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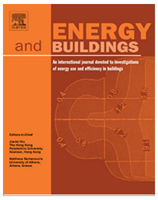

Integration of LCA and LCCA through BIM for optimized decision-making when switching from gas to electricity services in dwellings

Nao Shibata *, Francisco Sierra, Ahmed Hagras

Faculty of Environment and Technology, The University of the West of England (UWE), Bristol BS16 1QY, United Kingdom

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ABSTRACT

This study aims to assess electric heating system retrofit options and identify the optimal solution by applying a combined LCA and LCCA approach using BIM for existing UK homes. Exemplary case study illustrating an LCA and LCCA calculation using a BIM model of a house in Bristol (UK), to assess: (baseline) gas boiler; (i) electric boiler; (ii) air source heat pump; (iii) electric boiler + PV; and (iv) ASHP + PV. The optimal option overall is (iv) ASHP + PV, which reduces the $kgCO_2e$ emitted by 77% while increasing lifetime cost by 2.1%, compared to the classic gas boiler. This research also finds that embodied carbon still has a low impact on the decision, since the main impact of heating systems like ASHP (SCOP = 3.4) is to reduce $kgCO_2e$ by improving the efficiency of old gas boilers (COP = 0.76). Electric boilers are not the optimal alternative; they reduce $kgCO_2e$ by 47% but increase the lifetime cost of the system by 105% compared to gas boilers. The change in the "carbon factor" of electricity from 0.519 $kgCO_2$/kWh to 0.136 $kgCO_2$/kWh means that now dwellings using electrical systems emit 35% less $kgCO_2$ than those that use gas (0.210 $kgCO_2$/kWh).

1. Introduction

The construction industry accounts for 39% of energy-related CO_2 emissions [57]. This indicates that the industry has one of the highest environmental impacts. In order to reduce the negative environmental impact of the industry, a transition to sustainable and energy-efficient buildings is essential. In particular, as the housing sector accounts for more than half of the energy consumption in the whole building sector [29], there is a strong need to improve its energy efficiency.

Currently, 75% of the total energy demand in the UK housing stock comes from natural gas heating, with around 85% of UK homes being heated by natural gas boilers [9], constituting a significant proportion of household CO_2 emissions [25]. In the UK, the Heat and Buildings Strategy was published in November 2021, in which it was announced that the installation of new gas boilers would be phased out over the next few years [22]. The Boiler Upgrade Scheme has been in effect in the UK Government for residential and non-domestic buildings in England and Wales since May 2022, providing grants to replace gas boilers with ground-source heat pumps, air-source heat pumps and biomass boilers to encourage these installations [23].

The UK has the least energy-efficient housing stock in Europe [26], with more than half of existing homes built before 1964 [12]. According to the [19] the 29 million existing homes across the UK must be made "low-carbon, low-energy and resilient to a changing climate". In other words, most houses in the UK will need to undergo some form of retrofit if we are to reach the 2050 carbon target. Implementing energy efficiency retrofits for these older houses is considered one of the essential approaches to improve energy performance and reduce CO_2 emissions [27]. With sustainability becoming a priority, retrofitting has become an urgent issue [15]. Compared to reconstruction, the retrofitting of existing building stock can be a solution that saves resources and minimises environmental impact [28]. According to the International Energy Agency (IEA), progress in the energy-efficient retrofitting of existing buildings is currently low, with less than 1% of the existing building stock being retrofitted annually [36]. This low percentage of retrofits is due to the high initial costs [32,39], the lack of public awareness of the potential benefits [43], and the lack of incentives for homeowners.

The application of life cycle assessment (LCA) is widely accepted today as supporting the identification of optimal solutions in terms of sustainability and environmental impact [59]. LCA is a method for assessing the environmental impacts of energy, materials and environmental emissions, covering the entire life cycle of a building, from the design phase to demolition [43]. Regarding LCA, a

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* Corresponding author.
E-mail address: nshibata0117@gmail.com (N. Shibata).

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metric known as the carbon equivalent is usually used to quantify and report the overall global warming impact of the various greenhouse gases emitted through the lifecycle stages to facilitate comparison and reporting [4]. The carbon emissions considered in the LCA of a building can be divided into two main categories: embodied and operational carbon, each generated in the lifecycle of the building. Embodied carbon emissions are emissions from the materials associated with the building and the energy associated with the construction process [34], while operational carbon emissions are emissions from the energy consumed in operating the building. As embodied carbon emissions have been considered smaller than operational carbon, the construction industry has long focused on operational carbon-related energy consumption, with less attention paid to embodied carbon and the other stages of the lifecycle [34].

However, it has been pointed out that the relative impact of embodied carbon emissions over the entire lifecycle increases as operational carbon emissions are reduced through renewable energy technologies and improvements in building fabric to enhance its energy efficiency [21]. According to [56], the traditional ratio of 20% embodied energy to 80% operational energy has changed to 40% – 60% due to the global trend of constructing buildings with low energy demand during the operational phase. This study focuses on the retrofit of existing buildings. Therefore, we will find scenarios where embodied carbon represents less than 20% of the total, due to the low thermal efficiency of the fabrics of the existing housing stock.

A retrofit project entails an increase in the embodied energy of the building due to an increase in materials, technology and other equipment, while it reduces energy demand during the use phase [6]. Therefore, in retrofit projects, the embodied and operational carbon need to be considered together from a whole-lifecycle LCA perspective before deciding the retrofit strategy [53].

Furthermore, in housing retrofit projects, the assessment of lifecycle costs should be given equal importance to the lifecycle environmental impact, from the early stages of the retrofit project [33]. The reason for this is that the economic investment needed to carry out a retrofit and the potential energy cost savings play a key role in retrofit decisions [27]; consequently, financial incentives are crucial for homeowners deciding to retrofit their homes.

The literature reveals that lifecycle cost analysis (LCCA) has recently been applied in retrofit decision-making to improve the energy performance of buildings, considering cost as a variable to make decisions. [38] concluded through an LCC that, while buildings with better energy performance have lower energy costs during the operational phase, the initial construction costs are higher than those of conventional buildings [5]. There is also a significant correlation between energy performance optimisation and LCC, as choosing different materials and components for retrofit will significantly impact the LCC [51]. The application of the LCCA approach is, therefore, valuable for the early design phase in that it balances initial and future costs (e.g., operation, maintenance, repair and replacement costs) and helps to adopt options that reduce total costs [46]. However, this review reveals that the simultaneous application of LCA and LCCA is not common practice.

According to [50], improving the energy performance of existing buildings while minimising both CO_2 emissions and costs is critical in retrofit projects. For this purpose, it is beneficial to consider the environmental and economic impact of retrofitting together. [40] pointed out the trade-off relationship between capital costs and energy efficiency improvements in retrofit projects. The trade-off relationship in this context means that adopting higher energy standards to reduce the environmental impact can increase costs. Therefore, the trade-off relationships between LCC and LCA need to be considered together in the early design stage to identify the optimum point at which the total result of construction and energy costs is at the lowest level [40]. Conducting LCA and LCCA in parallel could facilitate optimising an economically and environmentally affordable retrofit plan among different retrofit options and energy efficiency levels [20].

This is also an efficient approach since LCA and LCCA share vital points: (i) they can be carried out at an early stage of a project to maximise its effectiveness; (ii) they can be carried out for a production system that includes all building elements and construction methods; and (iii) they form an analytical process that facilitates the selection of the best option by appraising the economic and environmental performance of alternative options [52]. However, in order to carry out both analyses efficiently, it is necessary to have access to structured information. Therefore, a Building Information Modelling (BIM) model with the necessary information would facilitate and speed up both processes. Correspondingly, BIM can support LCA by delivering accurate and comprehensive data about the building, including its materials, components, and systems. This information can be utilised to model the environmental impacts of the building throughout its lifecycle, from design and construction to operation and decommissioning [41]. While integrating BIM and LCA can support a more inclusive understanding of the sustainability impacts of a building or infrastructure, which can be employed for decision-making during its life cycle [44]. Furthermore, the integration can improve the identification of cost-effective strategies for selecting materials, technologies, and systems [45].

The construction industry is increasingly adopting BIM. In the last decade, research on the use of BIM for LCA has been increasing [42]. Concerning LCA-LCC integration, BIM could facilitate a blended approach regarding energy efficiency, cost and environmental impact [49]. The features of BIM offer great potential in managing and sharing complex LCA and LCC data [42]. For example, BIM enables the linking of objects to material information and their quantity information, as well as cost information, and can support the process of collecting and managing this information as a database and data analysis tool [7]. [48] developed a prototype tool that facilitates the simultaneous analysis of LCA and LCC in a BIM environment, demonstrating the effectiveness of BIM in facilitating the process. Several studies have investigated the integration of LCA and LCC through BIM for the optimization of decision making in the initial design phase. [55] proposed an analytical framework for glazing based on comprehensive BIM-based LCA and LCC, considering trade-off relationships between thermal efficiency, environmental impact and cost-effectiveness. [16] developed BIM-based 18 simulation scenarios with different combinations of exterior walls, roofs and floors to automate LCA and LCC analysis. Furthermore, several recent studies have examined BIM-based LCA-LCC integration in energy efficiency retrofitting of existing buildings [40,3,20,43]. [40] showed that BIM could be an information management platform for LCA and LCCA. They examined various retrofit options and their energy efficiency and found that BIM enables seamless updates of LCC and LCA calculations according to different retrofit options, which allows the most economical and least environmentally impactful option to be determined from the trade-off relationship between LCC and LCA. [3] developed three retrofit plans for a villa and an apartment depending on three budget levels – low cost, medium cost and high cost – and assessed the technical and economic aspects using a BIM-based approach. Energy consumption could be reduced by 13.79% to 56.9% per year for a villa and 22.84% to 58.5% for an apartment, with a payback period of 0.92 years to 25.15 years for a villa and 0.60 years to 24.60 years for an apartment. [20] proposed a comprehensive and integrated method for housing retrofits using BIM-enabled LCA, taking into account environmental compatibility, energy efficiency and profitability based on actual construction and energy consumption data. [43] showed that by incorporating detailed information related to materials and equipment, and climate data in the BIM model, an optimised mathematical model can be used to identify the optimal energy retrofit cost and measure in terms of energy savings and LCC reduction for different retrofit budget levels. Energy savings of between 24% and 58% could be achieved in the case studies in this study, depending on the homeowners' budget level (120 k to 300 k USD). These studies demonstrated that a BIM model could be used to quantitatively assess retrofit plans in terms of cost and environmental impact and to identify optimal retrofit plans. This is done using specific BIM software tools, such as One Click LCA.

Although several previous studies have investigated design optimisation through the simultaneous application of LCA and LCCA, the literature review revealed that no studies have focused on using LCA and LCCA for decision-making on heating systems during a UK housing retrofit. Such a study would be very timely and beneficial, because the Boiler Upgrade Scheme, introduced by the UK Government in May 2022, promotes a change of heating from gas to electric systems. Homeowners often do not have the time, information or expertise to evaluate the available options before deciding how to proceed. Therefore, retrofit measures for heating systems are often based only on the cost, without considering the embodied and operational carbon of the new systems.

This study aims to evaluate, for the first time, electric heating retrofit options in terms of environmental impact and lifecycle cost to identify the optimal option. For this purpose, a BIM model of an existing dwelling is developed to carry out efficiently a combined LCA and LCCA evaluation. Owners who face a heating system retrofit are provided with a clear comparison between the different options to lead to a reduction in CO_2 emissions at an optimal price.

2. Research methodology

The literature review revealed the lack of an LCA/LCCA study that helps to understand the impact of the available options in terms of residential electric heating systems, and which are the most optimal from that perspective. This gap must be filled so that, in the current transition between two different heating models, i.e., from gas to electricity, homeowners, landlords, councils, and energy assessors can make better informed and more sustainable decisions at a reasonable price.

This study has two stages. In the first stage, a literature review critically analyses the selected secondary sources published between 2012 and 2022. This review shows the magnitude of the need to undertake retrofit projects in the UK for residential buildings, the crucial moment for changing the heating system, and the lack of reference examples to take more cost-effective and sustainable decisions when changing the heating system.

In the second stage, an illustrative BIM case study is presented, which for the first time, shows a practical example of how to perform an LCA and LCCA using a BIM model to make decisions during the change of heating model for an existing dwelling in the UK (Fig. 1). The study also identifies the optimal option.

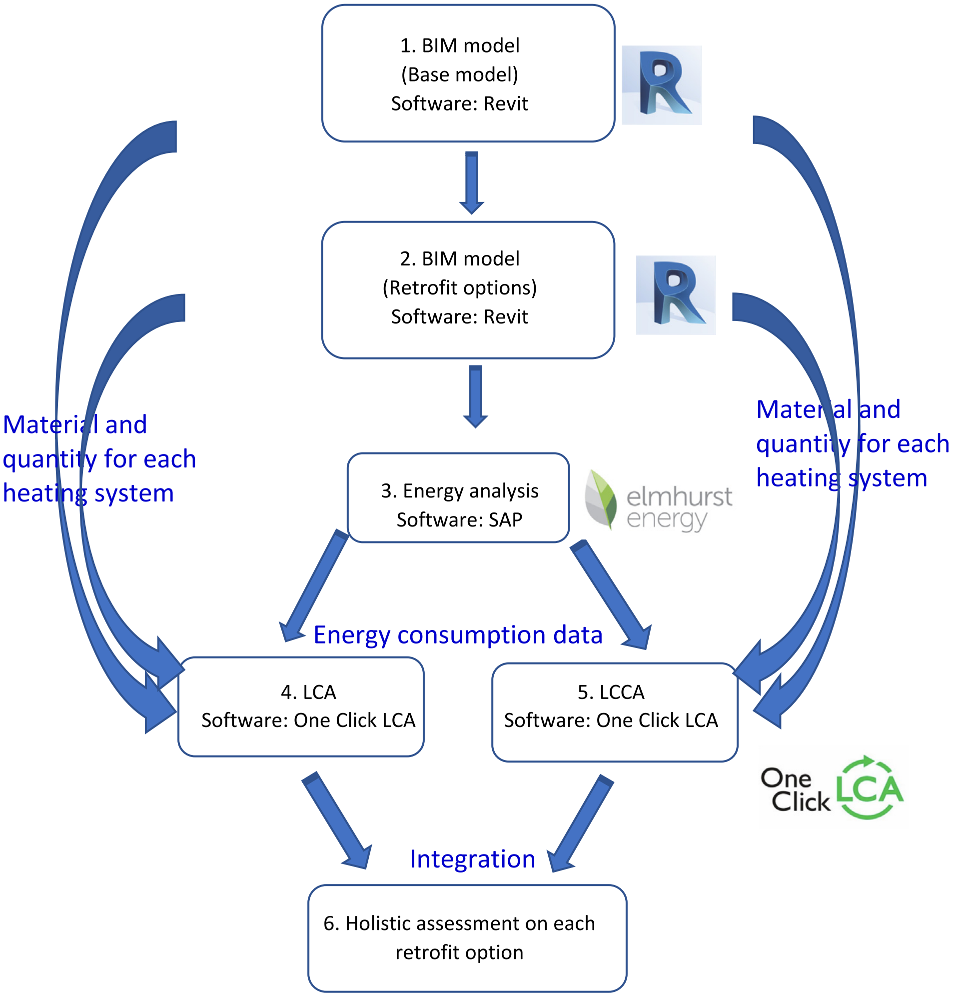

Fig. 1. Case study workflow.

1. The authors gathered the specifications of the dwelling.
2. Development of a BIM model, with a traditional gas boiler heating system, used as a reference/control case, to measure the impact of alternative retrofit solutions.
3. Development of a BIM model for each heating alternative to the base model.
4. The operational energy demand baseline of the control case is established, and the energy load is calculated for each retrofit option, following the current energy modelling regulations.
5. A whole LCA is conducted based on the materials and their quantities, the information exported from the BIM model and the operational energy demand calculation results.
6. LCCA is conducted based on the materials and their quantities, the information exported from the BIM model and the operational energy demand calculations.
7. The results of the LCA and LCCA are integrated to determine which retrofit option is optimal from both economic and environmental perspectives.

The LCA methodology applied in this study complies with EN 15978 [17] and the RICS Professional Statement Whole Life Carbon Assessment for the Built Environment [47], which is aligned with the EN standard. The LCCA methodology in this study follows ISO 15686–5:2017 [37] and its supplementary standardised Method of Life Cycle Costing for Construction Procurement [8].

2.1. BIM model for the case study

For this research, a two-storey semi-detached dwelling is adopted with a constructed area of 118 m^2, facing south and located in Bristol (Fig. 2). Table 1 shows the specifications of the model (control case) used to assess the different retrofit options for this research. The dwelling has two bedrooms, two bathrooms, one kitchen and one living room.

Fig. 3 shows the MEP model, created using BIM to explore the upgrade option related to the heating system. Autodesk Revit was used as the BIM software.

2.2. Retrofit options

Various options may be applied for a housing retrofit to improve energy efficiency, including external wall insulation, underfloor insulation and glazing upgrades. However, this study aims to investigate alternative heating systems as a replacement option for a gas boiler and establish an optimal option. The study focused on electric boilers (Option 1) and air-source heat pumps (Option 2). Ground-source heat pumps were not adopted for consideration in this case study, as additional external works are required in the garden, such as installing pipe trenches. Furthermore, in this case study, installation of photovoltaic (PV) panels is considered as an additional option (Option 3 and Option 4). Thus, a total of four options are considered in this study, as shown in Table 2.

Option 1 proposes to replace the existing gas boiler with a flow-based electric boiler. This only requires replacing the boiler, which involves minimal work and some additional pipes. Option 2 is an air-source heat pump. Unlike Option 1, air-source heat pumps provide hot water at a lower temperature than gas or electric boilers, so the flow rate needs to be increased. This requires larger-diameter pipework than in the case of existing gas boilers and larger radiators than existing ones. Therefore, in this case, in addition to the installation of air-source heat pump equipment, the existing pipework and radiators would need to be replaced with new ones.

Option 3 and Option 4 propose installing PV panels in addition to Option 1 or Option 2. In this study, considering the dwelling size, it is proposed to install 20 PV panels at 250 W each.

Details of the heating system assumed for each option are shown in Table 3. Capacities were assumed based on the dwelling size, number of radiators and bathrooms in the case-study dwelling.

2.3. Energy assessment

In this study, the Standard Assessment Procedure (SAP) was chosen as the assessment tool for the energy consumption of the dwelling and the operational CO_2 emissions. The SAP is the official methodology for predicting energy consumption and meeting CO_2 emission targets for a home in the UK. The prediction is based on assumptions about the typical occupancy and behaviour of UK residents. SAP-compliant software, Elmhurst Design SAP 10.2, developed by Elmhurst Energy Systems Ltd, was adopted in this study. RdSAP (Reduced Data SAP) would be used for an existing dwelling, but SAP allows us to add more information to the model and is more reliable than RdSAP [54]. In this guide, the SAP is the suggested calculation method for both the Dwelling Fabric Energy Efficiency (DFEE) and the Dwelling Emission Rate (DER) of a dwelling.

In the SAP methodology, the annual energy requirement for space heating, water heating, ventilation and lighting, is calculated. It does not include the energy consumed by cooking and other domestic appliances. The energy required for water heating is calculated based on the assumed standard occupant water use relative to floor area, taking into account storage and pipework heat losses and the efficiency of the water heater. The energy required for space heating is calculated based on the internal and external temperatures, solar and internal gains, and taking into account the efficiency of the heating system.

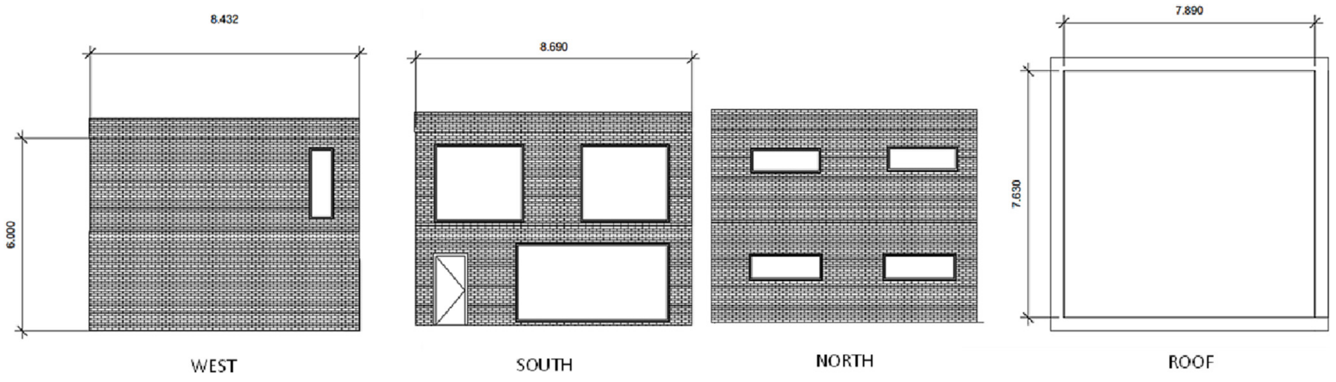

Fig. 2. The BIM model of the case study.

Table 1
The Case study overview.

Element	Description	Thickness	U-value	G-value
Orientation	South			
Number of houses	1			
Floor area	118 m^2			
Exterior wall	Masonry (Brick)	92 mm	0.49 W/m^{2}k	
	Rigid insulation	50 mm		
	Masonry (Concrete block)	193 mm		
	Plasterboard	16 mm		
Roof	Water-resistant barrier	6 mm	0.47 W/m^{2}k	
	Rigid insulation	76 mm		
	Plywood	19 mm		
	Plaster board	12 mm		
Floor	Concrete	127 mm	0.31 W/m^{2}k	
	Wood flooring	16 mm		
Windows	Double glazing with air cavity		3.40 W/m^{2}k	0.76
Door	Unglazed solid timber		3.00 W/m^{2}k	
Heating system	Gas fired boiler (Combi-boiler, non-condensing) for heating and hot water			
	Radiator			
Air change rate	10ACH at 50 Pa pressure			

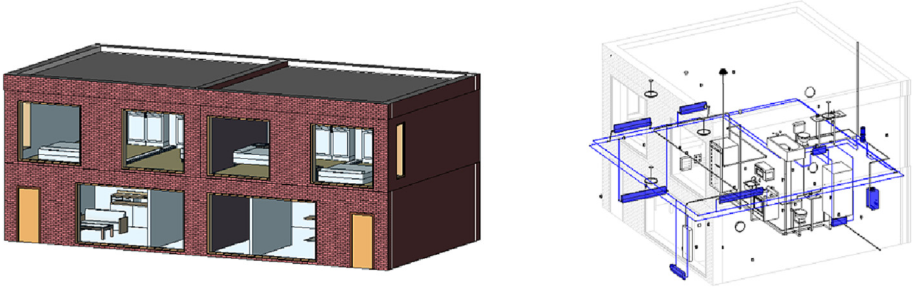

Fig. 3. MEP model and the two-storey semi-detached dwelling where the unit under study is included.

Table 2
Retrofit options assessed.

Option	Implementation detail
Option 1 Electric boiler	Replacement of existing gas boiler with direct-acting boiler with 150 l cylinder
Option 2 Air source heap pump	·Replacement of existing gas boiler with Air to water heat pump with 150 l cylinder ·Replacement of existing flow/return pipes with new flow/return pipes ·Replacement of existing radiators with new radiators
Option 3 Electric boiler + PV panel	·Replacement of existing gas boiler with direct-acting boiler with 150 l cylinder ·Installation of 20 PV panels at 250 W each(5kWp)
Option 4 Air source heap pump + PV panel	·Replacement of existing gas boiler with Air-to-water heat with 150 l cylinder ·Replacement of existing flow/return pipes with new flow/return pipes ·Replacement of existing radiators with new radiators ·Installation of 20 PV panels at 250 W each (5kWp)

Table 3
Heating systems for each option.

Heating system	Detail	
Existing	Boiler type	Non-condensing combi boiler
Gas boiler	Nominal heating power	25 kW
	Efficiency	Winter: 74%, Summer: 65%
	Hot water flow rate	11 l/min
	Flow temperature	60°
	Weight	33 kg
Option 1, 3 Electric boiler	Boiler type	Direct acting electric boiler
	Nominal heating power	15 kW
	Efficiency	100%
	Hot water flow rate	11 l/min
	Flow temperature	50°
	Weight	113 kg (cylinder included)
Option 2, 4 Air source heat pump	Heat pump type	Air to water heat pump
	Nominal heating power	6 kW
	Efficiency	340% (space), 187% (water)
	Hot water flow rate	17 l/min
	Flow temperature	35°
	Refrigerant	R32:2.2 kg
	Weight	170 kg (cylinder included)

2.4. LCA

The LCA methodology applied complies with EN 15978 [17], which defines the calculation method for LCA as a European standard. Furthermore, the process was undertaken following the RICS Professional Statement Whole Life Carbon Assessment for the Built Environment [47], which developed the UK guide for the practical implementation of the principles of BS EN 15978, establishing the technical details and calculation requirements. This study uses the Global Warming Potential (GWP) as an environmental impact indicator. Furthermore, One Click LCA is chosen as the software to perform LCA. The material and quantity of heating systems required for the embodied carbon calculation was exported from BIM to One Click LCA. This automated the export process and provided accurate data for the number and specification of the building services and the quantity of pipework.

An LCA was conducted, including two stages: A) The Production and Construction stages and B) The Use stage. In the A) Production and Construction stages, as this study focuses on retrofitting existing buildings, only retrofit work is included, not new construction of the existing building. The authors found a clear lack of EPDs for MEP products in the UK. When no EPD is available, and embodied carbon calculations for MEP equipment are required, TM65 [58] provides an alternative "Basic" calculation method. That method is used to cover A1-A4 as accurately as possible. A1 emissions from product materials were based on the list of individual product components included in French EPDs for pipes, electric boiler, gas boiler, water cylinder, radiator, pipes and PV panel. These weight "quantities" are then multiplied by the British "embodied carbon coefficient" (kg CO_2e/kg) [58] and [35]. Information was provided for at least 95% of the weight of each product. For the heat pump, the values for A1-A4 were extracted from a "mid-level" TM65 calculation that the manufacturer, Mitsubishi, provided [60].

B) In the use stage, the carbon emissions from B1: Use, B2: Maintenance, B3: Repair, B4: Replacement and B6: Operational energy use are included in the study. As this study aims to compare retrofit options of different heating systems, only emissions associated with the heating system were counted for embodied carbon in B1: Use, B2: Maintenance, B3: Repair, and B4: Replacement. B5: Refurbishment use was excluded, as it was not considered that the design alternatives would make a major difference to the results. In addition, B7: Water use was also excluded because the design of the building has little influence on water use [31].

Finally, the end of life stage (C) is not included in this study due to its relatively low environmental impact compared to other life cycle stages for residential buildings [10]. The LCA scope in this study is shown in Fig. 4.

In this study, the calculation period is set to 60 years. The life expectancy of the heating system and PV assumed for each retrofit option was set at 10 years for the gas boiler, 15 years for the electric boiler, 20 years for the heat pump and 25 years for PV, based on CIBSE M Indicative economic life expectancy [18]. The service life of each system affects the frequency of replacements during the 60-year analysis period.

2.5. LCCA

One Click LCA was chosen as the calculation software to conduct this LCCA. The costs over the life cycle of the building covered in this study must be consistent with the scope of the LCA described in the previous section. Therefore, in this study, the initial costs related to the retrofit and the costs related to maintenance, repair, replacement of heating systems and energy consumption during the use stage are included in the LCC analysis.

The cost data for materials were mainly sourced from the SPON'S price book [2,1], where cost data (total cost of material price + labour price) were applied. Regarding materials for which no data were available in SPON'S, the manufacturer's price for equipment was used as a reference for the cost estimation. For the costs associated with energy consumption, the annual energy costs were determined by multiplying the electricity and gas consumption, which was calculated in the energy assessment, by the energy unit price. The British Gas energy unit price as of 1st October 2022 [13] was adopted as the energy price in this study (Table 4). It was announced that the Energy Price Guarantee was to be applied from 1 October 2022 to 31 March 2023, reducing the unit cost of energy [24]. As it is uncertain whether this scheme will continue to be applied in the years ahead, the energy unit price not affected by this scheme was adopted in this study.

In addition, the prices need to be equivalent in time to add up and compare cash flows at different times in the building lifecycle. Accordingly, to make the cash flows time equivalent, the costs at each point in time are discounted to the retrofit point at a discount rate to calculate the total present value. A discount rate of 3.5% was adopted, based on the standard discount rate of 3.5% per annum in the Green Book [30].

The economic benefit obtained from the surplus electricity produced during the summer was also included. Currently, in the UK, the Smart Export Guarantee (SEG) provides a payment for the surplus electricity sent to the national grid. Companies sell a kWh of electricity used for 51,886 pence, while paying the home generator just 6.4 pence per kWh [14]. The prices vary from 15 to 2 pence kWh, depending on the company. The previous Feed-in Tariff (FIT) scheme, of incentives to install photovoltaic panels, initially paid more than 40 pence per kWh of exported electricity. This situation means that the economic impact of Options 3 and 4 is less than in the past. The life of a solar panel is at least 25 years. A reduction in the price of electricity will benefit Option 4 (ASHP + PV) from an economic point of view.

3. Results

3.1. Energy assessment

The annual energy consumption of the existing dwelling and each retrofit option calculated by SAP is shown in Table 5. Table 5

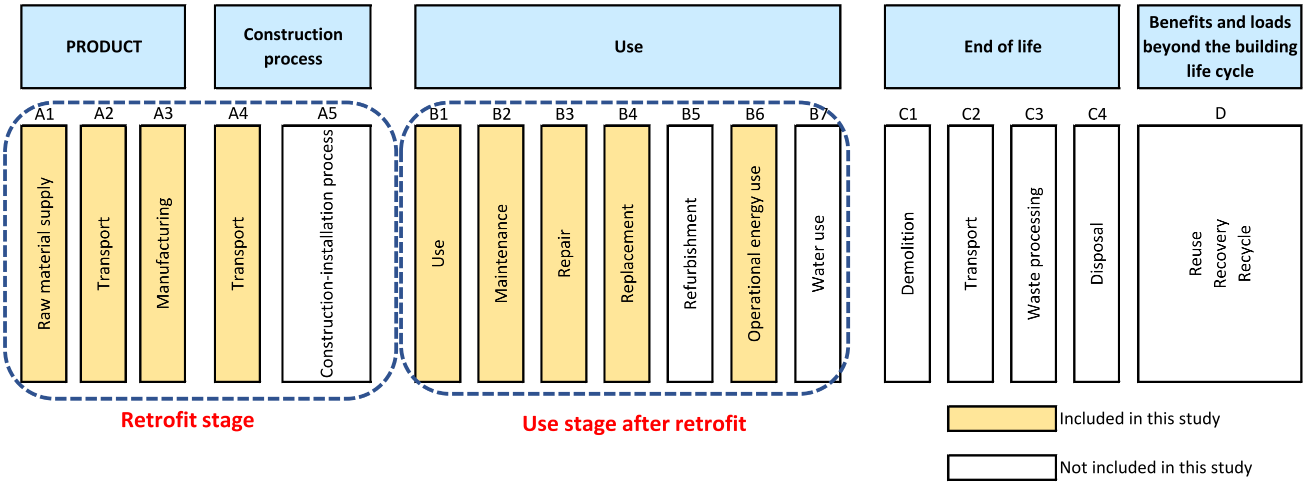

Fig. 4. LCA scope in this study.

Table 4
Energy unit price (Amended from [12]).

	October 2022 Unit rate per kWh		Average Unit rate under Energy Price Guarantee scheme	
	Unit rate per kWh	Standing charge per day	Unit rate per kWh	Standing charge per day
Electricity	51.886p	46.356p	34.037p	46.356p
Gas	14.758p	28.485p	10.330p	28.485p

Table 5
Annual energy consumption in kWh calculated by SAP.

Category		Existing Gas boiler	Option 1 Electric boiler	Option 2 ASHP	Option 3 Electric boiler + PV	Option 4 ASHP + PV
Space heating	Gas	14,747kWh	–	–	–	–
	Electricity	–	10,311kWh	3,350kWh	10,311kWh	3,350kWh
Water heating	Gas	3,806kWh	–	–	–	–
	Electricity	–	3,243kWh	2,236kWh	3,243kWh	2,236kWh
Pumps and fan	Electricity	765kWh	165kWh	0kWh	165kWh	0kWh
Lighting	Electricity	468kWh	468kWh	468kWh	468kWh	468kWh
Energy generation	Electricity	–	–	–	−2933kWh	−2706kWh
Annual energy consumption		19,786kWh	14,187kWh	6,054kWh	11,254kWh	3,348kWh
Annual CO_2 emissions		4,070kgCO_2e	2,141kgCO_2e	906 kgCO_2e	1,751kgCO_2e	546 kgCO_2e
Annual energy cost		£ 3,618	£ 7,530	£ 3,310	£ 6,096	£ 2,133

presents the annual energy consumption of the control system and each alternative system in kWh/year, taking into account the efficiency of each one. Therefore, these values change depending on the heating and hot water system. Each alternative had lower total energy usage than a gas boiler, ranging from 28.3% (Option 1) to 83.1% (Option 4) lower than the existing system with a gas boiler. Of the four options, the most energy-efficient option was found to be Option 4 (Air-source heat pump + PV).

On the other hand, the least energy-efficient option was Option 1 (Electric boiler). The breakdown of energy use shows that the reduction in energy consumption is most significantly affected by space heating, which has the highest energy consumption as a percentage of the total. In Option 3 and Option 4, electricity is generated by the installation of PV panels, which has a negative effect on energy consumption.

3.2. LCA

The results of the LCA on the retrofit and use stages for retrofit options are shown in Table 6 and Fig. 5. Comparing the existing gas boiler with the four retrofit options, the total GWP of these four options is significantly lower than the existing gas boiler, with a reduction ranging from 46.6% (Option 1) to 77.1% (Option 4). This is mainly explained by the fact that, as shown in Table 5, the retrofit results in a significant reduction in energy consumption and the energy source being changed from gas to electricity, which has a smaller carbon footprint. As a result, for all options, the reduction in GWP in B6: Energy exceeded the total GWP generated during the A: retrofit, B1: Use, B2: Maintenance, B3: Repair and B4 Replacement stages, resulting in a lower total GWP than in the existing system. Of the four retrofit options, option 4 (Air source heat pump + PV) had the highest GWP in the retrofit stage; however, it had the most significant reduction in GWP in the use stage, resulting in the lowest total GWP.

3.3. LCCA

The total present cost of the retrofit and use stages for the retrofit options are shown in Table 7 and Fig. 6. Comparing the retrofit options in terms of cost, Option 4 (Air source heat pump + PV) had the lowest total lifecycle costs among the four retrofit options. However, all of the four options exceeded the total cost of the existing gas boiler by 105.0% (option 1), 16.4% (Option 2), 84.1% (Option 3), and 2.1% (Option 4). The reasons that the total costs of the four options exceed those of the existing buildings are, first, that the unit cost of electricity concerning energy consumption is significantly higher than the unit cost of gas, as shown in Table 4, so the reduction in energy consumption did not lead to a reduction in energy costs. In addition, in terms of replacement of equipment, despite the longer service life of both electric boilers and air source heat pumps compared to gas boilers, the cost of equipment was higher than that of gas boilers, so the total cost of equipment replacement exceeded that of gas boilers in all options.

3.4. LCA and LCCA integration

The LCA and LCCA results conducted above are combined, as shown in Table 8. Among the four options, the air source heat pump with PV option is the optimal option, both environmentally and economically, with the lowest figures for both GWP and cost. However, under current high electricity prices, homeowners will be less incentivised to change the boiler, as all options lead to total costs that exceed those of the existing system.

4. Discussion

This is an exemplary case study, evaluating for the first time electric heating options to replace traditional gas boilers, based on low carbon emissions (LCA) and cost (LCCA) criteria to measure the environmental and cost impact of four alternative heating systems.

First, the baseline is established using the case study using a BIM model of a semi-detached house in Bristol with a combi-boiler. Then, the environmental and economic impacts are calculated of adding an electric boiler (i), an air-to-water heat pump (ii) and the impact of adding PV panels to each option (iii, iv).

The control case has the highest global warming potential GWP, almost double the impact in terms of CO_2 emissions, of the next, which is the electric boiler, and four times more than the air-source heat pump (ASHP), and this impact is simply based on its operational CO_2; since it is already installed, the embodied carbon is not taken into account. However, in terms of cost, this is the cheapest option, since you do not have to invest in a new system and, furthermore, the “Unit rate per kWh” of gas is almost 3 times lower than that of electricity.

Table 6
LCA results in $kgCO_2e$ calculated by One Click LCA.

Option	Retrofit stage	Use stage						$kgCO_2e$
	A1-A4	B1	B2	B3	B4	B6	Total	Total
	Material + Transport	Use	Maintenance	Repair	Replacement	Operational energy use	B1-B6	Retrofit + Use
Existing – Gas boiler	–	–	591	148	1,055	244,200	245,994	245,994
1 – Electric boiler	549	–	591	148	1,647	128,460	130,846	131,395
2 – ASHP	4,200	1,784	591	148	1,916	54,360	58,799	62,999
3 – Electric boiler + PV	5,169	–	591	148	10,887	105,060	116,686	121,855
4 – ASHP + PV	8,820	1,784	591	148	12,114	32,760	47,397	56,217

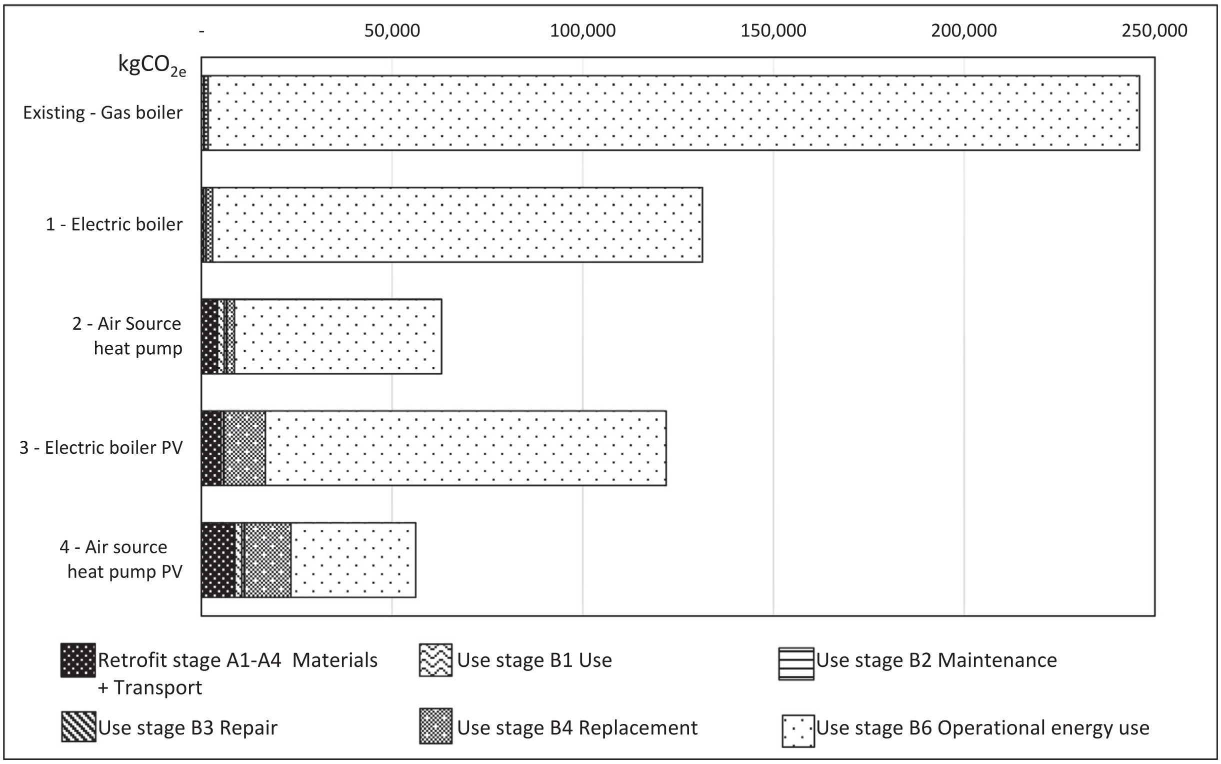

Fig. 5. LCA results (edited by author).

Table 7
LCCA results in pounds calculated by One Click LCA.

Option	Retrofit stage		Use stage					Total
	Retrofit	Total	Maintenance	Repair	Replacement	Energy	Total	Retrofit + Use
Existing – Gas boiler	–	–	£ 2,494	£ 624	£ 3,999	£ 90,250	£ 97,367	£ 97,367
1 – Electric boiler	£ 4,000	£ 4,000	£ 2,494	£ 624	£ 4,663	£ 187,834	£ 195,615	£ 199,615
2 – ASHP	£ 16,070	£ 16,070	£ 4,490	£ 1,123	£ 9,062	£ 82,567	£ 97,242	£ 113,312
3 – Electric boiler + PV	£ 13,625	£ 13,625	£ 2,494	£ 624	£ 10,459	£ 152,064	£ 165,641	£ 179,266
4 – ASHP + PV	£ 25,695	£ 25,695	£ 4,490	£ 1,123	£ 14,858	£ 53,207	£ 73,678	£ 99,373

Table 6 and Fig. 5 show that the main potential to reduce GWP is by reducing the operational energy consumption. Table 6 shows how the amount of emissions during the retrofit stage is much lower than that which occurs during the operational stage, and only in case (iv), ASHP + PV, embodied carbon represents more than a fifth of the total emissions. This makes embodied carbon start to be relatively significant in proportion, due to the massive reduction in operational emissions.

This study determines that, from the point of view of global warming, the most important factor is the efficiency of the heating system. The more efficient a system is, the less power will be consumed and lower emissions will be produced during the operational stage. An electric boiler with COP = 1 needs fewer energy units (kWh) to produce the same amount of heat than the old gas boiler (COP = 0.74). In turn, an air-water heat pump with a SCOP of 3.4 will produce, for every 1 kW of electricity, 2.4 kW more heat than an electric boiler. In terms of efficiency, air-water heat pumps are much more efficient in generating heat than other systems, as they require less energy. Therefore, they will emit the least CO_2 of all the alternatives.

The second determining factor to reduce the global warming impact of heating systems is the "Government conversion factor". Traditionally, electricity had a high "carbon factor", 0.519 $kgCO_2$/kWh, compared to 0.216 $kgCO_2$/kWh for gas. This meant that the

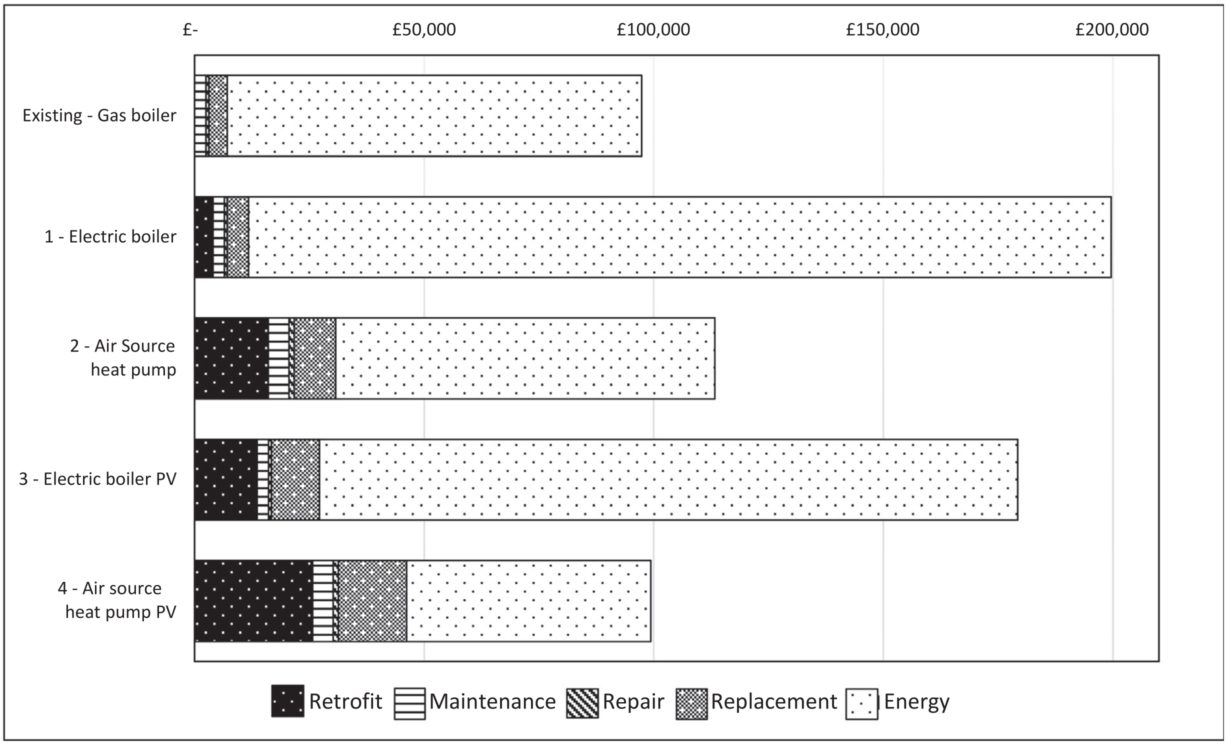

Fig. 6. LCCA results (edited by author).

Table 8
LCA and LCCA results integrated.

Option	Retrofit stage		Use stage		Total GWP $kgCO_2e$	Total cost
	GWP $kgCO_2e$	Cost	GWP $kgCO_2e$	Cost		
Existing Gas boiler	–	–	245,994	£ 97,367	245,994	£ 97,367
1 Electric boiler	549	£ 4,000	130,846	£ 195,615	131,395	£ 199,615
2 ASHP	4,200	£ 16,070	58,799	£ 97,242	62,999	£ 113,312
3 Electric boiler + PV	5,169	£ 13,625	116,686	£ 165,641	121,855	£ 179,266
4 ASHP + PV	8,820	£ 25,695	47,397	£ 73,678	56,217	£ 99,373

impact of homes in which the heating system used electricity was 2.4 times higher than those that used gas. However, the increasing use of renewable energy in the production of electricity for the national interconnected system has reduced its "carbon factor" by 73.8%; electricity now has a conversion factor of just 0.136 $kgCO_2/kWh$ (one-year average) [11]. The carbon factor of natural gas has also been reduced, but only by 2.8% to 0.210 $kgCO_2/kWh$. This change reduces the traditional high impact in terms of CO_2 emissions from electricity, and now houses that use electric systems will emit 1.6 times less CO_2 than those that use gas. In the future, the carbon conversion factor of electricity is expected to continue to decline; in other words, in terms of carbon emissions, the use of electricity for heating will become increasingly favorable. For all these reasons, and although condensing boilers can currently achieve efficiencies of 90%, the government's scheme to promote the use of electricity over gas with incentives, the greater efficiency of electrical systems and the new conversion factors of gas and electricity, which favour the latter, promote the switch to electric heating systems.

Traditionally, cost was considered the most important aspect and must continue to be taken into account for decisions to be cost-effective and affordable.

The electric boiler is the most affordable option upfront, while the heat pump is almost 4 times as expensive, and is almost twice as expensive to maintain/repair. However, the key cost for this criterion is the operational energy use cost, as seen in Table 7. Traditionally gas has been cheaper than electricity. However, the economic part of this study is affected by the recent strong increase in energy prices, especially of gas, which have a significant impact on the calculation of life cycle costs. Wholesale energy prices increased rapidly from the second half of 2021 onwards; such changes mean that the lifecycle cost results can differ significantly if this simulation is performed at different points in time.

There is currently a unit price difference between gas and electricity that makes gas more favourable from an economic point of view. The study, as shown in Table 8, also reveals that the higher the cost and embodied carbon emissions in the retrofit stage, the lower the energy consumption, resulting in lower cost and embodied carbon emissions in the use stage. The LCCA also shows that, due to the change in incentives, the installation of PV panels generates less money for the owner than before, since the kWh sent to the grid is paid now between 15 and 2 pence per kWh depending on the supplier.

Therefore, in terms of cost, ASHP is again the optimal option due to its low fuel consumption; the LCCA shows that, in 60 years, the electric boiler is more than £80 K more expensive than the heat pump, even though the initial investment and maintenance of the latter are higher. Also, the costs of heat pumps and electric boilers will fall in the same way that photovoltaic panels did in the early 2000s.

Finally, if we add PV panels to the optimal option, this increases the retrofit cost by 60% but reduces the lifecycle cost of system (iv) by 12%, while in terms of total GWP, it has a low impact, reducing the CO_2 emissions by 11%. Compared to options (ii) and (iv), electric boilers (i and iii) do not seem to be such an ideal option. Although they reduce $kgCO_2e$ by 47%, they represent an expense 105% greater than gas boilers.

As a result, the most ideal option of the four evaluated is the combination of air-source heat pump plus photovoltaic panels, since it simultaneously has the lowest GWP and lifecycle cost. Option (iv) offers great efficiency that produces a great reduction in energy consumption and CO_2 emissions, and in the long term it is a very cost-effective option. On the downside, it requires external space for the external unit and the internal unit is larger than the average boiler. However, this combination results in the highest energy savings in comparison to the baseline, saving 83%, which represents an 87% reduction on CO_2 emissions.

5. Conclusion

An update of heating systems will be vital in order to fulfil the reduction in CO_2 emissions goals to mitigate climate change. This paper aims to establish the optimal heating system in terms of CO_2 emissions and cost when undertaking a retrofit project. We can by no means expect this to happen on its own: the fabric comes first, and that should always be the approach during a retrofit project. That is the reason why heating installations have less and less output, because they are expected to be installed in houses with improved energy management qualities, and not those of the past.

This study has shown that the simultaneous application of LCA and LCCA can facilitate sustainable and cost-effective decision making by identifying the trade-off relationship between upgrade costs and energy savings. BIM creates a single platform where it is possible to calculate LCA and LCCA simultaneously, also facilitating the automatic extraction of the same information and quantities of materials. Reducing the calculation time and improving its accuracy. As a result, consistent LCA/LCCA results could be obtained for each retrofit option, facilitating the assessment of LCA/LCCA trade-off relationships for the optimisation of the retrofit. After calculating the environmental (LCA) and economic (LCCA) impact of adding an electric boiler (i), an air-water heat pump (ii) and the impact of adding photovoltaic panels to both options (iii, iv) it is possible to conclude that:

The main potential for heating systems to reduce GWP is through the improvement of their efficiency and subsequent reduction of their operational energy consumption. Electric systems have reduced operational carbon through two factors, their higher coefficient of efficiency and their lower carbon conversion factor. But still, embodied carbon has a low impact, and only starts to be relatively significant in proportion, when we assess (iv) ASHP, due to the fact that this option (SCOP = 3.4) is much more efficient compared to the old gas boilers (COP = 0.76). As explained at the beginning of these conclusions, in existing dwellings with low thermal performance, a change in the heating system must be accompanied by an improvement in the fabric, the main factor in reducing the proportion of operational carbon. It is then when embodied carbon begins to be relevant in our decisions.

Embodied carbon still has a low impact, and only starts to be relatively significant in proportion, when we assess (iv) ASHP, due to the fact that this option (SCOP = 3.4) is much more efficient compared to the old gas boilers (COP = 0.76).

The second determining factor to reduce the global warming impact of heating systems is the "Government conversion factor". Since the "carbon factor" of electricity was reduced from 0.519 $kgCO_2/kWh$ to 0.136 $kgCO_2/kWh$, houses that use electric systems will now have a 35% lower GW impact than those that use gas (0.210 $kgCO_2/kWh$).

The new heating system must also be cost-effective and affordable. This study shows how the key factor is operating cost, rather than system price and maintenance/repair cost. ASHP is again the best choice due to its low fuel consumption, even at higher initial and maintenance costs.

PV panels reduce the lifecycle cost of an ASHP by 12%, and its GWP impact by 11%.

Based on this analysis, the study concludes that electric boilers are not the ideal alternative, since, although they reduce $kgCO_2e$ by 47%, they increase the lifecycle cost of the system by 105% if compared to gas boilers. The optimal option of those evaluated is the combination of ASHP plus photovoltaic panels, since it is the most efficient, reducing the $kgCO_2e$ emitted by 77%. However, in terms of the life cycle cost, it is 2.1% higher compared to the classic gas boiler.

CRediT authorship contribution statement

Nao Shibata: Conceptualization, Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Francisco Sierra:** Project administration, Supervision, Validation, Writing – review & editing. **Ahmed Hagras:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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

References

[1] AECOM, Spon's Architects' and Builders' Price Book 2021, Taylor & Francis Group, London, (2020), https://doi.org/10.1201/9781003053675.

[2] AECOM, Spon's mechanical and electrical services price book 2019, Taylor & Francis Group, London, (2018), https://doi.org/10.1201/9780429464461.

[3] W. Ahmed, M. Asif, BIM-based techno-economic assessment of energy retrofitting residential buildings in hot humid climate, Energy and Buildings 227 (2020) p. 110406, https://doi.org/10.1016/j.enbuild.2020.110406.

[4] A. Akbarnezhad, J. Xiao, Estimation and Minimization of Embodied Carbon of Buildings: A Review, Buildings 7 (4) (2017) p. 5, https://doi.org/10.3390/buildings7010005.

[5] Alaloul, W. S. and Musarat, M. A. (2020) "Impact of Zero Energy: Sustainability Perspective", Taşeli, B. K. (Ed.), *Sustainable Sewage Sludge Management and Resource Efficiency*, IntechOpen, https://doi.org/10.5772/intechopen.92906.

[6] R. Assiego, de, Larriva, G. Calleja, Rodríguez, J. Cejudo López, M. Raugei, Fullana, i, Palmer,, P., A decision-making LCA for energy refurbishment of buildings: Conditions of comfort, Energy and Buildings 70 (2014) 333–342, https://doi.org/10.1016/j.enbuild.2013.11.049.

[7] A. Barbini, G. Malacarne, K. Romagnoli, G. Massari, D. Matt, Integration of Life Cycle Data in a BIM Object Library to Support Green and Digital Public Procurements, International Journal of Sustainable Development and Planning 15 (7) (2020) 983–990, https://doi.org/10.18280/ijsdp.150702.

[8] BCIS (2008) "PD 156865: 2008 Standardized method of life cycle costing for construction procurement. A supplement to BS ISO 15686-5 Building and constructed assets – Service life planning – Part 5: Life cycle costing".

[9] Bedingfield, W. (2019) "The Climate Crisis Issue that No One is Talking about? Your Gas Boiler" Available at: https://www.wired.co.uk/article/central-heating-gas-boiler-climate-change (Accessed 3 July 2022).

[10] M. Belucio, C. Rodrigues, C.H. Antunes, F. Freire, L.C. Dias, Eco-efficiency in early design decisions: A multimethodology approach, Journal of Cleaner Production 283 (2021), https://doi.org/10.1016/j.jclepro.2020.124630.

[11] BRE (2022) "The Government's Standard Assessment Procedure for Energy Rating of Dwellings, Version 10.2 (21-04-2022)" Available at: https://bregroup.com/sap/sap10/(Accessed 1 August 2022).

[12] BRE trust (2020) "The Housing Stock of the United Kingdom" Available at: https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf (Accessed 1 January 2022).

[13] British Gas (2022) "Energy news and the Energy Price Guarantee", Available at: https://www.britishgas.co.uk/energy/price-cap.html (Accessed 29 November 2022).

[14] British Gas (2023) "Smart Export Guarantee", Available at: https://www.britishgas.co.uk/help-and-support/my-account/smart-export-guarantee (Accessed 28 February 2023).

[15] Carbon Trust (2015) "Why low carbon refurbishment is crucial for building sustainable cities" Available at: https://www.carbontrust.com/news-and-events/insights/why-low-carbon-refurbishment-is-crucial-for-building-sustainable-cities (Accessed 27 June 2022).

[16] J.P. Carvalho, F.S. Villaschi, L. Bragança, Assessing life cycle environmental and economic impacts of building construction solutions with BIM, Sustainability 13 (16) (2021) 8914, https://doi.org/10.3390/su13168914.

[17] CEN (2011) "EN15978 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method".

[18] Chartered Institution of Building Services Engineers (2020) "Maintenance engineering and management Appendix 12. A1: Indicative economic life expectancy. CIBSE Guide M supplement: January 2020", Available at: https://cis.ihs.com/cis/document/327938 (Accessed 30 November 2022).

[19] Committee on Climate Change (2019) "UK housing: Fit for the future?" Available at: https://www.theccc.org.uk/wp-content/uploads/2019/02/UK-housing-Fit-for-the-future-CCC-2019.pdf (Accessed 25 November 2022).

[20] A. Dauletbek, P. Zhou, "BIM-based LCA as a comprehensive method for the refurbishment of existing dwellings considering environmental compatibility, energy efficiency, and profitability: A case study in China", *Journal of Building*, Engineering 46 (2022) p. 103852, https://doi.org/10.1016/j.jobe.2021.103852.

[21] D. Densley Tingley, B. Davison, Developing an LCA methodology to account for the environmental benefits of design for deconstruction, Building and Environment 57 (2012) 387–395, https://doi.org/10.1016/j.buildenv.2012.06.005.

[22] Department for Business, Energy & Industrial Strategy (2021) "Heat and buildings strategy" Available at: https://www.gov.uk/government/publications/heat-and-buildings-strategy (Accessed 6 January 2022).

[23] Department for Business, Energy & Industrial Strategy (2022) "Guidance Boiler Upgrade Scheme" Available at: https://www.gov.uk/guidance/check-if-you-may-be-eligible-for-the-boiler-upgrade-scheme-from-april-2022 (Accessed 3 July 2022).

[24] Department for Business, Energy & Industrial Strategy (2022) "Energy Price Guarantee" Available at: https://www.gov.uk/government/publications/energy-bills-support/energy-bills-support-factsheet-8-september-2022 (Accessed 30 November 2022).

[25] Energy Saving Trust (2019) "Significant Changes are Coming to the UK Heating Market" Available at: https://energysavingtrust.org.uk/significant-changes-are-coming-uk-heating-market/(Accessed 3 July 2022).

[26] Friedler, C., and Kumar, C., (2019) "Reinventing retrofit: How to scale up home energy efficiency in the UK. Green Alliance" Available at: https://green-alliance.org.uk/wp-content/uploads/2021/11/reinventing_retrofit.pdf (Accessed 25 November 2022).

[27] Gamtessa, S. (2013) "An explanation of residential energy-efficiency retrofit behavior in Canada", *Energy and Buildings*, 57, pp.155-164, https://doi.org/10.1016/j.enbuild.2012.11.006.

[28] P. Gaspar, A. Santos, Embodied energy on refurbishment vs. demolition: A southern Europe case study, Energy and Buildings 87 (2015) 386–394, https://doi.org/10.1016/j.enbuild.2014.11.040.

[29] Global Alliance for Buildings and Construction (2022) "2021 Global Status Report for Buildings and Construction" Available at: https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction (Accessed 20 May 2022).

[30] HM Treasury (2022) "The Green Book Central Government Guidance on Appraisal and Evaluation", Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1063330/Green_Book_2022.pdf (Accessed 16 August 2022).

[31] A. Hollberg, J. Ruth, LCA in architectural design—a parametric approach, The International Journal of Life Cycle Assessment 21 (7) (2016) 943–960, https://doi.org/10.1007/s11367-016-1065-1.

[32] N. Hrovatin, J. Zorić, Determinants of energy-efficient home retrofits in Slovenia: The role of information sources, Energy and Buildings 180 (2018) 42–50, https://doi.org/10.1016/j.enbuild.2018.09.029.

[33] M. Hu, Cost-Effective Options for the Renovation of an Existing Education Building toward the Nearly Net-Zero Energy Goal—Life-Cycle Cost Analysis, sustainability 11 (8) (2019) p. 2444, https://doi.org/10.3390/su11082444.

[34] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, Operational vs. embodied emissions in buildings—A review of current trends, Energy and Buildings 66 (2013) 232–245, https://doi.org/10.1016/j.enbuild.2013.07.026.

[35] ICE (2023) "Embodied Carbon – The ICE Database", Available at: https://circularecology.com/embodied-carbon-footprint-database.html (Accessed 28 February 2023).

[36] IEA (2021) "Net Zero by 2050" Available at: https://www.iea.org/reports/net-zero-by-2050 (Accessed 16 August 2022).

[37] ISO (2017) "ISO 15686-5: 2017 Buildings and constructed assets – Service life planning Part 5: Life-cycle costing".

[38] N. Kale, D. Joshi, R. Menon, Life cycle cost analysis of commercial buildings with energy efficient approach, Perspectives in Science 8 (2016) 452–454, https://doi.org/10.1016/j.pisc.2016.04.102.

[39] K. Kim, K. Park, Housing information modelling for BIM-embedded housing refurbishment, Journal of Facilities Management 16 (3) (2018) 299–314, https://doi.org/10.1108/JFM-09-2016-0037.

[40] K. Kim, K. Park, Delivering value for money with BIM-embedded housing refurbishment, Facilities 36 (13/14) (2018) 657–675, https://doi.org/10.1108/F-05-2017-0048.

[41] A. Kylili, P.A. Fokaides, J. Vaiciunas, L. Seduikyte, Integration of building information modelling (BIM) and life cycle assessment (LCA) for sustainable constructions, Journal of Sustainable Architecture and Civil Engineering 13 (4) (2015) 28–38, https://doi.org/10.5755/j01.sace.13.4.12862.

[42] K. Lu, X. Jiang, J. Yu, V. Tam, M. Skitmore, Integration of life cycle assessment and life cycle cost using building information modeling: A critical review, Journal of Cleaner Production 285 (2021), https://doi.org/10.1016/j.jclepro.2020.125438.

[43] M. Motalebi, A. Rashidi, M. Nasiri, "Optimization and BIM-based lifecycle assessment integration for energy efficiency retrofit of buildings", *Journal of Building*, Engineering 49 (2022) p. 104022, https://doi.org/10.1016/j.jobe.2022.104022.

[44] M. Najjar, K. Figueiredo, M. Palumbo, A. Haddad, Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building, Journal of Building Engineering 14 (2017) 115–126, https://doi.org/10.1016/j.jobe.2017.10.005.

[45] T. Potrč Obrecht, M. Röck, E. Hoxha, A. Passer, BIM and LCA integration: A systematic literature review, Sustainability 12 (14) (2020) 5534, https://doi.org/10.3390/su12145534.

[46] M. Rad, F. Jalaei, A. Golpour, S. Varzande, G. Guest, BIM-based approach to conduct Life Cycle Cost Analysis of resilient buildings at the conceptual stage, Automation in Construction 123 (2021) p. 103480, https://doi.org/10.1016/j.autcon.2020.103480.

[47] Royal Institution of Chartered Surveyors (2017) "RICS professional standards and guidance, UK. Whole life carbon assessment for the built environment", Available at: https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the–built-environment-november-2017.pdf (Accessed 20 August 2022)

[48] R. Santos, A. Costa, J. Silvestre, L. Pyl, Integration of LCA and LCC analysis within a BIM-based environment, Automation in Construction 103 (2019) 127–149, https://doi.org/10.1016/j.autcon.2019.02.011.

[49] R. Santos, A. Costa, J. Silvestre, T. Vandenbergh, L. Pyl, BIM-based life cycle assessment and life cycle costing of an office building in Western Europe, Building and Environment 169 (2020) p. 106568, https://doi.org/10.1016/j.buildenv.2019.106568.

[50] Y. Schwartz, R. Raslan, D. Mumovic, Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: A building retrofit case study, Energy 97 (2016) 58–68, https://doi.org/10.1016/j.energy.2015.11.056.

[51] S. Sharif, A. Hammad, Simulation-Based Multi-Objective Optimization of institutional building renovation considering energy consumption, Life-Cycle Cost and Life-Cycle Assessment, Journal of Building Engineering 21 (2019) 429–445, https://doi.org/10.1016/j.jobe.2018.11.006.

[52] Y. Shin, K. Cho, BIM Application to Select Appropriate Design Alternative with Consideration of LCA and LCCA, Mathematical Problems in Engineering 2015 (2015) 1–14, https://doi.org/10.1155/2015/281640.

[53] A. Shirazi, B. Ashuri, Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta, Building and Environment 171 (2020) 106644, https://doi.org/10.1016/j.buildenv.2020.106644.

[54] F. Sierra, L. Mahdjoubi, B. Gething, A. Alzaatreh, R. Fitton, A. Marshall, Comparison of prediction tools to determine their reliability on calculating operational heating consumption by monitoring no-fines concrete dwellings, Energy & Buildings 176 (2018) 78–94, https://doi.org/10.1016/j.enbuild.2018.07.012.

[55] Q. Tushar, M.A. Bhuiyan, G. Zhang, Energy simulation and modeling for window system: A comparative study of life cycle assessment and life cycle costing, Journal of Cleaner Production 330 (2022), https://doi.org/10.1016/j.jclepro.2021.129936.

[56] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life cycle assessment (LCA) of building refurbishment: A literature review, Energy and Buildings 135 (2017) 286–301, https://doi.org/10.1016/j.enbuild.2016.11.042.

[57] World Green Building Council (2019) "Bringing embodied carbon upfront" Available at: https://www.worldgbc.org/sites/default/files/WorldGBC_Bringing_Embodi ed_Carbon_Upfront.pdf (Accessed 16 August 2022).

[58] Chartered Institution of Building Services Engineers (2021) "Embodied carbon in building services: a calculation methodology CIBSE TM65: 2021", Available at: Embodied carbon in building services: a calculation methodology (TM65) | CIBSE (Accessed 30 November 2022)

[59] E. Romano, P. Negro, F. Taucer, Seismic performance assessment addressing sustainability and energy efficiency, Publications Office, Luxembourg, (2014). https://data.europa.eu/doi/10.2788/5391.

[60] Mitsubishi (2021) "PUZ-WM65VAA CIBSE TM65 Embodied Carbon Mid-Level Calculation" Available at: https://library.mitsubishielectric.co.uk/pdf/book/ecodan_hydrodan_TM65_Calculation#page-1 (Accessed 27 December 2022).