BHSs is obtained by multiplying the system's heating capacity (HC_{BHS}) in kW by the water consumption coefficient (WCC) in m^3/kW of that technology type as in Eq. **5-8** (Strazza et al., 2016):

$$FWC = HC_{BHS}.WCC \tag{5-8}$$

HC_{BHS} is the output size of the given system, which can be obtained through building thermal modelling in the design stages. WCC, however, can be extracted from available data sources. Generally, the databases of ÖKOBAUDAT, SimaPro, and PEP Ecopassport were used in this study for data extraction. The WCC values, however, were obtained based on the functional unit impacts[4] from the PEP Ecopassport database (P.E.P. ecopassport, 2023), verified with similar products in the ÖKOBAUDAT database (ÖKOBAUDAT, 2023). A summary of WCC values covering the whole life cycle of common BHSs from manufacturing to end of life are shown in Table 5-8.

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[4] According to the EN 15804 definitions, 'functional unit' is the quantified performance of a product for use as a reference unit. Functional unit values allow comparisons between different products or technical solutions as long as they fulfil the same function.

Table 5-8 Water consumption coefficient of the heating technologies over their life cycle (ÖKOBAUDAT, 2023; P.E.P. ecopassport, 2023)

Heating technology	Water consumption coefficient (m^3/kW)	Reference product
Gas condensing boiler	3.77	REMEHA: AVANTA ACE 24c
Biomass wood pellet boiler	7.43	FLAMME VERTE: H7 CLASSIC DROIT
Solar thermal heater	6.65	UNICLIMA INDUSTRIES ASSOCIATION: 2.16 m^2 Solar thermal collector
Direct electric radiator	17.50	MULLER INTUITIV: M144113
Direct electric boiler	15.45	HITACHI: Yutampo R32 version 190L
Air-water individual HP	3.24	LG ELECTRONICS INC.: THERMA V-HM163M U33
Air-air individual HP	1.51	LG ELECTRONICS INC.: Multi Split-FM57AH U34
Ground source individual HP	15.5	STIEBEL ELTRON: Gamme WPF 07

5.1.7 Land requirement (Env7)

5.1.7.1 Definition of indicator

The land requirement of energy systems is a matter of great concern for their evaluation, due to its strong impact on the environment, landscape, and the amount of investment (Wang et al., 2009). This factor, often referred to as land use in sustainability studies, represents the changes in the land and surrounding landscape that are occupied by energy systems. Apart from the most ever-lasting changes in the flora and fauna, land often carries the major economic share in the overall investment in energy plants (Saraswat and Digalwar, 2021). Land use also has clear social implications especially when human activities are affected by the energy systems' implementation. This happens when a piece of land that could have been used for the creation of public amenities is assigned to an energy system development (Wang et al., 2009).

Therefore, land use has been one of the most frequently used environmental SIs of energy production systems, as shown in Chapter 4. The land use evaluation could include direct land use, which is the land occupied by the system, or indirect land use, which is land associated with the fuel supply system and construction, operation and decommissioning of the energy system (Klein and Whalley, 2015). Estimation of indirect land use is often based on simplified assumptions and is also dependent on the reliability of the information. However, direct land use is estimated using existing datasets and analyses of benchmark projects. The land use factor in this thesis has not been found a prominent SI, mostly because individual BHSs have less land impact compared to electricity generation systems.

5.1.7.2 Quantification method

The land requirement values are generally found to be very uncertain as their estimation depends on several factors, e.g., specific site requirements, geographical conditions, and installation layout (Troldborg et al., 2014). Land use estimates also depend on whether the life-cycle land requirement of the technology or only the land use during its operation phase is considered. Furthermore, dual land use is possible in many cases (e.g., solar thermal panels can be installed on a geothermal plant) which effectively reduces the area required for the technology and complicates the estimations.

In this study, similar to the work by Troldborg et al. (2014), the land required for each of the technologies considered is assessed and expressed as m^2/kW of installed heating capacity. The life cycle land requirement (LR) for the selected technologies can be obtained by multiplying the system's heating capacity (HC_{BHS}) in kW by the land requirement coefficient (LRC) in m^2/kW of that technology type, according to:

$$LR = HC_{BHS}.LRC \tag{5-9}$$

HC_{BHS} is the output heating capacity, which has already been obtained through the building thermal simulation, and the LRC should be extracted from databases. Only a few studies exist which provide LRC analyses and their values vary from one source to another, although the technology rankings are similar. The data for LRC used in this study were compiled from several different sources, presented in Table 5-9. For the missing data, the values are interpolated based on subjective valuations from other studies. The final technology ranking was cross-checked with different resources to verify the estimates.

Table 5-9 Land requirement coefficient of the heating technologies over their life cycle (Afgan and Carvalho, 2002; Beccali et al., 2003; Troldborg et al., 2014; Kontu et al., 2015).

Heating technology	**Land requirement coefficient (m^2/kW)**
Gas condensing boiler	20
Biomass wood pellet boiler	400
Solar thermal heater	40
Direct electric radiator	20
Direct electric boiler	10
Air source HP	50
Ground source HP	60

5.1.8 Acidification potential (Env8)

5.1.8.1 Definition of indicator

The impact of GHG emissions is often communicated using their global warming potential (CO_2eq), eutrophication potential (PO_4eq), and acidification potential (SO_2eq) (Decano-Valentin et al., 2021). The global warming potential is investigated through the Env1 and Env3 indicators. The eutrophication potential has not been prominent in investigations concerning heating systems and was not shortlisted for the final set of SIs. The acidification potential, however, turns out to be more relevant to heating systems and should be taken into consideration. It is important to investigate acidification potential independently and separately from the GWP, as they do not correlate with each other (Žigart et al., 2018).

Acidification is the alteration of the chemical composition and decreases in the PH value of soil and water, resulting in acidified terrestrial and aquatic systems that threaten the survival of different living organisms (Kim et al., 2021). Sulphur dioxide (SO_2) emissions are the major factor contributing to acidification; however, there is a wide range of other contaminants including hydrogen sulphide (H_2S), ammonia (NH_3), nitrogen oxides (NO_x), and nitrogen monoxide (NO) (Decano-Valentin et al., 2021; Kim et al., 2021). The effect of this phenomenon can be measured in terms of acidification potential (AP), expressed in the form of kg SO_2-equivalents, by taking SO_2 as the reference substance (Kim et al., 2021). Using Env8, this study quantifies the embodied emissions of acidifying substances from the energy used by different BHSs during their life cycle that cause acid deposition on soil and water resources.

5.1.8.2 Quantification method

The AP analysis may strongly depend on the choice of the calculation method. EN-15804 provides a general guideline for LCA calculations and analyses in which AP is one of the core environmental impact indicators (BSI, 2021). This methodology is widely used by manufacturers to create environmental product declarations (EPDs), a document that quantifiably demonstrates the environmental impacts of products. According to this method, the overall AP of a product is calculated based on converting the impact of different emitted substances to SO_2eq, by multiplying the number of substances by their corresponding acidification potential characterisation factor (BSI, 2021). EPDs created according to this method have been collected in some databases that can be used as a reference in different analyses.

This study used the PEP Ecopassport and ÖKOBAUDAT databases to collect AP values. The values for AP per functional unit of kW, called acidification potential coefficient (APC) in this study, can also be found in these databases. Having the APC values for different heating technologies, overall AP scores in kgSO$_2$eq can be calculated using Eq. **5-10**, by multiplying the system's heating capacity (HC_{BHS}) in kW by the APC in kgSO$_2$eq/kW of that technology type (Strazza et al., 2016):

$$AP = HC_{BHS}.APC \tag{5-10}$$

Table 5-10 shows the average APC results of selected heat production technologies that can be used as a reference for this study.

Table 5-10 Acidification potential coefficient of the heating technologies over their life cycle (ÖKOBAUDAT, 2023; P.E.P. ecopassport, 2023)

Heating technology	Acidification potential coefficient (kgSO$_{2eq}$/kW)	Reference product
Gas condensing boiler	1.9	REMEHA: AVANTA ACE 24c
Biomass wood pellet boiler	8.69	FLAMME VERTE: H7 CLASSIC DROIT
Solar thermal heater	1.89	UNICLIMA INDUSTRIES ASSOCIATION: 2.16 m^2 Solar thermal collector
Direct electric radiator	5.23	MULLER INTUITIV: M144113
Direct electric boiler	0.39	HITACHI: Yutampo R32 version 190L
Air-water individual HP	14.10	LG ELECTRONICS INC.: THERMA V-HM163M U33
Air-air individual HP	5.63	LG ELECTRONICS INC.: Multi Split-FM57AH U34
Ground source individual HP	5.11	STIEBEL ELTRON: Gamme WPF 07

5.2 Economic Indicators

5.2.1 Operation and maintenance cost (Eco1)

5.2.1.1 Definition of indicator

Different economic indicators tackle different economic aspects of projects, reflecting various stakeholders' concerns. In other words, funding agencies, governments, developers, and end-users may find one or more indicators more critical than the others. For instance, tenants and owner-occupiers may be concerned about the operation and maintenance (O&M) costs, while life cycle costs might be of interest to policymakers (Aberilla, 2020). In this study, different economic indicators are considered to ensure that all perspectives are reflected. However, the O&M cost was found to be the most critical economic SI in this study in relation to BHSs. An identical high priority was given to this factor in other studies focused on the residential sector, e.g., (Kontu et al., 2015), which represents the sensitivity of this factor for this sector.

The O&M factor refers to all the costs expended during the operational life of the system. Concerning energy systems, this includes costs of labour, energy, products, services, and maintaining the energy system (Haddad et al., 2017). The O&M cost could also be divided into two subcategories: fixed annual costs (e.g., depreciation and labour), and variable annual costs (e.g., consumables, repair, fuel costs, and water supply), which are directly related to the amount of energy produced (Aberilla, 2020). The lifecycle O&M costs of heating technologies are quite significant (Mohammadpourkarbasi and Sharples, 2022). This is mainly due to maintenance requirements and the short service life of BHSs, aggravated by the recent energy crisis, which has led to an unprecedented surge in the running cost of energy services.

5.2.1.2 Quantification method

Operation and maintenance costs (OMC) per year can be derived from a building's yearly energy requirement estimated by the software, current fuel prices, and maintenance frequency. The O&M cost over the service life of the system can be expressed by using Eq. 5-11, where the discount factor is applied to discount the time series of running expenditures to present values (Mohammadpourkarbasi and Sharples, 2022). The accumulated O&M cost is also converted to an annual value using the capital recovery factor (CRF) to compare systems with different economic lifespans (Thygesen and Karlsson, 2013; Kumar et al., 2021).

$$OMC = \sum_{t=1}^{N} \left(\frac{OC_t + MC_t}{(1+r)^t}\right) \times CRF(r,N) \tag{5-11}$$

In the above equation, OC_t represents the operational expenditure in year *t*; MC_t is the fixed and variable maintenance expenditure in year *t*; N is the system service life; *r* is the real discount rate; and $CRF(r,N)$ is the capital recovery factor. The operational costs (OC) can be computed based on the annual energy usage from the house model and the average UK energy prices as follows:

$$OC = EC_{BHS}.UC^{E} + FC_{BHS}.UC^{F} \tag{5-12}$$

where EC_{BHS} and FC_{BHS} are the annual electricity consumption and fuel consumption of the heating system that are sourced from energy simulation, and UC^{E} and UC^{F} represents the unit cost of the respective energy carrier. Table 5-11 shows the average unit rates for the different energy carriers suitable for UK domestic properties.

Table 5-11 The unit price of energy carriers for the end-user in the UK, 2023 (Nottingham Energy Partnership; Rafique and Williams, 2021)

Energy carrier	Unit price (p/kWh)
Electricity (Standard tariff)	39.21
Natural gas	11.52
Biomass wood chips	30.96
Biomass wood pellets	49.60

Maintenance costs (MC), however, are difficult to quantify and based on assumptions. The Danish Energy Agency regularly publishes catalogues of technology data for energy technologies (Danish Energy Agency). This catalogue includes probably the most comprehensive European database that provides technical, economic, and environmental information about individual and industrial heating plants (Danish Energy Agency, 2021). Table 5-12 summarises the maintenance expenses across the set of heating systems for the newly built single-family houses. Prices are converted from Euro (EUR) to British Pound (GBP) with an average exchange rate of 0.853 in 2022.

Table 5-12 Annual maintenance cost of heating systems (Danish Energy Agency, 2021)

Heating technology	Maintenance cost (£/year)
Gas condensing boiler	160.7
Biomass wood pellet boiler	319.6
Solar thermal heater + gas boiler	55.6
Direct electric radiators + electric boiler	21.2
Air-water individual HP	244.6
Air-air individual HP + electric boiler	132.4
Ground source individual HP	242.8
Gas hybrid HP	316.1

Finally, the capital recovery factor ($CRF(r,N)$) over N years of project lifetime at a given interest rate of r (in real terms), used to annualise present values, can be derived through (Kumar et al., 2021):

$$CRF(r,N)=\frac{r\times(1+r)^{N}}{(1+r)^{N}-1} \quad \text{5-13}$$

5.2.2 Net present value (Eco2)

5.2.2.1 Definition of indicator

The net present value (NPV) as a metric for evaluating life cycle costs (LCC) was ranked as the second economic indicator through the experts' survey. The LCC reflects all relevant cost factors over the entire life of a product or a project and is evaluated using life-cycle cost analysis (LCCA) methods (Kubba, 2010). The LCCA has been researched and employed extensively to evaluate energy renovations, sustainable materials, building services, green buildings, etc. (Hajare and Elwakil, 2020). Several metrics may be used to perform the LCCA, e.g., the NPV, the payback period, and the internal rate of return (IRR).

Although the payback period was found to be the most commonly used indicator in the relevant literature in Chapter 4, it is usually calculated by considering the direct capital and operational costs without factoring in indirect costs and the time value of money. The NPV, however, can give more precise results in absolute terms, making it a more realistic financial appraisal tool (Jensen et al., 2018a). Therefore, the NPV is used in this study to evaluate the overall value of the BHSs over their lifespan. The NPV considers both the costs and benefits of a system by discounting the positive and negative future cash flows to the present value (Hajare and Elwakil, 2020). It represents the amount of investment today required to pay for the capital cost plus all future operating costs of a system. Often used by investors and decision-makers, the NPV is a standard capital budgeting method to analyse the feasibility and profitability of an investment or project (Wang et al., 2009).

5.2.2.2 Quantification method

To perform LCCA using the NPV, the guidelines outlined in the RICS professional guidance on life cycle costing (RICS, 2016) and the British Standards Document BS ISO 15686, part 5 on service life planning and life-cycle costing (BSI, 2017) were followed. According to these standards, NPV may be described as the sum of the discounted economic factors, including capital costs, utilities and operational costs, maintenance costs, and end-of-life costs, accumulated over the entire system's lifespan. It can be determined with the discount rate r by using Eq. 5-14. Similar to O&M cost, future expenditures are discounted to establish their present value (Mohammadpourkarbasi et al., 2016).

$$NPV = UC + \sum_{t=1}^{N} \left(\frac{OC_t + MC_t}{(1+r)^t}\right) + \frac{C_{EoL}}{(1+r)^N} \qquad 5\text{-}14$$

In the above equation, UC is the upfront cost which will be thoroughly explained in the next indicator; OC_t and MC_t are the operation and the maintenance expenditure in year t, discussed earlier in Section 5.2.1 ; N is the system service life; r is the real discount rate; and finally C_{EoL} is the end-of-life costs that should be observed to yield a more accurate estimate of the project's cost during the evaluation period.

End-of-life costs (C_{EoL}) include all the costs and/or revenues associated with waste transport and processing, disposal, and replacement of the system. In this study, as in (Mohammadpourkarbasi et al., 2016), the cost of replacement of major systems and components were considered in the calculations. The replacement costs were gathered from different resources as presented in Table 5-13. Ultimately, it should be noted that since the NPV in this study represents the cost of heating systems, it would be a negative factor which should be minimised in analyses.

Table 5-13 Replacement cost of heating systems at the end of their service life (Etude, 2018; Mohammadpourkarbasi and Sharples, 2022)

Heating technology	Replacement cost (£)
Gas condensing boiler	1860
Biomass wood pellet boiler	2500
Solar thermal heater + gas boiler	2150
Direct electric radiator + electric boiler	500
Air-water individual HP	3000
Air-air individual HP + electric boiler	3000
Ground source individual HP	3500
Gas hybrid HP	2500

5.2.3 Upfront Cost (Eco3)

5.2.3.1 Definition of indicator

The upfront cost, also named 'investment' or 'capital cost', is one of the key criteria used in assessing energy technologies and ranking the possible solutions (Vasić, 2018). Within building energy research, in particular, upfront costs are given greater priority by the professional public compared to operational costs, which in practice, is probably closer to the behaviour of owners or investors (Ren et al., 2009). This is why upfront costs are more often utilised in the literature (see Pareto chart of the economic indicators in Chapter 4), and upfront costs have been the most important economic factor in the assessment of industrial heating systems (Chinese et al., 2011). However, with the weighting factors obtained from the survey, some changes were made in the priority of cost factors, enough to bring the O&M cost indicator to the top of the SI list in our study.

The upfront cost refers to the expenses of the acquisition and installation of the required components. Thus, all the costs related to the purchase of equipment (boilers, pumps and valves, piping, heat storage, radiators, etc.) and their installation (engineering, civil works, grid connection, commissioning) should be included in this indicator (Vasić, 2018). From the standpoint of policymakers, the indicator of the upfront cost is what they need to assess how much the implementation of different transition scenarios would cost the economy (Brand and Missaoui, 2014).

5.2.3.2 Quantification method

The upfront cost used in this research includes all the costs incurred during the procurement of the equipment and its installation and commissioning. Concerning BHSs, upfront costs are often lower compared to lifecycle operational costs, but are still significant and considered to be one of the key barriers to further uptake of low-carbon technologies (Abbasi et al., 2021). This study defines the upfront cost of the heating system (UC) as a function of the installed heating capacity (HC_{BHS}) and the technology cost (TC) to facilitate comparisons between different case studies. Ultimately, the UC is represented using Eq. 5-15:

$$UC = HC_{BHS} \times TC \tag{5-15}$$

HC_{BHS} is the rated thermal capacity of the system in kW, obtained from the building thermal simulation. TC is the unit cost of technology per kW of heating capacity and is obtained from the same database (Danish Energy Agency, 2021) used for the O&M cost. The collected investment costs from this database are then benchmarked against the cost data available in other sources; namely, Spon's Mechanical and Electrical price book (Langdon, 2022) and (Kozarcanin et al., 2020). Table 5-14 shows the cost estimates used for individual heating plants. An average exchange rate of 0.853 was considered to exchange EUR to GBP values when needed.

Table 5-14 Total upfront costs for the procurement and installation of heating systems per unit of heat capacity (Kozarcanin et al., 2020; Danish Energy Agency, 2021)

Heating technology	Technology unit cost (£/kW)
Gas condensing boiler	207.6
Biomass wood pellet boiler	400.9
Solar thermal heater + gas boiler	537.4
Direct electric radiators + electric boiler	312.5
Air-water individual HP	1235.7
Air-air individual HP + electric boiler	630.1
Ground source individual HP	1648.7
Gas hybrid HP	1557.1

5.2.4 Economic lifetime (Eco4)

5.2.4.1 Definition of indicator

The economic lifetime, also referred to as 'service life' and 'life expectancy' is the operational period between the installation and decommissioning of a system. Regarding energy systems, it can be defined as the expected lifetime of the system, or the acceptable period of operation in service (Mourmouris and Potolias, 2013). This factor is often studied under economic criteria as it strongly affects other economic indicators e.g., O&M cost and LCC (Wang et al., 2009; Haddad et al., 2017). Incorporating the life expectancy of energy systems is necessary for performing an LCCA. This factor is specifically crucial concerning building energy services as they usually have shorter life spans in comparison with the other building components (Mohammadpourkarbasi et al., 2016). This, therefore, imposes a higher replacement cost, which could considerably affect the LCC at the end of the life cycle. The lifetime is also considered a design/decision factor for energy systems and is employed to select the best scheme from alternatives (Wang et al., 2009).

5.2.4.2 Quantification method

The economic lifetime of a BHS refers to the number of years the main heat generation system can operate before it needs to be replaced. For this study, the lifetime values reported in the Danish Energy Agency's technology database (Danish Energy Agency, 2021) are used. These data are gathered through investigations of several projects and survey responses from manufacturers and suppliers. The collected values are also validated by the BCIS (Building Cost Information Service Construction) online database in which the life expectancy of building services elements is gathered from real-world projects (BCIS, 2022). These two databases are often found to be consistent with each other. Table 5-15 provides the economic lifetime for the set of BHSs examined in this study. As shown in this table, among the selected BHSs, direct electrical systems have the most extended service life, whereas HPs have the shortest.

Table 5-15 The typical expected lifetime of selected heating systems (Danish Energy Agency, 2021)

Heating technology	Typical lifetime (year)
Gas condensing boiler	20
Biomass wood pellet boiler	20
Solar thermal heater + gas boiler	25
Direct electric radiators + electric boiler	25
Air-water individual HP	16
Air-air individual HP + electric boiler	13
Ground source individual HP	20
Gas hybrid HP	18

5.3 Social Indicators

5.3.1 Health impacts (Soc1)

5.3.1.1 Definition of indicator

Direct emissions from energy systems have negative health effects and indirect impacts on the social state of the community in terms of productivity and well-being (Lipošćak et al., 2006). The health impacts of air pollution have been studied for decades. It has been found that the most significant health effects are caused by airborne particulate matter (PM), also called ‘fine particles’ (Paunu, 2012). PMs are common by-products of combustion that penetrate deep into the lungs and the smallest can even enter the bloodstream. Exposure to PMs causes numerous health effects, ranging from unnoticeable symptoms to serious diseases and death (Paunu, 2012). The health risk size, distribution, microstructure, and chemical composition of PMs vary depending on the combustion process. The most harmful are particles with a diameter of less than 2.5 µm (PM2.5) (Aust et al., 2013).

Other key pollutants are nitrogen dioxide (NOx), volatile organic compounds (VOCs), ammonia (NH_3), and sulphur dioxide (SO_2), which cause harm to humans and the environment

(DEFRA, 2023b). To account for these harms to public health, decision-makers should incorporate air quality impacts into their appraisal process. This is facilitated in the current study using the indicator of health impact (Soc1), which was rated as the most important indicator of social sustainability in the experts' survey. Soc1 is a proxy indicator to represent the adverse health impacts due to key air pollutant emissions from BHSs. A similar approach, termed external health costs or social costs, has been used in other studies to evaluate the consequential health costs associated with different energy systems (Chapman et al., 2018).

5.3.1.2 Quantification method

There are several procedures for air quality appraisal. However, an economic appraisal is a common and consistent manner to measure the costs of the aftermath of health impacts. Several monetisation methodologies have been developed to aid air quality appraisal. This study uses a method called the impact pathways approach (IPA) (DEFRA, 2023b) for estimating the impact of air quality on public health resulting from different residential heating alternatives. Developed by the Department for Environment, Food and Rural Affairs (Defra) of the UK government, this method is one of the most thorough and detailed methods for valuing the impact of air pollution. This method uses atmospheric modelling to estimate the impact of changes in the ambient concentrations of air pollutants for a range of outcomes (DEFRA, 2023b).

The detailed IPA analysis can be resource- and time-intensive. Therefore, the Defra has developed the following methods, which are a set of pre-calculated values to be used instead of the IPA where air quality impacts are less than £50 million (DEFRA, 2023b):

- Damage Costs: A set of monetary impact values per tonne of emissions, used when changes in pollutant emissions are achievable
- Activity Costs: A monetary value per KWh energy used, used when changes in fuel consumption are achievable

Derived from the IPA, these methods enable a proportionately simpler analysis of the health impacts of a project or a policy. They quantify the societal and health risks associated with changes in pollutant emissions in a monetary format. Activity costs represent the impact of emissions per unit of fuel consumed, rather than per tonne of pollutant emitted, as is the case with the damage costs (BEIS, 2023b). As the fuel consumption of different heating alternatives can be obtained using the software simulation, the activity cost method was utilised in this study.

The activity cost method provides estimates for damage to public health due to air pollution in a common monetary unit of pence per kilowatt hour (p/kWh). The activity cost of fuels is calculated based on the emission factors of NOx, PM2.5 and SO_2. Emissions of NH_3 and VOCs contribute to the formation of PM and NOx, so they have not been valued on their own. Based on this method, the health impacts (HI) of BHSs can be calculated as follows:

$$HI = \sum_{t=1}^{N} \frac{EC_{BHS}.{AC^E}_t + FC_{BHS}.{AC^F}_t}{(1+r')^t} \qquad 5\text{-}16$$

In Eq. 5-16, EC_{BHS} and FC_{BHS} are the annual electricity consumption and fuel consumption of the BHS, respectively; r' is the health discount rate that is recommended to be 1.5% (DEFRA, 2023a). The use of the lower rate for the health discount rate, compared to the standard 3.5% discount rate, is to reflect increases in willingness to pay for avoidance of health outcomes over time; and ${AC^E}_t$ and ${AC^F}_t$ represent the activity cost of the electricity and the fuel in year *t*; The BEIS provids the fuel activity costs, broken down into geographical classifications, in the Green Book supplementary guidance (BEIS, 2023b). The national average rates of activity costs were used in this study, presented in Table 5-16.

Table 5-16 National average rates for air quality activity costs of energy carriers (BEIS, 2023b)

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

5.3.2 Fuel poverty (Soc2)

This study develops a novel indicator for fuel poverty to be used in multi-criteria analyses. Therefore, this indicator and its application are thoroughly explained separately in Chapter 6.

5.3.3 Thermal comfort (Soc3)

5.3.3.1 Definition of indicator

Thermal comfort is a subjective term that refers to a state of mind in which a person feels physically and psychologically comfortable in their environment (Karyono et al., 2020). It is a key aspect related to human life and well-being as people typically spend more than 80% of their time in buildings (Wu et al., 2019). It is also increasingly considered one of the primary concerns in the energy design/management context and has a significant impact on people's health and safety. Therefore, while decarbonisation of heating should be kept as a key priority of the heat transition, the comfort of a building's occupants should not be compromised. Thermal comfort is a complex interplay between various ambient parameters, such as temperature, humidity, air velocity, and radiant temperature, as well as personal parameters, such as clothing, metabolic rate, and individual preferences (Enescu, 2017). Figure 5-4 shows the factors influencing thermal comfort taken into consideration in different models.

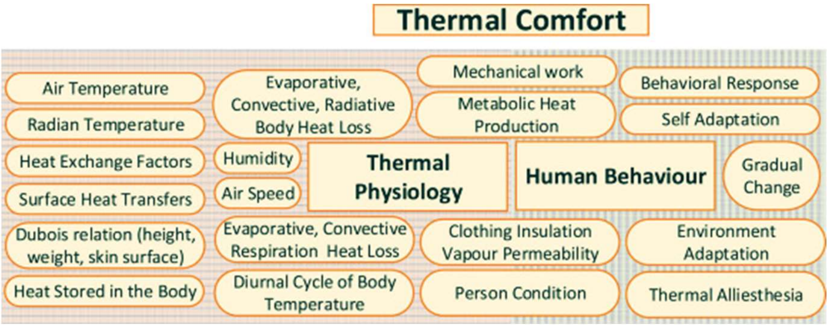

Figure 5-4 The thermal comfort parameters considered in different models (Karyono et al., 2020)

Several methods have been applied in the literature to objectively determine thermal comfort (Enescu, 2017). However, the predicted mean vote (PMV) and percentage of people dissatisfied (PPD) have been the most commonly used indicators for this purpose (Karyono et al., 2020). PMV is a numerical representation of the average level of thermal sensation as determined by a mathematical model that takes into account environmental and personal factors. PPD is a similar index that represents the percentage of people exposed to uncomfortable thermal conditions, with higher PPD values indicating a greater likelihood of discomfort (Rostam and Abbasi, 2021). The PMV and PPD have been recognized and adopted by current comfort standards, including ISO 7730 and ASHRAE 55, for evaluating static and air-conditioned spaces (Wu et al., 2019).

The PMV index assesses thermal sensation as a function of metabolic rate, clothing and the four environmental parameters of dry bulb temperature, mean radiant temperature, air velocity and relative humidity (Enescu, 2017). The PMV quantifies the thermal sensation of occupants on a seven-point scale, from -3, translated as too cold, to +3, translated as too hot, as depicted in Figure 5-5. In CIBSE TM52:2013, also compliant with the ISO 7730:2005 and European Standard EN15251, the recommended PMV/PPD limit is set based on building classifications as presented in **Table 5-17** (CIBSE, 2013). The acceptable PMV values for new buildings range between -0.5 and +0.5, corresponding with PPD values smaller than 10%.

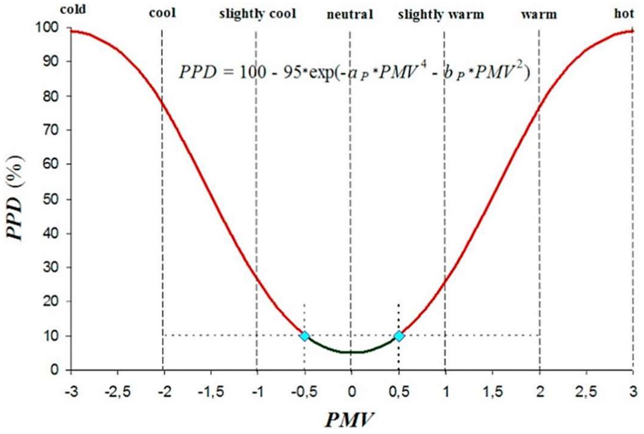

Figure 5-5 PMV and PPD function correlation (Enescu, 2017)

Table 5-17 Suggested building categories and their associated acceptable PMV/PPD range (CIBSE, 2013)

Category	Applicability	PMV range	PPD range
I	High level of expectation for spaces occupied by sensitive persons	± 0.2	≤ 6%
II	Normal expectation (for new buildings and renovations)	± 0.5	≤ 10%
III	A moderate expectation (used for existing buildings)	± 0.7	≤ 15%
IV	Low expectancy only acceptable for limited periods	> 0.7	> 15%

Thermal comfort has been recently recognised as one of the most critical social indicators in building assessments. The history of thermal comfort being studied under the notion of social sustainability is reviewed in (Rostam and Abbasi, 2021). Although the number of papers over the last decade in which occupants' comfort is analysed as a social factor is almost negligible (Toosi et al., 2020), an increasing number of research works have tried to incorporate this factor into their multi-criteria analyses. Similarly in this research, thermal comfort is determined as the third social SI (Soc3) and evaluated in conjunction with other factors.

5.3.3.2 Quantification method

In a novel approach in this study, the PMV and PPD are used to quantitatively indicate the BHSs' performance in relation to thermal comfort. Thermal comfort indicator (TCI) is defined as the annual percentage of occupied hours for which the heating systems were able to maintain satisfactory air conditions for residents. Adopted from (Ascione et al., 2017b; Ascione et al., 2019), comfort hours in this study are defined as the occupied hours during which the mean value of the PMV in the building thermal zones falls in the range of -0.5 to +0.5, thereby causing a PPD lower than 10%. Nevertheless, stricter thresholds can be defined depending on the study requirements and target occupants. The *TCI*, therefore, is a two-tailed indicator that measures the thermal comfort throughout the whole year and can be expressed as (Li et al., 2017):

$$TCI = \frac{\sum_{t=1}^{8760}(fc, h_o)_t}{\sum_{t=1}^{8760} h_{o_t}} \tag{5-17}$$

$$(fc, h_o) = \begin{cases} 1 \Leftrightarrow \ -0.5 < PMV_t < 0.5 \\ 0 \Leftrightarrow PMV_t < -0.5 \lor PMV_t > 0.5 \end{cases} \tag{5-18}$$

Eq. 5-17 calculates the thermal comfort indicator (TCI) by dividing the total comfort hours (fc, h_o) by total occupied hours (h_o) in a one-year period. The (fc, h_o), according to Eq. 5-18, counts the hours in which the PMV index in hour t (PMV_t) meets the comfort conditions of this study. The PMV_t with the defined limit of comfort zone needs to be calculated using a dynamic thermal simulation, which is one using IES-VE in this thesis.

Prediction of comfort levels using building simulation software is usually carried out by simulating a two-step process to achieve more accurate results. The space conditions are first set to provide thermal comfort over all the occupied hours. The thermal equipment is then sized based on the pre-set conditions and according to the sizing standards. In the second step, the building is modelled and equipped with a heating system with the size obtained from the first step. Thermal comfort analysis from the simulation in this step results in more realistic outputs because the heating system cannot produce extra energy (more than its capacity) to maintain thermal comfort in all circumstances. Using this methodology, a good estimate of the cumulative time can be obtained with comfort over the whole year during the occupancy period.

5.3.4 Safety (Soc4)

5.3.4.1 Definition of indicator

The issue of worker and end-user safety is a widely recognised factor to be included in sustainability assessments (Aberilla et al., 2020). Several major and minor accidents happen during the installation and operation of heating systems, costing lives or resulting in damage to human health and the environment. To mitigate these accidents, labour standards have been tightened up over the years and several safety measures have been taken. However, with the increasing implications of energy transitions, some new health and safety challenges have emerged. Accidents within the heating sector can be due to equipment failures, toxicity and combustibility of the material, leakage of the refrigerant, outdoor/indoor release of gases, dropping of the insulation layer, and electric shock.

Accidents can generally be divided into four levels based on their severity, number of casualties, and economic losses: especially serious accidents, major accidents, minor accidents, and general accidents (Zheng et al., 2020). In this study, serious accidents are taken into consideration because their data is typically well-reported, available and accurate (Sathaye et al., 2011), while there is no specific data about the less severe accidents caused by heating technologies. The risk of serious accidents corresponds to the probability that a person, i.e., worker or end-user, is killed as the result of an incident. Therefore, the safety indicator represents the risk of fatalities, using the frequency of occurrence of fatal accidents from past experience. A similar method has been used in the literature to assess the safety of energy systems (Burgherr and Hirschberg, 2014; Sovacool et al., 2016). This method enables the comparative assessment of accident risks associated with BHSs, which is a key component in a holistic safety evaluation of different alternatives.

5.3.4.2 Quantification method

In the context of heating systems, safety issues are only assessed in a few research studies using descriptive or qualitative approaches (Streimikiene et al., 2012; Taylan et al., 2020). However, no quantitative analysis has been found with a comparative analysis of the safety risks of BHSs. Within the wider energy sector, Sovacool, in a series of studies with various co-authors (Sovacool, 2008; Sovacool et al., 2015; Sovacool et al., 2016), has provided compelling analyses of the risk of energy accidents in low-carbon energy systems. Mostly focused on electricity generation systems, they provide an objective expression of accident risks for complete energy chains. Adopted from this method, a quantification method is developed in this thesis to determine the safety risks of BHSs. The safety issue indicator (SII) is defined in this study to represent the total frequency of the potential fatal accidents related to each technology, estimated based on the mix of heating technologies as follows (Aberilla et al., 2020):

$$SII = \sum\nolimits_{S} H_{Gen_S} \times FFR_S \tag{5-19}$$

where H_{Gen_S} represents the annual heat generation from the technology source S in TWh; and FFR_S is the normalised fatality frequency rate for the heat source S in no/GWh.year. The FFR_S

values were gathered from various sources and are listed in Table 5-18. The available data can serve as an order of magnitude check against other technologies with less data available. Therefore, missing data are estimated based on the available data and checked with qualitative safety ratings obtained through stakeholder comparative judgements.

Table 5-18 Fatal accident frequency rate for the heating sources normalised to the annual energy generation in GWh (Sathaye et al., 2011; Burgherr and Hirschberg, 2014; Sovacool et al., 2015; Element Energy, 2020)

Heating technology	Fatality frequency rate (no./GWh.year)
Gas condensing boiler	0.0679
Biomass wood pellet boiler	0.0149
Solar thermal heater	0.00025
Direct electric boiler	0.0005
Direct electric heater	0.0002
Air source HP	0.0010
Ground source HP	0.00174

5.3.5 Employment impact (Soc5)

5.3.5.1 Definition of indicator

The development of new energy technologies is beneficial to society by creating new jobs and improving the living quality of the local people (Wu et al., 2023). Energy systems potentially employ many people during their life cycle, from installation and operation until decommissioning (Wang et al., 2009). Therefore, the job-creating ability of energy systems has been one of the most common criteria used to assess the social sustainability of these systems (Aberilla et al., 2020). Employment impact, i.e., the direct and indirect creation of new professionals and potential job losses, is indispensably considered in planning and decision-making related to energy systems.

In this study, the Soc5 indicator analyses the employment effects of different heating technologies, representing the direct life-cycle labour impact of each heating generation scenario. Indirect hires (e.g., the production of system material) and induced hires (resulting from income spent by direct and indirect hires) are not included in this study due to the shortage and uncertainty of available data. Although the employment factor is strongly connected with the economic development of a country, it is generally classified as a social indicator of sustainability in studies (Maxim, 2014). This factor was found to be the most frequently used social indicator concerning building energy systems in Chapter 4. However, concerning BHSs in particular, this factor was rated fifth out of ten social SIs.

5.3.5.2 Quantification method

Finding the required data for establishing an accurate employment indicator for heating technologies is challenging. In the UK, the only official statistics from national energy associations are the total employment level of the electricity sector and the whole heating sector, not broken down to the fuel type or type of technology. Therefore, in this study, the employment impact of different scenarios is estimated based on the method used in (Aberilla et al., 2020; Wu et al., 2023). The index of employment impact (*EI*) is expressed as the number of full-time equivalent (FTE) direct jobs created per GWh of energy produced in one year. For each heating scenario, the potential number of jobs is obtained by multiplying the annual energy generation by the technology-specific employment rate as in Eq. 5-20 (Chen et al., 2020; Wu et al., 2023):

$$EI = \sum_{S} H_{Gen_S} \times EF_S \tag{5-20}$$

This is used to calculate the EI (the number of FTE jobs), where H_{Gen_S} denotes the annual heat generation from the technology source S in GWh; and EF_S is the employment factor for the heat source S in FTE/GWh.year. Due to the lack of data for the UK heating sector, international data and the existing literature should be used to obtain the direct employment factors. These data were collected from different sources and are summarised in Table 5-19. However, when the existing literature and databases failed to provide data for a certain technology, order-of-magnitude estimates were made according to the process explained in (Streimikiene et al., 2012).

Table 5-19 Direct full-time equivalent employment rate per unit of energy across heating sources (Wei et al., 2010; Meyer and Sommer, 2014; Baer et al., 2015).

Heating technology	Employment factor (FTE/GWh.year)
Gas condensing boiler	0.11
Biomass wood pellet boiler	0.21
Solar thermal heater	0.23
Direct electric boiler	0.05
Direct electric heater	0.05
Air source HP	0.49
Ground source HP	0.25

5.3.6 Reliability (Soc6)

5.3.6.1 Definition of indicator

Reliability of energy systems is another concern in the energy sector that has often been considered among the essential criteria in MCDA studies (Wang et al., 2009; Troldborg et al., 2014). This criterion typically reflects the availability, stability and maintainability attributes of an energy system and its components (Troldborg et al., 2014). The terms 'reliability' and 'availability' have been used interchangeably in the literature as appropriate to the context. Reliability can be defined as the capacity of a system to perform a required function as designed and under stated conditions for a specified period (Wang et al., 2009). In negative terms, this factor also represents the extent to which the energy system fails to meet the consumer's energy requirements due to insufficiency in energy resources, supply interruptions, or failure of a device.

The reliability of energy systems is often closely related to several factors, e.g., the specific location, type and scale of the system, maintenance requirements, equipment quality, and fuel type (Troldborg et al., 2014). The variety of the factors and their variability makes the evaluation of reliability challenging. For instance, while reliability for a fuelled energy technology relies heavily on the capacity factor, for solar systems it is more dependent on the site location and design. The reliability of BHSs is defined as a social indicator in this study, reflecting the stability of the technology in meeting the building's energy demand.

5.3.6.2 Quantification method

The reliability of energy systems is often evaluated qualitatively (Troldborg et al., 2014). There are also some examples in which reliability is evaluated quantitatively, e.g., using the availability factor (the ratio of time that the system is operating as designed) (Chatzimouratidis and Pilavachi, 2009) or using the unmet hours (annual time that the energy demand is not met by the proposed system) (Babatunde et al., 2019). However, the scarcity of available data makes the quantitative assessment challenging, without necessarily leading to more accurate and consistent results (Chinese et al., 2011). Therefore, in line with the method used in (Troldborg et al., 2014; Kontu et al., 2015), reliability was evaluated qualitatively in this research, using the ordinal scale, ranging from 1 (indicating highly unreliable heat supply) to 5 (indicating stable and reliable heating performance). The reliability indicator (*RI*) scores (Table 5-20) are derived from judgments and comparisons made by stakeholders, gathered from different resources.

Table 5-20 Reliability evaluation of the selected heating systems (Beccali et al., 2003; Mahapatra and Gustavsson, 2010; Kontu et al., 2015)

Heating technology	Reliability indicator
Gas condensing boiler	4
Biomass wood pellet boiler	2
Solar thermal heater + gas boiler	4
Direct electric radiators + electric boiler	4
Air-water individual HP	2
Air-air individual HP + electric boiler	3
Ground source individual HP	3
Gas hybrid HP	3

5.3.7 Usability and functionality (Soc7)

5.3.7.1 Definition of indicator

Usability is considered an important criterion when choosing a heating technology for residential buildings since the householders are directly involved in monitoring and controlling the heating system (Kontu et al., 2015). This factor is also important because some solutions like HPs can be beneficial for both consumers and the environment only if they are installed and used properly; otherwise, they can result in increased consumption and utility bills. Kontu et al. (2015), for the first time, studied the usability of heating systems within a multi-criteria evaluation. They built the usability factor on five criteria: provision of meaningful activity, ease of acquisition, care-free functionality, ease of use, and space requirements.

However, usability is a factor that is increasingly a matter of concern for scholars, particularly when it comes to heating technologies (Yang et al., 2018). Regarding electricity, the end-users only use the delivered energy as a service without interacting with the electricity generation technology. Therefore, this factor is chosen as the Soc7 indicator for assessing the ease of operating and maintenance of the BHSs for the residents. The term ‘usability and functionality’ is used to represent the technical complexity of BHSs and the quality of user interaction with these technologies in daily operations.

5.3.7.2 Quantification method

The usability and functionality indicator, just like many other social factors, cannot be measured quantitatively using an overarching method. Therefore, assessment of this factor for energy systems has often been carried out based on a qualitative comparison between the technical complexity of the alternative technologies, as well as the ease with which end-users can appropriately operate the technology. The qualitative comparison of the useability of BHSs, which has been addressed very limitedly in the literature, is usually based on residential users' experiences or some empirical evidence on criteria adopted by other stakeholders. Therefore, the usability indicator (*UI*) scores that are presented in Table 5-21 are collected or comparatively derived from different sources.

Table 5-21 Usability and functionality of the selected heating systems (Kontu et al., 2015; Džiugaitė-Tumėnienė et al., 2017; Yang et al., 2018)

Heating technology	Usability indicator
Gas condensing boiler	4
Biomass wood pellet boiler	2
Solar thermal heater + gas boiler	4
Direct electric radiators + electric boiler	5
Air-water individual HP	4
Air-air individual HP + electric boiler	4
Ground source individual HP	3
Gas hybrid HP	3

5.3.8 Social acceptance (Soc8)

5.3.8.1 Definition of indicator

Social acceptance is a widely considered issue under social sustainability that expresses the overview of public opinion regarding the hypothesised realisation of the different technologies or plans under review (Wang et al., 2009). Concerning heating plans, this factor reflects the popularity of the heating alternatives and the public perception of them. It is stated in studies that awareness of benefits and coherence with norms and value systems are the key components of social acceptability (Aberilla et al., 2020). However, a broader range of other factors, such as place attachment and identity, people's belief about the impacts of the proposed systems, uncertainty regarding the proposal, scale of the technology, and proximity to similar projects are also reported as impacting factors (Troldborg et al., 2014).

It is extremely important to address public perception or acceptability factor concerning the implementation of new energy projects. Public reluctance to the development of new projects and stakeholders' opposition to investing in them have long been recognised as crucial barriers to the expansion of renewables in different countries (Troldborg et al., 2014). Despite the public support for renewable energy in principle, many actual projects are seen to have underperformed or been terminated due to local opposition; sometimes leading to the phenomenon commonly referred to as ‘NIMBY’ (not in my backyard) (Troldborg et al., 2014). Therefore, social acceptance is taken into account as another social indicator (Soc8) to evaluate the chance of consensus or opposition over technology from different social groups. In the case of BHSs, public acceptance is likely associated with health and safety issues, affordability, disruption caused by the installation and maintenance process, noise level, and visual intrusion.

5.3.8.2 Quantification method

Social acceptance is a qualitative criterion that needs to be expressed quantitatively for incorporation into multi-criteria analysis. Assessment of this factor, however, is not straightforward due to the several driving factors involved. Referring to the existing literature, the most common and direct measurement method for the acceptability of energy technologies is using user inputs, based on the results of surveys or interviews carried out in the local community or between stakeholders (Wang et al., 2009). This factor can also be evaluated based on the statistical market (Kontu et al., 2015). For this study, the social acceptance indicator (SAI) assigned to the BHSs, presented in Table 5-22, was derived from different sources. These include the findings from several surveys (YouGov plc., 2013; BEIS, 2020b; Caiger-Smith and Anaam, 2020), as well as from some studies in which the acceptability of energy technologies was considered (Troldborg et al., 2014; Decker and Menrad, 2015; Kontu et al., 2015).

Table 5-22 Social acceptance of the selected heating systems (YouGov plc., 2013; Troldborg et al., 2014; Decker and Menrad, 2015; Kontu et al., 2015; BEIS, 2020b; Caiger-Smith and Anaam, 2020)

Heating technology	Acceptability indicator
Gas condensing boiler	5
Biomass wood pellet boiler	3
Solar thermal heater + gas boiler	1
Direct electric radiators + electric boiler	4
Air-water individual HP	2
Air-air individual HP + electric boiler	2
Ground source individual HP	3
Gas hybrid HP	3

5.3.9 Acoustic performance (Soc9)

5.3.9.1 Definition of indicator

Acoustic performance accounts for any noise disturbance arising from the productive activity of a system. Noise is the high-frequency propagation of sound that disrupts the activity or balance of human or animal life, and is usually harmful to a degree (Saraswat and Digalwar, 2021). Noise pollution can make physiological and psychological health damage to people, with the potential to cause noise-induced hearing loss in case of chronic exposure (Wang et al., 2009). According to Yadegaridehkordi et al. (2020), noise issues in buildings should be addressed at the early design and decision-making stages to provide an acoustic environment appropriate to the purpose of the building. Therefore, the indoor acoustic environment is increasingly attracting attention in the building industry and different regulations for analysing and setting the acoustical performance of buildings and technologies have emerged (Arif et al., 2016).

The acoustic performance of building energy technologies has been an important factor for stakeholders in decision-making processes. Noise created by some of the low-carbon heating technologies could be discouraging for households due to disturbance of the home's atmosphere and comfort (Caiger-Smith and Anaam, 2020). Thus, building regulations have started to include acoustic comfort as one of their standard criteria and noise has been considered as an environmental criterion or social criterion in the literature (Wang et al., 2009). In the present study, however, this factor is studied under social sustainability due to its potential impact on occupants' comfort.

5.3.9.2 Quantification method

Acoustic performance can be measured both objectively and subjectively. Some researchers have used occupant satisfaction with the indoor acoustical environment, described via subjective factors. Others measure the noise levels surrounding residents, using objective parameters such as sound power level and sound pressure level. Sound power is the acoustic energy emitted by a sound source and is an absolute value, irrespective of the environment or location of the listener. Sound pressure level, however, is what we hear, determined not just by the sound power of the source but also by the specific surroundings and the distance of the listener (Carbon Trust, 2020). In this study, sound pressure level is used to measure the noise level of BHSs in the same way as in (Cavallaro and Ciraolo, 2005). This criterion is measured in dB(A), which is a weighted scale for measuring sound that corresponds to the hearing threshold of the human ear. Table 5-23 presents the recommendations for sound pressure levels in different occupations based on the standard EN ISO 11690-1 (Schneider et al., 2006).

Table 5-23 Recommended limit for noise exposures in the work environment (Schneider et al., 2006)

Workplace	Recommended limit dB(A)
School rooms	30-40
Offices	30-40
Open plan offices	35-45
Laboratories with routine work	35-50
Manufacturing workplaces, workshops	65-70
Health sector	30-45

The noise level (*NL*) of heating systems is usually shown on the energy label or technical specification report. For this study, data was collected from various technical catalogues and testing reports for exemplary products in the market, presented in Table 5-24.

Table 5-24 Sound pressure level of the heating systems heard when close to the heating system

Heating technology	Noise level (dB(A))	Reference product
Gas condensing boiler	50	Ideal Logic2 Max Combi boiler 24kW
Biomass wood pellet boiler	55	BioMass Combo Boiler 25kW
Solar thermal heater + gas boiler	55	Vaillant auroTHERM VFK 145
Direct electric radiators + electric boiler	31	EHC Astro 12kW Electric Combo Boiler
Air-water individual HP	54	Viessmann Vitocal 300-A 8.6 kW
Air-air individual HP + electric boiler	37	Daikin Stylish FTXA42 5.4kW
Ground source individual HP	46	Vaillant flexoTHERM 8kW
Gas hybrid HP	60	Vaillant aroTHERM 8kW

5.3.10 Aesthetic aspects (Soc10)

5.3.10.1 Definition of indicator

The installation and the functioning of different energy generation units can create some visual nuisances or cause changes in the landscape. If substantial, these visual impacts are capable of triggering public reluctance to adopt new technologies (Mourmouris and Potolias, 2013). The indicator of aesthetic aspects, also referred to as visual impact, evaluates the aesthetics of the energy system's installations and its visual impact on the environment that surrounds it (Barros et al., 2015). This indicator has been assigned a major significance when it comes to evaluating the negative effects of energy systems on residents' quality of life (Carrera and Mack, 2010). As in building studies, visual impacts are deemed very important for the well-being and productivity of the occupants (Arif et al., 2016).

The criterion of aesthetic impacts is a subjective indicator, evaluated in qualitative terms, that reflects the sensual perception of energy systems and evaluates their aesthetic compatibility with their surrounding environment (Carrera and Mack, 2010). This indicator was studied as one of the indicators of social sustainability (Soc10) that could impact whether or not people decide to replace their heating with low-carbon alternatives.

5.3.10.2 Quantification method

Given the scope of this study, the aesthetic impact is communicated through a qualitative judgment, which is a common approach in the literature. Similar to the approach proposed by Troldborg et al. (2014), the visual impacts are assessed using a 5-point scale ranging from 1 (indicating very low aesthetic compatibility) to 5 (indicating very high aesthetic compatibility). Thus, the higher the aesthetic indicator score, the lower the visual impact that the heating technology could create. Different sources were reviewed to establish the input values. The qualitative data and judgments were first gathered from the literature (Caiger-Smith and Anaam, 2020; Element Energy, 2020). Then the aesthetic indicator (*AI*) scores were determined based on estimates provided in previous studies (Mourmouris and Potolias, 2013; Troldborg et al., 2014; Barros et al., 2015). Table 5-25 shows the aesthetic indicator assigned to each technology.

Table 5-25 Aesthetic indicator of the selected heating systems (Mourmouris and Potolias, 2013; Troldborg et al., 2014; Barros et al., 2015; Caiger-Smith and Anaam, 2020; Element Energy, 2020)

Heating technology	Aesthetic indicator
Gas condensing boiler	4
Biomass wood pellet boiler	2
Solar thermal heater + gas boiler	3
Direct electric radiators + electric boiler	5
Air-water individual HP	3
Air-air individual HP + electric boiler	3
Ground source individual HP	3
Gas hybrid HP	3

5.4 Chapter Summary

After identifying the critical set of SIs in Chapter 4, this chapter developed the measurement methods, mathematical models and required input values, referred to as the quantification method in this study, for the selected SIs. The outcome of this chapter will feed the next stage of the methodology to build up the LCSA framework. The data and methods have been researched through various resources, including the existing literature, national databases, and product datasheets to determine the best quantification methods and input data for each SI. The significance of this chapter thus lies in providing a complete and consistent set of quantification methods, as well as a comprehensive set of data, to be able to assess different heating technologies. For fuel poverty, however, a new indicator is devised, to allow its evaluation in the LCSA. This is further discussed in the next chapter due to the importance of this factor in heating sector studies.

The methods outlined in this chapter are also associated with some limitations, primarily due to the uncertainties in the input data. Regarding the quantitative data used to measure the selected SIs, while efforts were made to collect the most accurate and relevant data, several data points represent the latest UK national figures such as primary energy factors or GHG conversion factors, and these need to be updated for non-UK case studies. On the other hand, in cases where no statistical data is available, e.g., water consumption coefficient and noise level, data for specific market products are utilised. Regarding the qualitative data, Likert scale scores were used, which are quite subjective and retrospective, and subject to variability due to various factors such as national regulations and experts' competence or biases. These uncertainties may influence the outcome of the LCSA and lead to a less clear-cut comparison of the alternatives.

Chapter 6 Fuel Poverty as an Indicator of Sustainability

Fuel poverty is one of the social factors identified and is an essential consideration for designing effective, just, and user-centred interventions, but it is often overlooked in engineering processes. According to the literature, heating transition practices could result in aggravating the risk of social inequalities and fuel poverty in society, if the end-user requirements are not carefully considered (Sovacool et al., 2019). Therefore, one of the main objectives of this study was to connect the notion of fuel poverty to practice by bringing it forward from post-intervention assessments to the design and decision-making stages. Due to the importance and novelty of the issue, this Chapter exclusively investigates the ties between fuel poverty and heat decarbonisation interventions[1].

To do so, a new indicator, the Potential Fuel Poverty Index (PFPI), is developed to assess the likelihood of fuel poverty that future interventions can pose to households. The PFPI presents a targeted analysis of fuel poverty by reflecting the socio-spatial characterisation of the households. Using the PFPI, fuel poverty can be observed as a design/decision factor at the early stages of design and decision-making, in conjunction with other economic, environmental, and technical factors. The utility of the developed method is also demonstrated using a real case study, assessing the impact of heat decarbonisation through HPs on fuel poverty. Following the series of quantification methods developed in Chapter 5, this chapter completes the quantitative stage of the exploratory mixed methods study, as well as the inventory analysis of the LCA process.

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[1] This chapter was peer-reviewed and published as:
Abbasi, M.H., Abdullah, B., Castano-Rosa, R., Ahmad, M.W., Rostami, A. and Cullen, J., 2022. *Planning energy interventions in buildings and tackling fuel poverty: Can two birds be fed with one scone?*. Energy Research & Social Science, 93, p.102841.

6.1 The proposed fuel poverty indicator

Drawing upon the gaps highlighted in the literature review and the need for novel methods to incorporate fuel poverty into the design stages of energy interventions for buildings, a new method, is proposed in this section; the Potential Fuel Poverty Index (PFPI). The PFPI is developed to identify the impact of future building energy interventions on fuel poverty before implementing them.

6.1.1 Quantification method

The PFPI is a two-dimensional objective indicator proposed to define fuel poverty based on the level of income and modelled energy cost at the scale of individual households. The proposed approach is characterised as predictive, identifying fuel poverty based on required energy costs rather than actual spending. This approach is supported by literature, acknowledging that required energy expenditure more accurately reflects energy deprivation levels. It accounts for the specific needs and customs of vulnerable households, such as “households' self-rationing” in low-income families or the extensive energy use of households with infirm and disabled members (Castaño-Rosa et al., 2020b). Therefore, in the first step, the total energy demand of the dwellings after implementing the energy interventions is predicted using energy simulation tools. This demand encompasses energy for space heating, hot water, lights, appliances, and cooking, tailored to the specific requirements of each household. The total energy cost can then be calculated based on current unit prices of energy sources for business-as-usual analyses or projected prices for life-cycle analyses of future scenarios.

Once the post-intervention energy costs are estimated, the likelihood of experiencing fuel poverty for households with a certain range of income can be achieved using the PFPI indicator. The PFPI is based on the subjective indicator of the Multi-dimensional Energy Poverty Index (MEPI) developed by Okushima (Chapman and Okushima, 2019; Okushima, 2019) and the objective indicator of Low Income High Cost (LIHC) developed by Hills (Hills, 2012). In this method, the principles of fuel poverty measurement from the MEPI model, which is primarily devised to fit the Japanese context, are combined with the threshold determination and equivalisation rules from the LIHC. To comply with the predictive nature of the proposed index, simulated energy costs are employed instead of actual energy consumption used in (Okushima, 2019) or the subjective assessment of households' energy deprivation used in (Chapman and Okushima, 2019). As a result, an objective version of MEPI, aligned with the principles of the LIHC standard, and applicable in the UK context, is developed.

Combinations of fuel poverty evaluation methods have already been used and endorsed in a few studies, suggesting that standalone methods may not be sufficient to make a holistic fuel poverty evaluation (Chapman and Okushima, 2019). By doing so, the proposed method improves the LIHC instructions in terms of recognition of the household typology in response to occupants' behavioural variations. Reflecting occupants' attitudes and preferences at the centre of energy retrofits is increasingly being adopted in the literature (Ben and Steemers, 2020). This approach helps to target different groups of households more effectively and design interventions tailored to the demands of specific demographic groups (Ben and Steemers, 2020), whereas, by setting a single threshold for income and fuel cost at the national level, the LIHC indicator ignores the critical relationship between households' demands and their socio-spatial conditions.

Therefore, in the present method, households are classified into four types (households with at least one person aged 65 years or over; households with at least one person with a disability; households in rural areas[1]; and other households) across twelve standard UK regions, so that they are not treated as a homogeneous group, facilitating more targeted measures. The government statistics produced by the Office for National Statistics (ONS) are the base from which this classification system is produced. The ONS presents annual household disposable income and energy expenditure statistics broken down into four groups identifiable based on household composition across the country's standard regions (ONS, 2022). Therefore, the required data corresponding to this typology will always be available, which is critical for the verifiability of the proposed indicator.

The PFPI, therefore, defines fuel poverty and severe fuel poverty as the intersection of two dimensions of F_i and E_i as follows:

$$\text{Household } i \text{ is in fuel poverty} \Leftrightarrow F_i < 1 \wedge E_i > 1 \tag{6-1}$$

$$\text{Household } i \text{ is in severe fuel poverty} \Leftrightarrow F_i^s < 1 \wedge E_i > 1 \tag{6-2}$$

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[1] The classification scheme uses the Rural/Urban Definition by the UK government, defining areas as rural if they fall outside of settlements with a population of more than 10,000 residents.

where F_i and F_i^s are the income dimensions, representing the financial vulnerability of the households in fuel poverty and severe fuel poverty, respectively. E_i is the energy cost dimension, representing the vulnerability related to energy use of the households. The parameters of F_i, F_i^s, and E_i can be obtained as follows:

$$F_i = \frac{EDI_i}{PT_{t_{(i)}}} \tag{6-3}$$

$$F_i^s = \frac{EDI_i}{SPT_{t_{(i)}}} \tag{6-4}$$

$$E_i = \frac{EEC_i}{ECT_{t_{(i)}}} \tag{6-5}$$

where EDI is the household's equivalised disposable income, PT is the monetary poverty threshold, SPT is the severe poverty threshold, EEC is the household's equivalised energy cost, and ECT is the energy cost threshold. $t_{(i)}$ identifies the type that the household i belongs to. Types of the household in this study refer to the aforementioned four groups of households living across the standard twelve regions of the UK. Therefore, based on the PFPI definition, household i is classified as fuel poor or severely fuel poor if both income and energy cost dimensions apply.

6.1.1.1 The income dimension

The income dimension (F_i or F_i^s) of the PFPI represents the financial vulnerability of the household based on the household's equivalised disposable income (EDI). Disposable income is the available amount of money that households can spend or save after income taxes have been deducted. For households, the disposable income should be equivalised to reflect the number of people in the dwelling. This study follows the equivalisation procedure and uses the equivalisation factors (Table 6-1) provided by the LIHC methodology handbook (BEIS, 2020a). To do so, the household's disposable income is divided by the sum of the relevant equivalisation factors to obtain the EDI. Generally, equivalisation increases the income rate for single people and decreases the income for larger families, intending to make them comparable. In a case where the household income data is unavailable, or for unknown future households, regional average incomes can be extracted from available databases. In England and Wales, the mean average equivalised disposable annual household income for local areas is available at (ONS, 2023) [1].

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[1] The database provides the average equivalised disposable annual household income at the Middle layer Super Output Area (MSOA) level in England and Wales for the financial year ending 2018.

Table 6-1 Income equivalisation factors for household members, according to the LIHC indicator (BEIS, 2020a)

People in the household	Income equivalisation factor
First adult in the household	0.58
Subsequent adults (including children aged 14+)	0.42
Children under 14	0.20

PT and SPT are poverty and severe poverty thresholds for each household type classified based on the composition of the households and their residence region. Following the prevailing definition of monetary poverty in Europe, PT and SPT are set at 60% and 40% of the median for equivalised disposable income, respectively (Castaño-Rosa et al., 2020a). The poverty thresholds are also equivalised to account for the number of people in each household. Table 6-2 presents the PTs and SPTs for different household types in the UK, based on the latest UK National Statistics data (ONS, 2022).

Table 6-2 Monetary poverty thresholds for household types based on the equivalised disposable income per household by government region, UK (calculated by the authors)

UK Region	Households with at least one person aged 65 years or over (£/year)		Households with at least one person with a disability (£/year)		Households in rural areas (£/year)		Other households (£/year)	
	PT	SPT	PT	SPT	PT	SPT	PT	SPT
North East	15391	10260	14620	9746	15778	10518	16055	10703
North West	13571	9048	14114	9409	18808	12538	15805	10536
Yorkshire and The Humber	14043	9362	14676	9784	17057	11371	16032	10688
East Midlands	14543	9696	16009	10673	18164	12109	16636	11090
West Midlands	14880	9920	14682	9788	19449	12966	16015	10677
East	14880	9920	14682	9788	19449	12966	19834	13222
London	16798	11198	17164	11443	NA	NA	20956	13970
South East	16562	11042	17785	11856	20820	13880	19588	13058
South West	16612	11075	16922	11281	18260	12174	17764	11842
Wales	14269	9513	14423	9615	15818	10546	15863	10576
Scotland	14708	9806	14903	9935	16760	11174	16351	10901
Northern Ireland	14345	9564	14323	9548	NA	NA	15146	10097

6.1.1.2 The energy cost dimension

The energy cost dimension (E_i) of the PFPI represents the energy vulnerability of the household according to the required energy cost. The EEC is the household's equivalised total energy cost required for achieving an adequate level of comfort after implementing an intervention, obtained from the software simulation. The simulated energy costs should be equivalised, similar to the income, by applying the relevant equivalisation factor for each household. To do so, the required energy cost is divided by the corresponding factor, which is recommended by the LIHC standard (BEIS, 2020a), given in Table 6-3.

Table 6-3 The energy cost equivalisation factors for households, according to the LIHC indicator (BEIS, 2020a)

Number of people in the household	Energy cost equivalisation factor
One	0.82
Two	1.00
Three	1.07
Four	1.21
Five or more	1.32

The ECT is the threshold for energy expenditure and equals the median of the energy costs for the household typology in the location of the study, equivalised to the average household size in the corresponding area. Household size refers to the number of residents (irrespective of age) living in a household. The median equivalised energy cost is used in this study as the threshold, instead of 60% of the median energy use in the initial MEPI method, to comply with UK standards. The median energy costs of household types in UK regions based on the 2020 data can be found in (ONS, 2022). Dividing the median energy cost by the equivalisation factor, the ECTs can be calculated for each household type. Following these instructions, the ECTs for UK households are shown in Table 6-4, based on the UK's energy expenditure data (ONS, 2022), equivalisation factors (BEIS, 2020a), and household size data (Statista, 2022).

Table 6-4 Energy cost thresholds (ECTs) for household types based on the equivalised fuel cost by government region, UK (calculated by the authors)

UK Region	*ECT* for households with at least one person aged 65 years or over (£/year)	*ECT* for households with at least one person with a disability (£/year)	*ECT* for households in rural areas (£/year)	*ECT* for other households (£/year)
North East	898	970	962	1015
North West	1035	1020	914	1024
Yorkshire and The Humber	972	1021	888	1002
East Midlands	913	939	929	982
West Midlands	1055	1078	1130	1053
East	1047	1047	1044	1059
London	1048	1031	NA	992
South East	1023	1043	1092	1006
South West	955	1005	928	992
Wales	898	859	542	915
Scotland	973	1056	1050	1056
Northern Ireland	962	971	NA	1046

6.1.2 Utility of the PFPI in multi-criteria analyses

The PFPI can be used as a binary indicator that, for a given household, indicates whether implementing a certain intervention is likely to result in fuel poverty or severe fuel poverty. Following Okushima (Okushima, 2017), a binary identification function of $\rho(F_i, E_i)$ with two elements of income and energy cost can be set up in such a way that $\rho(F_i, E_i) = 1$ when the household *i* is fuel poor and $\rho(F_i, E_i) = 0$ otherwise. Thus, $\rho(F_i, E_i)$ can be defined as follows:

$$\rho(F_i, E_i) = 1 \;\Leftrightarrow\; F_i < 1 \wedge E_i > 1 \tag{6-6}$$

$$\rho(F_i, E_i) = 0 \;\Leftrightarrow\; F_i \geq 1 \vee E_i \leq 1 \tag{6-7}$$

Likewise, the identification function for severe fuel poverty can be defined as follows, where $\rho(F_i^s, E_i) = 1$ suggests that household *i* is exposed to severe fuel poverty and $\rho(F_i^s, E_i) = 0$ otherwise. Accordingly, analysts can predict if household *i* is likely to be exposed to fuel poverty or severe fuel poverty after the building intervention has taken place.

$$\rho(F_i^s, E_i) = 1 \;\Leftrightarrow\; F_i^s < 1 \wedge E_i > 1 \tag{6-8}$$

$$\rho(F_i^s, E_i) = 0 \;\Leftrightarrow\; F_i^s \geq 1 \;\vee\; E_i \leq 1 \qquad \textbf{6-9}$$

Although the PFPI is primarily defined in binary terms, it is also fit for indicating the intensity of fuel poverty as a scalar index. For this purpose, subject to fulfilment of the income criteria ($F_i < 1$), E_i can be used in MCDA or optimisation algorithms, representing domestic energy deprivation levels. In these algorithms, the objective should be to minimise E_i in trade-off with other criteria to find the best option or optimal solution. Following the above steps, the PFPI could estimate the potential fuel poverty that arises as a result of future building energy interventions. The whole process of the PFPI and how it can be applied is illustrated in Figure 6-1.

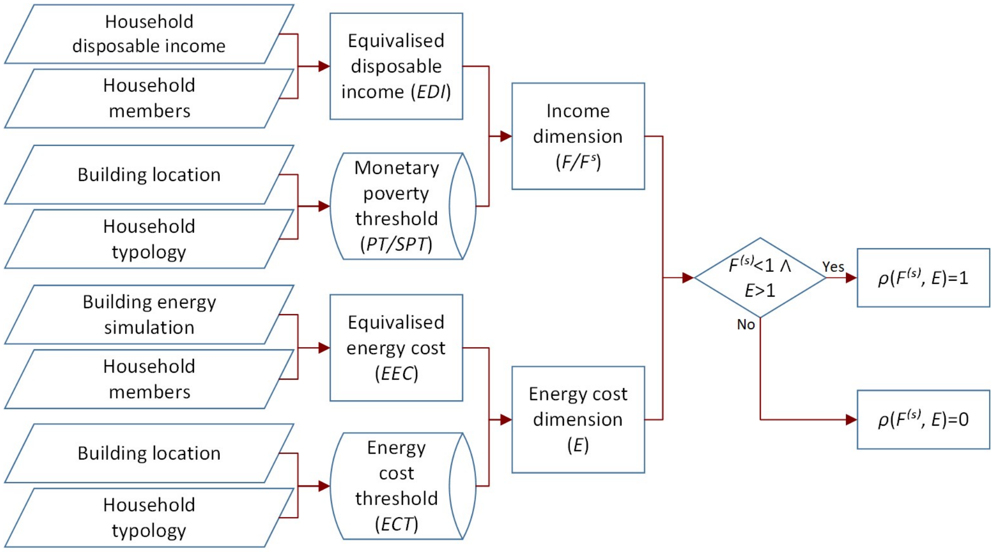


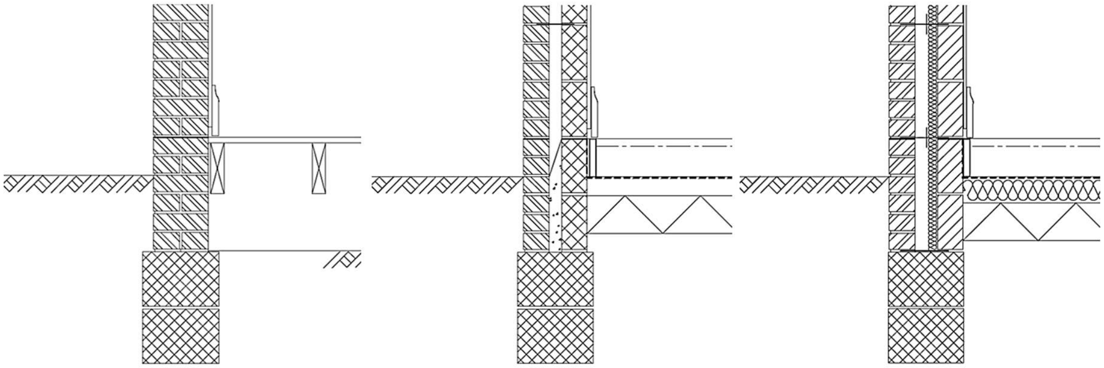
Figure 6-1 The PFPI calculation flow diagram

6.2 Testing the proposed method

A pilot appraisal of an energy intervention scenario is carried out in this section to demonstrate the potential capabilities and functionality of the proposed indicator.

6.2.1 Case study

The study uses the Liverpool John Moores University (LJMU) Exemplar Houses as the case study to represent the real environment (LJMU, 2016). In partnership with the Building Research Establishment (BRE), the LJMU has built three houses in Liverpool, UK, compliant with the standards of the 1930s, 1970s and 2010s to test and develop new green technologies and building methods in the different housing generations (LJMU, 2016). These houses represent three different generations of three-bedroom terraced dwellings with their specific design and construction norms. The houses' pictures, layouts and simulated models can be found in Appendix Figures C-1 to C-3. The houses are similar in terms of size, location, and exterior design, but they differ in buildings' envelope and slightly in interior layout. Figure 6-2 illustrates the main differences of the building types in the walls and flooring (further details of buildings are given in Appendix Table C-1).



(a) Wall: 215mm thick solid masonry wall (two bricks wide)
Floor: 22mm floorboards and 200mm joists on well-compacted MOT1

(b) Wall: 102mm outer face brick, 50mm clear cavity, 100mm light-weight block, and 13m plaster skim to inner face
Floor: 175mm concrete slab and 75mm sand blinding on well-compacted MOT1

(c) Wall: 102mm outer face brick, 50mm clear cavity, 40mm insulation board, 100mm medium-density block, and 13mm Gyproc wallboard
Floor: 175mm concrete slab and 100mm rigid insulation on well-compacted MOT1

Figure 6-2 Schematic drawing and characteristics of the walls and flooring in the a) 1930s, b) 1970s, and c) 2010s building types

The three houses are pre-equipped with individual gas-fired boilers to heat the building space using water radiators and to provide domestic hot water. In a renovation scenario, Air-Source Heat Pumps (ASHP) are considered to replace the existing heating devices, in line with the UK's decarbonisation strategies. ASHPs are a crucial technology for delivering heat transition, but they could also result in an increase in energy cost which needs to be investigated in the planning and design stages to reduce potential fuel poverty risks (Abbasi et al., 2021). For the current case studies, the existing hot water pipework and water radiators will be used for HPs to distribute the heat throughout the house. No changes in the existing heating circulation system nor thermal improvements in the buildings have been considered to minimise the upfront costs and installation work. Table 6-5 shows the specifications of the existing heating system and HP alternative.

Table 6-5 Configuration of the heating systems, the current gas boiler and the alternative heat pump

Heating source	Existing gas boiler	Air-to-water heat pump
Space heating system	Central heating via water radiators	Central air-to-water system via radiators
Heating capacity (kW)	21	8
Seasonal efficiency	0.91	3.10
Heating SCoP	0.81	2.77
DHW delivery efficiency	0.95	0.95
Storage volume (L)	-	300
Space heating setpoint (℃)	20.0	20.0
Hot water supply setpoint (℃)	60.0	60.0

6.2.2 Fuel poverty investigation

The developed method for evaluating fuel poverty under the interventions is applied to investigate the case study. For this analysis, a family of three members, comprising a couple, both aged under 65 and employed and a child aged over 14, is assumed to live in each house. The buildings are modelled in the IES-VE and calibrated with field measurements to make them valid for energy simulations. The income dimension of the PFPI is first analysed for the given family. Assuming a total disposable income of £21k/year for the household considered (family of two adults and a child aged +14), the value of equivalised disposable income (EDI) to be used in the PFPI method equals £14,789/year. The EDI is achieved by dividing the disposable income by the equivalisation factor from Table 6-1 which is 1.42 (=0.58+0.42+0.42) in this case. Locating in Northwest England, the PT and SPT for the family living in the three case studies are £15805 and £10536 per year, respectively. Accordingly, the values of F_i and F_i^S are obtained to be 0.94 and 1.40, indicating that, in terms of the economic dimension only, the assumed family is prone to be in fuel poverty but secure from severe fuel poverty.

Next, the energy cost dimensions of the PFPI are calculated and given in Table 6-6. Energy costs are first estimated based on the simulation results and the average domestic gas and electricity unit rates in the UK regions (Department for Energy Security and Net Zero, 2023). Energy costs are then divided by the equivalisation factor of 1.07 (given in Table 6-3), corresponding to the assumed family, to obtain the equivalised energy cost (EEC). The EECs for the 1930s and 1970s houses, both in current and future scenarios, are more than the corresponding threshold ECTs. Therefore, the E_i values for these houses are greater than one, indicating that, with regards to energy costs, dwellers in these houses are exposed to fuel poverty. The fuel poverty gap is also presented in Table 6-6, which represents the required reduction in energy bills to no longer be fuel poor (BEIS, 2021b). This equals the difference between the household energy costs and the energy cost threshold ($\boldsymbol{Fuel\,poverty\,gap} = \boldsymbol{EEC_i} - \boldsymbol{ECT_{t_{(i)}}}$), representing the depth of fuel poverty (Imbert et al., 2016).

Table 6-6 Energy cost parameters of the PFPI for the case studies

Results	1930s house		1970s house		2010s house	
	Gas boiler	*ASHP*	*Gas boiler*	*ASHP*	*Gas boiler*	*ASHP*
$\boldsymbol{EEC}$ (£/year)	1,313.5	1,498.4	1,091.4	1,231.7	889.2	923.4
$\boldsymbol{ECT}$ (£/year)	1024	1024	1024	1024	1024	1024
$\boldsymbol{E}$	1.28	1.46	1.06	1.20	0.86	0.90
Fuel poverty gap	289.5	474.4	67.4	207.7	NA*	NA*

* Fuel poverty gap is not applicable for the 2010s house as the household energy cost is less than the energy cost threshold.

By gathering F_i and E_i elements into the PFPI indicator, it can be shown that $\rho(F_{1930s\,\&\,1970}\ , E_{19\quad\&\,1970}\ ) = 1$ and $\rho(F_{2010s}, E_{2010s}) = 0$, indicating that ASHP installation will exacerbate fuel poverty in the 1930s and 1970s households. Table 6-6 suggests that the installation of ASHPs in older dwellings could further increase energy costs, and consequently, inflate the intensity and prevalence of fuel poverty. This risk could counteract the potential energy and environmental benefits of HPs. These results corroborate previous works on HPs (Abbasi et al., 2021; Gaur et al., 2021), confirming that this technology performs more efficiently and affordably in well-insulated buildings with lower energy demands. It is also noticeable that $\rho(F^s_{1930s\,\&\,1970\ \ \&\,2010}\ , E_{1930s\,\&\,1970s\,\&\,2010}\ ) = 0$, indicating that the assumed family will not experience severe fuel poverty in any of the building models.

Furthermore, what stands out in Table 6-6 is that the E_i factor in the PFPI closely correlates with the fuel poverty gap, making it an applicable indicator to get a sense of the depth of fuel poverty. Accordingly, options with a lower value of E_i should be favoured in decision-making or analyses. It can be seen that properties with higher ages correlate with higher energy demand and a higher E_i factor, resulting in a larger fuel poverty gap. These findings are consistent with national figures from the 2022 annual fuel poverty report in England. Figure 6-3 shows that the trend generally correlates with the decreasing fuel poverty gap in more recently built buildings, as energy efficiency broadly improves with decreasing property age (BEIS, 2022a).

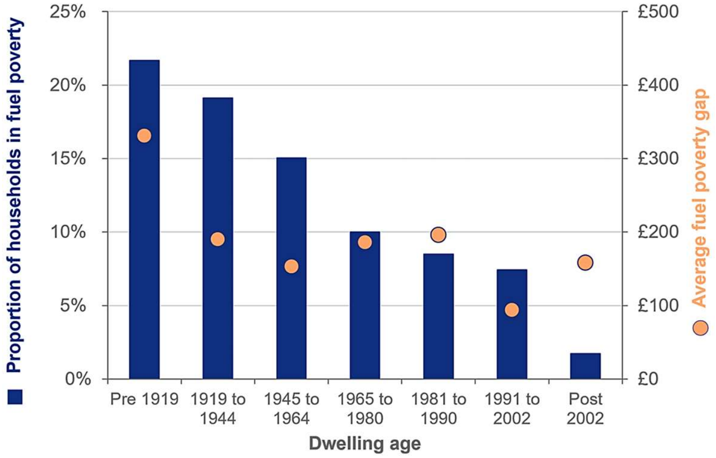


Figure 6-3 The proportion of households in fuel poverty and average fuel poverty gap by property age, England, 2022 (BEIS, 2022a)

This investigation demonstrates how the PFPI can be applied to assess the fuel poverty impacts of future building interventions. The findings of the case study also suggest that revenues from the ASHP interventions could be seriously undermined if they are not accompanied by sufficient energy conservation measures and modification of energy prices, as they can result in increasing the likelihood and depth of fuel poverty. This accords with the concern expressed by major stakeholders in the UK over the readiness of the building stock for the widespread roll-out of heat pumps (Abbasi et al., 2021; Gaur et al., 2021).

6.3 Contributions of the proposed method

As pointed out in the literature review, fuel poverty indicators have commonly been criticised for not being sensitive to all influencing factors, leading to inadequate understanding of the issue and non-inclusive identification of vulnerable households. Reflections of these limitations can be found in some policies, which cannot prioritise people in fuel poverty and consequently fail to support them through the right measures (Middlemiss, 2017). Most of the existing indicators of fuel poverty assess the current status of fuel poverty primarily based on households' income and energy expenditure and compare them with national-level thresholds. There are two major drawbacks associated with these income/expenditure-based indicators that the proposed method attempts to address.

The first concerns setting the thresholds and underrepresenting the socio-spatial vulnerabilities in national-scale comparisons (Robinson et al., 2018b). It has been acknowledged that some socio-spatial considerations, namely particular geographical requirements or those associated with disability and illness, older populations, lone parents, and young children, can be better reflected at sub-national scales (Herrero, 2017). Poverty and energy cost thresholds can be set in a more targeted manner by categorising the community based on socio-spatial characteristics. Therefore, these thresholds in the present study are set at the regional scale and broken down into four household types.

The second highlighted drawback is that existing indicators usually cannot differentiate between actual and required energy costs. Therefore, one of their common pitfalls is the failure to reflect the underconsumption of energy services in poor monetary situations or the overconsumption of households with special requirements (Herrero, 2017; Castaño-Rosa and Okushima, 2021). To address this, an energy simulation of the households can be used instead of actual energy use. Using energy simulations could bring some advantages to fuel poverty investigations, including:

- Measuring fuel poverty based on the energy model could avoid underestimation of the risk of fuel poverty (false negative) that may arise due to the poor energy performance of the buildings or inadequate use of energy services. Many fuel-poor households self-ration their energy consumption or even self-disconnect energy services in serious instances of vulnerability (Barrella et al., 2022). Using energy demand, households who restrict their energy use below comfort levels due to a lack of monetary resources, known as hidden energy poverty (HEP), can be identified (Castaño-Rosa et al., 2020a).
- Today's energy simulation tools can include multiple factors in their calculations to produce accurate and reliable predictions. The impact of a wide range of factors on building energy performance, such as thermal and physical characteristics of dwelling components, the efficiency of heating systems, ventilation rates, household characteristics, and home appliances, are usually taken into account in these simulations (Okushima, 2019).
- Household characteristics are a crucial element of fuel poverty that is not often represented in the common measurement methods. Incorporating household-driven parameters along with building-physics calculations in the software tools can give a more realistic basis for

fuel poverty assessments. Multiple household-related parameters, such as level of activity, energy use pattern, and comfort conditions, can be taken into account in simulations. For instance, the comfort temperature of elderly and infirm households can be set to 23ºC, whereas 21ºC is often considered sufficient for most other occupants (Walker et al., 2014).

- This method also offers an important advantage of accounting for geographical specifics and local parameters like local energy tariffs and climatic conditions. Therefore, the proposed indicator can provide a more realistic estimate of energy demand and expenditure, which may lead to a more meaningful prediction of fuel poverty status.
- This method significantly reduces the time and effort required for data collection and facilitates studies on larger scales, avoiding the need for the complexities of post-occupancy building assessments and household surveys.

6.4 Chapter summary

This chapter develops a method to include fuel poverty in the early stages of selecting or sketching interventions as a design/decision factor in conjunction with other economic, environmental, and social factors. The PFPI, composed of two dimensions of households' income and required energy expenditure, is developed, which minimises the need for complex building assessment tools, robust databases, and household surveys. Using the PFPI, decision-makers will be able to uncover the linkage between future building interventions and fuel poverty, assisting them in designing more targeted measures. The PFPI can also be incorporated into MCDA and LCSA frameworks, allowing trade-offs between fuel poverty and other decision criteria through a unified multi-criteria analysis. The proposed approach gives precedence to fuel poverty, bringing it forward from the post-intervention stage to the design and decision-making phase.

For applying the proposed method, a new classification of household types based on their location and the composition of the inhabitants is presented to reflect demographic variations. This allows more precise thresholds to be defined for financial and energy vulnerability and consequently improves the existing indicators. Furthermore, income and costs are equivalised to detach the fuel poverty investigation from household size and composition. Having said that, some constraints can be expressed using the PFPI, mostly due to potential flaws of building energy simulations in reflecting behavioural complexity and diversity of the occupants. As a result of these uncertainties and unpredictable factors, the new method may not be able to precisely predict the probability and depth of fuel poverty, especially for unknown future occupants. However, the PFPI could shed light on possible fuel poverty challenges that future building interventions could impose, enabling the shift from a remedial to a preventive approach. The method proposed in this chapter, along with the series of quantification methods developed in Chapter 5, provides all the required material for measuring the selected SIs and so to construct the LCSA framework in the next chapter.

Chapter 7 Development of a Life-Cycle Sustainability Assessment Framework

Once all the SIs and their quantification methods are determined, an integrated analytical framework is required to allow sustainability to be incorporated into decision-making processes. Life Cycle Sustainability Assessment (LCSA) is a holistic approach that has great potential to be revised into a useful framework and applied in sustainability analysis. LCSA encompasses E-LCA for environmental assessment, LCC for economic analysis, and S-LCA for social performance evaluation. The main advantage of LCSA is transparency and presentation of trade-offs between different and conflicting SIs. Using LCSA, decision-makers can identify the most sustainable solution among different alternatives using hybrid information covering the entire life cycle of the energy system.

LCSAs require the management and analysis of a wide variety of information types, parameters, and uncertainties in an integrated way. In this complex domain, multi-criteria decision analysis (MCDA) is regarded as a set of reliable methods to perform sustainability evaluations based on multiple criteria. The integration of MCDA techniques into LCSA provides a structured and systematic basis for evaluating and ranking alternatives and identifying the most sustainable options. MCDA methods also allow weights to be incorporated to reflect the relative importance of each criterion, as well as facilitating the dialogue between stakeholders, analysts, and decision-makers.

In this chapter, a workflow to perform LCSA of heating technologies is developed on the basis of an MCDA method. The outcome is a practical framework tailored specifically for the evaluation of BHSs to make informed choices that align with sustainability goals and stakeholder priorities. The developed framework provides an instrument for the integration of all the quantitative and qualitative data and models which were obtained in the previous sequences of the methodology. This instrument also enables the impact assessment stage of the ISO 14040

LCA process based on the inventory data collected in previous steps. The following sections will delve into the conceptualisation of the MCDA framework, present the decision analysis algorithms, develop the tool, and discuss the verification methods. Figure 7-1 shows a flow diagram of the present chapter.

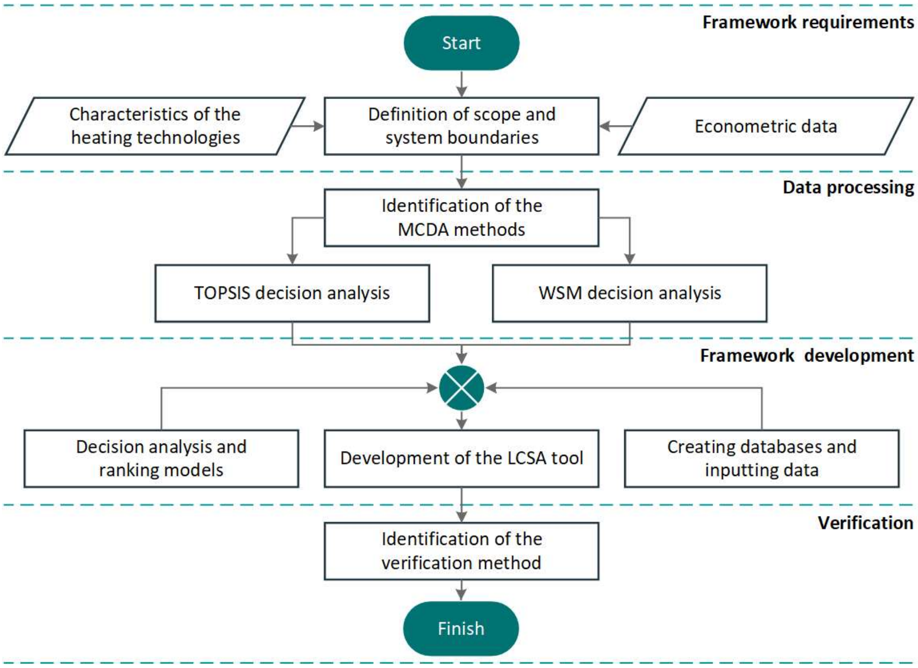


Figure 7-1 Chapter flowchart and development stages

7.1 Providing framework requirements

Aside from the identified SIs and the datasets and quantification methods given in Chapter 5, further inventory data is required to build an integrated LCSA framework. With the complementary information and datasets provided in this section, the framework can be established as a valid practical tool.

7.1.1 Assessment scope and system boundaries

The assessment scope and system boundaries must be defined to develop a consistent LCSA framework. These elements are derived based on the goal of the study which is presenting an analysis of life cycle sustainability and impacts of BHSs at the early stages of the project. Therefore, the LCSA scope is from cradle to grave to ensure that burdens throughout the entire life cycle are accounted for. The scope encompasses various stages of the product life cycle, including raw material extraction, production, construction, use, and end-of-life disposal or recycling, as schematically presented in Figure 7-2. This applies to both the heating technology and fuel. Also, the research focuses on assessing the implications of BHSs at an individual product level, rather than at the system or building level. Accordingly, system boundaries are set to be around the technology, isolated from the building it serves. Further details on the assessment scope and boundaries were described in Section 1.7.

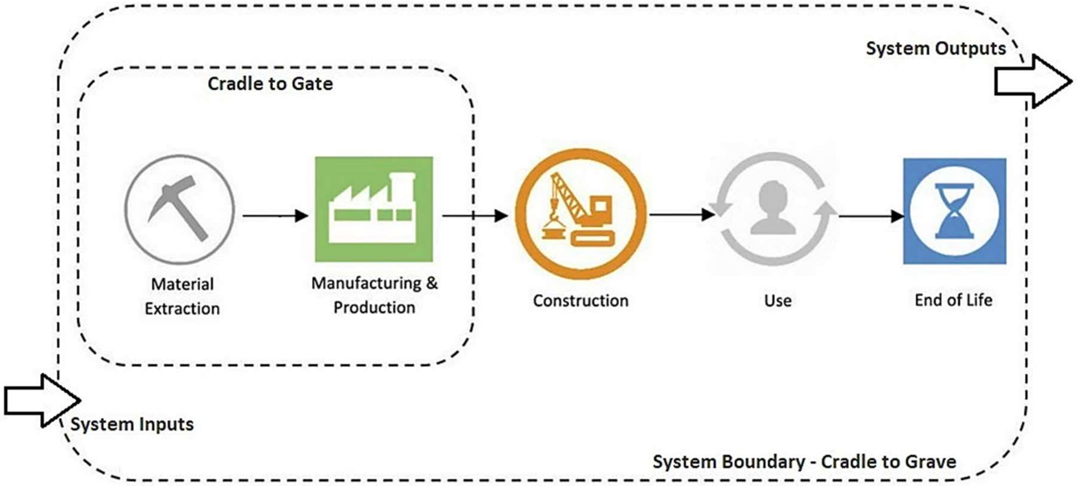


Figure 7-2 Assessment scope and system boundaries for the LCSA framework

Furthermore, to provide a fair comparison between different BHSs, LCSA calculations for each scenario are performed over 25 years. The 25-year period equals the lifetime of the BHS with the longest expected service life, so that at least one time of system replacement needs to be considered for all the selected systems.

7.1.2 Economic analysis indices

All values in life cycle economic analyses are expressed in real prices relating to the first year of the appraisal. This is known as time value or present monetary value which reflects the changes in investment value and price movements over time. The first economic index that should be taken into account in assessments is the inflation rate. Inflation is defined as the rate of increase in the general price level, reflecting a decline in the purchasing power of money (RICS, 2016). The effects of general inflation should be removed from any cost estimation for future times. The annual rate of general inflation, based on the RPI (retail prices index), is assumed to be 6.6%, as measured by the BCIS (Building Cost Information Service) at the end of 2022.

The next economic factor is the discount factor, which is the basic parameter for life cycle financial modelling. In these analyses, the cash invested at the current time is assumed to increase in value by a percentage rate of return. The discount rate is essentially defined based on the difference between investment earnings and the inflation rate. Discounting converts future costs and benefits into present-day terms to allow comparative calculations between different investment options. The current UK discount rate recommended by HM Treasury's Green Book for assessment periods up to 30 years is 3.5% (HM Treasury, 2022). This is the real rate, which does not need to be adjusted with inflation for discounting purposes. Using the real rate, all future expenditures and incomes of the projects can be discounted to their present values.

7.1.3 Material composition of the heating technologies

To accurately calculate the life cycle environmental impact of a product, it is necessary to know the composition of the material, including the type and amount of each constituent element. According to the embodied carbon calculation instructions in section 5.1.3, material information must be provided for at least 95% of the product weight. However, the lack of data on material composition is one of the biggest challenges regarding heating technologies. Currently, there is not much information available on the raw materials of BHSs, mainly due to the lack of Environmental Product Declarations (EPDs) provided by manufacturers (CIBSE, 2021b). For this study, the main inventory analysis databases (i.e., International EPD System, SimaPro, ÖKOBAUDAT, PEP Ecopassport, Ecoinvent, and the EPD online tool of the Institut Bauen und Umwelt e.V. (IBU)) were searched to find valid EPDs for heating equipment. However, only Ecoinvent and PEP Ecopassport databases provide ecological data and EPDs for BHSs in compliance with EN 15804.

Table 7-1 presents inventory data on the type and quantity of materials for the heating technologies under study. Data regarding material composition breakdown were sourced primarily from the Ecoinvent version 3.9.1 database (ecoinvent, 2022). Data were cross-checked, or extracted when not available in Ecoinvent, from the PEP Ecopassport and the literature. Collected data were primarily referred to UK sources, when possible, and to European sources secondarily. The presented bill of materials includes pipework, electrical wiring, and insulation needed for central appliances and the distribution system. To represent the quantities, the unit of kg per kW of heating capacity is used, based on the model used in (Verbeeck and Hens, 2010).

Table 7-1 Material composition of the heating appliances and distribution components (Ardente et al., 2005; Verbeeck and Hens, 2010; Greening and Azapagic, 2012; Li, 2012; Chen et al., 2020; Jeswani et al., 2020; Raluy and Dias, 2021; ecoinvent, 2022; P.E.P. Association, 2022)

Material (kg/kW)	**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	-	-	-	-	0.06	-	-
Aluminium	0.75	-	1.1	0.13	-	5.5	3.2
Brass	0.05	-	-	-	0.06	-	-
Copper	0.3	0.2	3	0.18	0.7	1.25	2.2
Expanded polystyrene	-	0.72	-	-	0.13	-	-
Glass	-	-	0.8	-	-	-	-
Insulation (elastomere, etc)	0.89	-	1.31	-	-	1	4
Polyethylene (PE)	-	0.22	-	0.27	0.47	1	5
Polyurethane foam	-	-	-	-	1.7	-	-
Polyvinylchloride (PVC)	-	-	4.7	-	-	-	0.1
Stainless steel	0.5	1.2	1.15	2.36	0.66	3.6	4
Steel (low-alloyed or galvanised)	11.5	19.72	4.75	4.36	6.4	10.1	7.5
Electronic components	0.15	0.18	0.2	0.5	0.5	1	1
Refrigerant (R-134a)	-	-	-	-	-	0.192	0.205

7.1.4 Equipment sizing method

It is crucial to correctly size heating, electric, and hot water equipment to ensure accurate results from the building energy simulation that can lead to effective sustainability assessment. Sizing heating equipment involves three steps:

a) Determine the building's heating and hot water load

b) Choose the appropriate equipment and sizing factor

c) Verify equipment sizing by simulation

The first step is to calculate the building's heating and hot water demand, using building energy modelling. Once the building loads are estimated, the peak energy demands throughout the year can be taken as the basis of the sizing method. However, building models often come with many uncertainties, which can significantly affect the projections. Uncertainties are caused by a variety of factors, such as model assumptions, simplified calculation, inaccurate building simulation, measurement limitations and the random nature of some input factors like occupancy or weather (Domínguez-Muñoz et al., 2010). These uncertainties can result in the under- or over-sizing of the building energy equipment.

To account for the impact of uncertain simulation results, designers tend to select a heating capacity that exceeds the peak duty by applying a sizing factor in order to guarantee the fulfilment of the real demand. The sizing factor is also designed to rectify the effect of the performance gap of system components (difference between the actual performance and nominal design) and coincident peak demand impacts. Thus, choosing an appropriate sizing factor based on the considered heating equipment gives a margin of safety to the design (Sun et al., 2014). The sizing factor, however, should be correctly determined to ensure that the system is not oversized; an oversized system will not only increase the initial and ongoing costs but also deviate significantly from its optimal efficiency (Sun et al., 2014).

Despite many attempts to find the optimum sizing for the BHSs (Wang et al., 2018; Ding et al., 2021), there is still no well-defined standard to determine the right sizing factor. Designers usually refer to the best practices which are recorded in some databases, such as the BCIS online database (BCIS, 2022). In research studies, a sizing factor of 50 to 100% for individual cases and 25 to 36% for communal systems has usually been considered (Johnson, 2011; Guo and Goumba, 2018). In this thesis, the sizing factor of 50% is used to ensure the heating capacity covers the unprecedented peak demands. The CIBSE Guide B1: Heating (CIBSE, 2016) provides the detailed procedure for heating system design, sizing and installation. Based on the 'Simple Model' described in this guidebook, the size of the heat generator can be obtained by:

$$HC_{BHS} = HL_{peak} + (HL_{peak} \times SF) \qquad \textbf{7-1}$$

where HC_{BHS} is the heating capacity or size of the system, HL_{peak} is the peak heating load on the coldest day of the year, and SF is the sizing factor. As the final step, building energy simulation with sized heating equipment should be run again for all scenarios to ensure the heating needs of the building can be met throughout the year and verify the sizing process.

7.2 Data processing using MCDA methods

MCDA techniques allow the incorporation of the three pillars of sustainability in an integrated process and the evaluation of trade-offs between multiple and sometimes conflicting elements to reach a final selection solution (Siksnelyte-Butkiene et al., 2021a). MCDA provides a decision support tool that is suitable for addressing complex problems featuring high uncertainty, different forms of data and information, conflicting objectives, and multiple interests and perspectives. MCDA methods are increasingly being utilised for the sustainability assessment of energy systems because of their complex and evolving biophysical and socio-economic context and the multi-dimensionality of sustainability as a goal (Wang et al., 2009). Hence, this thesis uses MCDA methods for processing the wide arrays of SIs, stakeholder judgments, and project requirements to determine which BHSs would lead to the best achievements according to these considerations.

A large number of MCDA methods and assessment instruments have been applied in energy sustainability studies. The history and the state of the art of the MCDA methods dealing with assessing the sustainability of energy systems were reviewed in Chapter 2. In the literature referred to, the main MCDA techniques applied to sustainable energy problems were AHP, TOPSIS, WSM, ELECTRE, and fuzzy set methodologies (Wang et al., 2009). It is generally assumed that none of these methods is better or worse, but some methods are a better fit than others to a particular decision problem (Khishtandar et al., 2017). In this thesis, however, TOPSIS and WSM were found to be most consistent with the goal and scope of the research. The following sections summarise the main features of the two methods, the reasons behind employing them, and their calculation process.

7.2.1 WSM decision analysis

7.2.1.1 Description and features

The WSM (Weighted Sum Method), developed by Zadeh (Zadeh, 1963), is a widely used MCDA technique that allows decision-makers to systematically assess and rank alternatives based on multiple criteria and their weighted importance. This approach, also known as the simple additive weighting method, follows an assumption additive unity to determine the best solution. The WSM offers a structured, transparent, and straightforward approach to account for various sustainability factors. Despite its simplicity, WSM often provides similar results to more sophisticated methods (Tscheikner-Gratl et al., 2017). Applications of this method can be found in national energy planning (Moreira et al., 2015), local sustainable development (Jovanović et al., 2009), and down to technology-level assessments (Ekholm et al., 2014).

The WSM and AHP, which have been the most widely used methods in sustainable energy decision-making (Wang et al., 2009), are identical in foundation, in that both methods are built on the hierarchy of criteria and their importance weightings. AHP is preferred when the information on decision criteria is available on Saaty's scale, which involves making pairwise comparisons of alternatives by decision-makers. However, when pairwise comparisons are not available and, instead, values of the criteria are directly given on a cardinal scale, alternatives can be prioritised by employing the WSM. Another major limitation of AHP is that the maximum number of alternatives should be kept to less than seven to achieve consistency in the pairwise comparisons (Kalbar et al., 2012), which makes WSM a better option when there are larger numbers of alternatives.

7.2.1.2 Execution process

The criteria hierarchy, weightings, and values obtained in the previous chapters are applied to obtain the overall scoring of each alternative and to prioritise them following the WSM steps below (Hacatoglu et al., 2015; Chen et al., 2020):

a) Normalise the values of the indicators

Since the identified environmental, economic, and social SIs have different measurement dimensions, they need to be scaled into dimensionless values so that they can be analysed and compared. This process is called normalisation, in which the indicators are transformed to a common scale of 0 to 1 using the distance-based normalisation method as follows:

$$r_{ij}^{+} = \frac{x_{ij}}{\max x_{ij}} \qquad \textbf{7-2}$$

$$r_{ij}^{-} = \frac{\min x_{ij}}{x_{ij}} \qquad \textbf{7-3}$$

where r_{ij}^{+} is the normalised vector for the benefit indicators (if increasing the score of an indicator contributes to sustainability) and r_{ij}^{-} is for the cost indicators (if decreasing the score of an indicator contributes to sustainability). x_{ij} represents the value of the j^{th} indicator for i^{th} alternative when there are n indicators ($j = 1, \dots, n$) and m alternatives ($i = 1, \dots, m$).

b) Calculate the weighted normalised scores

When the normalized values of each SI for each alternative and their corresponding weights are available, the weighted scores (a_{ij}) for each indicator and alternative can be calculated as follows:

$$a_{ij} = w_j r_{ij} \; ; \; \sum_{j=1}^{n} w_j = 1 \qquad \textbf{7-4}$$

where w_j is the local weight of the j^{th} indicator, obtained using the AHP weighting method described in Chapter 4, and r_{ij} is the normalised value of the j^{th} indicator for i^{th} alternative.

c) Aggregation of the weighted scores

The steps outlined above lead to an aggregation procedure that constructs a composite index for each dimension of TBL sustainability. These category indices are then summed for a specific alternative to yield an overall composite index that measures the joint impact of all of the SIs. This study implements linear aggregation, which first calculates composite sustainability indices for each sustainability dimension (CSI_i^{Env}, CSI_i^{Eco}, and CSI_i^{Soc}), denoted as:

$$CSI_i^{Env} = \sum_{j=1}^{n} a_{ij}^{Env} \qquad \textbf{7-5}$$

$$CSI_i^{Eco} = \sum_{j=1}^{n} a_{ij}^{Eco} \qquad \textbf{7-6}$$

$$CSI_i^{Soc} = \sum_{j=1}^{n} a_{ij}^{Soc} \qquad \textbf{7-7}$$

where a_{ij}^{Env}, a_{ij}^{Eco}, and a_{ij}^{Soc} are the weighted normalised scores for environmental, economic, and social indicators, respectively. These category indices can now be synthesised into an overall composite sustainability index (CSI_i^{OA}) as follows:

$$CSI_i^{OA} = CSI_i^{Env} w^{Env} + CSI_i^{Eco} w^{Eco} + CSI_i^{Soc} w^{Soc} \qquad \textbf{7-8}$$

In this equation, w^{Env}, w^{Eco}, and w^{Soc} represent the weights of each sustainability dimension, which were assigned in Chapter 4 according to the experts' judgments through the AHP. This step integrates E-LCA, LCC, and S-LCA into a single sustainability index.

d) Ranking alternatives

The index of CSI_i^{OA} can be used to rank, screen, or select the alternatives. The alternative with the highest CSI_i^{OA} score is considered the most favourable and prioritised. The CSI_i^{OA} of the ideal solution is equal to 1, which can result from the highest possible value of each indicator.

7.2.2 TOPSIS decision analysis

7.2.2.1 Description and features

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions), developed by Hwang and Yoon (1981), has been one of the most widely used MCDA methods. It is a utility-based compensatory approach to MCDA that follows an easy-to-understand algorithm, mimicking human logic. TOPSIS is based on the concept that the ideal alternative has the best possible level on all criteria, whereas the negative ideal option is the one with all the worst possible criteria values. Accordingly, it identifies the best alternative, i.e., the one which has the shortest distance from the positive ideal solution while having the greatest distance from the negative ideal solution values (Wang et al., 2009). This can be applied through a straightforward mathematical algorithm to rank the alternatives.

Within the context of energy planning and technology assessments, TOPSIS has been one of the most competitive and popular MCDA methods (Siksnelyte et al., 2018), with a history of application in sustainability assessments e.g., (Afsordegan et al., 2016; Siksnelyte-Butkiene et al., 2021a). Similar to WSM, TOPSIS is useful when information on decision criteria is available on a cardinal scale. This method is also preferred when there are a large number of alternatives, in contrast to the inconsistency of the AHP method with more than seven alternatives (Kalbar et al., 2012). The vector normalization used in TOPSIS is also advantageous as it considers all the values observed when normalising a certain criterion (Siksnelyte-Butkiene et al., 2021a). Furthermore, this method offers a fast and reliable computation process with no major weaknesses identified, which makes it a perfect approach for this study (Siksnelyte et al., 2018).

7.2.2.2 Execution process

The step-by-step implementation of the TOPSIS method for the selection of appropriate BHS alternatives, as described in (Siksnelyte-Butkiene et al., 2021a) and (Kalbar et al., 2012), is presented below:

a) Formulation of the normalised decision matrix

The first step is establishing a decision matrix with normalised vectors. Normalisation is necessary because SI values are available in different measurement units. In vector normalisation, the normalised score matrix (r_{ij}) is determined as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \ ; \ i = 1, \dots, m \ ; \ j = 1, \dots, n \qquad \textbf{7-9}$$

where x_{ij} is the value of the j^{th} indicator for the i^{th} alternative when there are n indicators and m alternatives.

b) Formulation of the weighted normalised matrix

This matrix is used to estimate the distance matrices and relative distance from the positive and negative ideals. The weighted normalisation vectors of the matrix (a_{ij}) are calculated as follows:

$$a_{ij} = w_j r_{ij} \ ; \ \sum_{j=1}^{n} w_j = 1 \qquad \textbf{7-10}$$

where w_j is the weight of the j^{th} indicator. These weights are obtained using the AHP weighting method described in Chapter 4.

c) Identification of the positive ideal (A^+) and the negative ideal (A^-) solutions

These are normalized positive and negative ideals which will be the reference point for ranking the other alternatives.

$$\begin{aligned} A^+ &= \{(\max a_{ij} \mid j \in J_1), (\min a_{ij} \mid j \in J_2) \mid i = 1, \dots, m\} \\ &= \{a_1^+, a_2^+, \dots, a_j^+, \dots, a_n^+\} \end{aligned} \qquad \textbf{7-11}$$

$$\begin{aligned} A^- &= \{(\min a_{ij} \mid j \in J_1), (\max a_{ij} \mid j \in J_2) \mid i = 1, \dots, m\} \\ &= \{a_1^-, a_2^-, \dots, a_j^-, \dots, a_n^-\} \end{aligned} \qquad \textbf{7-12}$$

where J_1 is a set of benefit indicators, J_2 is a set of cost indicators, and $J_1 + J_2 = n$, i.e., the total number of SIs.

d) Calculation of separation measures

The separation (distance) between SIs is measured by the *n*-dimensional Euclidean distance. The distance of each solution from the positive A^+ and negative A^- ideal solutions can be calculated as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(a_{ij} - a_j^+\right)^2} \ ; \ i = 1, \dots, m \qquad \textbf{7-13}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(a_{ij} - a_j^-\right)^2} \ ; \ i = 1, \dots, m \qquad \textbf{7-14}$$

where a_j^+ is the j^{th} indicator value of the ideal solution A^+ and a_j^- is the j^{th} indicator value of the negative ideal, A^-.

e) Obtaining the similarities to the positive ideal solution

This step can be done by calculating the relative distance of each alternative to the ideal solution using the below equation.

$$CD_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{7-15}$$

This is also called the closeness degree which is $0 \leq CD_i \leq 1$.

f) Ranking alternatives

Select the best alternative, i.e., the one which has the maximum closeness to the ideal solution, i.e., highest CD_i. Subsequently, other alternatives can be ranked based on the values of CD_i, sorted from the largest value to the smallest value.

7.3 Development of the tool framework

Having determined all the required data and analysis methods, this step aims to combine them to develop an integrated and operational LCSA framework. Nonetheless, it should be noted that there is no need or added value in developing highly sophisticated, computationally rigorous software application, because several commercial MCDA tools are already available. Efforts need to be focused on developing a comprehensive framework which can independently perform sustainability assessment of the BHSs. Thus, a user-friendly and simplified framework was created using the Microsoft Excel platform, which may be used by different stakeholders. All the relevant data and models are programmed in Excel spreadsheets to make a generic tool, not dependent on household characteristics or building type.

A database comprised of a series of datasets collected in the previous chapters was created to supply analyses. Also, some forms were created to collect user inputs regarding the alternatives, analysis scenarios, and decision-making parameters. Once the input data were complete, the developed LCSA framework was used to process data to perform the E-LCA, LCC and S-LCA. The results were then normalised and weighted, before proceeding to the MCDA step, where the alternatives were ranked through the WSM and TOPSIS methods. Finally, the optimal BHSs were selected, based on their economic, environmental, and social performance, as well as their overall sustainability score. The whole LCSA framework is modifiable so that a user can add more alternative technologies or analysis scenarios to the process. Figure 7-3 schematically exhibits the overall architecture and workflow of the developed framework and snapshots from the framework are shown in Appendix Figures D-1 to D-3.

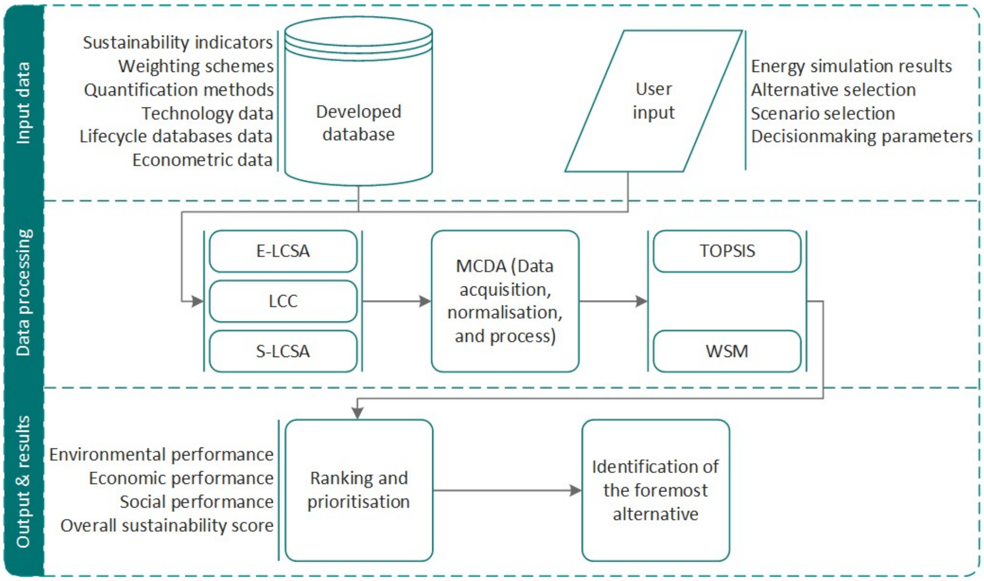


Figure 7-3 Architecture of the developed LCSA framework and its workflow

7.4 Verification of the MCDA model

The validation of the MCDA requires the decision criteria to be identified and weighted properly, criteria values to be measured correctly, and the reliability of the applied analysis method to be approved. The criteria (SIs) and their measurement methods were previously verified in their respective chapters. Experts' intuition and the consistency check were used in Chapter 4 to ensure the reliability of the selected SIs and their priority weights. Criteria values and models in Chapters 5 and 6 were collected and quantified using valid databases and references, complemented by simulation results which were cross-checked via benchmarking. Ultimately, in this section, the validity of the decision model needs to be checked to ensure the robustness of the whole MCDA process.

The decision-making model can be validated through various techniques, including sensitivity analysis, expert evaluation, benchmarking, case studies, stakeholder feedback, or any combination of them tailored to the specific context. Broadly speaking, these techniques rely on real system measurements, experts' intuition, or theoretical analysis. Some of these approaches are less feasible or more difficult to implement for this study, e.g., using real system measurements, which would require the monitoring of an actual case study in operation throughout the entire lifecycle of its heating system, and ideally comparing different technologies in identical buildings. Likewise, relying solely on experts can introduce subjectivity and bias into the validation process, as experts' intuition may be limited in capturing the full complexity of the problem. For this thesis, however, theoretical analysis can help provide a more comprehensive and robust validation process. Therefore, sensitivity analysis is employed to assess the robustness of the MCDA process.

7.4.1 Sensitivity analysis

Sensitivity analysis is a powerful method for assessing the robustness of a model using quantitative risk assessment techniques. In MCDA methods, where variation in input data is inevitable, sensitivity analysis can determine the sources of uncertainty in the output of a model (Saad et al., 2019). In other words, sensitivity analysis determines how changes in the input parameters can affect the output of the model. In a sustainability assessment model, this will determine the effect of each SI on the overall sustainability and identify the most critical factors with the most significant impacts. Therefore, sensitivity analysis was employed to assess the reliability of the MCDA model and to analyse the interdependencies among the SIs.

Sensitivity analysis has been widely used to validate both engineering models and social models (Ford and Gardiner, 1979). The outcome of sensitivity analysis can be used to adjust the decision parameters, re-formulate the model, highlight any unrealistic model behaviour, and finally better interpret the results (Smith et al., 2008). The risks and uncertainties embodied in the MCDA model can also be better understood after a sensitivity analysis. It is also considered a powerful tool to enhance the validity of prediction models or hypothetical assessments by studying how different parameters of uncertainty can impact the model's overall uncertainty.

7.4.2 Sensitivity analysis methods

Sensitivity analyses in MCDA are typically carried out by changing criteria weights (dynamic analysis), varying criteria measurement (performance analyses), and comparing results using different MCDA methods (Hussain Mirjat et al., 2018; Baumann et al., 2019). All three approaches are employed in this thesis to address the limitations of the MCDA and minimise its inherent uncertainty.

7.4.2.1 Dynamic sensitivity analysis

Dynamic sensitivity analysis is used to illustrate how changing the priorities of the criteria could affect the alternatives' ranking (Ling et al., 2021). This can be conducted by redefining the weights assigned to the SIs to analyse whether small changes in weights lead to significant changes in the WSM rankings, or if the rankings remain relatively stable. This helps to assess the robustness of the MCDA model and to identify the most sensitive SIs. For this study, dynamic sensitivity analysis was performed using four scenarios with different weighting profiles according to (Siksnelyte-Butkiene et al., 2021a). The defined scenarios are explained in Table 7-2.

Table 7-2 Scenario definitions for dynamic sensitivity analysis

Code	Scenario	Explanation	Applied modifications
Sce1	Equal dimensions of sustainability	Three dimensions are considered equivalent and are given equal weights.	$w_{Env} = 0.33$; $w_{Eco} = 0.33$; $w_{Soc} = 0.33$
Sce2	Priority of the environmental dimension	The highest importance is attributed to the environmental dimension. Other dimensions are weighted equally.	$w_{Env} = 0.50$; $w_{Eco} = 0.25$; $w_{Soc} = 0.25$
Sce3	Priority of the economic dimension	The highest importance is attributed to the economic dimension. Other dimensions are weighted equally.	$w_{Env} = 0.25$; $w_{Eco} = 0.50$; $w_{Soc} = 0.25$
Sce4	Priority of the social dimension	The highest importance is attributed to the social dimension. Other dimensions are weighted equally.	$w_{Env} = 0.25$; $w_{Eco} = 0.25$; $w_{Soc} = 0.50$

7.4.2.2 Performance sensitivity analysis

Performance sensitivity analyses the impact of varying performance measurement data for different criteria on the final alternative ranking (Baumann et al., 2019). This is a valuable technique for validating MCDA as it provides a controlled environment to test the model's performance under different hypothetical scenarios, evaluate its sensitivity to input parameters, and identify biases or limitations. Undertaking performance sensitivity analysis on the most uncertain parameters can help mitigate the limitations of LCSA by testing the variations in key assumptions on the outcomes (Pombo et al., 2016a). This analysis is hence performed on the most important uncertain parameters of the problem.

The first critical assumption, which reflects on some of the MCDA parameters, i.e., GHG conversion factors and renewable energy ratio of the national grid, is the extent of decarbonisation in the power system. The first scenario is, therefore, established based on the UK's Treasury's Green Book (HM Treasury, 2022) projection for the decarbonisation extent by 2030. The future energy price is also critical but uncertain. The next scenario is defined to account for the evolution of energy prices over time, again according to the Green Book projections (BEIS, 2023a). The last performance analysis deals with the type of refrigerant in the selected HPs. Refrigerant losses through in-use leakage and end-of-life recovery have a significant global warming impact; the last scenario, therefore, is modelled assuming the replacement of low-carbon refrigerants in the HPs. These scenarios, presented in detail in Table 7-3, are believed to cover all critical variations in the model.

Table 7-3 Scenario definitions for performance sensitivity analysis

Code	Scenario	Explanation	Applied modifications
Sce5	Decarbonisation of the power supply	The 2030 grid decarbonisation target is assumed to be met. The emission and energy factors are adjusted accordingly.	$CF_{Ovr}^{E} = 0.10$ kgCO$_{2eq}$/kWh [8]; $r_g = 0.8$ [9]
Sce6	Adjustment of the energy tariffs	The 2030 energy prices used are based on the UK Green Book projections.	$UC^{E} = 19.39$ p/kWh; $UC^{NG} = 8.04$ p/kWh; $UC^{WP} = 30.96$ p/kWh [10]
Sce7	Using low GWP refrigerants in HPs	The R410A refrigerant presumed in the base case is replaced with R32 in heat pumps.	$GWP_{R32} = 677$ kgCO$_{2eq}$/kg [11]

7.4.2.3 Sensitivity analysis of the MCDA method

Results achieved by the use of a single MCDA procedure are not sufficient to provide a reliable solution independently from the decision problem under consideration. Here, comparing the results using different decision analysis methods helps validate final rankings (Baumann et al., 2019). Therefore, to validate the sustainability ranking of the heating technologies for the case study, another MCDA method was utilised in this study. The TOPSIS method is incorporated in the developed LCSA framework as a secondary decision-making approach, in addition to the primary WSM. Hence, the last sensitivity analysis scenario is defined as in Table 7-4.

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[8] The 2030 GHG conversion factor of the domestic electricity, based on the Long-run marginal projection scenario, Table 1 of the Green Book supplementary guidance.

[9] Renewable energy ratio of the UK's national grid based on the target of 80% decarbonisation by 2030.

[10] The 2030 prices are based on the Scenario D, Tables 4-8 of the Green Book supplementary guidance, assuming that high fuel prices will remain constant in the long term.

[11] Global warming potential ratio for R32, a single-component HFC refrigerant that has a significantly lower GWP compared to traditional refrigerants and is increasingly used in residential HP systems.

Table 7-4 Scenario definitions for MCDA method sensitivity analysis

Code	Scenario	Explanation	Applied modifications
Sce8	Using a different MCDA method	The TOPSIS method is used to validate the results achieved by the WSM	TOPSIS prioritisation process is used, explained in Section 7.2.2

By conducting a range of aforementioned sensitivity analyses, the model's response to variations in input parameters and analysis method can be assessed, ultimately enhancing the credibility of the analyses. This section has explained the logic behind the sensitivity analyses and the process of carrying them out, while their application to the case study is addressed in the next chapter.

7.5 Chapter summary

Combining sustainability assessment principles with multi-criteria analysis can create a powerful decision-supporting tool that fosters sustainability in the built environment. This chapter is concerned with developing an LCSA framework that encompasses cradle-to-grave E-LCA, LCC, and S-LCA and processes their results using MCDA methods to rank the BHSs. In this framework, all the previously derived datasets, quantification methods, and analysis models are integrated and processed using TOPSIS and WSM analysis methods. The outcome is a practical and comprehensive Excel-based framework which can assist decision-making processes. Furthermore, sensitivity analysis scenarios are introduced to confirm the validity and stability of the developed framework. This chapter was only focused on the development of the framework. The application and functionality of the framework, however, will be tested and discussed in the next chapter.

The developed LCSA framework, nevertheless, has some limitations that can be addressed by further extensions. Firstly, eight heating systems are predefined in the framework which are the most common individual heating technologies in the UK market. More heating options could be added by users provided that the required input data such as the material composition is available. Secondly, it is important to note that sensitivity analysis alone may not be sufficient to fully validate the results. Combining different validation approaches could provide a more comprehensive evaluation of the MCDA method and its outcomes, enhancing confidence in the validity of the results.

Chapter 8 Functionality of the framework: Case study and validation

In the previous chapter, an LCSA framework was analysed to analyse the performance and effectiveness of various BHSs in terms of the sustainability of these systems. While this framework is theoretically well-grounded, its real-world functionality and application might require validation through empirical evidence and practical examples. This is where case studies could play a crucial role. Using a case study assessment, this chapter demonstrates the functionality and application of the developed framework. Also, by examining various assessment scenarios, concrete evidence of the framework's effectiveness in guiding sustainability-oriented decision-making is provided.

The developed framework is, therefore, employed to evaluate eight identical case studies, equipped with the selected heating systems. The findings are then discussed and interpreted for each case study under different assessment scenarios. Eventually, sensitivity analysis is carried out to test the effect of key parameters and assumptions that could influence the outcomes of the study. This chapter correlates with the interpretation stage of the exploratory mixed methods approach, in which all the quantitative and qualitative data are processed to extract results and derive a meaningful understanding of the system.

8.1 Case study selection

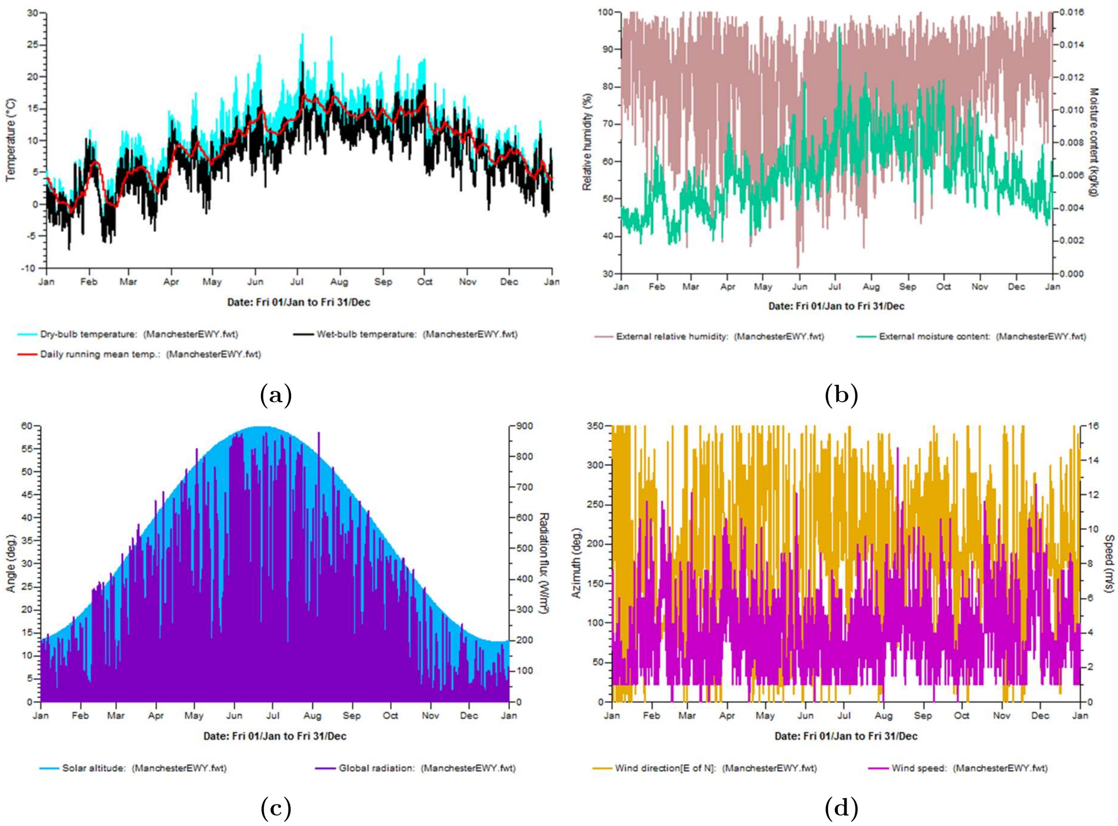
A two-floor semi-detached house with a total floor area of 102.75m^2, built in the 2020s in Liverpool, UK, was chosen as the case study. This building was chosen from one of the development projects of the Bellway Company in the Liverpool city region. Bellway is one of the major UK residential property builders, with several projects across the region. The building includes three bedrooms, a living room, a kitchen, and dining area, and two bathrooms. This is consistent with typical single-family homes in the UK, where nearly half of all properties are 3-

bedroom dwellings (Office for National Statistics, 2023b). Figure 8-1 and Figure 8-2 show the selected case study building and the layout of its floors.

Figure 8-1 The selected case study house from a new development project in Liverpool

Figure 8-2 Floor plans of the case study building

The case study is located in Liverpool, UK, and it is modelled based on the geographic and climatic conditions of this location. The environmental parameters, including ambient temperature, humidity, solar beam irradiance, and wind pattern, are shown in Figure 8-3.



(a) (b)

(c) (d)

Figure 8-3 Environmental parameters of the case study location; (a) Mean, wet-bulb, and dry-bulb temperatures; (b) External air relative humidity and moisture content; (c) Global radiation and solar altitude; (d) Wind direction and speed pattern

8.2 Building modelling and thermal simulation

The case study buildings were analysed using IES-VE (Integrated Environmental Solutions-Virtual Environment) software - version 2023 - which complies with several national and international standards. IES-VE is a widely validated software, mostly used by building designers and engineers to explore various design alternatives under varying construction, climate, and mechanical dynamics. The case study model is populated with the thermo-physics of the building, construction parameters, and household energy factors that are covered in this section.

8.2.1 Building Geometry

As mentioned earlier, a 2-floor, 3-bedroom, semi-detached house was selected, which is representative of the typical family dwellings in the region. The total floor area of the building is 105.75 m^2, the average main ceiling height is 3.3 m, and the total area of windows and glazing is 13% of the wall area. Table 8-1 presents the main figures of the building geometry, followed by the geometric 3D model of the building designed in the IES-VE in Figure 8-4.

Table 8-1 The key geometric parameters of the case study model

Item	Amount	Unit
Volume	463.43	m^3
Floor area (ground/exposed)	59.84	m^2
Net internal area (NIA)	102.75	m^2
Conditioned floor area	94.5	
External wall (net)	215.97	m^2
External windows and glazing	28.71	m^2
Internal wall (net)	91.45	m^2
External door (count)	5	
External door (area)	5.38	m^2
Internal door(count)	10	
Internal door (area)	15.6	m^2

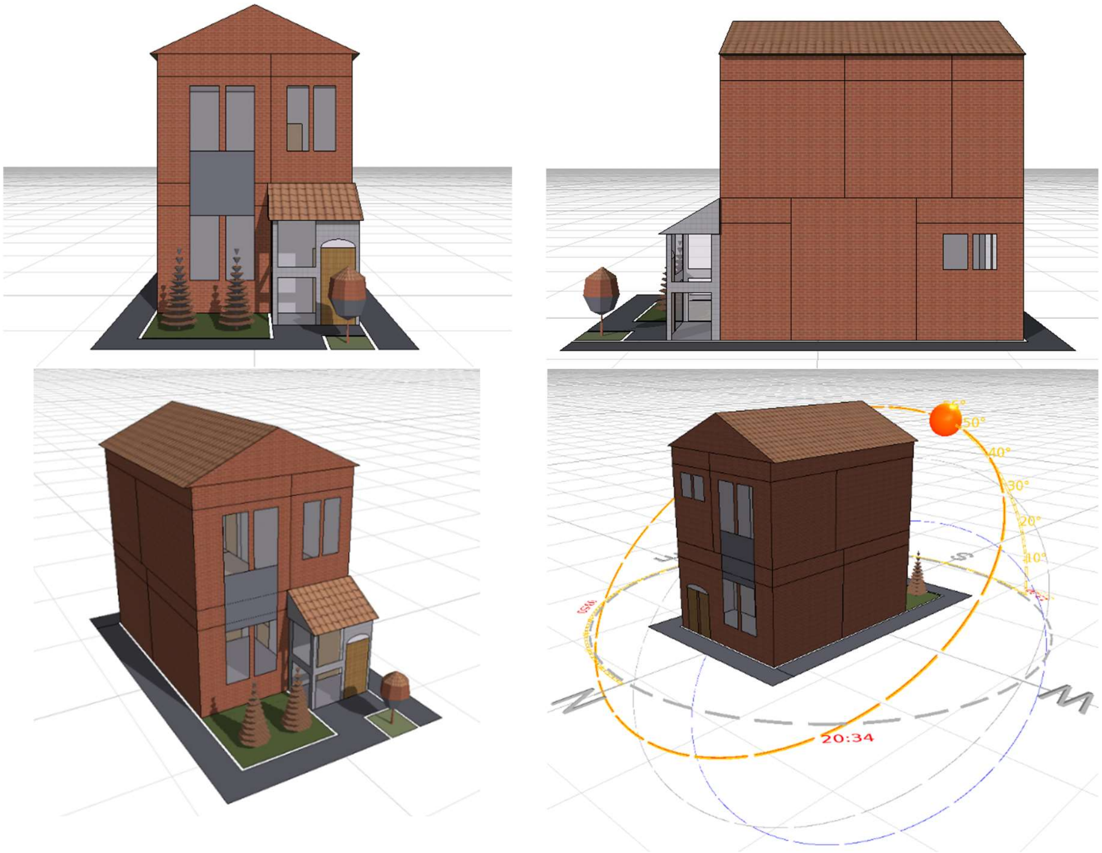


Figure 8-4 3D views of the case study building model in IES-VE

8.2.2 Construction materials

The selection of the building features has been conducted considering the research scope. As the research idea has been developed in response to the government's commitment to implement low-carbon BHSs in new homes from 2025, building models are set to comply with the 2025 notional standards. The model's setting for building envelope, structure, materials and shades, and heat transfer coefficients are set based on the latest revision of Part L1A (Conservation of fuel and power) of the Building Regulations (CIBSE, 2023). Part L1A set the maximum permitted values for fabric performance of future domestic buildings, which has been the reference for the present model. Table 8-2 presents the Part L1A standard for a notional dwelling, followed by Table 8-3, showing the specifications of the case study model.

Table 8-2 Thermal properties of a notional dwelling from Part L1A (CIBSE, 2023)

Element	U-value ($W/m^2 \cdot K$)	Highest U-value ($W/m^2 \cdot K$)	Key layer elements
External wall	0.15	0.18	Mineral wool batt
Party wall	0	0.20	Cavity sock
Floor	0.11	0.11	EPS insulation
Roof	0.11	0.15	Mineral wool roll, mineral wool batt, insulated lining board
Openings	1.19	1.20	Windows, external doors, roof windows

Table 8-3 Thermal/Physical properties of the elements of the IES-VE model

Item	U value ($W/m^2 \cdot K$)	Thickness (mm)
Internal floor/ceiling	0.929	92
Internal door	1.276	35
External door	1.897	45
External windows	1.106	28
Ground/Exposed floor	0.117	300
Internal partition/wall	1.594	105
External roof	0.117	202
External wall	0.155	286
Porch external wall	1.570	130

8.2.3 Indoor environment

The next step is to specify the environmental parameters associated with the space conditions, such as system controls, temperature setpoints, internal gains, air exchanges, illuminance level, and humidity. CIBSE Guide A: Environmental design (CIBSE, 2021a) provides guidance for indoor design conditions for a range of rooms and building types. The model has been designed in compliance with the CIBSE Guide A recommendations for dwellings. The data presented in Table 8-4 were used as the default configuration in all the heating scenarios.

Table 8-4 Model's indoor environment criteria, based on CIBSE Guide A for domestic applications (CIBSE, 2021a)

Space type	Winter operative temperature (°C)	Summer operative temperature (°C)	Infiltration max flow (ACH)	Natural ventilation max flow (ACH)	Maintained illuminance (lux)	Humidity (%$_{RH}$)
Bathrooms	20–22	23–25	0.6	1	150	-
Bedrooms	17–19	23–25	0.25	0.5	100	40-60
Hall/stairs/landings	19–24	21–25	0.6	1	100	-
Kitchen	17–19	21–25	0.25	1	150-300	40-60
Living rooms	22–23	23–25	0.25	0.5	50-300	40-60
Toilets	19–21	21–25	0.6	1	100	-

Summer conditions are associated with air-conditioned spaces and cooling loads but are not applied in the model because the buildings are not equipped with a cooling system. Regarding the humidity, CIBSE recommends an operative humidity range of 30–70%$_{RH}$ for UK homes. For the design conditions, a range of 40-60%$_{RH}$ is considered to maximise comfort conditions for human occupancy and minimise the risk of mould growth and build-up of static electricity. Furthermore, internal gains due to the presence of inhabitants, electrical appliances, cooking, and lighting are considered in the model.

8.2.4 Domestic hot water use

Concerning the DHW needs, recommendations by the CIPHE (Chartered Institute of Plumbing and Heating Engineering) guidebook on plumbing and services design (CIPHE, 2020) have been used. This reference specifies the daily DHW demand for different building types, as presented in Table 8-5. So, in the present work, coherently with the building's size, 165 l/day DHW demand is considered for the simulation.

Table 8-5 Hot water demand from the CIPHE's design standard (CIPHE, 2020)

Building type	Daily (l/day/bedroom)	Stored (l/day/bedroom)
1-bedroom dwelling	115	115
2-bedroom dwelling	75	115
3+ bedroom	55	115
Student accommodation	70	20
Nurses home	70	20
Elderly sheltered	70	25
Care home	90	25

8.2.5 Electric appliances

The case study household is assumed to consume electrical energy for refrigeration, lighting, computers, cooking and some miscellaneous applications. The electrical equipment and lighting usage profile can be found in Appendix Figure E-1. The cooking for all scenarios is also assumed to be by electric oven and electric hobs. Table 8-6 shows electricity and heat rate of the main home appliances.

Table 8-6 Electricity usage and heat gain of the household's appliances

Appliance	Max power	Max sensible heat gain
Refrigeration	110 (W)	50 (W)
Lighting	1 (W/m^2/100lux)	1 (W/m^2)
Cooking	250 (W/pers)	200 (W/pers)
Computers	50 (W/pers)	5 (W/pers)
Miscellaneous usage	10 (W/pers)	1 (W/pers)

8.2.6 Building thermal loads

Having determined all the construction and environmental parameters, the thermal performance of the building can be simulated in IES-VE to obtain the hourly heating and cooling loads. The analysis in this section is independent of the building heating system as it only calculates the building's thermal demands. Simulations are calibrated with real buildings to achieve valid results consistent with benchmarks (further discussed in 8.3.3). The monthly and hourly heat demand of the building is shown in Figure 8-5 and Figure 8-6, showing a daily range from 0 to 8.2 kW, with the main demand concentrated in the night hours during the winter months.

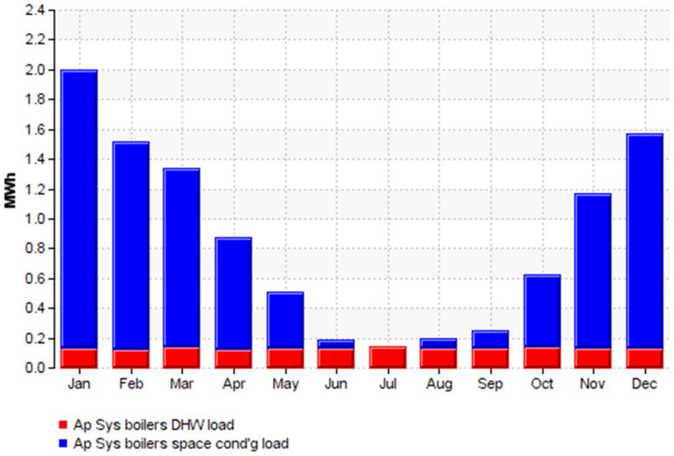


Figure 8-5 Monthly load for space heating and DHW of the case study building

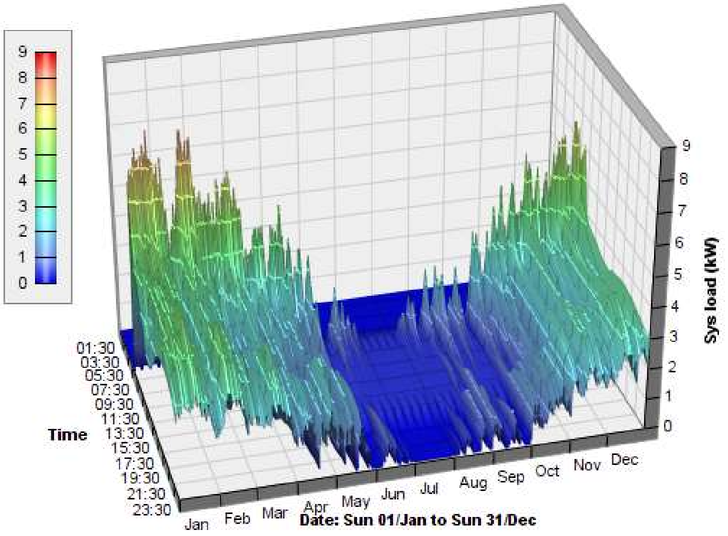


Figure 8-6 Total hourly heat load of the case study building

8.3 Modelling of the heating systems

The next step is to model the eight selected BHSs using the IES-VE's Apache System module, based on the system settings that are defined as follows.

8.3.1 Setting and configuration of the heating systems

As previously discussed in the Methodology Chapter, eight different BHSs were selected for investigation in this study. These are some of the currently most-used technologies and emerging technologies that are mostly considered in the UK's heat road maps. The technical details of the technologies are gained from different sources. Top-rated gas boilers typically operate on an efficiency rate of 0.88 to 0.97% (Self et al., 2013). Thus, the efficiency of the boiler is assumed to be 0.91 in this study. The solar system also uses the same electric boiler, assisted by a 3m^2 flat solar collector with a 50 l/(h.m^2) flow rate. Biomass boilers also offer a similar output of 88 to 91% of energy efficiency. Electric boilers are assumed to operate with their maximum potential efficiency. Thus, the efficiency of 0.99% is used for them in these simulations. The efficiency (COP) of the ASHPs in the market is typically 2.3 to 3.5 (Self et al., 2013), but an average rate of 3, achieved by Gaur (2021), is used in this study. The COP of GSHPs is normally higher than that of ASHPs, in a range of 3.5 to 4, depending on many parameters such as flow rate, borehole design, ground properties, and local climate (Gaur et al., 2021). For this study, an average COP of 3.7 is assumed for the GSHP system.

Table 8-7 Configuration and model setting of the selected heating systems

Heating system settings		Individual gas condensing boiler	Biomass wood pellet boiler	Solar thermal + gas boiler	Direct electric heating + electric boiler	Air-water individual HP	Air-air split HP + electric boiler	Ground-source individual HP	Gas hybrid HP
Space heating	Heating source	Low-temperature hot water (LTHW) gas boiler	Low-temperature hot water boiler	Solar thermal collector + gas boiler	Electric radiator panels	Air-water HP	Air-air HP	Ground-source water-based HP	Air-water HP
	Distribution mechanism	Central heating using convector radiators	Central heating using convector radiators	Central heating using convector radiators	Local unfanned electric panels	Central heating using convector radiators	Local fanned split systems	Central heating using convector radiators	Central heating using convector radiators
	Efficiency (COP)	0.91	0.90	0.95	0.99	3	3	3.7	3
	Seasonal efficiency (SCoP)	0.82	0.81	0.88	0.99	2.68	2.74	3.21	2.68
	Main setpoint (°C)	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
	Setback temperature (°C)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Cooling and ventilation	Cooling source	Mechanical ventilation							
	Air supply mechanism	Local ventilation units, e.g., windows, extractor fans, wall vents.							
	Natural ventilation max flow (ach)	1							
Domestic hot water	Water heating source	Gas boiler	Biomass boiler	Solar thermal collector + gas boiler	Electric boiler	Air-water HP	Electric boiler	Ground-source HP	Gas boiler
	DHW delivery efficiency	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	Water storage	No	Hot water cylinder	Water cylinder with immersion heater	Water cylinder with immersion heater	Hot water cylinder	Water cylinder with immersion heater	Hot water cylinder	Water cylinder with immersion heater
Cooking	Cooking source	Gas	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity	Electricity

8.3.2 Setting of the hot water storage

A hot water storage tank is a key component of heating systems, and it is important that this is selected correctly to ensure that the system is cost-effective and safe. No single technique for sizing water tanks exists that fits all types of buildings and heat sources. There are many 'rules of thumb' and guidelines such as the British Standard EN 15450:2007 (BSI, 2007) which suggests a water cylinder volume of 12 to 35 l/kW for ASHPs, 25 to 80 l/kW for GSHPs, and 10 to 20 l/kW for biomass boilers. This study, however, follows Part G3 of the UK Building Regulations (HM Govenment, 2016), by which the size of the cylinder is set to meet the household's hot water demand during the coldest day of the year, as well as fit the various heating system requirements. Accordingly, a directly heated unvented tank with a capacity of 300 litres and standard insulation was selected. The identical tank is assumed to be implemented in all BHS alternatives. In hybrid systems, e.g., air-air HPs, solar thermal, and direct electric systems, the tank is equipped with an internal electric coil to supplement the heat demand.

The set point temperature in the tank is 60°C in line with the HSE (UK Health and Safety Executive) instructions for prevention of Legionnaire's disease (Health and Safety Executive, 2014), which recommend that regardless of the type of building or heater, hot water must be stored at 60°C by ensuring it is heated at least once a day up to this temperature. On the other hand, the set point does not exceed 60°C because HPs work more efficiently in a lower range of temperature difference between the heat source and the outlet hot water. Detailed specifications of the tank can be found in Table 8-8. Furthermore, daily profiles of heating and hot water demand are presented in Figure E-1 of the Appendix.

Table 8-8 Technical specifications of the hot water storage (HM Govenment, 2016)

Type	Unvented water storage cylinder
Storage volume (Litres)	300
Heating type (in systems with auxiliary heating)	Direct resistance heating coil
Material	Copper
Insulation	Fire retardant expanded polyurethane
Insulation thickness (mm)	60
Storage losses (kWh/(l.day))	0.00470
ErP rating (Energy rated performance)	C
Hot water supply temperature (°C)	60
Cold water inlet temperature (°C)	10

8.3.3 Energy simulation of the heating systems

Once the case study buildings were equipped with the BHSs, the energy performance of the whole household could be simulated to obtain the annual hourly use of electricity and fuels for each end-use, including heating systems, service fans and pumps, refrigeration, etc. Performing the energy simulation for the reference case study, it was found that 16.17 MWh of energy, comprised of 11.93 MWh of natural gas and 4.24 MWh of electricity, would be consumed during a year to serve the building's demands. Results were validated against data from real-world cases and the UK average figures, presented in Table 8-9. The mean absolute error (MAE) was also calculated, indicating a maximum of 0.79 MWh difference between the simulated and real-world values, which is acceptable for this study.

Table 8-9 Comparison of the reference case study with other benchmarks (Bridgeman, 2020; BCIS, 2022; Ofgem, 2022)

Appliance	Electricity usage (MWh/year)	Gas usage (MWh/year)
Reference case study model	3.62	11.92
Ofgem[12] average for a 2-3 bedroom house	2.78	11.51
Ofgem average for the Archetype 9 households [13]	3.20	10.44
A well-insulated 3-bedroom house from BCIS database	3.92	12.59
Mean Absolute Error (MAE)	0.64	0.79
Mean Absolute Percentage Error (MAPE)	25.6%	3.2%

The hourly energy consumption of the reference case study for the start date of each season is shown in Figure 8-7 (**a**) to (**d**). Following that, Figure 8-8 presents the daily energy use of the case study with gas boiler BHS. While fuel consumption increases with decreasing outdoor temperature, electricity consumption seems to be less sensitive to seasonal variations.

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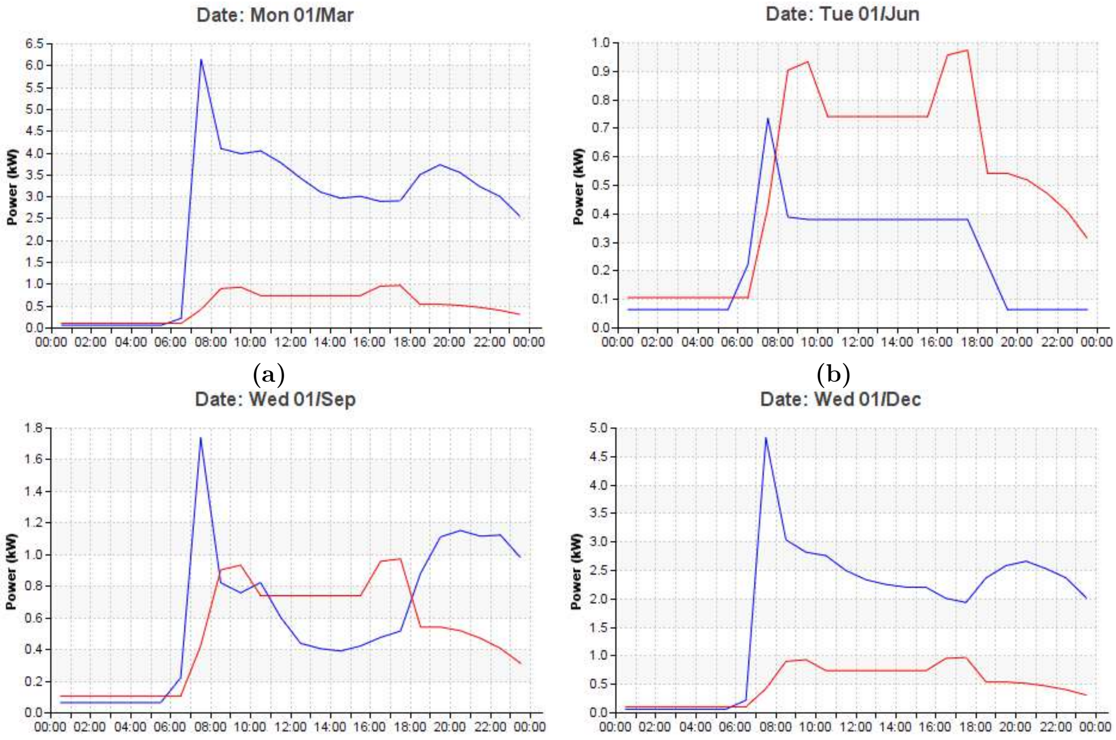
[12] The Office of Gas and Electricity Markets (Ofgem) is the government regulator for the electricity and downstream natural gas markets in UK.

[13] Ofgem divides UK households into 12 different archetypes based on their demographic characteristics and heating fuel type. Archetype 9 represents average-size, average income, gas-heated households, representing 34% of UK households.



(a) (b)

(c) (d)

Figure 8-7 Hourly electricity (red graph) and gas (blue graph) consumption of the reference household on (a) March 1st; (b) June 1st; (c) September 1st; and (d) December 1st

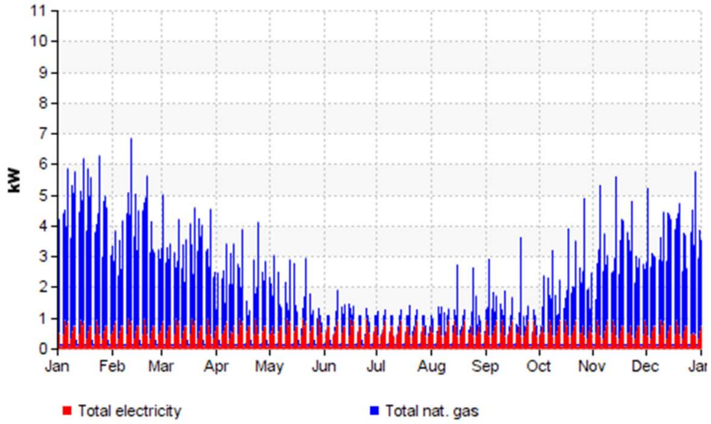


Figure 8-8 Daily electricity and fuel consumption of the household with the gas boiler system

The above analysis was carried out for the rest of the buildings with other heating systems. Figure 8-9 exhibits the total annual energy consumption, broken down by the end-use type. The bar chart clearly distinguishes the HP-equipped buildings from other dwellings in respect of their total energy consumption. It can be seen that this gap is mainly driven by the variation in space heating energy demand. The air-water HP, for instance, consumes a third as much energy as the gas- or biomass-fired systems. Moderate changes can also be seen in the water heating and process energy across the case studies. Figure 8-9 displays fewer variations in the other end-use sections, e.g., lighting, refrigeration, and cooking, suggesting that there is a slight relationship between these end users and type of the BHS. Further details of the energy simulation of the BHSs are given in Appendix Tables E-1 and E-2 and Figures E-2 and E-3.

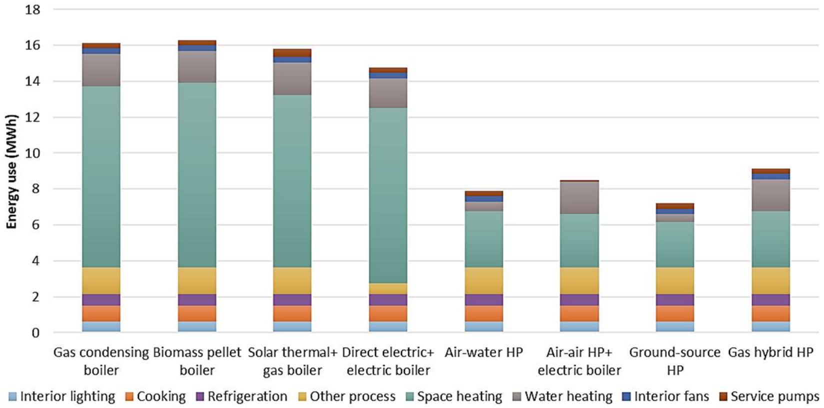


Figure 8-9 Total annual energy consumption of the households, broken down by the end-use

8.4 Sustainability assessment results and analyses

Building simulation results add the finishing touches to the input requirements of the LCSA framework and enable us to perform the analyses. This section discusses the results of the sustainability assessment of the eight BHSs under various study scenarios.

8.4.1 Initial values of the sustainability indicators

Using the quantification methods and material, plus the thermal modelling results, the values of the SIs are calculated for each technology. The detailed calculation methods, equations, and datasets used for each indicator are thoroughly explained in Chapter 5. Table 8-10 presents the initial values of the SIs for the alternatives before normalisation and applying weights. This table also highlights the numbers of each row using a colour scale and ranks the alternative values concerning each indicator. The results are discussed in the following sub-sections.

Table 8-10 The initial values of the sustainability indicators for the selected heating system

Main criteria	Sub-criteria		Building heating systems							
Sustainability dimensions	*Sustainability indicators*		*Gas condensing boiler*	*Biomass wood pellet boiler*	*Solar thermal + gas boiler*	*Direct electric + electric boiler*	*Air-water individual HP*	*Air-air HP + electric boiler*	*Ground-source HP*	*Gas hybrid HP*
Environmental	Operational carbon emissions	Env1 value (kgCO$_2$eq/year)	2,700.93	730.53	2,576.70	3,146.81	1,099.32	1,243.56	920.24	1,343.51
		Env1 rank	2	8	3	1	6	5	7	4
	Primary energy consumption	Env2 value (kWh/year)	16,385.36	13,384.97	15,611.97	18,062.58	6,310.05	7,138.01	5,282.17	7,845.33
		Env2 rank	2	4	3	1	7	6	8	5
	Embodied carbon emissions	Env3 value (kgCO$_2$eq)	1,792.71	2,449.57	2,202.60	1,622.10	5,357.42	3,505.55	4,427.69	3,679.56
		Env3 rank	7	5	6	8	1	4	2	3
	Share of renewable energy	Env4 value (kWh/kWh)	0.020	0.974	0.178	0.430	0.430	0.430	0.430	0.288
		Env4 rank	8	1	7	5	2	2	2	6
	Energy efficiency	Env5 value (kWh/kWh)	0.868	0.858	0.866	0.951	2.583	2.203	3.086	1.986
		Env5 rank	6	8	7	5	2	3	1	4
	Water consumption	Env6 value (m^3)	52.22	104.04	109.19	234.38	14.82	30.66	57.89	16.09
		Env6 rank	5	3	2	1	8	6	4	7
	Land requirement	Env7 value (m^2)	277.02	5,601.00	480.20	253.05	228.75	156.93	224.10	182.18
		Env7 rank	3	1	2	4	5	8	6	7
	Acidification potential	Env8 value (kgSO$_2$eq/year)	26.32	121.68	22.51	61.87	64.51	16.41	19.09	44.90
		Env8 rank	5	1	6	3	2	8	7	4
Economic	O&M cost	Env9 value (£/year)	1,764.05	4,283.00	1,639.98	4,739.61	1,892.95	1,997.03	1,622.64	1,960.05
		Env9 rank	6	2	7	1	5	3	8	4
	Net present value	Env10 value (£)	32,736.81	77,261.77	35,248.89	82,583.84	38,121.44	37,023.72	34,382.46	40,654.30
		Env10 rank	8	2	6	1	4	5	7	3
	Upfront cost	Env11 value (£)	2,875.47	5,613.60	7,309.71	4,256.25	5,653.33	2,840.18	6,157.89	7,291.90
		Env11 rank	7	5	1	6	4	8	3	2
	Economic lifetime	Env12 value (years)	20	20	25	25	16	13	20	18
		Env12 rank	3	3	1	1	7	8	3	6
Social	Health impacts	Env13 value (£)	387.71	8,764.00	367.91	349.07	121.94	137.94	102.08	162.38
		Env13 rank	2	1	3	4	7	6	8	5
	Fuel poverty	Env14 value (£/£)	2.45	4.36	2.44	4.67	2.49	2.66	2.27	2.48
		Env14 rank	6	2	7	1	4	3	8	5
	Thermal comfort	Env15 value (%)	84.90	83.50	85.70	83.90	75.90	78.80	75.50	79.50
		Env15 rank	2	4	1	3	7	6	8	5
	Safety	Env16 value (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
		Env16 rank	1	3	7	8	5	6	4	2
	Employment impact	Env17 value (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
		Env17 rank	7	5	6	8	1	3	4	2
	Reliability and security	Env18 value (Likert scale)	4	2	4	4	2	3	3	3
		Env18 rank	1	7	1	1	7	4	4	4
	Usability and functionality	Env19 value (Likert scale)	4	2	4	5	4	4	3	3
		Env19 rank	2	8	2	1	2	2	6	6
	Social acceptance	Env20 value (Likert scale)	5	3	1	4	2	2	3	3
		Env20 rank	1	3	8	2	6	6	3	3
	Acoustic performance	Env21 value (dB(A))	50.0	55.0	35.0	31.0	54.0	37.0	46.0	60.0
		Env21 rank	4	2	7	8	3	6	5	1
	Aesthetic aspects	Env22 value (Likert scale)	4	2	4	5	3	3	3	3
		Env22 rank	2	8	2	1	4	4	4	4

8.4.1.1 Analysis of environmental indicators

The first aim of heat transition is to mitigate the environmental footprint of the current heating generation and distribution systems. Thus, Figure 8-10 compares the environmental indicators of each alternative with the reference gas boiler system and shows the changes in the SIs in percentage.

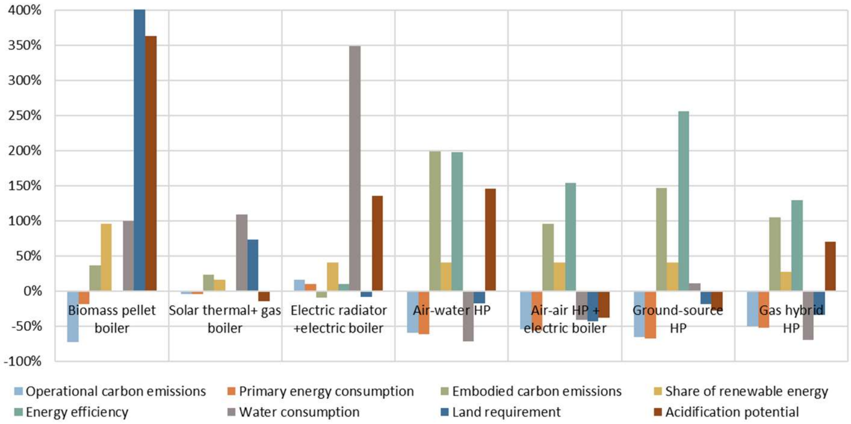
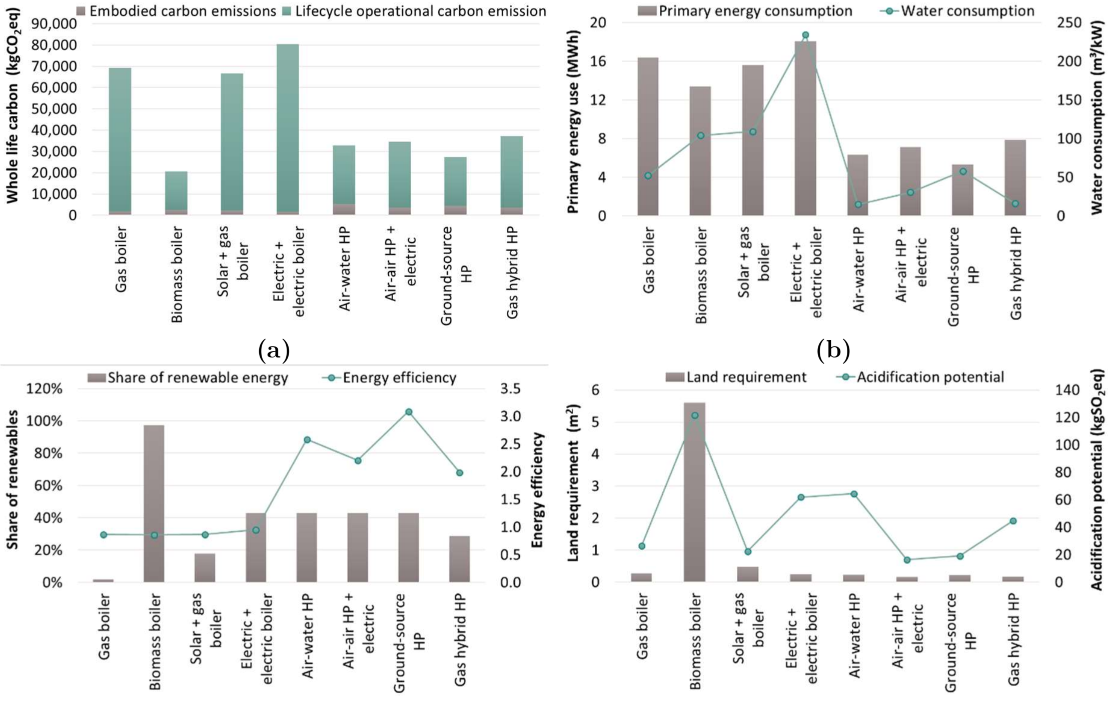


Figure 8-10 Changes in environmental indicators of the alternative BHSs compared to the reference gas boiler system

Many scattered variations in environmental SIs are noticeable in Figure 8-10 and Table 8-10, which means that none of the alternatives stand out as showing better performance on all of the SIs. In other words, all the alternatives will result in some improvements on some SIs and some negative impacts on the other indicators. In terms of carbon emissions, for instance, the factors of operational emissions versus embodied emissions correlate inversely. As shown in Figure 8-10, CO_2eq. emissions of annual heat production reduced markedly in scenarios using HPs. From an estimated 2.7 tCO_2eq for a gas boiler in the semi-detached case study in the UK, these emissions fell by 66% to a minimum of 0.92 tCO_2eq in the GSHP system. On the flip side, the embodied CO_2eq impact of HP systems is much higher than conventional systems, reaching 5.4 tCO_2eq for air-water HPs (198% rise) due to their high material content and the refrigerant used.

It should be noted that Env1 addresses only GHG emissions over one year of operation. Taking the whole life span of the BHSs into consideration, the whole life carbon (WLC) of the BHSs can be calculated. The WLC gives a fairer comparison of GHG emissions, as it represents the sum of embodied and operational CO_2eq over the standard service life of 25 years. Figure 8-11(a) exhibits the calculated WLCs for each technology and the contribution of lifecycle operational and embodied carbon emissions to the final values. This shows that the largest WLC emission saving can be achieved through biomass boiler and GSHP, resulting in reductions of 49 and 42tCO$_2$ over 25 years, respectively. The largest influence of embodied carbon is in the air-water HP and GSHP, where 16% of the WLC is composed of embodied emissions. This confirms the finding in (George et al., 2019) that embodied carbon becomes more important as operational carbon reduces. The study also shows that the direct electric and solar-assisted systems cause the highest lifetime environmental burden of all the alternatives due to their electricity consumption.



(a) (b)

(c) (d)

Figure 8-11 The initial values of the environmental indicators; (a) Contribution of the embodied and operational emissions to the whole life carbon emissions; (b) Annual primary energy and water consumption; (c) Share of renewable sources and energy efficiency; (d) Life cycle land requirements and acidification potential

The WLC results correspond very closely to the primary energy use of heating systems, except in the case of the wood pellet boiler, as can be seen in Figure 8-11(b). This is because the primary energy factor of wood pellet fuel is not as low as its conversion factor. It is also noticeable in this graph that primary energy use decreases in all the alternatives, except in the direct electric system due to its high dependency on the national grid, which is predominantly fed by fossil fuels. For the same reason, the direct electric system has the largest water consumption (234.4 m^3) during its life span, 349% higher than the reference BHS. Electricity generation is a water-intensive industry and therefore, with an increasing share of electric heating, water consumption becomes a more important factor in the heating sector. Electricity generation is now accountable for 60% of the total water consumption in the residential sector, greater than the direct water consumption of householders (Onat et al., 2014).

Table 8-10 also shows that the share of renewable sources in total heat production increases in all BHSs, rising from 2% in the gas boiler system to a range of 29 to 97% in the alternative systems. The biomass boiler stands out here with the highest rate, as it merely relies on renewable wood pellets for the heating supply. HPs and direct electric systems, as can be seen in Figure 8-11(c), remain at the same level of RES utilisation (43%), expected to increase in the future due to rising penetration of renewables in the grid. The advantage of HP systems, however, is more evident from the energy efficiency point of view. While neither of the non-HP installations can give an annual energy efficiency higher than 0.95, HPs function with efficiencies between 2.2 to 3.1 for the whole heating system. Variations in HP systems stem from their type, material input and electricity for operation (Blom et al., 2010).

The trade-off of alternatives in terms of land occupation and acidification impact is also in favour of air-air HPs and GSHPs (see Figure 8-11(d)). While electric BHSs are getting more compact to better fit properties with space constraints, the biggest influence on land use, by far, is made by biomass boilers as the only alternative relying on agricultural land for crop cultivation. In the current case, the level of life cycle heat generation would require about 5600m^2 of land, which is 11 times more than the solar system as the second-ranked alternative. This is one of the most discussed disadvantages of biomass and restricts the use of this resource in heat and electricity generation (Stamford and Azapagic, 2014). The acidification potential of biomass boilers is also remarkably higher than other appliances, due to the large amount of NO_x and SO_2 by-products in wood-based fuel combustion.

8.4.1.2 Analysis of economic indicators

Obtaining the values for each economic SI independently, it was found that no single alternative performs best across all the considered SIs. The numbers given in Table 8-10 and Figure 8-12 demonstrates the changes in SIs in comparison with the gas boiler system. The economic analysis results, however, may differ between technologies due to competition, innovation or maturation of the technologies and market (Rafique and Williams, 2021).

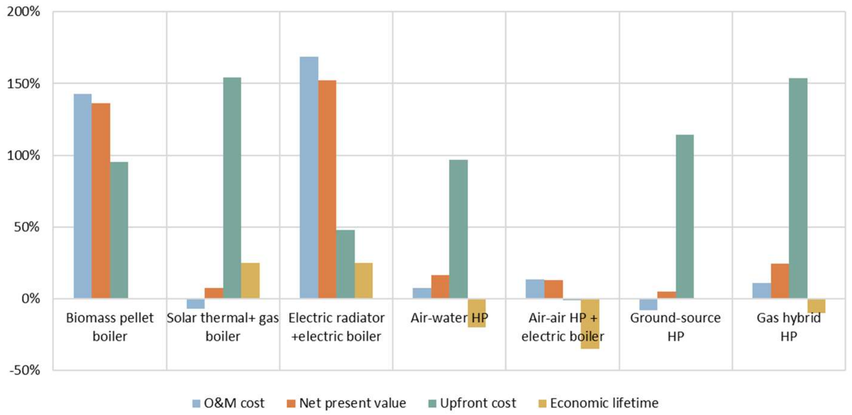


Figure 8-12 Changes in economic indicators of the alternative BHSs compared to the reference gas boiler system

The above figure illustrates that under the baseline scenario, the hypothetical households can only make a small saving, up to £142 (8% reduction) in yearly O&M costs using GSHP and solar-assisted gas boiler. While HPs offer the potential for cost savings, both investigated ASHPs operate with higher running costs. Their economic benefit is not guaranteed and requires proper design, installation, and maintenance, as well as tariff optimisation. In line with previous findings (Mohammadpourkarbasi and Sharples, 2022), it was also found that heating improvements often require higher capital investment, covering the cost of labour and installation of distribution, storage and emitters. Among the low-carbon alternatives, only the air-air split system remains competitive with the prevailing gas-fired system and that is because these systems do not require extensive pipework to deliver the heat through water circulation.

However, when the whole life cycle is considered, a better financial comparison across the alternatives can be made. The annualised LCC over the lifetime of 25 years is presented in the format of NPV, covering the total cost of energy, maintenance, and replacement plus the upfront cost of each scenario, which is an indicator with a negative impact. The NPV changes negatively in all BHSs, with biomass (£82k) and direct electric (£77k) systems likely to present the largest financial burden over the study period, mostly driven by their high O&M costs. In comparison, the best economic viability is found in the GSHP (£34k) and solar systems (£35k), which are slightly higher (around 6%) than the gas boiler life cycle costs. A comparison of the NPV for the eight BHSs is summarised in Figure 8-13, presenting the contribution of the upfront cost, end-of-life cost, and O&M costs.

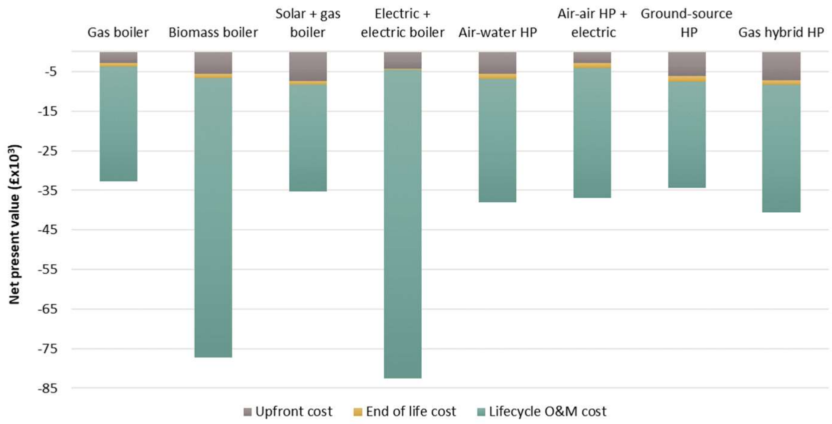


Figure 8-13 Present value of the life cycle costs of heating systems (NPVs are shown in negative values to reflect the nature of NPV cost in this thesis)

8.4.1.3 Analysis of social indicators

Under the social category, a set of 10 indicators are calculated that are analysed independently while having a combined effect on the so-called social sustainability. Figure 8-14 demonstrates how these SIs vary compared to the gas-fired boiler, based on the values calculated in Table 8-10.

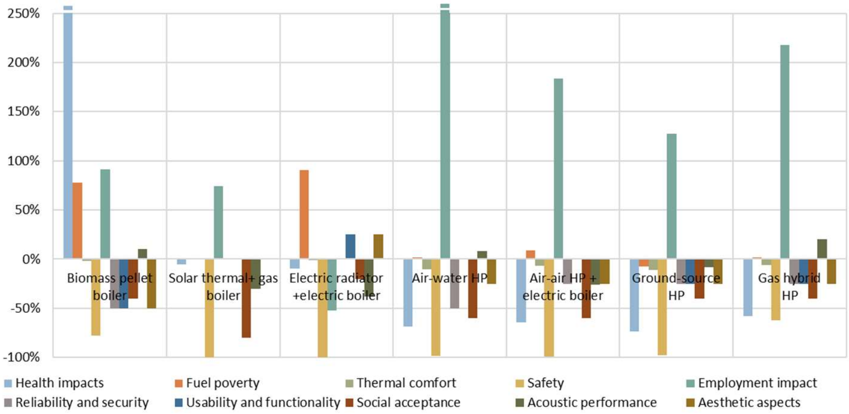
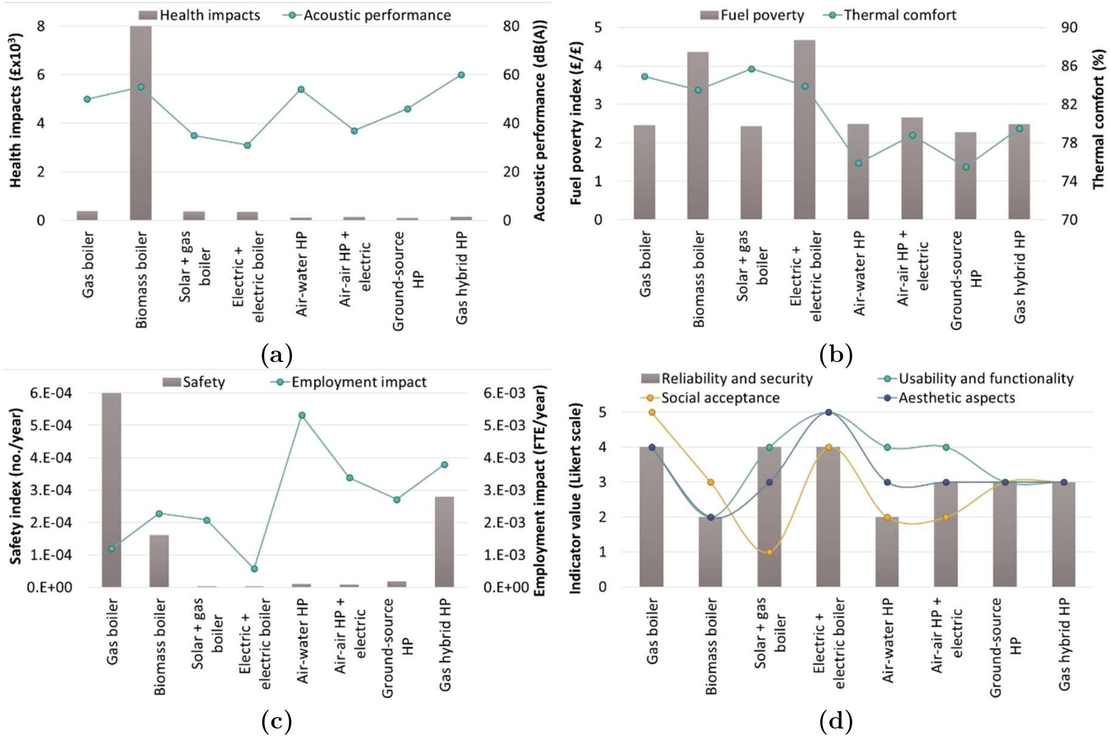


Figure 8-14 Changes in social indicators of the alternative BHSs compared to the reference gas boiler system

Focusing on the social costs arising from the health impacts of GHG and air pollutant emissions, it can be seen in Figure 8-14 that all the considered technologies except the biomass boiler show a decrease in this indicator. The biomass-based system is by far the worst option, with an impact of £8.7k (22 times more than the reference system), mainly contributed by NOx, $PM_{2.5}$ and SO_2 emissions during the combustion of wood (Ekholm et al., 2014). The best option appears to be the GSHP, with £102, followed by the air-water HP with £122, resulting in 73% and 68% lower health impacts compared to the reference system. These systems, however, tend to have more acoustic and noise issues than others due to the outdoor condenser fans.

Exposure to excessive noise from heating systems over time can negatively impact hearing and health. Health impacts and acoustic performance of BHSs are also visualised in Figure 8-15(a).



(a) (b) (c) (d)

Figure 8-15 The initial values of the social indicators; (a) Health impacts and acoustic performance; (b) Fuel poverty and thermal comfort; (c) Safety and employment impact; (d) Reliability, usability, acceptability, and aesthetic factors

The trade-off between the risk of fuel poverty and thermal comfort is also analysed as two potential challenges that arise from the heat transition (Figure 8-15(b)). The findings show that, despite providing a satisfactory level of indoor comfort, the biomass boiler and the direct electric system will considerably increase (up to 90%) the risk of fuel poverty for households. Moreover, with the applied tariffs in the current energy crisis, the hypothetical household is already exposed to fuel poverty, even by using the reference system. On the other hand, HP-based systems make it difficult for households to meet their comfort requirements. The findings suggest that revenues from the low-carbon heating interventions could be seriously undermined if they are not accompanied by a supplemental heating source and modification of the energy prices, as they can result in increasing the likelihood and depth of fuel poverty (Abbasi et al., 2022b).

Safety and employment impact, as both deal with workers' issues, are analysed together in Figure 8-15(c). Safety index, which represents workers' serious accident rates, differs greatly among the alternatives. Throughout the whole life cycle, about 0.02 fatal accidents are associated with the gas boiler, which is the least safe option as a result of exposure to natural gas leaks and explosions. The best option from this perspective is the direct electric, causing only 7x10^{-5} accidents during the same time. This system also has the lowest impact on the job market, creating 0.014 FTE over the entire period. However, a significant number of skilled workers are necessary to deliver the level of HP installation required to meet the existing targets (600,000 per annum by 2028) (UKERC, 2022b). For instance, as the most labour-intensive technology, each air-water HP creates 0.13 FTE, which is 345% higher than the reference technology.

Ultimately, variations of the qualitative indicators of reliability, usability, acceptability, and aesthetic aspects across the alternatives are presented in Figure 8-15(d). From the reliability point of view, all the low-carbon alternatives rate lower than the reference system. HPs can be prone to failure in extremely cold weather, whereas biomass boilers may require more maintenance and repairs due to their mechanical complexity. In terms of usability, HPs, solar thermal, and direct electric offer convenient control with thermostats and straightforward operation. Biomass boilers, however, involve fuel loading and ash removal, which can be more labour-intensive for users. Not surprisingly, the new low-carbon technologies are not yet viewed favourably, compared to the higher acceptance rate of conventional gas boilers and direct electric systems. Finally, aesthetically, HPs and solar systems are believed to have moderate visual impacts, whereas biomass boilers may be less visually appealing.

8.4.2 WSM decision analysis results

Results of the MCDA using the WSM method are presented in the next section, containing normalised and weighted SI values and aggregation results of the BHSs' sustainability performance.

8.4.2.1 Normalised sustainability vectors

The first step of the MCDA process is to transform all criteria values to a common dimensionless scale, allowing diverse metrics like costs, emissions, risks, etc. to be compared on an equivalent basis. Full results of the normalised values of indicators, calculated using the distance-based normalisation method are displayed in Table F-1 of the Appendix. A representation of the normalised decision matrix is shown in **Figure** 8-16 utilising radar graphs.

In these graphs, each radius represents an SI, and each coloured line is a different heating alternative. The farther the line is from the centre, the better the alternative is with respect to each indicator. Using this information, it is not possible to rank the alternatives, as no system stands out across all criteria. However, performing a weighted comparison of the factors enables the optimal heating solution to be identified.

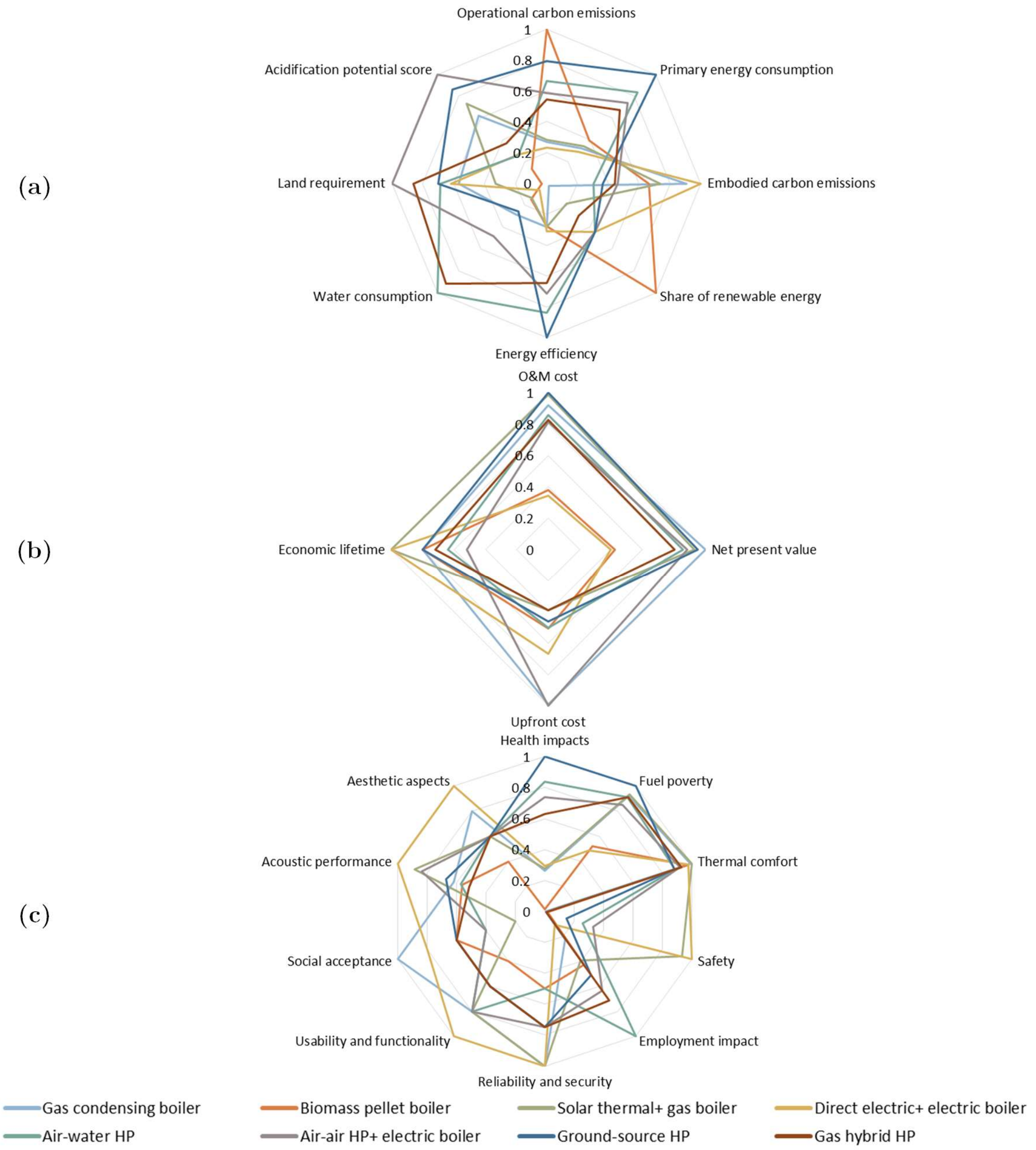


Figure 8-16 Presentation of the normalised values of the (a) Environmental indicators; (b) Economic indicators; and (c) Social indicators of sustainability

8.4.2.2 Weighed normalised scores

After normalisation, weighted values of the normalised SIs were calculated to integrate the experts' perspectives and decision priorities into the analysis. The entire set of results calculated under the baseline scenario can be observed in Table F-2 of the Appendix. These results are visualised in Figure 8-17 where the variations of global weighted SIs can be followed across the alternatives.

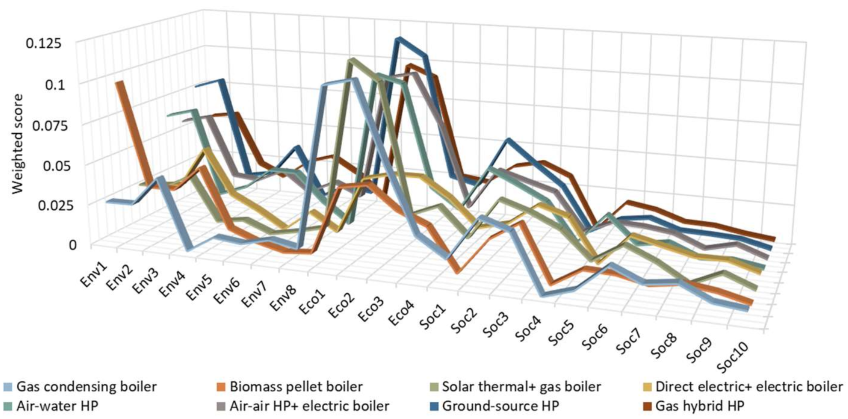
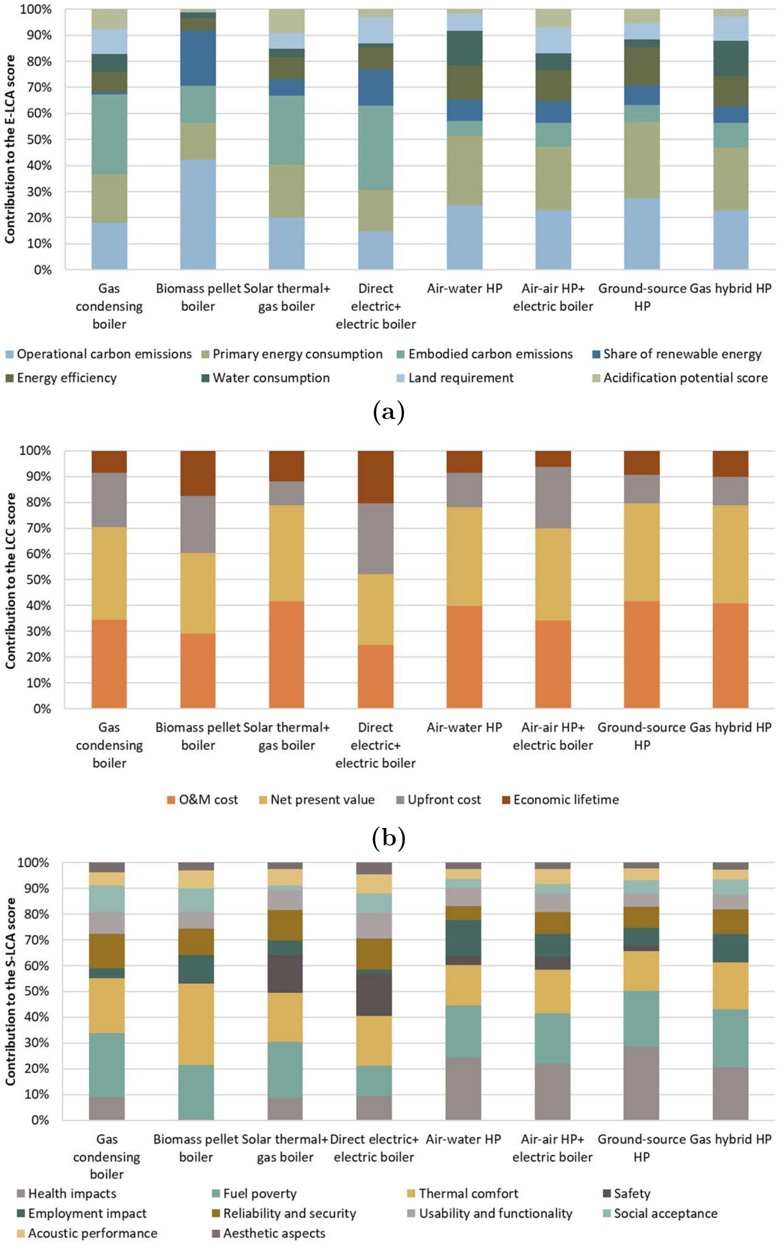


Figure 8-17 Global weighted and normalised values of the sustainability indicators

Using Figure 8-17, however, it is not easy to capture the distribution of sustainability performance among the contributing factors in the environmental, economic, and social impact categories. Thus, the resulting numbers are scaled on a range of 0 to 100, Figure 8-18(a) to Figure 8-18(c), to represent the contribution of each SI to the combined sustainability impact. For instance, an overall view of Figure 8-18(b) shows that economic sustainability is composed of four SIs, of which O&M costs and NPV contribute at least 70% to the total economic sustainability of the gas boiler system. The contribution of the latter two SIs, upfront cost, and lifetime cost, makes an average of 28% of the economic sustainability across all alternatives. These weighted models are essential for capturing the order of magnitude of each SI, but still are not adequate for making accurate and defendable multi-criteria decisions.



(a)

(b)

(c)

Figure 8-18 Contribution of the weighted sustainability indicators to the (a) E-LCA score; (b) LCC score; (c) S-LCA score of alternative heating systems

8.4.2.3 Aggregated sustainability scores

In the final step of WSM, aggregation combines the normalised weighted scores of the SIs into an overall score, named the composite sustainability index (*CSI*) in this thesis. This consolidates the evaluations into a unified overall assessment and allows ranking and comparison of the alternatives on a common numerical scale. To avoid bias owing to the different number of SIs for each dimension of sustainability, the *CSI* score was first calculated for each dimension and then they were summed to obtain a single score for overall sustainability. Table 8-11 presents the final *CSI* scores for each dimension and CSI^{OA}, which is the overall sustainability score of the alternatives. Based on these numbers, a multi-actor view of the final results of the MCDA can be constructed as Figure 8-19. In this graph, the objective axis on the left of the graph depicts the CSI score of each category. The alternatives axis on the right represents the priority weight of each element of the sustainability assessment. On the 'Overall LCSA' column, weights and scores of the sustainability dimensions are combined into an overall score (CSI^{OA}), also showing the rank of each alternative.

Table 8-11 WSM sustainability score and rank of alternatives concerning E-LCA, LCC, S-LCA, and overall sustainability

Assessment category	Item	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*
E-LCA	**Weight**	0.395							
	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	**Weight**	0.332							
	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	**Weight**	0.273							
	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
Overal LCSA	**Weight**	1							
	CSI^{OA}	0.6257	0.4933	0.6066	0.4966	0.7138	0.7254	0.7683	0.6485
	Overal LCSA Rank	5	8	6	7	3	2	1	4

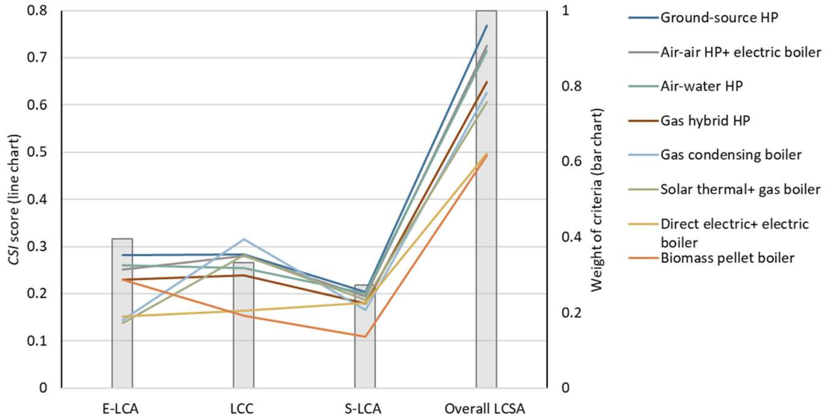


Figure 8-19 Composite sustainability index of sustainability categories and their importance weight

Based on the above figures and from the environmental sustainability perspective, the GSHP performed the best, with the highest score for the E-LCA (28%), followed by the air-water HP. The solar-assisted system and gas boiler scored lowest on E-LCA (14%) as both primarily use natural gas to supply the heat demand. In terms of economic sustainability, the gas boiler and the GSHP were the most cost-effective options, with the highest economic scores (31% and 28%) over the 25 years of assessment. The biomass boiler was the least economical option (15%) owing to substantial fuel costs and maintenance requirements. The direct electric system's LCC scores are only slightly higher than the biomass boiler due to the high cost of electricity use. For social sustainability assessment (S-LCA), the GSHP ranked highest (20%), closely followed by the air-water HP, primarily owing to their positive impact on health and fuel poverty. Biomass and gas boilers had poor social performance because of air pollution and health effects from emissions.

Overall, based on the final LCSA score (CSI^{OA}), the GSHP system is the preferred alternative for the given case study. The GSHP is superior in all ratings, except for the economic dimension, in which it scores second after the gas boiler. The results generally highlight the sustainability benefits of HP systems, with the ground source performing slightly better than air-source systems. Interestingly, while biomass boilers are fuelled by renewable wood pellets and are often considered low carbon in theory, the results of this thesis found them the least sustainable option. Although a biomass boiler is a moderately environmentally friendly alternative, it significantly lags on economic and social dimensions. This can be described as a result of the life cycle and multi-dimensional approach of the present evaluation which takes into account some of the less studied factors such as supply chain emissions, health consequences, and land use change. Direct electric systems also perform very poorly and score just slightly higher than biomass boilers. This is in contrast to an increasing trend towards installing direct electric BHSs in UK homes in recent years, which may be alarming.

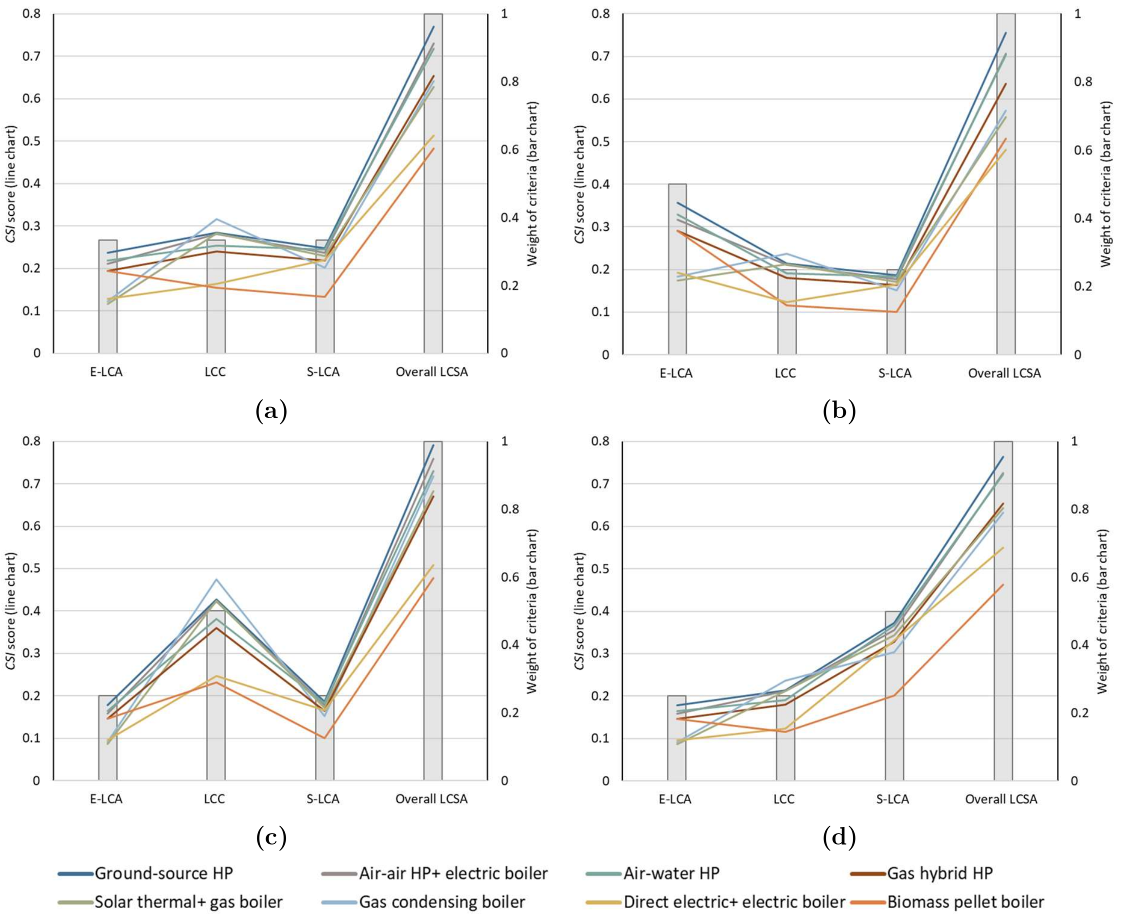
It should be remarked that the ranking results discussed above are only valid for the given case study and within the limits of the defined scope. While the study showcases the functionality of the LCSA framework, the results should be viewed tentatively and cannot be expected to apply universally. Also, decision-making based only on the overall *CSI* is a simplistic analysis that ignores the distribution of SI results and the importance of the issues addressed by each indicator. This underlines the importance of analysing the scenario assumptions and variables' sensitivity before reaching final decisions.

8.5 Sensitivity analysis results

To validate the MCDA results and their calculation process, sensitivity analysis based on the eight scenarios defined in Section 7.4.2 is carried out and discussed as follows.

8.5.1 Dynamic sensitivity analysis

Sensitivity analysis of the indicator weights could provide further insights into the weaknesses and strengths of each alternative and trade-offs between environmental, economic, and social factors (Baumann et al., 2019). This is carried out by changing the weights of the main criteria (sustainability dimensions) while the local weights of sub-criteria (SIs) remain unchanged. In scenario 1, an equal weight of 0.333 was assigned to all dimensions of sustainability. This was followed by scenarios 2 to 4, in which a weight of 0.5 was assigned to make each dimension dominant in turn, while an equal weight of 0.25 was assigned to the other dimensions. After applying the new criteria weights, the steps of WSM were repeated for each scenario to determine the overall score and ranking of the eight alternatives. Here, similar to the baseline scenario, the results of the syntheses are shown on the two-axis graph in Figure 8-20.



(a) (b)

(c) (d)

Figure 8-20 Composite sustainability index of alternatives and priority weight of criteria for (a) Scenario 1: Equal dimensions of sustainability; (b) Scenario 2: Priority of the environmental dimension; (c) Scenario 3: Priority of the economic dimension; (d) Scenario 4: Priority of the social dimension

Figure 8-20 depicts some changes in the ranking of BHSs when criteria weights are altered. It is found that the three strongest candidates, those ranked 1 to 3 in the baseline scenario, remain unchanged under these scenarios. The GSHP received the highest rank in the E-LCA and S-LCA in all weighting profiles, which made it the preferred BHS in all scenarios, followed by the air-air and air-water HPs. The rank of hybrid HP as the 4th preferred option was also stable with the only exception occurring in scenario 3, where the gas boiler appeared to be more favourable. However, more alterations were noticed at the bottom of the table, where three out of four weighting profiles led to a rank reversal between the less preferred options. The wood pellet boiler was still the least attractive option under most of the established scenarios, even under E-LCA dominance. The gas boiler's rank proved very sensitive to the weights of the criteria, changing frequently between 4 to 6 under different weighting schemes.

The results of dynamic sensitivity analysis show that the impact of weighting changes on the final MCDA outcome is not significant and, as seen, similar priorities, especially concerning the top-selected systems, are obtained under the different scenarios. This suggests that the rankings of BHSs are generally consistent between the experts' weighted profiles and the established intuitive weighting profiles, affirming the stability of the LCSA model and its functionality.

8.5.2 Performance sensitivity analysis

Another way to verify the proposed algorithm is by undertaking sensitivity analyses on the key uncertain parameters. This will build more insight into the problem setting by testing the impact of variations in key assumptions on the outcomes (Pombo et al., 2016a). In the present study, there is a high degree of uncertainty relating especially to the price and emissions of the electricity grid, as well as the impact of refrigerant in the HP systems that need to be analysed. Therefore, these parameters were tested through three scenarios defined in Section 7.4.2.2 and the results are shown using the dynamic graphs in Figure 8-21.

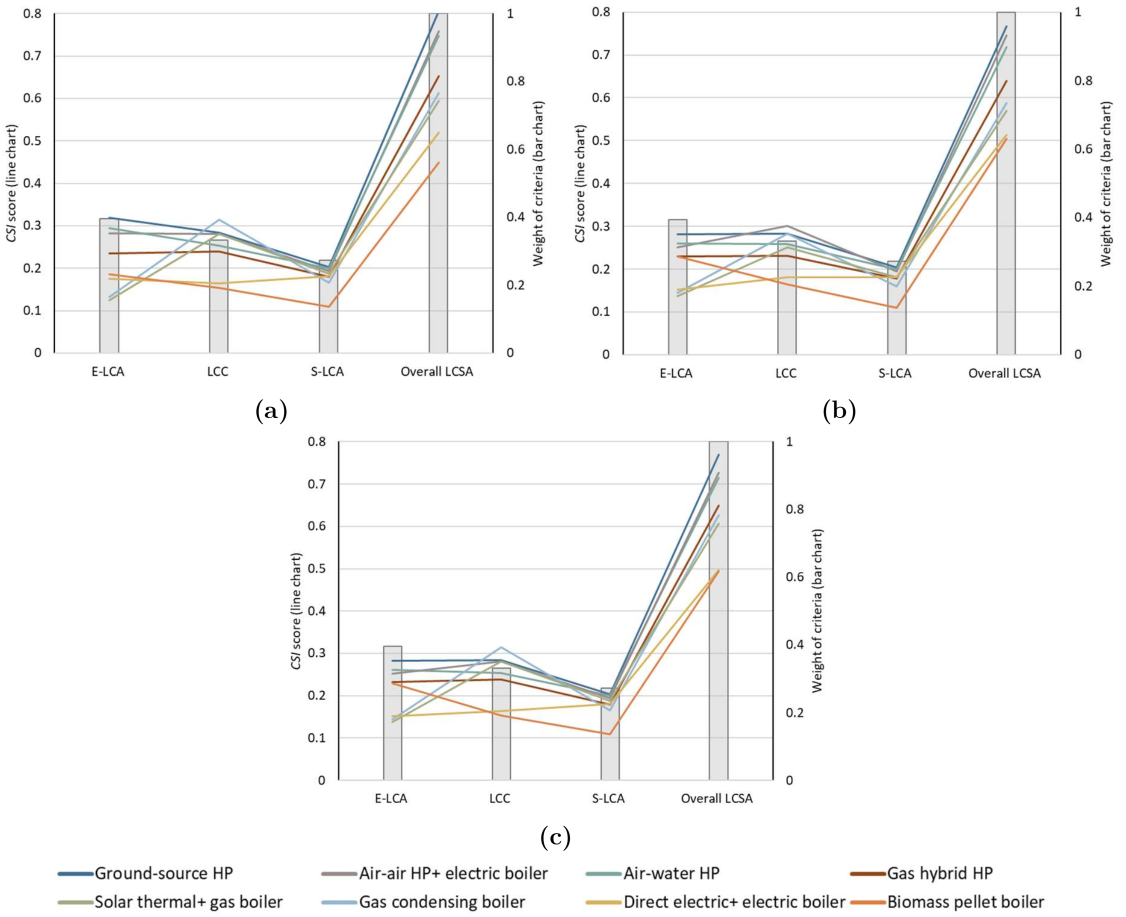


Figure 8-21 Composite sustainability index of alternatives and priority weight of criteria for (a); Scenario5: Decarbonised power supply (b) Scenario 6: Adjusted energy tariffs; and (c) Scenario 7: Using low GWP refrigerants in HPs

Decarbonisation of the network is expected to be a major sensitivity point for the current analyses, as electricity use accounts for a range of 89 to 83% of WLC emissions of the HP-based BHSs (see Table 8-10 of initial SI values)(in line with (Johnson, 2011)). Under scenario 5, if the UK power emission factor sinks from its current level of 0.26 kg CO_2eq/kWh to the hoped-for level of around 0.1 kg CO_2eq/kWh by 2030 (BEIS, 2023b) and presumably remains at that level thereafter, then the WLC footprint of the GSHP, for instance, would fall by 51%, as can be seen in Figure 8-22. The renewable energy ratio of the national grid is another parameter changed in this scenario, which leads to up to 83% greater Env 4 values than the baseline scenario. The sensitivity analysis, however, showed the ranking of the alternatives remains the same under the decarbonised grid scenario, as seen in Figure 8-21(a), leaving the baseline case robust. In fact, increasing penetration of renewables in the national grid makes the superior position of the HP systems stronger in the future.

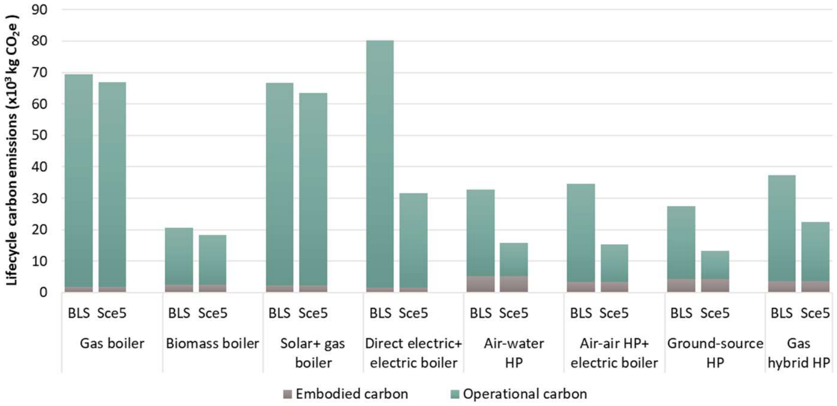


Figure 8-22 Comparison of the whole-life carbon emissions under the baseline scenario (BLS) and scenario 5 (Sce5)

Next, the sensitivity of the model to variations in the energy price was analysed under scenario 6. Here, energy tariffs were reduced by 50, 30, and 51% for electricity, gas, and wood pellets, respectively, based on the UK government's projections for 2030 (BEIS, 2023b). Using the new tariffs, the NPV of GSHP and air-air HP dropped 33% and 42%, respectively, making them a more economically viable option than the gas boiler, with a 26% decrease in NPV. Energy price also significantly influenced the fuel poverty index, leading to around 50% reduction in Soc2 values of the HP-equipped systems, which can be game-changing for mitigating fuel poverty. However, despite the considerable changes in these factors and overall CSI scores, the preferred solutions were identical in the final ranking as can be seen in Figure 8-21(b).

The energy price sensitivity analysis highlights the fact that not only the absolute costs but also the relative prices of electricity and gas are influential in determining the best options. Historically, electricity has been significantly more expensive than gas for on-grid UK households. Supported by our results, many argue that the current energy prices in the UK hinder the decarbonisation of heating in the country (Turner et al., 2023). For instance, switching from gas boiler to air-water HP currently results in a 9% increase in O&M costs. However, reducing the electricity:gas price ratio from 3.4 in the current situation to 2.4 in scenario 6 can lead to a 14% drop in O&M costs. This generally indicates that when the electricity:gas price ratio decreases, electricity-based technologies become more financially attractive. It was found from the present analysis that the breakeven point in the electricity:gas price ratio is 2.9 for the air-water HP. In other words, where the ratio is greater than this, air-water HPs are more expensive to operate than gas boilers.

The last parameter investigated through performance sensitivity analysis was the impact of refrigerant. The global warming impact of refrigerants can represent a significant proportion of a BHS's embodied emissions. The selected air-water HP, employing R134a refrigerant, generates more than twice the emissions of the gas boiler over 25 years. However, looking from the WLC perspective, refrigerants make up a very low proportion of the WLC emissions, if the refrigerant leakage rate remains constant. In our case study, if R32 is used, with 52% less GWP compared to R134a, the overall WLC footprint of the air-water HP reduces negligibly by 1%. Thus, the refrigerant type is hardly visible in the LCSA results and does not change the alternative rankings (see Figure 8-21(c)). Similar results were found by Johnson (2011) who describes the sensitivity to refrigerant impact as modest. This modesty, however, relies on using refrigerant with a low GWP and reducing the leakage rate through maintenance.

8.5.3 Sensitivity analysis of the MCDA method

Ultimately, the validity of the decision model was assessed by another MCDA method. Baumann et al. (2019) argue that the results achieved by a single MCDA process are not sufficient to draw solid conclusions and it is desirable to compare the results using different methods to validate final rankings. Therefore, the TOPSIS, as explained in Section 7.2.2, was also employed to determine the sustainability sequence of the alternatives. The initial SI values in Table 8-10 were normalised and weighted using the global weights for further TOPSIS analysis. Figure 8-23 shows the TOPSIS scores of SIs. Subsequently, by identifying the positive ideal and negative ideal points, the Euclidean distance of each alternative can be measured, as presented in Table 8-12. The table also presents the closeness degree or TOPSIS score with respect to each alternative, indicating some changes compared to the WSM ranking.

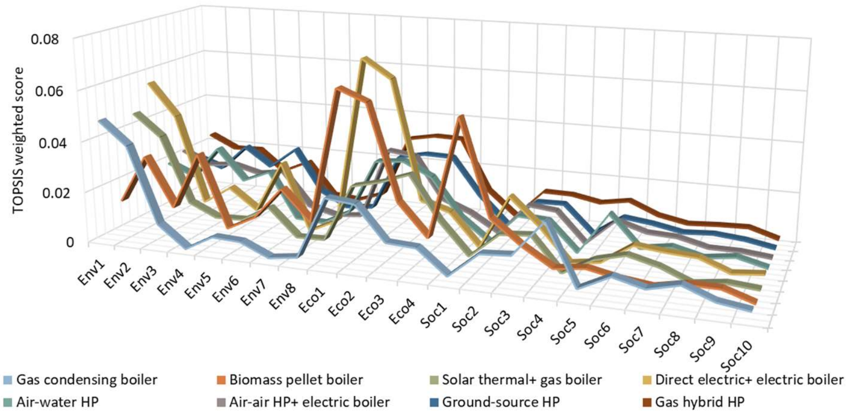


Figure 8-23 TOPSIS weighted and normalised values of the sustainability indicators

Table 8-12 TOPSIS processing results, sustainability scores and alternative rankings

		Building heating systems							
TOPSIS element	**Description**	***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

Using TOPSIS, air-air HP was recognised as the most sustainable, followed by GSHP, gas hybrid system, and air-water HP. Rank reversals were observed between the 1st and 2nd options, as well as between 3rd and 4th. It can be argued here that both methods advantage HP-based alternatives and disadvantage the gas-fired ones, which represents a general consistency between the two methods. However, this thesis prioritises WSM over TOPSIS for this application. Firstly, in this study, decision variables form a two-level hierarchy of main criteria (sustainability dimensions) and sub-criteria (sustainability indicators). The WSM arguably is better suited to these problems, with different levels of decision criteria. In the WSM model, the set of main criteria and each set of sub-criteria are weighted and processed separately. Therefore, it is convenient to analyse and identify the most significant factors in each level of hierarchy. This avoids the bias problem where the weight of the main criteria implicitly depends on the number of sub-criteria (Kontu et al., 2015), and helps decision-makers to untangle the interconnectivities between criteria. In contrast, the TOPSIS model analyses all the decision criteria at one level and does not recognise hierarchical problem structures. Secondly, MCDA methods based on the weighted aggregation of numerical parameters, such as the WSM, are immune to rank reversals, meaning that the introduction or removal of another alternative does not change the relative ranks of other alternatives (Salo and Hämäläinen, 2010).

8.6 Concluding discussions and propositions

8.6.1 Final discussion of MCDA results

The results of the sustainability assessment show that there are notable trade-offs between different SIs and dimensions of sustainability for the various BHS alternatives. No single BHS emerges as superior across all environmental, economic, and social dimensions and results demonstrate the complexity of evaluating sustainability across these dimensions. The WSM provides a simple way to aggregate indicator scores but masks nuances of indicator trade-offs. Presenting disaggregated results for each SI alongside overall scores, as done in Figure 8-24, gives greater insight into the strengths and weaknesses of each BHS option. Sensitivity analysis also highlights where conclusions are robust versus uncertain due to assumptions.

Gas condensing boiler

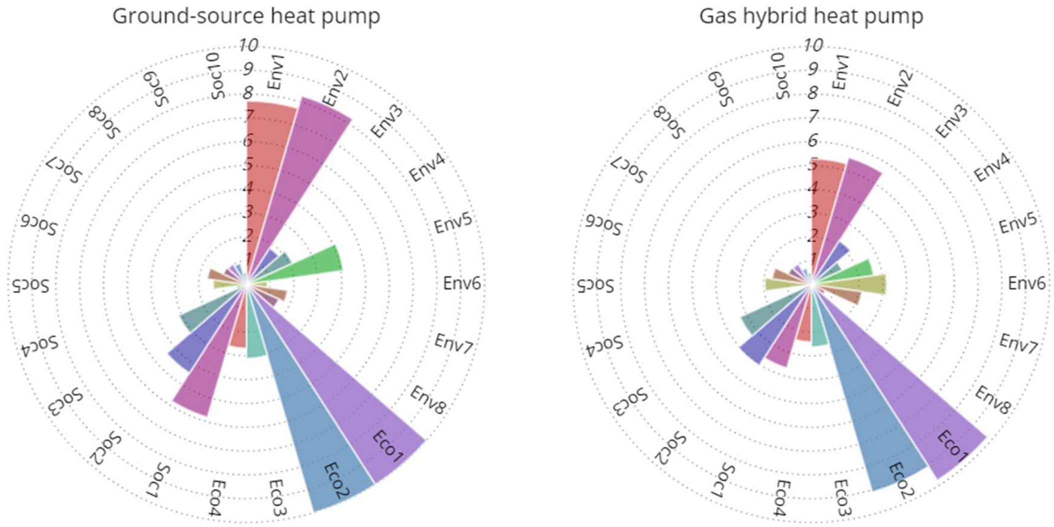
Biomass pellet boiler

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

Figure 8-24 Polar graphs for each heating system case study, mapping the contribution percentage of the 22 sustainability indicators to the final *CSI* score

Based on the MCDA, HP-based BHSs were the most widely preferred heating alternative for the given case study across the analysis scenarios. For environmental indicators, the analysed HP systems led to substantial reductions in life cycle carbon emissions, despite the impact of high material content and the refrigerant used in HPs. Although many debates still take place discussing whether HPs can be more environmentally friendly than gas boilers (Johnson, 2011; Greening and Azapagic, 2012), this study shows that HPs can cause the lowest environmental burden of all the assessed BHS, if a wider range of criteria is taken into consideration. From an economic point of view, reducing the price of electricity relative to gas would make HPs more competitive. The analysis of social indicators also shows that HPs rank at the top, while concerns remain valid over thermal comfort and noise pollution (Gaur et al., 2021). However, for policymakers to provide effective incentives and homeowners to employ these technologies requires an improved understanding of the impacts and trade-offs among the SIs.

This study, in line with some others (Greening and Azapagic, 2012; Usman et al., 2022), has found residential GSHP technologies to be the most favourable system in the long term. There are several reasons for selecting the GSHP as the best alternative; to name a few, this system operated 40% more efficiently and produced 26% lower operational carbon emissions than the air-air HP. Nonetheless, providing fiscal support would be an essential driver for the development of this technology as it requires a relatively high upfront investment. This study suggests the air-air HP as the second sustainable option for the hypothetical household. Nevertheless, these technologies are less popular in the UK, which can attributed to the historic dominance and popularity of central heating plants in the UK (74% of households in England and Wales use gas central heating (Office for National Statistics, 2023a)). A plausible explanation for ranking air-air HPs as the second-best alternative might be the fact that, firstly, these systems can be bought and installed at a very competitive price to gas boilers. Secondly, these systems provide better control of the indoor environment for each space through remote controllers, resulting in better thermal comfort and reliability. On the flip side, these HPs do not supply hot water and need to be combined with supplementary heating technology.

Although the air-air HP system has been ranked second in most of the assessment scenarios, it cannot be always suggested for households with restrictions in space and system integration. Air-air HPs often require separate air handling units or ductwork for distributing heated or cooled air throughout the building, which can be complicated and costly to retrofit into existing homes. Therefore, in regions with a higher proportion of houses with central heating systems, air-water HPs might be a more natural fit. These systems which are the third most favourable alternative in most scenarios, can easily integrate with existing heating systems, such as radiators and underfloor heating, without major modifications. Air-water HPs can also be coupled with gas boilers in the form of hybrid HPs, a technology identified by the Committee on Climate Change (CCC) as offering a range of short-term benefits for making an incremental low-carbon transition (Element Energy, 2021). Nevertheless, the use of this transitional technology should be selective, based on the specific building and grid context.

HPs' superiority over other BHSs, however, should be viewed in the light of several facts. First, the electricity:gas price ratio was found to be an influential driver of the benefits of HPs from both economic and social perspectives. For instance, regarding the air-water technology, the breakeven point in the electricity:gas ratio was found to be 2.9, above which, the environmentally favourable air-water HPs are economically unfavourable compared to gas boilers. Under prevailing market conditions with fluctuating energy prices and high electricity:gas ratio (3.4 based on 2022 prices), the economic benefits of HPs are marginal or not evident, unless they are additionally subsidised (Turner et al., 2023). Similarly, the wider environmental benefits of HPs rely heavily on the decarbonisation of the electricity grid and the refrigerant. Greener electricity, using refrigerants with lower GWP, and minimising leakage over lifetime operation would substantially cut the overall HP footprint (Johnson, 2011).

Supplementary solar heating did not perform as anticipated in this analysis. Adding solar thermal panels to the gas-fired system imposed additional upfront costs but did not result in significant benefits. This technology can lower operating costs, primary energy use, and carbon emissions only marginally. This can be explained due to the relatively intense weather conditions of the case study location and its poor solar gain. However, even with these conditions, solar-assisted BHSs could perform economically and socially better than other hybrid systems, namely hybrid HP, and save up to 13.7 t kg CO_2eq over 25 years. It can be argued that solar heat is very much dependent on the case study location. These systems may turn out to be the superior option in regions with moderate suitability for solar systems, as found in (Yang et al., 2018), whereas they do not considerably improve the system's performance where the coincidence of sunshine and heat demand is poor, as found in this study and (Kontu et al., 2015).

The direct electric system was another alternative with not a lot of desirable qualities. Although this technology has long been considered as a way to transition towards electrified heat, this study shows that it will potentially increase the climate impacts of domestic heating. This is also confirmed by Rafique and Williams (2021), who argue that, without a renewable-dominated electricity grid, installation of direct electric boilers would produce more life cycle emissions than gas boilers. If the electricity is substantially generated by low-carbon resources, environmental performance will improve, but not for all SI categories. Water consumption is another concern with regard to direct electric systems. The relatively high contribution of these systems to the depletion of water resources is caused by the large and growing share of water demand in power plants. From the end-users point of view, the advantageous qualities of this option, e.g., its reliability, controllability, and minimal visual impact, can be degraded by its running costs as a result of soaring electricity prices.

Regarding biomass boilers, results are somehow surprising, indicating that the pellet boiler ranks as the last option under most of the scenarios. A major concern regarding wood pellet boilers lies in the fact that they generate substantial particulate emissions and nitrous oxide, etc., which impose huge impacts on human health and acidification of natural resources. Indeed, this conforms to findings observed in other studies, e.g., (Yang et al., 2018) and (Nyborg and Røpke, 2015). However, the performance of these systems might be different using advanced emission control systems, e.g., scrubbers and catalysts, that reduce SO_2 and NO_x emissions. The biomass system also stands out for its huge land-change potential, which can interfere with agricultural lands and crop cultivation. Nonetheless, this BHS was the most viable option in terms of WLC so it can only be ruled out with certainty in specific circumstances, such as off-grid rural areas.

8.6.2 Final discussion on sensitivity analyses

A set of sensitivity analysis tests was carried out with different parameters and criteria weight combinations. The sustainability assessment results were fairly sensitive to the weighting of criteria and to future decarbonisation and pricing of electricity generation, but less sensitive to the refrigerant impact. However, MCDA ranking results were often stable, which denotes that decision-makers can trust the proposed MCDA approach. In Table 8-13, the frequency of the appearance of each BHS in different ranks is presented. The ranking count includes the baseline scenario plus the eight sensitivity analysis scenarios.

Table 8-13 Frequency of ranking position of each alternative across the analysis scenarios

Heating system	Frequency of BHS to be ranked:							
	1st	2nd	3rd	4th	5th	6th	7th	8th
Gas condensing boiler				1	6	2		
Biomass pellet boiler							1	8
Solar thermal+ gas boiler					3	6		
Direct electric+ electric boiler							8	1
Air-water HP			8	1				
Air-air HP+ electric boiler	1	8						
Ground-source HP	8	1						
Gas hybrid HP			1	7		1		

According to the results from Table 8-13, GSHP and air-air HP systems were the most suitable alternative BHSs for the given case study. The ranking of these systems remained stable in all WSM analyses and they swapped positions only in the TOPSIS analysis. The air-water HP is ranked 3rd almost in all scenarios, except for the TOPSIS scenario, where this technology was ranked 4th after the hybrid HP. Although gas-fired systems incurred some rank reversals in overall sustainability, they remained the most economic BHS in all scenarios. This suggests an answer to why they have continued to be the widely preferred system for space and water heating systems. On the other hand, the biomass boiler and the conventional direct electric system were the least preferred selections in almost all the analyses. Generally, since the priority of the alternatives remained mostly unchanged throughout the analyses, it can be argued that the selection of a BHS technology is not dependent on the values of individual parameters. In such situations, there will be greater confidence in the conclusions drawn on the basis of results of the MCDA (Ekholm et al., 2014).

8.7 Chapter summary

The present chapter aims to demonstrate how the LCSA tool can be employed to make holistic, sustainability-minded decisions in selecting household heating appliances. The developed tool was applied to test various BHSs in the case study of a typical single-family house in Liverpool, built under the future homes' standard. The yearly heat demand of the case study building with 102m^2 floor area and four adults living in it was estimated to be about 11 MWh, 2 MWh of which was used for DHW supply. The study calculated the indicators associated with cradle-to-grave sustainability assessment, followed by evaluating and ranking the alternatives using the MCDA methods. Furthermore, the research explored the potential trade-offs and different analysis scenarios to validate the stability of the LCSA model. In conclusion, HP-based systems were found the most preferred alternative to transit away from gas boilers. By delving into real-life scenarios, the case study provided tangible evidence of how the LCSA framework can be used to handle complexity in decision-making.

The results of the case study provide valuable insights but have limitations for broader policymaking or application to other contexts due to the case-specific nature of the analysis. This chapter conducted a sustainability assessment for a particular case study and the ranking of BHSs could vary significantly for different building geometries, topologies, household requirements, timeframes, and market conditions. While the study illuminates trade-offs between SIs and offers a methodology for integrated sustainability assessment, the quantitative results cannot be expected to apply universally or be reliably extrapolated to form policy. Rather, similar rigorous case analyses using localised data would need to be conducted to determine optimal solutions for different regions accounting for their unique circumstances. This underscores the importance of transparent study scope and assumptions, as well as sensitivity analysis when utilising the LCSA framework.

Chapter 9 Conclusions and Highlights

Despite the strategic and crucial role of heating in achieving net zero targets by 2050, the current literature fails to provide a solid framework to assess the sustainability of heating systems in the built environment. This gap can be traced back to the lack of a thorough and holistic understanding of the notion of sustainability and its indicators regarding building heating systems (BHSs). As a result, the limited extant literature disproportionately represents sustainability dimensions, disregards stakeholders' preferences, or overlooks lifecycle impacts on households and the community. To address these gaps, a novel, multicriteria, and integrated lifecycle sustainability assessment (LCSA) framework in light of triple bottom line (TBL) sustainability dimensions is proposed to evaluate the low-carbon heating alternatives. The developed framework enables trade-offs between multidisciplinary costs and benefits of decarbonisation scenarios and ranks them based on their lifetime sustainability performance. This can help stakeholders in design and decision-making processes to establish more informed pathways towards a just, sustainable, and resilient net-zero future.

The research aims are achieved through the following five objectives and their corresponding methodological stages. The first objective identifies and weights the key sustainability indicators (SIs), reflecting all facets of sustainability and stakeholders' priorities. The developed set of SIs is then quantified for a set of prevalent heating technologies in the UK to address the second research objective. The third objective is designated to fuel poverty and develops a method that is well suited to analysing the interrelations between this factor and heat transition. The collected datasets, measurements, and methods are then integrated into the fourth research objective, leading to the development of the LCSA framework that addresses the unique challenges of BHSs. Finally, a case study is evaluated to determine the priority order for heat decarbonisation options in a typical UK house, as well as validate the functionality of the developed case study as the fifth research objective.

The research focuses on the lifecycle implications of the heat transition at the product level for households because it is the scale level at which the interrelations between heating technology, energy justice, and sustainability are not explored sufficiently. The lifecycle scope of this research is cradle-to-grave, a consistent assessment boundary for investigating individual heating appliances. In terms of geographical scope, research analyses apply to the UK market and the research results are generated based on the conditions of a case study in Liverpool. The developed framework can be useful to consulting engineers, building contractors, and sustainability specialists as a template for lifecycle thinking and sustainability-oriented decision-making. It is therefore hoped that the research findings can contribute to scholarship by promoting the holistic notion of sustainability in decision-making and policy analyses, specifically concerning energy systems within the built environment.

9.1 Main contributions and conclusions

The main conclusions and contributions of the present work are organised into five sub-sections according to the five research objectives, each of which answers one of the research questions presented in Section 1.4.

1. *Identification and prioritisation of the sustainability indicators*: Regarding this objective and responding to the first research question: “What does sustainability entail in this context and what factors contribute to it?” the following conclusions can be derived:
    1.1. The existing assessment frameworks have not equitably considered the three dimensions of sustainability, having been primarily focused on the environmental impacts of energy systems. What is often found to be underrated or not included in the literature is social sustainability, due to the complex nature and subjectivity of the term.
    1.2. A methodological workflow comprised of three phases of identification, refinement, and prioritisation was developed to pinpoint and prioritise the most important quantitative and qualitative sustainability criteria in energy systems. This method renews the focus on the proportional representation of all facets of sustainability and reflection of the stakeholders’ priorities to address the existing gaps in the assessment frameworks.
    1.3. Applying this workflow to the case of heating systems in the built environment, a set of 22 SIs, consisting of 4 economic, 8 environmental, and 10 social indicators, were identified

as the critical set of indicators which can holistically represent the sustainability of the BHSs.

1.4. The environmental dimension was found to be the most crucial element of sustainability (39.5% of the overall weight), followed by the economic (33.2%) and social (27.3%) dimensions. The weight values are determined for the case of residential buildings according to the judgment of UK-based experts and may be different under other circumstances.

1.5. Based on the obtained priority weights, the O&M cost and net present value were the most individually impactful SIs, followed by the operational carbon emissions and primary energy consumption rated third and fourth critical indicators.

1.6. Although indicators of social sustainability received relatively lower weights, this category appeared to have the highest number of indicators. This could be explained by the fact that heating systems have more direct connections with the end-users and have a wider domain of impact on their health, comfort, and well-being compared to other energy systems.

1.7. The identified set of SIs suggests that elements of social sustainability and energy justice are no longer marginal and subjective concepts in energy transition research and practices. These issues are moving rapidly to the centre of energy research, programs, and interventions.

2. *Development of quantification methods and datasets*: The second research objective and question explore “how sustainability of BHSs can be measured at the early stages of projects”. This is addressed in Chapter 5 where the following conclusions are developed:

2.1. One of the methodological challenges of the lifecycle assessment of energy systems is the variety of measurement and quantification methods for each indicator. These methods vary in terms of measurement resolution, functional units, and system boundaries across studies. To build an integrated and workable framework, the developed methods need to be consistent with each other, as well as with the research goals and scope.

2.2. LCSAs are always associated with some degree of uncertainty of input data that could limit the utility of these tools in practice. Therefore, quantification methods should be defined based on valid and accessible data so that they can be independently used by practitioners. In the case of BHSs, a considerable part of this uncertainty stems from the lack of technical and environmental data about heating technologies.

2.3. There is a crucial need to engage the supply chain and encourage manufacturers to report Environmental Product Declarations (EPDs) for their products. However, because of the complexity of heating equipment and their supply chains, very few manufacturers offer EPDs regularly. Even in international databases, e.g., SimaPro, ÖKOBAUDAT, Ecopassport, and Ecoinvent, it is not easy to find exhaustive and consistent EPD data for heating appliances.

2.4. Developing an integrated framework also necessitates the quantification of several qualitative factors which enable the incorporation of social sustainability into decision-making and engineering processes. On the flip side, it also increases the uncertainties due to experts' bias, incompetence, or retrospective judgments.

3. *Fuel poverty, a missing factor in multi-criteria analyses*: Responding to the third research question about "the methods by which social factors such as fuel poverty can be integrated into design and decision-making processes", the following points can be highlighted:

3.1. Fuel poverty is widely recognised as a complex societal challenge in the existing body of research. However, not all driving forces of fuel poverty are equally represented in the existing studies. The technical nuances of fuel poverty cannot be precisely uncovered and addressed in solely social terms, but rather more holistic approaches are required to incorporate technological and engineering factors, expanding the traditional boundaries of fuel poverty scholarship.

3.2. This thesis also argues that implementing low-carbon measures without considering their impacts on fuel poverty could potentially expose more households to the risk of energy deprivation. Therefore, fuel poverty should be brought forward from post-intervention evaluations to the design and decision-making stages. Observing fuel poverty drivers at the primary stages of projects could ultimately result in more informed, effective, and accurately targeted interventions.

3.3. The PFPI method proposed in this thesis can provide a vision of the potential impacts of the interventions on fuel poverty at the early stages of projects. The PFPI can be quantified, weighted, and incorporated into multi-criteria analyses. Using the PFPI, engineers and decision-makers will be able to account for fuel poverty as a design/decision factor in conjunction with other environmental, economic, and technical parameters.

3.4. The PFPI presents a targeted analysis of fuel poverty by reflecting the socio-spatial characterisation of the households. A new household typology based on the location and the composition of the inhabitants is presented in this study to reflect the occupants' behavioural variations. This allows for defining more precise thresholds for financial and energy vulnerability.

4. *Development of a life-cycle sustainability assessment (LCSA) framework*: The fourth research objective explores “how all the identified indicators and developed methods can be integrated to form an LCSA framework”. The answer to this question can be summarised as follows:

4.1. It was shown that all the collected data, quantification methods, and analysis models can be integrated to construct a unified LCSA framework. LCSA encompasses E-LCA for environmental assessment, LCC for lifecycle costing, and S-LCA for social assessment. The MCDA can assist in identifying the trade-offs between different and conflicting SIs, as well as engaging the stakeholders in the analysis process.

4.2. An LCSA tool was developed that encompasses cradle-to-grave E-LCA, LCC, and S-LCA and prioritises the alternatives using MCDA methods. The outcome, is a practical Excel-based tool which can be used at a local level to support authorities and developers to identify the BHSs that suit their priorities and resources.

4.3. This thesis favours WSM over other multi-criteria analysis methods because it recognises the hierarchical levels of sustainability criteria. This avoids the bias problem where the weight of the main criteria implicitly depends on the number of sub-criteria, and helps decision-makers to untangle the interconnectivity between different levels of criteria. The WSM is also immune to rank reversals in which adding or removing one alternative could change the relative ranks of other alternatives.

4.4. The employment of different methods of sensitivity analysis can provide a more comprehensive and robust validation process. This explores the uncertainties embodied in the MCDA model and the SIs and discovers the interactions and interdependencies between them. Therefore, all three types of sensitivity analysis, dynamic analysis, performance analyses, and using different MCDA methods, are carried out in this study to enhance the robustness of the model.

5. *Functionality of the developed framework: Case study and validation*: The developed tool was applied to a case study to answer the fifth research question, “How will the low-carbon alternatives be compared and rated concerning life cycle sustainability performance?”. The main conclusions of this part are summarised as follows:
    5.1. Case studies play a vital role in demonstrating the application and validity of LCSA frameworks. By delving into real-life scenarios, case studies provide tangible evidence of the framework’s functionality and its ability to handle complexities. Furthermore, case studies identify the strengths and limitations of the LCSA and foster its continuous improvement.
    5.2. The results and trade-offs presented in this study are associated with the case of a semi-detached house in northwest England with eight different heating systems. For houses with different geometries or topologies, the alternatives, preference information, and decision parameters need to be modified per case requirements as appropriate.
    5.3. The overview of the results shows that no single technology has superior attributes in all indicators of sustainability. This explains why none of the available heating alternatives will dominate in the coming decades as much as gas boilers do today. Low-carbon BHSs are not in competition with one another but are seen to complement one another in the future energy system. Therefore, there is a need to develop a range of reliable technologies to be able to cater sufficiently for a wide range of building types, climatic conditions, local potentials, and constraints.
    5.4. The MCDA outcome suggests that HPs are the key technology for the decarbonisation of domestic heating, with GSHPs proving to be the most promising option in overall sustainability performance. Air-air and air-water HPs also have unique advantages and are very close competitors. The environmental and social benefits of HPs are visible in the analysis results. However, under the prevailing market conditions, with supply chain constraints and the high relative price of electricity to gas, the bill savings and wider economic benefits are not evident.

5.5. In general, the findings support the government's initiative to increase the number of HP installations to 600,000 a year by 2028. However, the choice between HP alternatives should be case-wise, depending on the building conditions and the household's needs and preferences. For instance, air-air multi-split systems require either separate ductwork or multiple indoor units to deliver the heated or cooled air throughout the home (often serving up to 6 conditioned spaces). This limits the integrability and application of air-air HPs. On the other hand, air-water HPs can be more easily retrofitted into existing homes as a stand-alone system, but at the expense of higher upfront costs.

5.6. Direct electric systems not only could not mitigate the environmental impacts of gas boilers, but also will disproportionately inflate household costs, both in upfront and operational aspects. Significant social implications, such as the risk of fuel poverty and poor employment potential, are also found in the utilisation of direct electric systems. Thus, these systems are not recommended for widespread electrification of heating.

5.7. The added value provided by supplementary solar thermal collectors depends greatly on location due to variances in solar radiation and climate. For the present case, this has been marginal in terms of environmental and social benefits, due to the low solar intensity of the study location, whilst imposing high additional upfront costs.

5.8. The findings regarding the biomass boiler were not anticipated, as this system turned up to be the least attractive option under the majority of the established scenarios. The sustainability issues with biomass heating are multi-faceted, namely huge land-change (deforestation) potential and releasing high levels of PM, SO_2, and NO_x which cause negative health impacts and acidification of natural resources. Biomass rollout merits more study regarding its wider sustainability impacts.

5.9. While stand-alone renewable heating technologies are limited in variety and availability, hybridisation (i.e., coupling of multiple technologies) can provide a transitional solution to incrementally mitigate the environmental impacts of existing systems. For instance, in off-grid or very cold areas with gas-fired systems, it may be worthwhile to consider coupling a solar system or an HP to the existing system, rather than to transition directly to fully electric systems.

5.10. The dynamic sensitivity analyses reveal additional insights and validate the stability of the LCSA model. The results for overall sustainability are consistent across different combinations of the weighting schemes. However, subtracting the weight of economic factors and adding it to social factors can further strengthen the position of renewables in the overall decision outcomes.

5.11. It can often be heard from the business sector that the sustainability of HPs depends greatly on green electricity generation. This study challenges this narrative by arguing that grid decarbonisation could only yield significant improvements in HPs' carbon footprint. However, to judge the overall sustainability of these technologies, a holistic view should be taken attending to all crucial aspects, e.g., affordability and reliability of HPs and their impact on thermal comfort and fuel poverty.

5.12. Sensitivity analyses also revealed the great impact of energy cost on the economic attractiveness of the BHSs. With the ongoing energy crisis and soaring prices, HPs do not lead to cost reduction in either CAPEX, OPEX, or LCC, explaining why gas boilers continue to be the preferred technology for space heating. Crucially, the importance of a broader rethink around the relative price of electricity to gas, rather than their absolute prices, was found through the analyses. It was found that the breakeven point in the electricity:gas price ratio should be 2.9 (it is 3.4 at the time); only lower than that will the use of ASHPs become cost-saving.

Ultimately, the scientific journey that has been condensed in this piece of work has also benefitted the author through both personal and professional growth and brought new and refreshing ideas to the research team. The authors now agree that a paradigm shift toward community-centred and transdisciplinary thinking is required to ensure a sustainable, just, and resilient net-zero future. Indeed, this thesis is both the conclusion of a PhD process and the beginning of a research journey that still has much to contribute to the energy system and society.

9.2 Recommendations for policy and community development

The findings of this work can be applied to develop more sustainable decarbonisation policies in the UK and similar areas. The following key recommendations drawn from this thesis can be offered to practitioners and policymakers:

- Policymakers must understand how critical it is to embrace cross-disciplinary thinking for sustainable transitions. This would fundamentally shift the narrow perception of sustainability as just an environmental concern. In this study, for instance, it is found that the heat transition is highly susceptible to broader sociotechnical drivers such as fuel poverty and thermal comfort, which are often disregarded in public policy. Taking this holistic approach, policymakers would be able to articulate transition pathways which can collectively contribute to the planet, profit, and the people.
- This study suggests that stakeholders' engagement and the lifecycle approach are two crucial elements of successful transition strategies. We demonstrate how expert judgment and lifecycle assessment can be integrated to facilitate decision-making at the household level. This can be extended to strategic policymaking, combining retrospective evaluation of experts and prospective impact assessment of proposals.
- It was found that in the absence of any supportive interventions, gas boilers are likely to continue to be the most affordable BHSs, which would counteract the climate mitigation goals. Therefore, policies need to be introduced to cover the added energy costs imposed by low-carbon alternatives. This, coupled with the continuing trend of reducing the relative price of electricity to gas, is required to accelerate the transition away from gas heating if decarbonisation targets are to be achievable.
- Best alternatives also require higher capital costs, presenting another barrier to people without the capital to switch away from gas boilers. Meanwhile, the existing support schemes, e.g., the UK Government's Boiler Upgrade Scheme, are easier to adopt by owner-occupiers. Thus, more targeted policies should be developed, tailored to assist households in social housing and the private rented sector with the upfront costs. Interventions also need to be in place for manufacturers to expand the supply chain and control the market.

- Furthermore, it is argued that vulnerable groups have been under-represented in decarbonisation plans and have faced worsened social inequalities after implementing the interventions. These households must be protected to ensure that a consequence of cleaner heating is not an increase in fuel poverty. This study suggests that some of the social implications of transition measures can be addressed through predictive models, as fuel poverty was brought forward to the decision-making stage in the present work.

9.3 Limitations of the study

Each methodological stage of the present thesis had some limitations that were acknowledged and discussed in the corresponding chapter. This section, however, summarises the research limitations and uncertainties from a broader perspective:

- First, the number and range of the considered SIs, although selected and backed up by the experts, do not necessarily reflect all the nuances of sustainability in all circumstances. The set of SIs could be augmented and their corresponding weights could be modified through a broader survey of stakeholders with a more diverse spectrum of viewpoints and backgrounds.
- It is important to note that the proposed method has attempted to incorporate social sustainability into quantitative decision-making. However, due to the complex and subjective nature of social factors, it is difficult to precisely predict the probability and depth of social impacts. These uncertainties, such as households' physiological and psychological differences, cannot be modelled using computer models, making social sustainability a complex issue that stretches far beyond a simple model of cause and effect. Such nuances of social sustainability could possibly be captured only through in-depth surveys and prolonged monitoring of households. Nevertheless, the present method sheds light on potential social challenges that future energy interventions could impose, enabling the move from a remedial to a preventive approach.
- The presented LCSA framework is primarily developed for the sustainability assessment of BHSs at the product level. Hence, the results are not sufficiently comprehensive to provide conclusive policy advice on developing national strategies. Also, the results and analyses are limited to eight individual BHSs, only consistent with the UK national context. However, there are some other low-carbon heating options, e.g., communal systems and hydrogen

boilers, that are excluded from this study due to the limitation of scope or lack of available data.

- Another limitation of this study is that the input data for the different heating alternatives and their lifecycle impact are often associated with some uncertainties. These data are scarce and gathered from different sources to create the required impact assessment database along with other data selectively collected from the literature. For instance, some LCA data such as water usage, acidification potential, and material compositions, are gathered from Ecoinvent, PEP Ecopassport, and ÖKOBAUDAT databases that may not always be consistent due to different calculation methodologies. Such uncertainties could influence the outcome of the LCSA and lead to a much less clear-cut ranking of the alternatives. This is why it was highlighted above that manufacturers should be pushed to provide standard EPD datasheets with their products to be able to create exhaustive databases.
- Lastly, this thesis places its emphasis on low-carbon heating technologies in an effort to decarbonise domestic heating. However, it is worth noting that the increasing cooling demand is a topic that seems to receive less attention in the UK research and policy landscape, despite the clear technological overlaps associated with electrification. By simultaneously addressing both cooling and heating demands, more holistic evaluations and pathways can be developed to support the decarbonisation of both sectors.

9.4 Further research

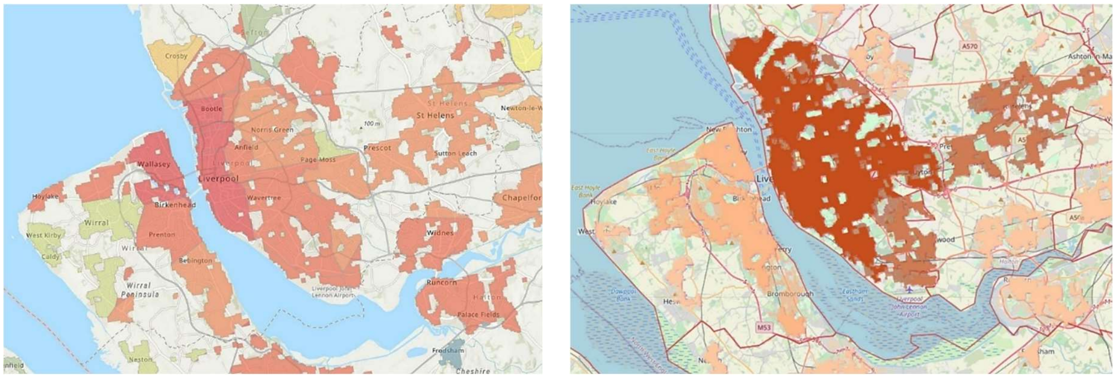
This thesis has presented a starting point for further study on the challenges and prospects of heat decarbonisation, as well as an integrated sustainability assessment of pathways and alternatives. The following extensions to the research are recommended for future work:

- Concerning the developed LCSA framework, several improvements could be explored in further work. The framework can be programmed into an automated software tool integrated with the building energy simulation. The SI structure can be expanded to include more factors such as recyclability, hazardous waste, and the integrability of technologies in the existing homes. Another study can be directed to the development of a framework from the end-user's perspective to compare the results with the views of expert decision-makers.

Moreover, other low-carbon technologies, e.g., hydrogen or district heating, that are not covered here due to lack of data and evidence can be analysed in further studies.

- While the present framework has been proposed to manage heating systems at the micro level, macro-level analytical tools for analysing the strategic transition plans are still missing in the extant literature. This gap suggests future research to develop an evaluation tool for assessing the sustainability of the heating sector at the national level. This would require recognition of a new set of SIs such as energy security and reliance on imported fuel which has been increasingly challenging in the current energy crisis. The suggested framework could be applied nationally to compare decarbonisation scenarios and to track the achievements of national policies and transition strategies.
- Building retrofits are an inseparable part of heat decarbonisation. Alongside the deployment of new heating technologies, a range of business models are required to deliver energy efficiency and retrofit measures at scale, leveraging the benefits of the low-carbon transition. Therefore, further research can be extended to integrate building retrofits into analyses, investigating the synergies and interactions between building efficiency upgrades and low-carbon technology deployments.
- This study developed a predictive indicator for fuel poverty as one of the main social sustainability issues of the heating sector, paving the way for fuel poverty to be tackled at the early stages of design and decision-making. This forms the basis for further research and practice to investigate the effectiveness of such methods, by checking the predictive models against the field data from real-world projects. In a broader sense, this study suggests that some aspects of social sustainability could be addressed by incorporating them into engineering design processes. More research is needed to devise such models for other social implications of transitions, tackling these issues before they arise.
- Heat synergy and waste heat recovery have a huge potential to push heat decarbonisation forward. Research in Europe shows that a major fraction of demand in high-heat-density regions can be balanced with excess heat resources in their neighbourhood. However, heat synergies have long been overlooked in energy models and decarbonisation strategies. Future research, therefore, is highly encouraged to explore the utilisation of surplus heat using HPs and district heating applications. Recently developed thermal maps, such as “Peta” and

"Hotmaps", can facilitate the development of these plants by identifying regions with a positive heat-balance. Figure 9-1 shows excess heat levels around the Merseyside area, UK, from these online tools. More information such as heat demand, heat density, district heating potential, renewables potential, etc., can be obtained through these online tools to help future studies.



(a) **(b)**

Figure 9-1 Mapping of excess heat levels around Merseyside, UK; screenshot from online tools (a) Peta; and (b) Hotmaps

- Finally, the present study provides a foundation for further work to enhance the TBL approach in sustainability assessments. These holistic assessments are needed in energy research and practice to enable just, effective, and sustainability-oriented policies and planning. This study examined the functionality of the TBL framework in the context of BHSs but paves the way for future scholarship to holistically explore sustainability in different domains.

9.5 Publications and Dissemination

Journal papers:

- M.H. Abbasi, B. Abdullah, R. Castaño-Rosa, M.W. Ahmad, A. Rostami, "**A framework to identify and prioritise the key sustainability indicators: Assessment of heating systems in the built environment**", *Sustainable Cities and Society*, Volume 95, 104629, 2023, https://doi.org/10.1016/j.scs.2023.104629.
- M.H. Abbasi, B. Abdullah, R. Castaño-Rosa, M.W. Ahmad, A. Rostami, J. Cullen, "**Planning energy interventions in buildings and tackling fuel poverty: Can two**

birds be fed with one scone?", *Energy Research & Social Science*, Volume 93, 102841, 2022, https://doi.org/10.1016/j.erss.2022.102841.

- M.H. Abbasi, B. Abdullah, R. Castaño-Rosa, M.W. Ahmad, A. Rostami, J. Cullen, "**Towards a just heat transition in the building sector: A study on social indicators of sustainability**", *Science Talks*, Volume 4, 100092, 2022, https://doi.org/10.1016/j.sctalk.2022.100092.
- M.H. Abbasi, B. Abdullah, M.W. Ahmad, A. Rostami, J. Cullen, "**Bringing fuel poverty forward from post-intervention evaluations to design and decision-making stages**", *People, Place and Policy*, Volume 16 (1), 98-106, 2022, https://doi.org/10.3351/ppp.2022.9393348874.
- M.H. Abbasi, B. Abdullah, M.W. Ahmad, A. Rostami, J. Cullen, "**Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology**", *Sustainable Energy Technologies and Assessments*, Volume 48, 101630, 2021, https://doi.org/10.1016/j.seta.2021.101630.

Conference papers and presentations:

- Poster presentation (Best poster prize winner), "**Heat decarbonisation in buildings: Can low-carbon technologies serve a just and sustainable transition?**", *UKERC International Summer School: Global Just Transition and Equity in Net Zero*, 2023, Newcastle, UK.
- Oral presentation (Selected for publication), "**Towards a just low-carbon heat transition in the UK's households: A study on social indicators of sustainability**", *3rd International Conference on Energy Research & Social Science: Energy and Climate Transformations*, 2022, Manchester, UK.
- Oral presentation, "**Mandating the end of residential fossil fuel heating systems: How it could promote or hinder the indicators of fuel poverty?**", *5th Energy and Society Conference*, 2020, Trento, Italy.
- Oral presentation, "**Risks at the intersection of fuel poverty, climate change and heat decarbonisation**", *7th Fuel Poverty Research Network Conference (FPRN7)*, 2019, Cardiff, UK.

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Abbasi, M.H., Abdullah, B., Castano-Rosa, R., Ahmad, M.W., Rostami, A. and Cullen, J. (2022b) Planning energy interventions in buildings and tackling fuel poverty: Can two birds be fed with one scone? *Energy Research & Social Science*, 93, 102841.

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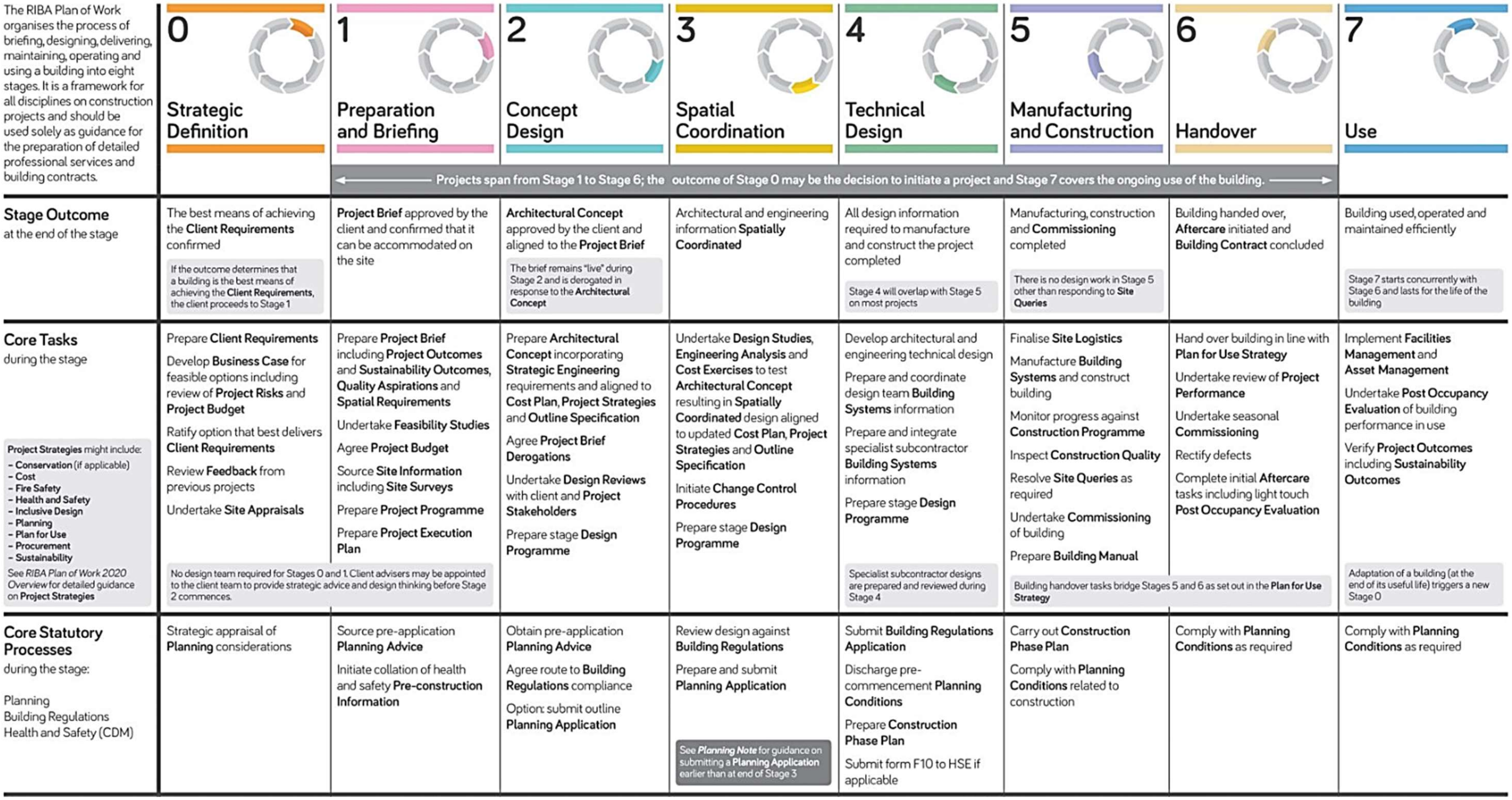
Appendices

Appendix A



The RIBA Plan of Work organises the process of briefing, designing, delivering, maintaining, operating and using a building into eight stages. It is a framework for all disciplines on construction projects and should be used solely as guidance for the preparation of detailed professional services and building contracts.	0 Strategic Definition	1 Preparation and Briefing	2 Concept Design	3 Spatial Coordination	4 Technical Design	5 Manufacturing and Construction	6 Handover	7 Use
		Projects span from Stage 1 to Stage 6; the outcome of Stage 0 may be the decision to initiate a project and Stage 7 covers the ongoing use of the building.						
Stage Outcome at the end of the stage	The best means of achieving the **Client Requirements** confirmed If the outcome determines that a building is the best means of achieving the **Client Requirements**, the client proceeds to Stage 1	**Project Brief** approved by the client and confirmed that it can be accommodated on the site	**Architectural Concept** approved by the client and aligned to the **Project Brief** The brief remains "live" during Stage 2 and is derogated in response to the **Architectural Concept**	Architectural and engineering information **Spatially Coordinated**	All design information required to manufacture and construct the project completed Stage 4 will overlap with Stage 5 on most projects	Manufacturing, construction and **Commissioning** completed There is no design work in Stage 5 other than responding to **Site Queries**	Building handed over, **Aftercare** initiated and **Building Contract** concluded	Building used, operated and maintained efficiently Stage 7 starts concurrently with Stage 6 and lasts for the life of the building
Core Tasks during the stage **Project Strategies** might include: - **Conservation** (if applicable) - **Cost** - **Fire Safety** - **Health and Safety** - **Inclusive Design** - **Planning** - **Plan for Use** - **Procurement** - **Sustainability** See *RIBA Plan of Work 2020 Overview* for detailed guidance on **Project Strategies**	Prepare **Client Requirements** Develop **Business Case** for feasible options including review of **Project Risks** and **Project Budget** Ratify option that best delivers **Client Requirements** Review **Feedback** from previous projects Undertake **Site Appraisals** No design team required for Stages 0 and 1. Client advisers may be appointed to the client team to provide strategic advice and design thinking before Stage 2 commences.	Prepare **Project Brief** including **Project Outcomes** and **Sustainability Outcomes**, **Quality Aspirations** and **Spatial Requirements** Undertake **Feasibility Studies** Agree **Project Budget** Source **Site Information** including **Site Surveys** Prepare **Project Programme** Prepare **Project Execution Plan**	Prepare **Architectural Concept** incorporating **Strategic Engineering** requirements and aligned to **Cost Plan**, **Project Strategies** and **Outline Specification** Agree **Project Brief Derogations** Undertake **Design Reviews** with client and **Project Stakeholders** Prepare stage **Design Programme**	Undertake **Design Studies**, **Engineering Analysis** and **Cost Exercises** to test **Architectural Concept** resulting in **Spatially Coordinated** design aligned to updated **Cost Plan**, **Project Strategies** and **Outline Specification** Initiate **Change Control Procedures** Prepare stage **Design Programme**	Develop architectural and engineering technical design Prepare and coordinate design team **Building Systems** information Prepare and integrate specialist subcontractor **Building Systems** information Prepare stage **Design Programme** Specialist subcontractor designs are prepared and reviewed during Stage 4	Finalise **Site Logistics** Manufacture **Building Systems** and construct building Monitor progress against **Construction Programme** Inspect **Construction Quality** Resolve **Site Queries** as required Undertake **Commissioning** of building Prepare **Building Manual** Building handover tasks bridge Stages 5 and 6 as set out in the **Plan for Use Strategy**	Hand over building in line with **Plan for Use Strategy** Undertake review of **Project Performance** Undertake seasonal **Commissioning** Rectify defects Complete initial **Aftercare** tasks including light touch **Post Occupancy Evaluation**	Implement **Facilities Management** and **Asset Management** Undertake **Post Occupancy Evaluation** of building performance in use Verify **Project Outcomes** including **Sustainability Outcomes** Adaptation of a building (at the end of its useful life) triggers a new Stage 0
Core Statutory Processes during the stage: Planning Building Regulations Health and Safety (CDM)	Strategic appraisal of **Planning** considerations	Source pre-application **Planning Advice** Initiate collation of health and safety **Pre-construction Information**	Obtain pre-application **Planning Advice** Agree route to **Building Regulations** compliance Option: submit outline **Planning Application**	Review design against **Building Regulations** Prepare and submit **Planning Application** See ***Planning Note*** for guidance on submitting a **Planning Application** earlier than at end of Stage 3	Submit **Building Regulations Application** Discharge pre-commencement **Planning Conditions** Prepare **Construction Phase Plan** Submit form F10 to HSE if applicable	Carry out **Construction Phase Plan** Comply with **Planning Conditions** related to construction	Comply with **Planning Conditions** as required	Comply with **Planning Conditions** as required

Figure A-1 Eight stages of building projects based on the RIBA Plan of Work 2020

Appendix B

Table B-1 Preliminary list of sustainability indicators and their categorisation, collected from the extensive literature review

Dimension	Indicator	References
Economic	Upfront cost	(Vasić, 2018; Ascione et al., 2019; Rostam and Abbasi, 2021)
	O&M cost	(Vasić, 2018; Rutz et al., 2019; Saleem and Ulfat, 2019)
	Life cycle cost	(Wu et al., 2017; Hajare and Elwakil, 2020; Rostam and Abbasi, 2021)
	Payback period	(Si et al., 2016; Yang et al., 2018; Zhang et al., 2019a)
	Net present value	(Borzoni et al., 2014; Fan and Xia, 2017; Taylan et al., 2020)
	Energy cost	(Chou and Ongkowijoyo, 2014; Rutz et al., 2019; Siksnelyte-Butkiene et al., 2021a)
	Availability of funds and subsidies	(Chapman et al., 2016; Boran, 2018; Taylan et al., 2020)
	Economic Lifetime	(Atabaki and Aryanpur, 2018; Ghenai et al., 2020; Taylan et al., 2020)
	Annualised cost	(Atilgan and Azapagic, 2016; Chen et al., 2020; Fonseca et al., 2021)
	Levelised cost of energy	(Lee and Chang, 2018; Yang et al., 2018)
	Affordability	(Väisänen et al., 2016)
	Reduced energy cost	(Yang et al., 2018)
	Global cost	(Rostam and Abbasi, 2021)
	Commercial viability	(Hacatoglu et al., 2015)
	Market Maturity	(Vasić, 2018)
	Waste disposal cost	(Traverso et al., 2012)
	Benefit–cost ratio	(Rostam and Abbasi, 2021)
	Share of households in costs	(Kuznecova et al., 2017)
	Financial risk	(Hashemi et al., 2021)
	Internal rate of return	(Hashemi et al., 2021)
	Taxes and Tariff	(Taylan et al., 2020)
	Discount rate for year	(Džiugaitė-Tumėnienė et al., 2017)
	Residual value of technology	(Džiugaitė-Tumėnienė et al., 2017)
	Life cycle flow	(Rostam and Abbasi, 2021)
	End-of-life costs	(Gencturk et al., 2016)
	Costs of grid connection	(Streimikiene et al., 2012)
	Peak load response	(Streimikiene et al., 2012)
	Sensitivity to energy price fluctuations	(Zhang et al., 2019a)
	Duration of implementation	(Passoni et al., 2021)
	System capacity	(Saleem and Ulfat, 2019)
	Technology cost	(Ahmad and Tahar, 2014)
	Research & development cost	(Büyüközkan and Güleryüz, 2016)
Environmental	Global warming potential	(Vasić, 2018; Aberilla et al., 2020; Fonseca et al., 2021)
	Land/space requirement	(Grafakos et al., 2017; Hehenberger-Risse et al., 2019; Passoni et al., 2021)
	Primary energy consumption	(Russo et al., 2014; Salata et al., 2017; Ascione et al., 2019)
	Water consumption	(Gencturk et al., 2016; Aberilla et al., 2020; Fonseca et al., 2021)

	PM emissions	(Brand and Missaoui, 2014; Rutz et al., 2019; Aberilla et al., 2020)
	Share of renewable energy	(Kuznecova et al., 2017; Yang et al., 2018; Diemuodeke et al., 2019)
	Energy efficiency	(Brand and Missaoui, 2014; Chapman et al., 2016; Katal and Fazelpour, 2018)
	Acidification potential	(Ekholm et al., 2014; Russo et al., 2014; Pombo et al., 2016a)
	GHG saving	(Si et al., 2016; Yang et al., 2018; Ren and Toniolo, 2020)
	NOx emissions	(Rutz et al., 2019; Chen et al., 2020)
	SO_2 emissions	(Hehenberger-Risse et al., 2019; Rutz et al., 2019)
	Fossil fuel depletion	(Russo et al., 2014; Grafakos et al., 2017)
	Waste generation	(Kurka, 2013; Passoni et al., 2021)
	Noise pollution	(Barros et al., 2015; Grafakos et al., 2017)
	Climate change impact	(Ekholm et al., 2014; Atilgan and Azapagic, 2016)
	Ozone layer depletion potential	(Pombo et al., 2016a; Aberilla et al., 2020)
	Abiotic depletion potential	(Santoyo-Castelazo and Azapagic, 2014; Ren and Toniolo, 2020)
	Life-cycle CO_2 emission	(Chen et al., 2020)
	Hazardous waste	(Onat et al., 2014)
	Use of reused materials	(Yadegaridehkordi et al., 2020)
	Use of recycled materials	(Yadegaridehkordi et al., 2020)
	Use of local material	(Diemuodeke et al., 2019)
	Biodiversity impact	(Bachmann, 2013)
	Exergy efficiency	(Nzila et al., 2012)
	Thermal energy demand	(Ascione et al., 2017a)
	Energy saving ratio	(Chen et al., 2020)
	Water saving	(Si et al., 2016)
	Energy intensity	(Rostam and Abbasi, 2021)
	Landscape respect	(Bachmann, 2013)
	Radioactive waste	(Bachmann, 2013)
	Eutrophication potential	(Ren and Toniolo, 2020)
	Ecotoxicity	(Gencturk et al., 2016)
	Radionuclide external costs	(Streimikiene et al., 2012)
	Environmental external costs	(Streimikiene et al., 2012)
	Ratio of solar electricity	(Chen et al., 2020)
	Embodied energy	(Ren and Toniolo, 2020)
	Emergy	(Rostam and Abbasi, 2021)
	Water Pollution	(Taylan et al., 2020)
	Storability	(Taylan et al., 2020)
	Use of recycled water and rainwater	(Yadegaridehkordi et al., 2020)
	Seasonal performance factor	(Poppi et al., 2018)
	Impact on ecosystem	(Boran, 2018)
	Land use change	(Rojas-Zerpa and Yusta, 2015)
	Waste disposal	(Si et al., 2016)
	Soil contamination	(Hashemi et al., 2021)
	Habitat loss and damage	(Hashemi et al., 2021)
	Recyclability	(Passoni et al., 2021)
Social	Job creation	(Onat et al., 2014; Yuan et al., 2018; Chen et al., 2020)
	Thermal comfort	(Chinese et al., 2011; Li et al., 2017; Vasić, 2018)

	Social acceptance	(Kontu et al., 2015; Saleem and Ulfat, 2019; Seddiki and Bennadji, 2019)
	Health impacts	(Ekholm et al., 2014; Gencturk et al., 2016)
	Acoustic performance	(Bachmann, 2013; Yadegaridehkordi et al., 2020; Yadegaridehkordi and Nilashi, 2022)
	Reliability and security	(Chinese et al., 2011; Si et al., 2016; Yang et al., 2018)
	Safety	(Li and Froese, 2017; Aberilla et al., 2020; Taylan et al., 2020)
	Usability and functionality	(Kontu et al., 2015; Ahmad and Thaheem, 2017; Džiugaitė-Tumėnienė et al., 2017)
	Severe accidents	(Streimikiene et al., 2012; Grafakos et al., 2017; Aberilla et al., 2020)
	Social benefits	(Wu et al., 2018; Zhang et al., 2019a; Taylan et al., 2020)
	Aesthetic aspects	(Ahmad and Thaheem, 2017; Grafakos et al., 2017; Li and Froese, 2017)
	Adaptability with technological innovations	(Bachmann, 2013; Passoni et al., 2021)
	Support local businesses	(Brand and Missaoui, 2014; Taylan et al., 2020)
	Innovative technology design	(Grafakos et al., 2017)
	Durability	(Si et al., 2016)
	Indoor environmental quality	(Ahmad and Thaheem, 2017)
	Accessibility	(Kontu et al., 2015)
	Political acceptance	(Taylan et al., 2020)
	Luminous comfort	(Yadegaridehkordi et al., 2020)
	User guide and manual	(Taylan et al., 2020)
	Mould prevention	(Yadegaridehkordi et al., 2020)
	Integration with cultural values	(Neugebauer et al., 2015)
	Gender equity	(Ren and Toniolo, 2020)
	Sociocultural awareness	(Taylan et al., 2020)
	Compatibility with local heritage	(Ahmad and Thaheem, 2017)
	Use of professional ethics	(Afshari et al., 2022)
	Education and knowledge availability	(Neugebauer et al., 2015)
	Maintenance convenience	(Vasić, 2018)
	Public participation	(Chapman et al., 2016)
	Human toxicity potential	(Aberilla et al., 2020)
	Food safety risk	(Streimikiene et al., 2012)
	Arrears on utility bills	(Siksnelyte-Butkiene et al., 2021a)
	Energy poverty	(Siksnelyte-Butkiene et al., 2021a)
	Visual comfort	(Rostam and Abbasi, 2021)
	Contribution to country's independence	(Zhang et al., 2019a)
	Occupant wellbeing improvement	(Si et al., 2016)
	Architectural compatibility	(Ahmad and Thaheem, 2017)
	Social trust & fairness	(Taylan et al., 2020)
	Indoor environmental quality	(Si et al., 2016)

Table B-2 Characteristics of the experts who participated in the survey

Characteristic	Details	Number of participants	(%)
Region of residence/career	North West (England)	12	48%
	Outside the UK	3	12%
	South East (England)	2	8%
	West Midlands	1	4%
	East Midlands (England)	1	4%
	London	1	4%
	East of England	1	4%
	South West (England)	1	4%
	Yorkshire and the Humber	1	4%
	Scotland	1	4%
	Wales	1	4%
Type of affiliation	Industry-technical	9	36%
	Academic	9	36%
	Professional/governmental institutions	3	12%
	Industry-management	2	8%
	Research institutes	2	8%
Years of experience in the field	1-5 years	12	48%
	More than 10 years	9	36%
	6-10 years	4	16%
Education	Master	10	40%
	PhD	6	24%
	Bachelor	6	24%
	Not mentioned	2	8%
	Further education (college, sixth form,...)	1	4%
Level of knowledge/expertise in building services and energy systems	5 (Expert)	9	36%
	4 (Proficient)	8	32%
	3 (Competent)	6	24%
	2 (Advanced beginner)	2	8%
	1 (Novice)	0	0%
Level of knowledge/ expertise in buildings energy performance and efficiency	5 (Expert)	11	44%
	4 (Proficient)	9	36%
	3 (Competent)	4	16%
	2 (Advanced beginner)	1	4%
	1 (Novice)	0	0%
Level of knowledge/ expertise in sustainability of the buildings and energy systems	5 (Expert)	10	40%
	4 (Proficient)	12	48%
	3 (Competent)	2	8%
	2 (Advanced beginner)	1	4%
	1 (Novice)	0	0%

Table B-3 A list of questions included in the online survey

Section / Page	**Questions/Information**
1	Title of Survey: **Sustainability Indicators of Heating Systems in Domestic Buildings** LJMU's Research Ethics Committee Approval Reference: **21/BUE/005**
2	Please take time to read the Participant Information Sheet.

Key points:

- The aim of this survey is to identify the sustainability indicators of domestic heating systems and prioritise them based on the experts' judgment.
- Your answers will be used for research purposes only.
- This survey is carried out anonymously and it does not involve personal data collection.
- This study is organised by a PhD research team in Liverpool John Moores University and is reviewed by the Research Ethics Committee.
- The estimated time to complete the survey is 15-20 minutes.

Please read the questions carefully before responding and contact us if any clarifications are needed.

Thank you for reading this information and for helping us in this study.

3 **Consent agreement**

1. By completing this survey, you are indicating that you have read the Participant Information Sheet and agree with the terms as described.

4 **Contributors' Background**

2. Region of residence/career?
2.a. If you selected outside the UK, please specify.
3. Type of affiliation?
4. Area of expertise/job role/department?
5. Years of experience in this field/role?
6. Highest education?
7. To what extent do you agree/disagree with the following statements?
7.a. I have good knowledge/experience in building services and energy systems.
7.b. I have good knowledge/experience in buildings energy performance and efficiency.
7.c. I have good knowledge about the sustainability in buildings and energy systems.

5 **Pillars of sustainability**

Sustainability is defined as meeting the needs of the present without compromising the ability of future generations to meet theirs. It has three main pillars: economic, environmental, and social (informally referred as profit, planet, and people).

Particularly regarding building heating systems, a heating system is considered sustainable if it fulfils the following criteria:

Economic Criteria in heating systems refer to cost factors, e.g., capital cost, operating cost, etc.

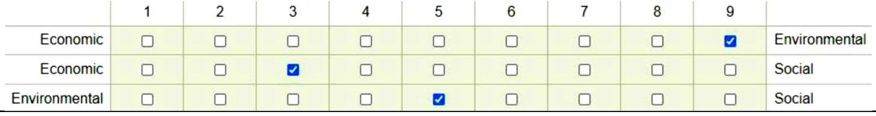
Environmental Criteria in heating systems refer to their emissions and resources, e.g., GHG emissions, fossil fuels use, etc.

Social Criteria in heating systems refer to other impacting factors on households, e.g., thermal comfort, fuel poverty, etc.

8. With respect to the main pillars of sustainability, please state how important do you think each criteria is compared to others in selecting a building heating system (1 refers to extreme importance of the left criteria, 5 refers to equal importance, 9 refers to extreme importance of the right criteria).

* Guidance: The table wants you to make pairwise comparisons between criteria. As an example, an answer like the picture below communicates that:

1st row: Environmental factors are extremely more important than economic factors.
2nd row: Economic factors are moderately more important than social factors.
3rd row: Environmental factors are equally as important as social factors.



	1	2	3	4	5	6	7	8	9	
Economic	☐	☐	☐	☐	☐	☐	☐	☐	☑	Environmental
Economic	☐	☐	☑	☐	☐	☐	☐	☐	☐	Social
Environmental	☐	☐	☐	☐	☑	☐	☐	☐	☐	Social

6 **Economic Sustainability**

To be sustainable, an energy system must be economically feasible and support long-term economic growth. In this research, economic sustainability is defined by the below main economic indicators:

Upfront costs: Refers to costs that the first buyer/investor should pay for the complete installation of the heating system in the building. This includes all costs associated with equipment, installation, labour, and transportation.

Operational costs: Costs that the user should pay for the operation of the heating system over its lifetime. This includes all costs associated with utilities and maintenance.

Life cycle costs: Includes upfront and operational costs, plus all costs associated with end-of-life stages.

Economic lifetime: The expected time that the energy system will remain fully operational.

Availability of funds and subsidies: Availability of public grants and subsidies to support installation of the heating system.

9. With respect to the defined economic indicators, please state how important you think each indicator is compared to others for selecting a building heating system (1 refers to extreme importance of the left indicator, 5 refers to equal importance, 9 refers to extreme importance of the right indicator).

(Participants can make pairwise comparisons between the criteria and see the results on a visual graph)

10. Do you think that there are other economic factors affecting the life cycle sustainability of the heating systems that need to be taken into consideration in decision-makings? If yes, please suggest them.

10.a. If you have added any economic factors, how do you score their importance compared to the indicators given above?

7 **Environmental Sustainability**

A sustainable energy system should minimize negative environmental impacts, conserve energy and natural resources. In this research, environmental sustainability of the heating systems is defined by the below indicators:

Primary energy consumption: Demand for primary energy which has not undergone any conversion or transformation.

Operational carbon: Refers to the amount of GHG emissions during the operational or in-use phase of a system.

Embodied carbon: Refers to GHG emissions released during the manufacturing, transportation, construction, and end-of-life phases of the heating system.

Share of renewable energy: Share of renewable energy resources in gross final energy consumption.

Water consumption: Lifecycle fresh water consumption of the heating systems per unit of energy generated.

Energy efficiency: The ratio of the final obtained energy and the overall consumed energy.

Land requirement: Direct and indirect land use associated with the production and installation of technologies.

Acidification potential: Annual SO_2, NOx, HCl and NH3 emissions transformed into SO_2 equivalents.

11. With respect to the defined environmental indicators, please state how important you think each indicator is compared to others for selecting a building heating system (1 refers to extreme

	importance of the left indicator, 5 refers to equal importance, 9 refers to extreme importance of the right indicator). *(Participants can make pairwise comparisons between the criteria and see the results on a visual graph)* *12.* Do you think that there are other environmental factors affecting the life cycle sustainability of the heating systems that need to be taken into consideration in decision-makings? If yes, please suggest them. *12.a.* If you have added any environmental factors, how do you score their importance compared to the indicators given above?
8	**Social Sustainability** Social sustainability is about the impacts of technology on people and their quality of life over the product's lifecycle. In the context of this study, social indicators of sustainability for heating systems are defined as follows: **Thermal Comfort:** Capability of the heating system to provide comfort and quality of the indoor environment. **Health impacts:** Health risks associated with air quality and particulate matter (PM2.5 and PM10) emissions. **Safety:** Frequency of serious occupational accidents and fatalities over the life cycle. **Job creation:** Direct or indirect jobs created due to change of technology. **Reliability:** Probability of failures which is the ratio of the actually available hours to the nominal running hours. **Social acceptability:** Public preference for utilisation of the energy technology among the local population. **Usability and functionality:** The extent to which the system is understandable, simple in use and adjustable. **Acoustic performance:** Occupant satisfaction with the indoor acoustical environment, described in terms of soundproofing level and noise level. **Aesthetic aspects:** Perceived visual connection with the surrounding landscape. *13.* With respect to the defined social indicators, please state how important you think each indicator is compared to others for selecting a building heating system (1 refers to extreme importance of the left indicator, 5 refers to equal importance, 9 refers to extreme importance of the right indicator). *(Participants can make pairwise comparisons between the criteria and see the results on a visual graph)* *14.* Do you think that there are other social factors affecting the life cycle sustainability of the heating systems that need to be taken into consideration in decision-makings? If yes, please suggest them. *14.a.* If you have added any social factors, how do you score their importance compared to the indicators given above?
9	**General Comments** *15.* If you think there are other factors that have not been covered in this survey, please note them here. *16.* If you have any comments to enhance the clarity and functionality of the selected list of indicators, please mention them here. *17.* If you have any additional comments that you would like to make about any aspect of this research, please note them here. *18.* If you would like us to make you informed about the research outcomes or publications in future, please provide your email address.
10	Thank you for your time and contribution. We would always be happy to share more information about the research and hear your thoughts and advice. To contact us please email us at: m.h.abbasi@2019.ljmu.ac.uk. For SurveyCircle users (www.surveycircle.com): The Survey Code is: 111T-S89Q-5HM3-KHK2

Appendix C

Figure C-1 Case study building for fuel poverty example analysis, LJMU Exemplar houses

Figure C-2 Case study model for fuel poverty example analysis, IES-VE model

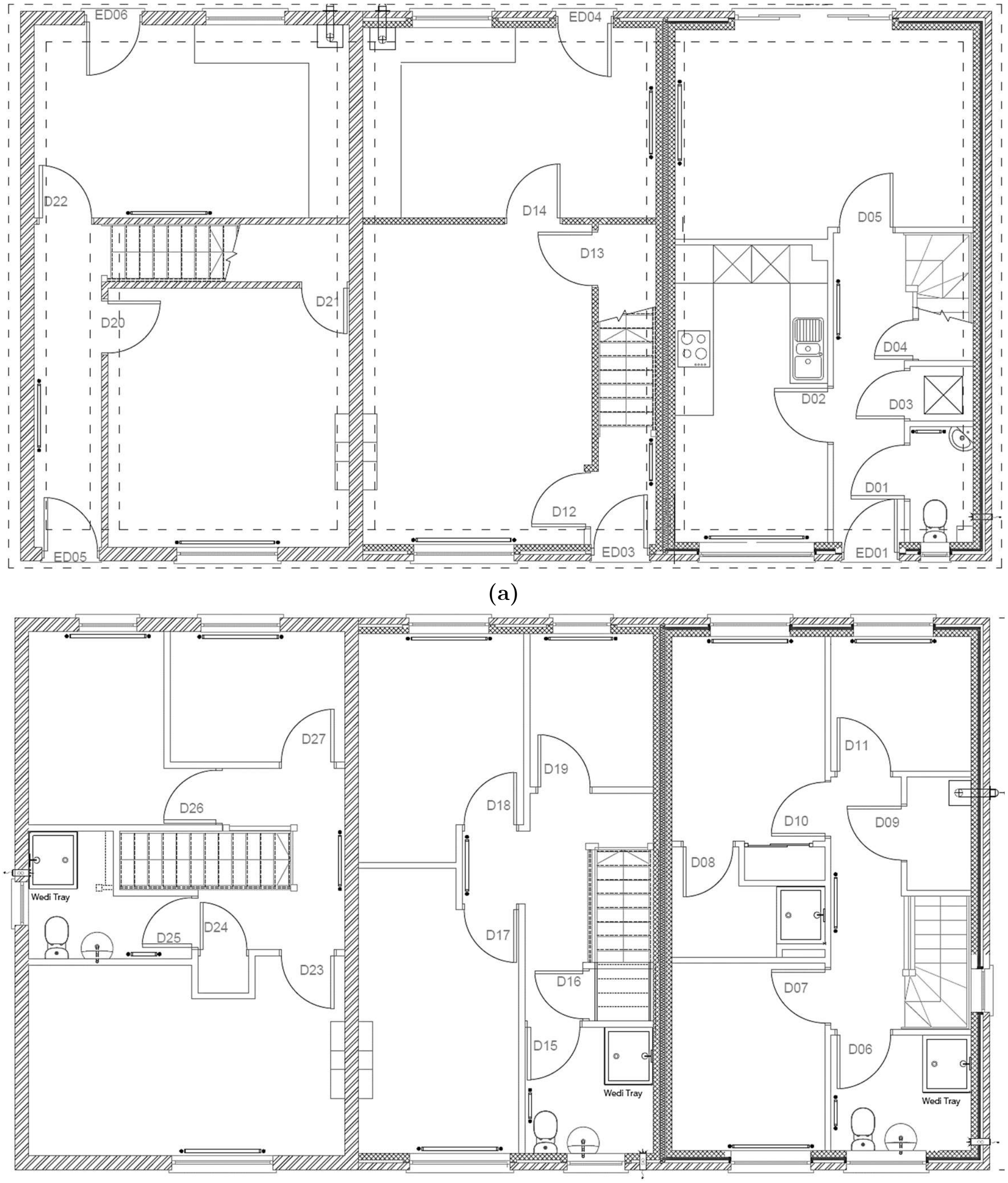


Figure C-3 Layout of the case study for fuel poverty example, 1930s house on the left, 1970s house in middle and 2010s house on the right; a) Ground floor, b) First floor

Table C-1 Modelling parameters and assumptions for the fuel poverty analysis

Modelling parameters	**1930s house**	**1970s house**	**2010s house**
Building parameters			
Exterior wall U-value (W/m²K)	1.65	0.63	0.26
Roof U-value (W/m²K)	1.46	0.76	0.17
Floor U-value (W/m²K)	0.99	0.83	0.18
Glazing U-value (W/m²K)	4.12	2.11	1.54
Ventilation max rate (ACH)	1	1	1
Infiltration max flow (ACH)	0.95	0.55	0.25

General model settings	
Available living area (m^2)	88.4
Building conditioned volume (m3)	373.5
Number of occupants	3 (2 adults and 1 child aged +14)
Hot water demand (L/day)	150
Internal gain sources	Occupants and electric appliances
Max sensible heat gain (W/person)	50
Design weather	
Weather station	Liverpool Airport
Weather data source	ASHRAE design weather database v6.0
Max dry-bulb temperature (℃)	28.1
Min dry-bulb temperature (℃)	8.5
Winter design temperature (℃)	-2.2
Max humidity (%)	100.0
Min Humidity (%)	29.0
Mean humidity (%)	82.3

Appendix D

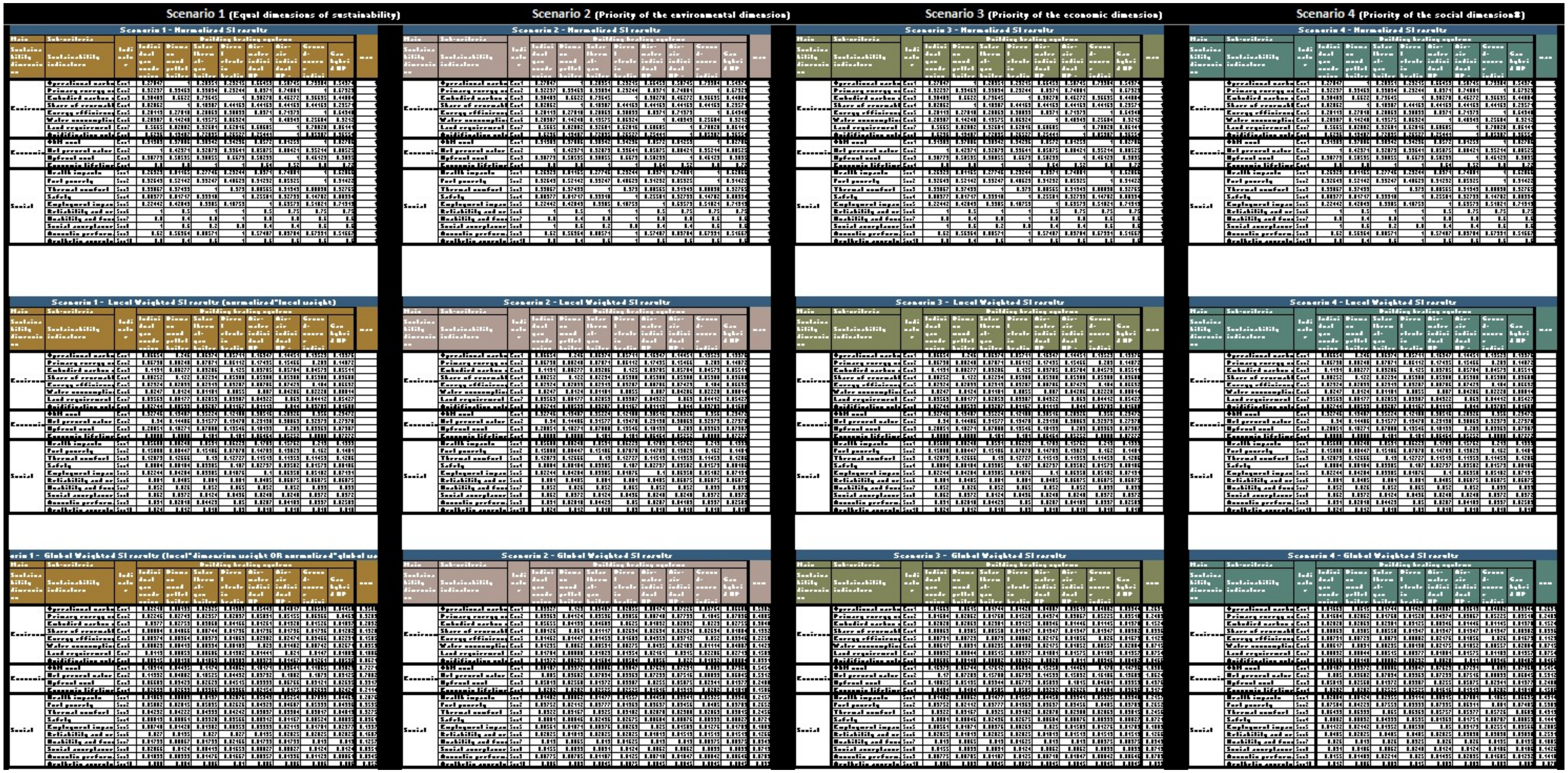


Figure D-1 A view of the developed framework: data analysis tables and calculations related to different scenarios[1]

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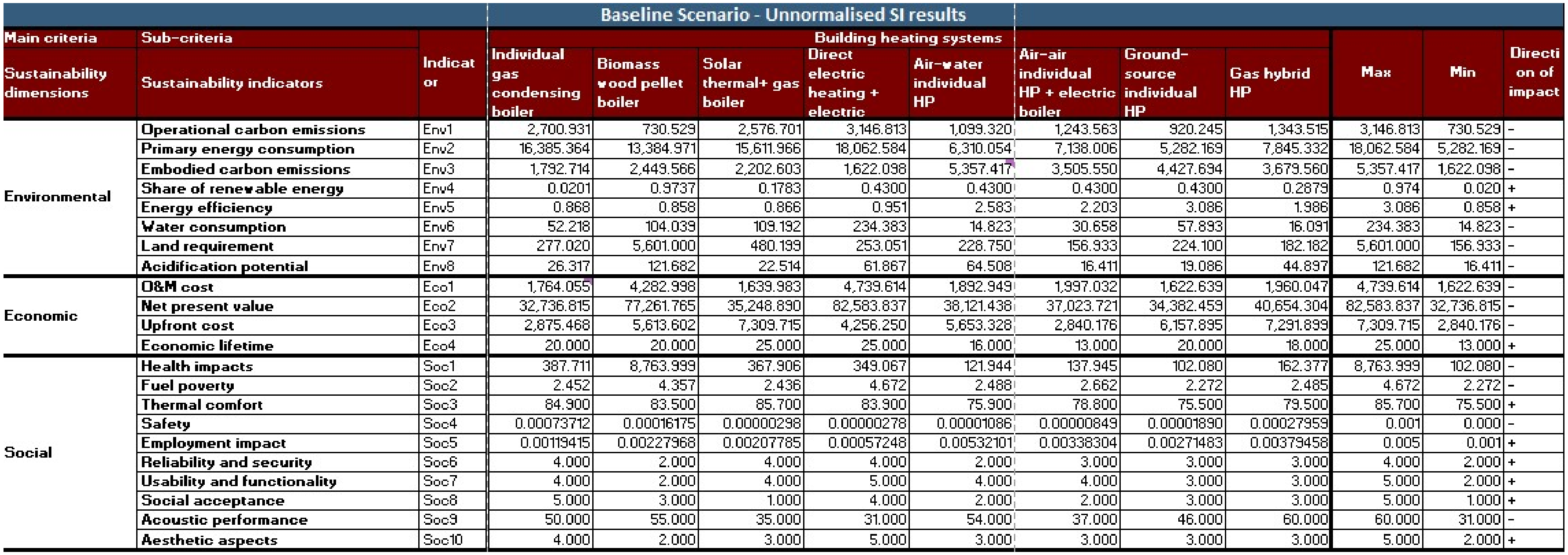
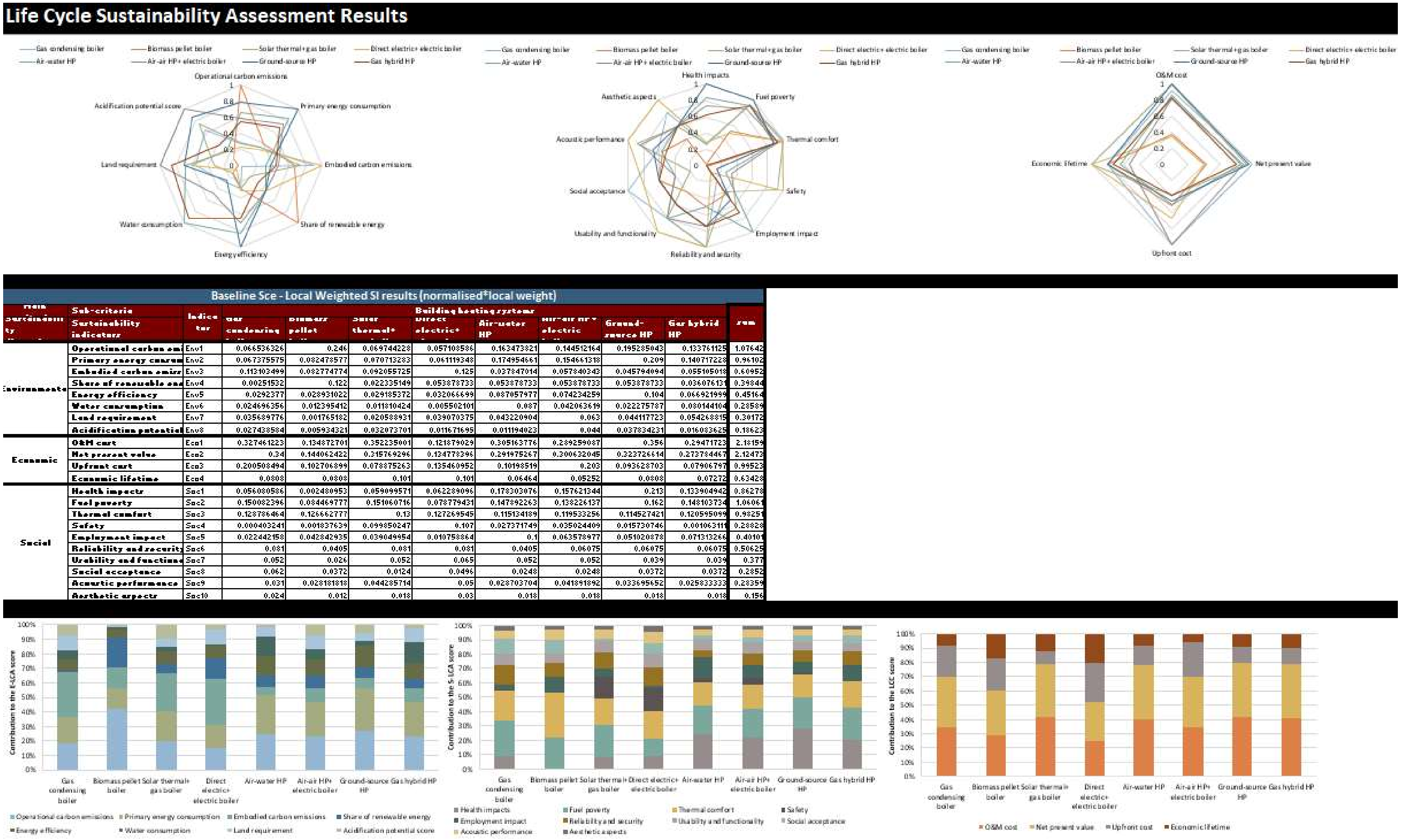
[1] The figure only demonstrates a snapshot of the developed framework. The calculation outputs and results are discussed in Chapter 8.



Baseline Scenario - Unnormalised SI results

Main criteria	Sub-criteria	Indicator	Building heating systems								Max	Min	Direction of impact
Sustainability dimensions	Sustainability indicators		Individual gas condensing boiler	Biomass wood pellet boiler	Solar thermal+ gas boiler	Direct electric heating + electric	Air-water individual HP	Air-air individual HP + electric boiler	Ground-source individual HP	Gas hybrid HP			
Environmental	Operational carbon emissions	Env1	2,700.931	730.529	2,576.701	3,146.813	1,099.320	1,243.563	920.245	1,343.515	3,146.813	730.529	-
	Primary energy consumption	Env2	16,385.364	13,384.971	15,611.966	18,062.584	6,310.054	7,138.006	5,282.169	7,845.332	18,062.584	5,282.169	-
	Embodied carbon emissions	Env3	1,792.714	2,449.566	2,202.603	1,622.098	5,357.417	3,505.550	4,427.694	3,679.560	5,357.417	1,622.098	-
	Share of renewable energy	Env4	0.0201	0.9737	0.1783	0.4300	0.4300	0.4300	0.4300	0.2879	0.974	0.020	+
	Energy efficiency	Env5	0.868	0.858	0.866	0.951	2.583	2.203	3.086	1.986	3.086	0.858	+
	Water consumption	Env6	52.218	104.039	109.192	234.383	14.823	30.658	57.893	16.091	234.383	14.823	-
	Land requirement	Env7	277.020	5,601.000	480.199	253.051	228.750	156.933	224.100	182.182	5,601.000	156.933	-
	Acidification potential	Env8	26.317	121.682	22.514	61.867	64.508	16.411	19.086	44.897	121.682	16.411	-
Economic	O&M cost	Eco1	1,764.055	4,282.998	1,639.983	4,739.614	1,892.949	1,997.032	1,622.639	1,960.047	4,739.614	1,622.639	-
	Net present value	Eco2	32,736.815	77,261.765	35,248.890	82,583.837	38,121.438	37,023.721	34,382.459	40,654.304	82,583.837	32,736.815	-
	Upfront cost	Eco3	2,875.468	5,613.602	7,309.715	4,256.250	5,653.328	2,840.176	6,157.895	7,291.899	7,309.715	2,840.176	-
	Economic lifetime	Eco4	20.000	20.000	25.000	25.000	16.000	13.000	20.000	18.000	25.000	13.000	+
Social	Health impacts	Soc1	387.711	8,763.999	367.906	349.067	121.944	137.945	102.080	162.377	8,763.999	102.080	-
	Fuel poverty	Soc2	2.452	4.357	2.436	4.672	2.488	2.662	2.272	2.485	4.672	2.272	-
	Thermal comfort	Soc3	84.900	83.500	85.700	83.900	75.900	78.800	75.500	79.500	85.700	75.500	+
	Safety	Soc4	0.00073712	0.00016175	0.00000298	0.00000278	0.00001086	0.00000849	0.00001890	0.00027959	0.001	0.000	-
	Employment impact	Soc5	0.00119415	0.00227968	0.00207785	0.00057248	0.00532101	0.00338304	0.00271483	0.00379458	0.005	0.001	+
	Reliability and security	Soc6	4.000	2.000	4.000	4.000	2.000	3.000	3.000	3.000	4.000	2.000	+
	Usability and functionality	Soc7	4.000	2.000	4.000	5.000	4.000	4.000	3.000	3.000	5.000	2.000	+
	Social acceptance	Soc8	5.000	3.000	1.000	4.000	2.000	2.000	3.000	3.000	5.000	1.000	+
	Acoustic performance	Soc9	50.000	55.000	35.000	31.000	54.000	37.000	46.000	60.000	60.000	31.000	-
	Aesthetic aspects	Soc10	4.000	2.000	3.000	5.000	3.000	3.000	3.000	3.000	5.000	2.000	+

Figure D-2 A view of the developed framework: SI calculations related to the baseline scenario

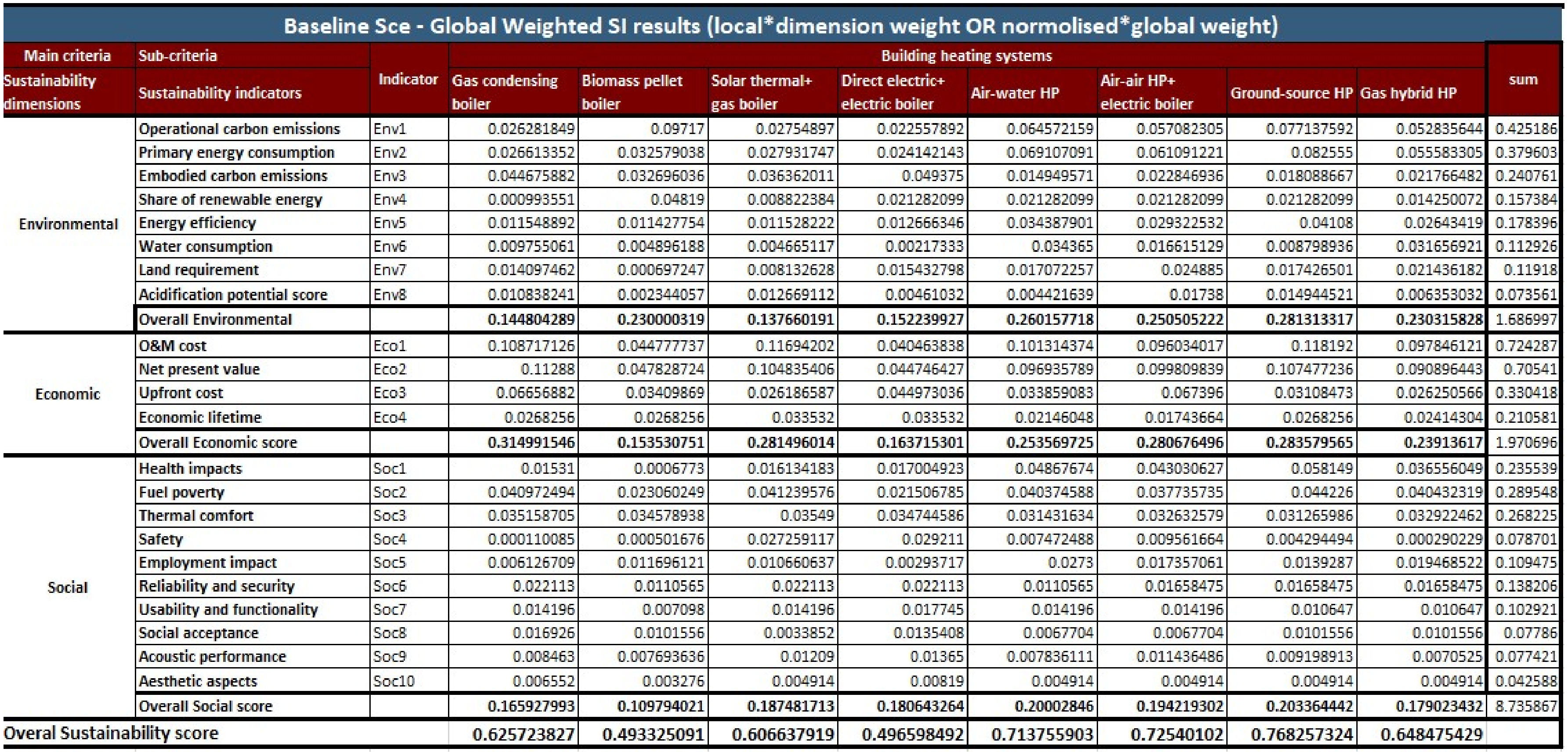


Life Cycle Sustainability Assessment Results

Baseline Sce - Local Weighted SI results (normalised*local weight)

Main sustainability	Sub-criteria Sustainability indicators	Indicator	Building heating systems								sum
			Gas condensing	Biomass pellet	Solar thermal+	Direct electric+	Air-water HP	Air-air HP+ electric	Ground-source HP	Gas hybrid HP	
Environmental	Operational carbon emi	Env1	0.066536326	0.246	0.069744228	0.057108586	0.163473821	0.144512164	0.195285043	0.133761125	1.07642
	Primary energy consum	Env2	0.067375575	0.082478577	0.070713283	0.061119348	0.174954661	0.154661318	0.209	0.140717228	0.96102
	Embodied carbon emiss	Env3	0.113103499	0.082774774	0.092055725	0.125	0.037847014	0.057840343	0.045794094	0.055105018	0.60952
	Share of renewable ene	Env4	0.00251532	0.122	0.022335149	0.053878733	0.053878733	0.053878733	0.053878733	0.036076131	0.39844
	Energy efficiency	Env5	0.0292377	0.028931022	0.029185372	0.032066699	0.087057977	0.074234259	0.104	0.066921999	0.45164
	Water consumption	Env6	0.024696356	0.012395412	0.011810424	0.005502101	0.087	0.042063619	0.022275787	0.080144104	0.28589
	Land requirement	Env7	0.035689776	0.001765182	0.020588931	0.039070375	0.043220904	0.063	0.044117723	0.054268815	0.30172
	Acidification potential	Env8	0.027438584	0.005934321	0.032073701	0.011671695	0.011194023	0.044	0.037834231	0.016083625	0.18623
Economic	O&M cost	Eco1	0.327461223	0.134872701	0.352235001	0.121879029	0.305163776	0.289259087	0.356	0.29471723	2.18159
	Net present value	Eco2	0.34	0.144062422	0.315769296	0.134778396	0.291975267	0.300632045	0.323726614	0.273784467	2.12473
	Upfront cost	Eco3	0.200508494	0.102706899	0.078875263	0.135460952	0.10198519	0.203	0.093628703	0.07906797	0.99523
	Economic lifetime	Eco4	0.0808	0.0808	0.101	0.101	0.06464	0.05252	0.0808	0.07272	0.63428
Social	Health impacts	Soc1	0.056080586	0.002480953	0.059099571	0.062289096	0.178303076	0.157621344	0.213	0.133904942	0.86278
	Fuel poverty	Soc2	0.150082396	0.084469777	0.151060716	0.078779431	0.147892263	0.138226137	0.162	0.148103734	1.06061
	Thermal comfort	Soc3	0.128786464	0.126662777	0.13	0.127269545	0.115134189	0.119533256	0.114527421	0.120595099	0.98251
	Safety	Soc4	0.000403241	0.001837639	0.099850247	0.107	0.027371749	0.035024409	0.015730746	0.001063111	0.28828
	Employment impact	Soc5	0.022442158	0.042842935	0.039049954	0.010758864	0.1	0.063578977	0.051020878	0.071313266	0.40101
	Reliability and security	Soc6	0.081	0.0405	0.081	0.081	0.0405	0.06075	0.06075	0.06075	0.50625
	Usability and functiona	Soc7	0.052	0.026	0.052	0.065	0.052	0.052	0.039	0.039	0.377
	Social acceptance	Soc8	0.062	0.0372	0.0124	0.0496	0.0248	0.0248	0.0372	0.0372	0.2852
	Acoustic performance	Soc9	0.031	0.028181818	0.044285714	0.05	0.028703704	0.041891892	0.033695652	0.025833333	0.28359
	Aesthetic aspects	Soc10	0.024	0.012	0.018	0.03	0.018	0.018	0.018	0.018	0.156

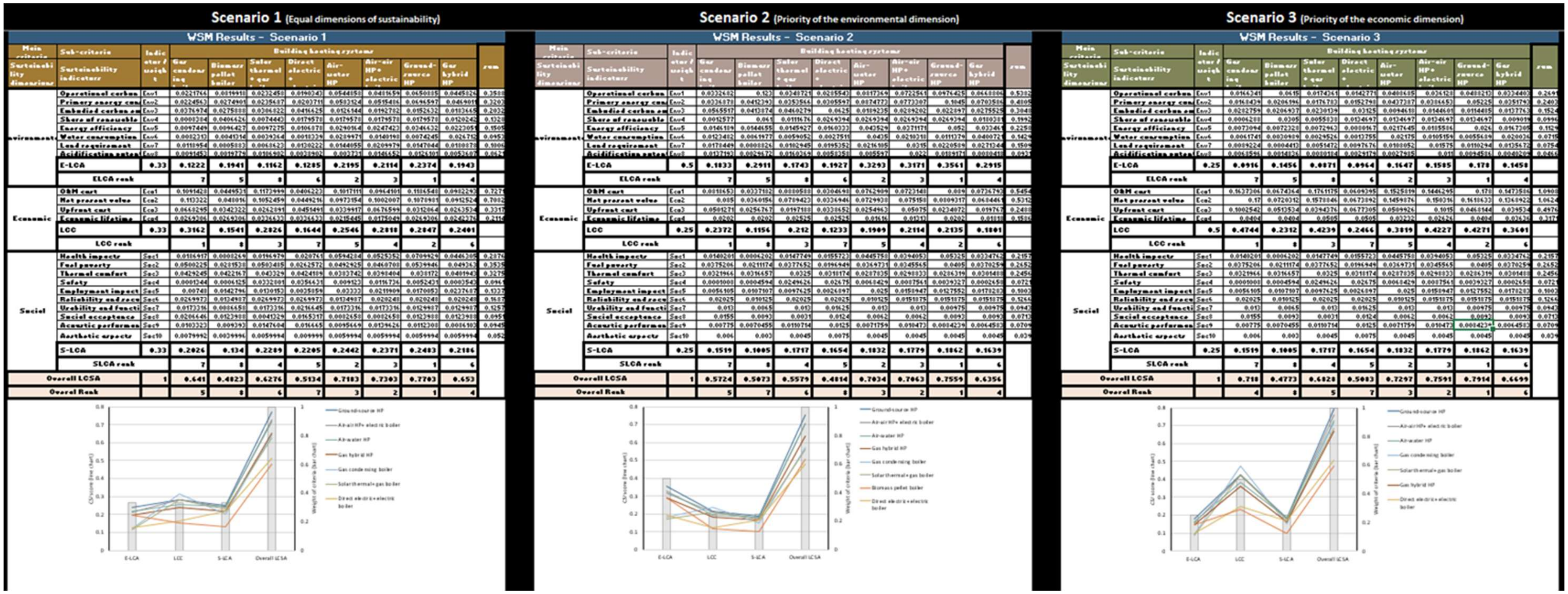
Figure D-3 A view of the developed framework: Sustainability assessment calculations and generated graphs



Baseline Sce - Global Weighted SI results (local*dimension weight OR normolised*global weight)

Main criteria	Sub-criteria	Indicator	Building heating systems								sum
Sustainability dimensions	Sustainability indicators		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	Env1	0.026281849	0.09717	0.02754897	0.022557892	0.064572159	0.057082305	0.077137592	0.052835644	0.425186
	Primary energy consumption	Env2	0.026613352	0.032579038	0.027931747	0.024142143	0.069107091	0.061091221	0.082555	0.055583305	0.379603
	Embodied carbon emissions	Env3	0.044675882	0.032696036	0.036362011	0.049375	0.014949571	0.022846936	0.018088667	0.021766482	0.240761
	Share of renewable energy	Env4	0.000993551	0.04819	0.008822384	0.021282099	0.021282099	0.021282099	0.021282099	0.014250072	0.157384
	Energy efficiency	Env5	0.011548892	0.011427754	0.011528222	0.012666346	0.034387901	0.029322532	0.04108	0.02643419	0.178396
	Water consumption	Env6	0.009755061	0.004896188	0.004665117	0.00217333	0.034365	0.016615129	0.008798936	0.031656921	0.112926
	Land requirement	Env7	0.014097462	0.000697247	0.008132628	0.015432798	0.017072257	0.024885	0.017426501	0.021436182	0.11918
	Acidification potential score	Env8	0.010838241	0.002344057	0.012669112	0.00461032	0.004421639	0.01738	0.014944521	0.006353032	0.073561
	Overall Environmental		**0.144804289**	**0.230000319**	**0.137660191**	**0.152239927**	**0.260157718**	**0.250505222**	**0.281313317**	**0.230315828**	1.686997
Economic	O&M cost	Eco1	0.108717126	0.044777737	0.11694202	0.040463838	0.101314374	0.096034017	0.118192	0.097846121	0.724287
	Net present value	Eco2	0.11288	0.047828724	0.104835406	0.044746427	0.096935789	0.099809839	0.107477236	0.090896443	0.70541
	Upfront cost	Eco3	0.06656882	0.03409869	0.026186587	0.044973036	0.033859083	0.067396	0.03108473	0.026250566	0.330418
	Economic lifetime	Eco4	0.0268256	0.0268256	0.033532	0.033532	0.02146048	0.01743664	0.0268256	0.02414304	0.210581
	Overall Economic score		**0.314991546**	**0.153530751**	**0.281496014**	**0.163715301**	**0.253569725**	**0.280676496**	**0.283579565**	**0.23913617**	1.970696
Social	Health impacts	Soc1	0.01531	0.0006773	0.016134183	0.017004923	0.04867674	0.043030627	0.058149	0.036556049	0.235539
	Fuel poverty	Soc2	0.040972494	0.023060249	0.041239576	0.021506785	0.040374588	0.037735735	0.044226	0.040432319	0.289548
	Thermal comfort	Soc3	0.035158705	0.034578938	0.03549	0.034744586	0.031431634	0.032632579	0.031265986	0.032922462	0.268225
	Safety	Soc4	0.000110085	0.000501676	0.027259117	0.029211	0.007472488	0.009561664	0.004294494	0.000290229	0.078701
	Employment impact	Soc5	0.006126709	0.011696121	0.010660637	0.00293717	0.0273	0.017357061	0.0139287	0.019468522	0.109475
	Reliability and security	Soc6	0.022113	0.0110565	0.022113	0.022113	0.0110565	0.01658475	0.01658475	0.01658475	0.138206
	Usability and functionality	Soc7	0.014196	0.007098	0.014196	0.017745	0.014196	0.014196	0.010647	0.010647	0.102921
	Social acceptance	Soc8	0.016926	0.0101556	0.0033852	0.0135408	0.0067704	0.0067704	0.0101556	0.0101556	0.07786
	Acoustic performance	Soc9	0.008463	0.007693636	0.01209	0.01365	0.007836111	0.011436486	0.009198913	0.0070525	0.077421
	Aesthetic aspects	Soc10	0.006552	0.003276	0.004914	0.00819	0.004914	0.004914	0.004914	0.004914	0.042588
	Overall Social score		**0.165927993**	**0.109794021**	**0.187481713**	**0.180643264**	**0.20002846**	**0.194219302**	**0.203364442**	**0.179023432**	8.735867
Overal Sustainability score			**0.625723827**	**0.493325091**	**0.606637919**	**0.496598492**	**0.713755903**	**0.72540102**	**0.768257324**	**0.648475429**	

Figure D-4 A view of the developed framework: Sustainability assessment calculations for the baseline scenario



Scenario 1 (Equal dimensions of sustainability)

WSM Results - Scenario 1

Sustainability dimensions	Sustainability indicators	Indicator / weight	Gas condensing	Biomass pellet boiler	Solar thermal + gas	Direct electric +	Air-water HP	Air-air HP+ electric	Ground-source HP	Gas hybrid HP
Environmental	E-LCA	0.33	0.1222	0.1941	0.1162	0.1285	0.2195	0.2114	0.2374	0.1943
	ELCA rank		7	5	8	6	2	3	1	4
Economic	LCC	0.33	0.3162	0.1541	0.2826	0.1644	0.2546	0.2818	0.2847	0.2401
	LCC rank		1	8	3	7	5	4	2	6
Social	S-LCA	0.33	0.2026	0.134	0.2289	0.2205	0.2442	0.2371	0.2483	0.2186
	SLCA rank		7	8	4	5	2	3	1	6
Overall LCSA		1	0.641	0.4823	0.6276	0.5134	0.7183	0.7303	0.7703	0.653
Overal Rank			5	8	6	7	3	2	1	4

Scenario 2 (Priority of the environmental dimension)

WSM Results - Scenario 2

Sustainability dimensions	Sustainability indicators	Indicator / weight	Gas condensing	Biomass pellet boiler	Solar thermal + gas	Direct electric +	Air-water HP	Air-air HP+ electric	Ground-source HP	Gas hybrid HP
Environmental	E-LCA	0.5	0.1833	0.2911	0.1743	0.1927	0.3293	0.3171	0.3561	0.2915
	ELCA rank		7	5	8	6	2	3	1	4
Economic	LCC	0.25	0.2372	0.1156	0.212	0.1233	0.1909	0.2114	0.2135	0.1801
	LCC rank		1	8	3	7	5	4	2	6
Social	S-LCA	0.25	0.1519	0.1005	0.1717	0.1654	0.1832	0.1779	0.1862	0.1639
	SLCA rank		7	8	4	5	2	3	1	6
Overall LCSA		1	0.5724	0.5073	0.5579	0.4814	0.7034	0.7063	0.7559	0.6356
Overal Rank			5	7	6	8	3	2	1	4

Scenario 3 (Priority of the economic dimension)

WSM Results - Scenario 3

Sustainability dimensions	Sustainability indicators	Indicator / weight	Gas condensing	Biomass pellet boiler	Solar thermal + gas	Direct electric +	Air-water HP	Air-air HP+ electric	Ground-source HP	Gas hybrid HP
Environmental	E-LCA	0.25	0.0916	0.1456	0.0871	0.0964	0.1647	0.1585	0.178	0.1458
	ELCA rank		7	5	8	6	2	3	1	4
Economic	LCC	0.5	0.4744	0.2312	0.4239	0.2466	0.3819	0.4227	0.4271	0.3601
	LCC rank		1	8	3	7	5	4	2	6
Social	S-LCA	0.25	0.1519	0.1005	0.1717	0.1654	0.1832	0.1779	0.1862	0.1639
	SLCA rank		7	8	4	5	2	3	1	6
Overall LCSA		1	0.718	0.4773	0.6828	0.5083	0.7297	0.7591	0.7914	0.6699
Overal Rank			4	8	5	7	3	2	1	6

Figure D-5 A view of the developed framework: multi-criteria decision analysis and generated graphs[1]

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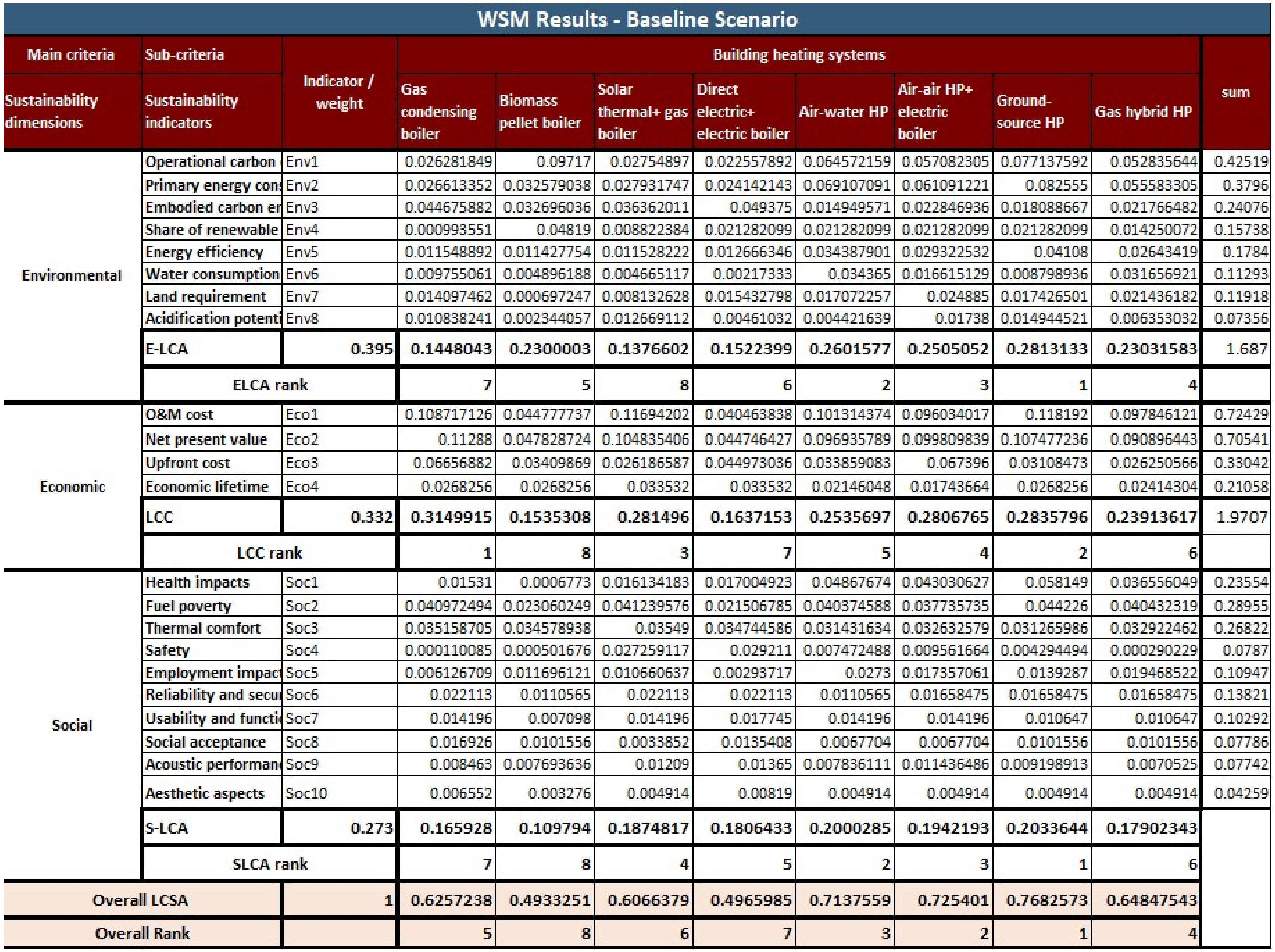
[1] The figure only demonstrates a snapshot of the developed framework. The calculation outputs and diagrams are discussed in Chapter 8.

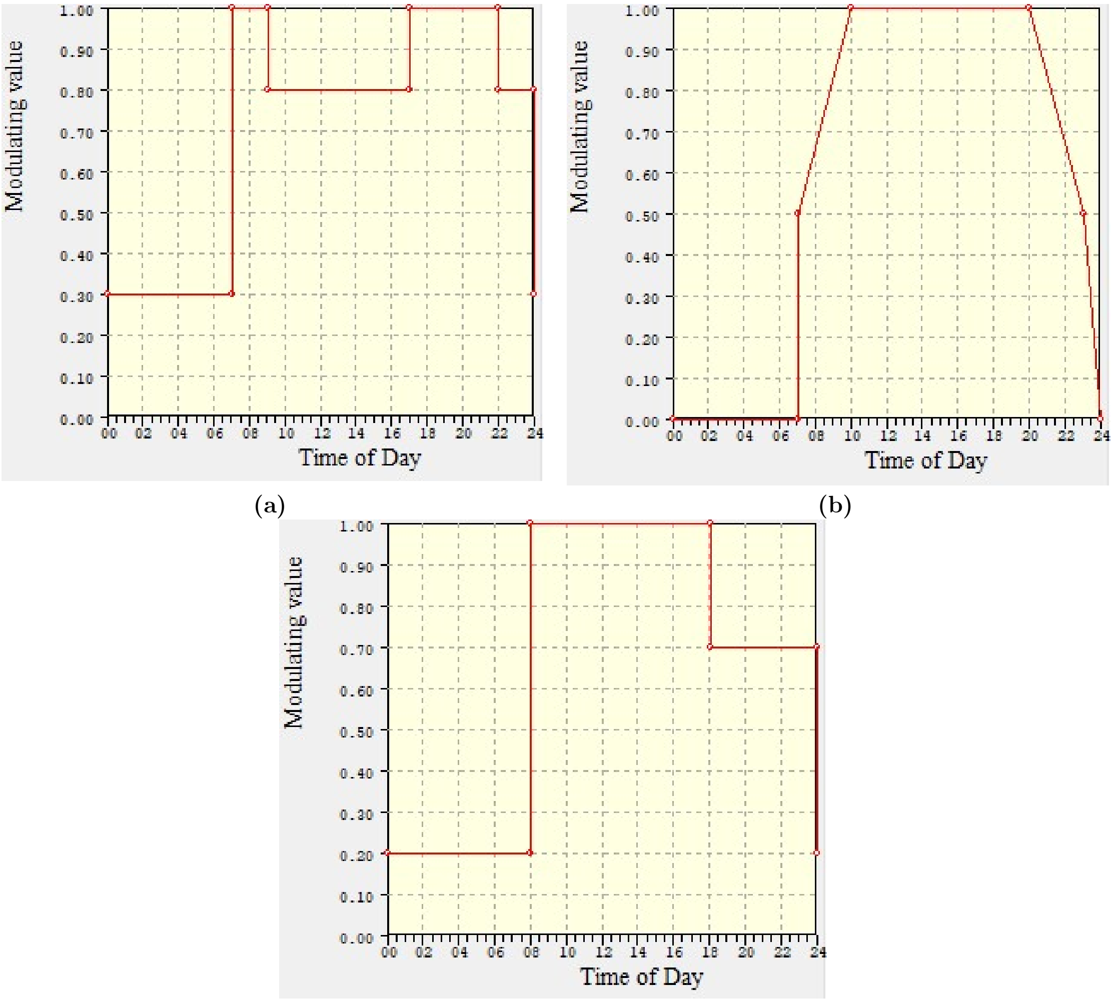


WSM Results - Baseline Scenario

Main criteria	Sub-criteria	Indicator / weight	Building heating systems								sum
Sustainability dimensions	Sustainability indicators		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	Env1	0.026281849	0.09717	0.02754897	0.022557892	0.064572159	0.057082305	0.077137592	0.052835644	0.42519
	Primary energy con	Env2	0.026613352	0.032579038	0.027931747	0.024142143	0.069107091	0.061091221	0.082555	0.055583305	0.3796
	Embodied carbon er	Env3	0.044675882	0.032696036	0.036362011	0.049375	0.014949571	0.022846936	0.018088667	0.021766482	0.24076
	Share of renewable	Env4	0.000993551	0.04819	0.008822384	0.021282099	0.021282099	0.021282099	0.021282099	0.014250072	0.15738
	Energy efficiency	Env5	0.011548892	0.011427754	0.011528222	0.012666346	0.034387901	0.029322532	0.04108	0.02643419	0.1784
	Water consumption	Env6	0.009755061	0.004896188	0.004665117	0.00217333	0.034365	0.016615129	0.008798936	0.031656921	0.11293
	Land requirement	Env7	0.014097462	0.000697247	0.008132628	0.015432798	0.017072257	0.024885	0.017426501	0.021436182	0.11918
	Acidification potenti	Env8	0.010838241	0.002344057	0.012669112	0.00461032	0.004421639	0.01738	0.014944521	0.006353032	0.07356
	E-LCA	**0.395**	**0.1448043**	**0.2300003**	**0.1376602**	**0.1522399**	**0.2601577**	**0.2505052**	**0.2813133**	**0.23031583**	1.687
	ELCA rank		**7**	**5**	**8**	**6**	**2**	**3**	**1**	**4**	
Economic	O&M cost	Eco1	0.108717126	0.044777737	0.11694202	0.040463838	0.101314374	0.096034017	0.118192	0.097846121	0.72429
	Net present value	Eco2	0.11288	0.047828724	0.104835406	0.044746427	0.096935789	0.099809839	0.107477236	0.090896443	0.70541
	Upfront cost	Eco3	0.06656882	0.03409869	0.026186587	0.044973036	0.033859083	0.067396	0.03108473	0.026250566	0.33042
	Economic lifetime	Eco4	0.0268256	0.0268256	0.033532	0.033532	0.02146048	0.01743664	0.0268256	0.02414304	0.21058
	LCC	**0.332**	**0.3149915**	**0.1535308**	**0.281496**	**0.1637153**	**0.2535697**	**0.2806765**	**0.2835796**	**0.23913617**	1.9707
	LCC rank		**1**	**8**	**3**	**7**	**5**	**4**	**2**	**6**	
Social	Health impacts	Soc1	0.01531	0.0006773	0.016134183	0.017004923	0.04867674	0.043030627	0.058149	0.036556049	0.23554
	Fuel poverty	Soc2	0.040972494	0.023060249	0.041239576	0.021506785	0.040374588	0.037735735	0.044226	0.040432319	0.28955
	Thermal comfort	Soc3	0.035158705	0.034578938	0.03549	0.034744586	0.031431634	0.032632579	0.031265986	0.032922462	0.26822
	Safety	Soc4	0.000110085	0.000501676	0.027259117	0.029211	0.007472488	0.009561664	0.004294494	0.000290229	0.0787
	Employment impact	Soc5	0.006126709	0.011696121	0.010660637	0.00293717	0.0273	0.017357061	0.0139287	0.019468522	0.10947
	Reliability and secu	Soc6	0.022113	0.0110565	0.022113	0.022113	0.0110565	0.01658475	0.01658475	0.01658475	0.13821
	Usability and functi	Soc7	0.014196	0.007098	0.014196	0.017745	0.014196	0.014196	0.010647	0.010647	0.10292
	Social acceptance	Soc8	0.016926	0.0101556	0.0033852	0.0135408	0.0067704	0.0067704	0.0101556	0.0101556	0.07786
	Acoustic performan	Soc9	0.008463	0.007693636	0.01209	0.01365	0.007836111	0.011436486	0.009198913	0.0070525	0.07742
	Aesthetic aspects	Soc10	0.006552	0.003276	0.004914	0.00819	0.004914	0.004914	0.004914	0.004914	0.04259
	S-LCA	**0.273**	**0.165928**	**0.109794**	**0.1874817**	**0.1806433**	**0.2000285**	**0.1942193**	**0.2033644**	**0.17902343**	
	SLCA rank		**7**	**8**	**4**	**5**	**2**	**3**	**1**	**6**	
Overall LCSA		**1**	**0.6257238**	**0.4933251**	**0.6066379**	**0.4965985**	**0.7137559**	**0.725401**	**0.7682573**	**0.64847543**	
Overall Rank			**5**	**8**	**6**	**7**	**3**	**2**	**1**	**4**	

Figure D-6 A view of the developed framework: WSM calculations for the baseline scenario

Appendix E



(a) (b)

(c)

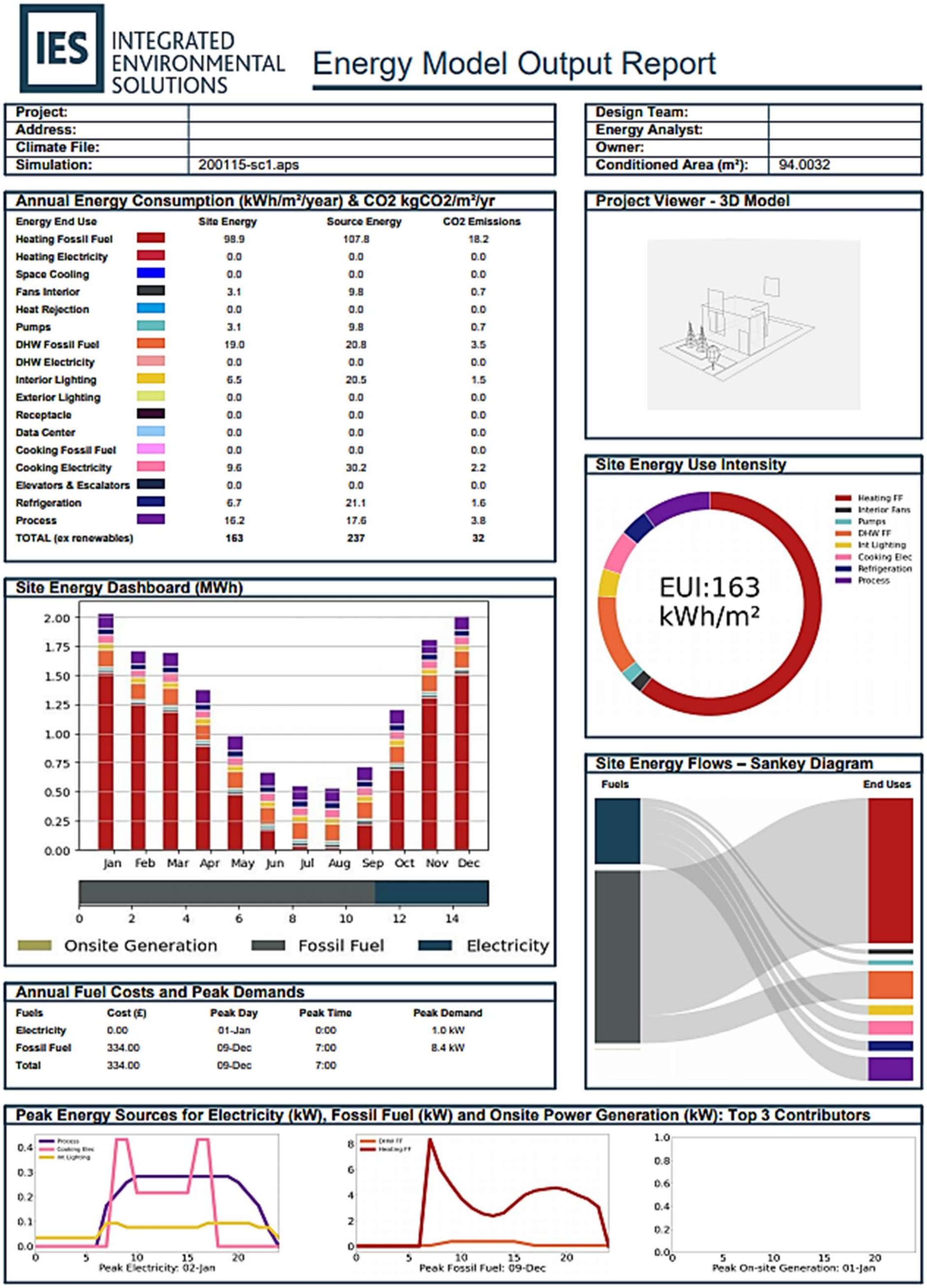
Figure E-1 Daily load profiles of the (a) Space heating; (b) Hot water consumption; (c) Electrical appliances

Table E-1 Energy breakdown of the households' total annual energy consumption by the source of energy

End use	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
Electricity (MWh)	4.24	4.24	4.43	14.76	7.86	8.41	7.18	7.32
Fuel (MWh)	11.92	12.06	11.11	0	0	0	0	1.81
Total energy (MWh)	16.17	16.31	15.74	14.76	7.86	8.41	7.18	9.13

Table E-2 Energy breakdown of the households' total annual energy consumption by the end use section

End use	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
Interior lighting (MWh)	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
Cooking (MWh)	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Refrigeration (MWh)	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Other process (MWh)	1.5	1.52	1.52	0.6	1.52	1.52	1.52	1.52
Space heating (MWh)	10.13	10.25	9.63	9.82	3.13	2.95	2.52	3.12
Water heating (MWh)	1.81	1.81	1.81	1.63	0.54	1.81	0.44	1.81
Interior fans (MWh)	0.30	0.30	0.30	0.30	0.30	0.1	0.30	0.30
Service pumps (MWh)	0.31	0.31	0.46	0.31	0.31	0.1	0.31	0.31
Total energy (MWh)	16.17	16.31	15.74	14.76	7.86	8.41	7.18	9.13



IES INTEGRATED ENVIRONMENTAL SOLUTIONS

Energy Model Output Report

Project:	
Address:	
Climate File:	
Simulation:	200115-sc1.aps

Design Team:	
Energy Analyst:	
Owner:	
Conditioned Area (m²):	94.0032

Annual Energy Consumption (kWh/m²/year) & CO2 kgCO2/m²/yr

Energy End Use		Site Energy	Source Energy	CO2 Emissions
Heating Fossil Fuel	🟥	98.9	107.8	18.2
Heating Electricity	🟥	0.0	0.0	0.0
Space Cooling	🟦	0.0	0.0	0.0
Fans Interior	⬛	3.1	9.8	0.7
Heat Rejection	🟦	0.0	0.0	0.0
Pumps	🟦	3.1	9.8	0.7
DHW Fossil Fuel	🟧	19.0	20.8	3.5
DHW Electricity	🟥	0.0	0.0	0.0
Interior Lighting	🟨	6.5	20.5	1.5
Exterior Lighting	🟨	0.0	0.0	0.0
Receptacle	⬛	0.0	0.0	0.0
Data Center	🟦	0.0	0.0	0.0
Cooking Fossil Fuel	🟪	0.0	0.0	0.0
Cooking Electricity	🟥	9.6	30.2	2.2
Elevators & Escalators	⬛	0.0	0.0	0.0
Refrigeration	🟦	6.7	21.1	1.6
Process	🟪	16.2	17.6	3.8
TOTAL (ex renewables)		163	237	32

Project Viewer - 3D Model

Site Energy Use Intensity

Site Energy Dashboard (MWh)

Site Energy Flows – Sankey Diagram

Annual Fuel Costs and Peak Demands

Fuels	Cost (£)	Peak Day	Peak Time	Peak Demand
Electricity	0.00	01-Jan	0:00	1.0 kW
Fossil Fuel	334.00	09-Dec	7:00	8.4 kW
Total	334.00	09-Dec	7:00	

Peak Energy Sources for Electricity (kW), Fossil Fuel (kW) and Onsite Power Generation (kW): Top 3 Contributors

Figure E-2 Detailed IES-VE output report for the case study building with the reference heating system

Figure E-3 Total annual energy consumption of the households with different heating systems, broken down by the end use section

Appendix F

Table F-1 Normalised values of indicators for the reference system, calculated using the distance-based normalisation

Sustainability dimensions	Sustainability indicators	Indicator	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	Env1	0.270	1.000	0.284	0.232	0.665	0.587	0.794	0.544
	Primary energy consumption	Env2	0.322	0.395	0.338	0.292	0.837	0.740	1.000	0.673
	Embodied carbon emissions	Env3	0.905	0.662	0.736	1.000	0.303	0.463	0.366	0.441
	Share of renewable energy	Env4	0.021	1.000	0.183	0.442	0.442	0.442	0.442	0.296
	Energy efficiency	Env5	0.281	0.278	0.281	0.308	0.837	0.714	1.000	0.643
	Water consumption	Env6	0.284	0.142	0.136	0.063	1.000	0.483	0.256	0.921
	Land requirement	Env7	0.567	0.028	0.327	0.620	0.686	1.000	0.700	0.861
	Acidification potential score	Env8	0.624	0.135	0.729	0.265	0.254	1.000	0.860	0.366
Economic	O&M cost	Eco1	0.920	0.379	0.989	0.342	0.857	0.813	1.000	0.828
	Net present value	Eco2	1.000	0.424	0.929	0.396	0.859	0.884	0.952	0.805
	Upfront cost	Eco3	0.988	0.506	0.389	0.667	0.502	1.000	0.461	0.389
	Economic lifetime	Eco4	0.800	0.800	1.000	1.000	0.640	0.520	0.800	0.720
Social	Health impacts	Soc1	0.263	0.012	0.277	0.292	0.837	0.740	1.000	0.629
	Fuel poverty	Soc2	0.926	0.521	0.932	0.486	0.913	0.853	1.000	0.914
	Thermal comfort	Soc3	0.991	0.974	1.000	0.979	0.886	0.919	0.881	0.928
	Safety	Soc4	0.004	0.017	0.933	1.000	0.256	0.327	0.147	0.010
	Employment impact	Soc5	0.224	0.428	0.390	0.108	1.000	0.636	0.510	0.713

	Reliability and security	Soc6	1.000	0.500	1.000	1.000	0.500	0.750	0.750	0.750
	Usability and functionality	Soc7	0.800	0.400	0.800	1.000	0.800	0.800	0.600	0.600
	Social acceptance	Soc8	1.000	0.600	0.200	0.800	0.400	0.400	0.600	0.600
	Acoustic performance	Soc9	0.620	0.564	0.886	1.000	0.574	0.838	0.674	0.517
	Aesthetic aspects	Soc10	0.800	0.400	0.600	1.000	0.600	0.600	0.600	0.600

Table F-2 Weighted values of normalised indicators for the reference system, calculated using AHP weighting method

Sustainability dimensions	Sustainability indicators	Indicator	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	Env1	0.026	0.097	0.028	0.023	0.065	0.057	0.077	0.053
	Primary energy consumption	Env2	0.027	0.033	0.028	0.024	0.069	0.061	0.083	0.056
	Embodied carbon emissions	Env3	0.045	0.033	0.036	0.049	0.015	0.023	0.018	0.022
	Share of renewable energy	Env4	0.001	0.048	0.009	0.021	0.021	0.021	0.021	0.014
	Energy efficiency	Env5	0.012	0.011	0.012	0.013	0.034	0.029	0.041	0.026
	Water consumption	Env6	0.010	0.005	0.005	0.002	0.034	0.017	0.009	0.032
	Land requirement	Env7	0.014	0.001	0.008	0.015	0.017	0.025	0.017	0.021
	Acidification potential score	Env8	0.011	0.002	0.013	0.005	0.004	0.017	0.015	0.006
	Overall Environmental score		**0.145**	**0.230**	**0.138**	**0.152**	**0.260**	**0.251**	**0.281**	**0.230**
Economic	O&M cost	Eco1	0.109	0.045	0.117	0.040	0.101	0.096	0.118	0.098
	Net present value	Eco2	0.113	0.048	0.105	0.045	0.097	0.100	0.107	0.091
	Upfront cost	Eco3	0.067	0.034	0.026	0.045	0.034	0.067	0.031	0.026

	Economic lifetime	Eco4	0.027	0.027	0.034	0.034	0.021	0.017	0.027	0.024
	Overall Economic score		**0.315**	**0.154**	**0.281**	**0.164**	**0.254**	**0.281**	**0.284**	**0.239**
Social	Health impacts	Soc1	0.015	0.001	0.016	0.017	0.049	0.043	0.058	0.037
	Fuel poverty	Soc2	0.041	0.023	0.041	0.022	0.040	0.038	0.044	0.040
	Thermal comfort	Soc3	0.035	0.035	0.035	0.035	0.031	0.033	0.031	0.033
	Safety	Soc4	0.000	0.001	0.027	0.029	0.007	0.010	0.004	0.000
	Employment impact	Soc5	0.006	0.012	0.011	0.003	0.027	0.017	0.014	0.019
	Reliability and security	Soc6	0.022	0.011	0.022	0.022	0.011	0.017	0.017	0.017
	Usability and functionality	Soc7	0.014	0.007	0.014	0.018	0.014	0.014	0.011	0.011
	Social acceptance	Soc8	0.017	0.010	0.003	0.014	0.007	0.007	0.010	0.010
	Acoustic performance	Soc9	0.008	0.008	0.012	0.014	0.008	0.011	0.009	0.007
	Aesthetic aspects	Soc10	0.007	0.003	0.005	0.008	0.005	0.005	0.005	0.005
	Overall Social score		**0.166**	**0.110**	**0.187**	**0.181**	**0.200**	**0.194**	**0.203**	**0.179**
Overall Sustainability score			**0.626**	**0.493**	**0.607**	**0.497**	**0.714**	**0.725**	**0.768**	**0.648**