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Carbon footprint of low-energy buildings in the United Kingdom: Effects of mitigating technological pathways and decarbonization strategies

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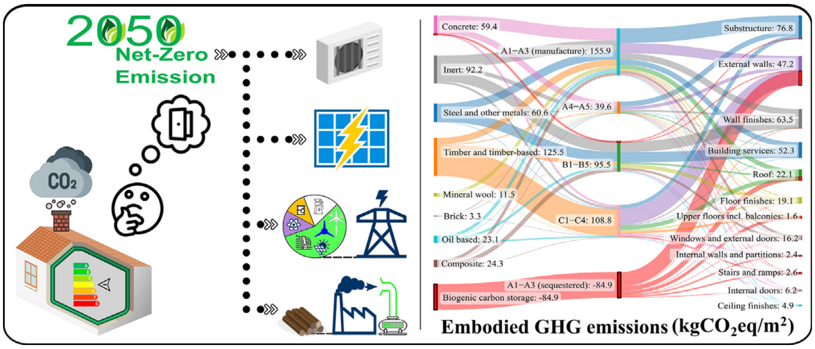
HIGHLIGHTS

- Carbon footprint is evaluated for a UK low-energy building *via* an LCA perspective.
- Three different widely applicable HVAC strategies in UK dwellings are analyzed.
- Electricity decarbonization reflects a significantly lower GHG emission by ~50 %.
- Improvement of the timber's waste treatments decreases embodied emissions by ~23 %.
- Further reduction in GHG emissions can achieve with appropriate material selection.

GRAPHICAL ABSTRACT



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ABSTRACT

There is a limited comprehensive analysis of the effectiveness of adopted carbon mitigation strategies for buildings over their life cycle, that are concerned with temporal perspectives of emissions. Accordingly, this paper explores a life cycle assessment (LCA) to address the concerns regarding mitigating the carbon footprint of a UK timber-frame low-energy dwelling. In particular, it aims to investigate the potential greenhouse gas (GHG) emission reduction in terms of three different heating and ventilation options, and to analyze the influence of decarbonization of electricity production as well as the technological progress of the waste treatment of timber on the building's environmental performance. Thus, the whole life-carbon of the building case studies was evaluated for a total of eight investigated prospective scenarios, and they were compared to the LCA results of the baseline scenario, where the existing technology and context remained constant over time. Results show that using a compact heat pump would lead to a significant whole life-cycle emission reduction of the dwelling, by 19 %; while GHG emission savings can be reinforced if the

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Abbreviations: ASHRAE, The American society of heating, refrigerating and air-conditioning engineers [-]; BECCS, Bioenergy with Carbon Capture and Storage [-]; BIM, Building Information Modeling [-]; BIPV, Building Integrated Photovoltaics [-]; BIPVT, Building Integrated Photovoltaic with Thermal [-]; CCC, Climate Change Committee [-]; CCS, Carbon Capture and Storage [-]; CO_2, Carbon dioxide [$kgCO_2$]; CO_2eq, Carbon dioxide equivalent [$kgCO_2eq$]; CH4, Methane [$kgCO_2eq$]; DEFRA, Department for Environment, Food and Rural Affairs [-]; DB, DesignBuilder software [-]; EC, Embodied Carbon [$kgCO_2eq$]; EoL, End-of-Life [-]; EPD, Environmental Product Declaration [-]; EPS, Expanded Polystyrene Insulation [-]; ESL, Estimated Service Life [year]; FES, Future Energy Scenarios [-]; FSC, Forest Stewardship Council [-]; FU, Functional Unit [-]; gbXML, Green Building Extensible Markup Language [-]; GGBFS, Ground Granulated Blast-Furnace Slag [-]; GHG, Greenhouse Gas [$kgCO_2eq$]; GIA, Gross Internal Area [m^2]; GWP, Global Warming Potential [$kgCO_2eq$]; HVAC, Heating, Ventilation and Air Conditioning [-]; ISO, International Organization for Standardization [-]; LCA, Life Cycle Assessment [-]; LCI, Life Cycle Inventory [-]; LCIA, Life Cycle Impact Assessment [-]; LETI, London Energy Transformation Initiative [-]; MVHR, Mechanical Ventilation with Heat Recovery [-]; nZEB, Nearly Zero-Energy Building [-]; OC, Operational Carbon [$kgCO_2eq$]; PCRs, Product Category Rules [-]; PEFC, Programme for the Endorsement of Forest Certification [-]; PV, Photovoltaic [-]; RES, Renewable Energy sources [-]; RICS, Royal Institution of Chartered Surveyors [-]; RSP, Reference Service Period [year]; SAP, Standard Assessment Procedure [-]; SCOP, Seasonal Coefficient of Performance [-]; SCMs, Supplementary Cementitious Materials [-]; U-value, Thermal Transmittance [$W/(m^2K)$]; UKGBC, UK Green Building Council [-]; WRAP, Waste and Resources Action Programme, UK organisation [-]; XPS, Extruded polystyrene Insulation [-].

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assessed systems are employed simultaneously with grid decarbonization, exhibiting a 25 %–60 % reduction compared to the baseline scenario. Moreover, technological changes in the waste treatments of timber products could substantially reduce the buildings' embodied emissions, representing 3 %–23 %. From these emission-saving measures, the contribution of material efficiency strategies to achieve more embodied carbon savings should be highlighted in future construction practices.

1. Introduction

Climate change, mainly associated with human activities (anthropogenic), is one of the most global challenges in damaging the environment (Mahmoud and Gan, 2018). Global warming, as a result of greenhouse gas (GHG) emissions, has been growing at an alarming rate, and they are considered to have the highest potential to intensify worldwide environmental concerns (Benato and Stoppato, 2019; López et al., 2023). To comply with the European Green Deal (European Parliament, 2020), the European Commission has put forward a plan to cut down GHG emissions by at least 55 % compared to 1990 levels by 2030, and an ambitious aim at a climate-neutral economy by 2050 (European Environment Agency (EEA), 2020). Among the various GHG emitters, the construction sector is a critical area for global carbon neutrality and achieving sustainable development (Chen et al., 2022; Norouzi et al., 2021a). For example, in the United Kingdom (UK), the construction of buildings is directly responsible for 13 % of total emissions through manufacturing and construction activities, and indirectly responsible for a further 18 % due to heating, cooling, and lighting of buildings (CCC, 2021). Besides, due to the population growth and to ensure human well-being, the government set a target to build 300,000 new homes per year by the mid-2020s in England (about an annual 1.7 % increase trend by 2030) (Feng et al., 2022; POST, 2021), while continuously contributing to the GHG emission (*i.e.,* CO_2eq emission). In this light, stronger efforts are needed in the construction industry to shift from the current paradigm toward the co-benefits of low-carbon buildings through directives, building regulations, as well as proper environmental management (Din and Brotas, 2016).

The quantity of GHG emissions caused by buildings can be measured comprehensively, across their entire life cycle, through whole life-carbon assessment. The objective is two-fold: (i) reducing emissions associated with the various energy demands during the operational phase of a building including heating, cooling, ventilation, and lighting; and (ii) lowering those embodied carbon emissions in materials, associated with the GHG emissions produced by the manufacturing, renovation, maintenance, and end-of-life of building materials. So far, the main focus of policymakers and practitioners were primarily to concentrate on efforts the decarbonizing operational emissions, through improving energy efficiency to reduce the building energy demand (Röck et al., 2020). This enhancing energy efficiency in building design and systems may reduce the site energy-related emissions from the buildings, but it can potentially lead to an increase in environmental loads of source energy-related emissions from the electricity mix production, and the potential of buildings for efficient heating, ventilation, and air conditioning (HVAC) systems (Rahif et al., 2022). At present, central heating from a natural gas-fired boiler is the most common system in UK residential buildings (~92 % in 2017 (Lin et al., 2021)), while Government has set to end fossil-fuel heating systems in new houses from 2025 as a result of Future Homes Standard on a national scale (HM Government, 2019a). The potential of low-carbon HVAC systems such as heat pumps was underlined as a prominent option to reduce the use of fossil fuels, lowering GHG emissions (Scamman et al., 2020). However, their large-scale deployment is not widely spread in the UK, mainly due to three concerns: (i) it may lead to an increase in the peak demand of electricity consumption; (ii) their considerably higher investment cost than for gas boilers, even though the higher efficiency of heat pumps reduces the required heater capacity; and (iii) due to high carbon intensity of electricity, they may not necessarily result in lower environmental performance than condensing gas boilers (Greening and Azapagic, 2012; Lin et al., 2021). In this context, the Government has attempted to encourage manufacturers to reduce the costs of heat pumps by at least 25–50 % by 2025 (POST, 2021). Further, with respect to the decarbonization of power generation, there is significant progress made by the UK (from ~3 % in 2000 to ~43 % of electricity generation from renewable sources in 2020 (DUKES, 2021)), while a net-zero emissions system necessitates radical changes across all energy sectors to mitigate carbon emissions (Wang et al., 2022a, 2022b). Under the EU Emissions Trading System (EU ETS) regulation, the UK is legally bound to speed up the transformation by 3–17 years for different parts of the electricity system and produce at least 74 % of the electricity from renewable resources by 2030 (Pietzcker et al., 2021).

Giving the focus solely on reducing the emissions from the building operation requires more extensive construction materials (*i.e.,* thicker insulation, energy-efficient glazing, etc), which might involve boundary passing the environmental impacts from the use phase to other building life cycle modules (Asdrubali et al., 2019). Moreover, it is suggested that improving the environmental performance of the operation phase can significantly increase the relative importance of embodied emissions, sometimes exceeding the impact of the operational phase (LETI, 2020a; Saade et al., 2020; UKGBC, 2019). Within this purview, focusing on material efficiency is critical for climate change mitigation of buildings (Lausselet et al., 2021). Several material efficiency strategies have been identified as more intense use of building materials and extending their lifetimes, using lighter and less emissions-intensive materials, improving construction waste processing, and applying circularity principles through the reuse and recycling of building components (Hertwich et al., 2019; Pomponi and Moncaster, 2016). At a national level, the UK Green Building Council (UKGBC) has set out a framework definition that aims to support progress toward net-zero carbon buildings (UKGBC, 2019). To achieve these targets, identifying and applying the effectiveness and possible CO_2 emissions reductions in the building would, therefore, include tackling not only the operational carbon (OC) emissions but also the embodied carbon (EC) emissions (Brooks et al., 2021; POST, 2021). Hence, the broad analysis involving whole life-carbon (including particularly embodied carbon) would provide a more complete picture of the GHGs during the building's life cycle and enables the identification of carbon hotspots and optimal combined mitigation strategies.

Furthermore, the use of timber as a construction material for buildings is growing significantly in the UK over the last decade. According to the Structural Timber Association (STA), the timber frame market represented 28.4 % of UK houses in 2016, and its demand was expected to increase by an annual 10 % trend by 2021 (STA, 2016). The possibility of storing carbon and achieving carbon sink effects through the increased use of bio-based building materials is now included in the UK's Climate Change Committee (CCC) as one of the most effective options for zero-carbon buildings (CCC, 2018). According to the study (Hafner and Schäfer, 2017), single/two-family residential buildings can potentially reduce 35 % up to 56 % GHG emissions in timber houses compared to mineral buildings. Even though studies that compare methodological assumptions exist (Arehart et al., 2021; Hoxha et al., 2020), the treatment of biogenic carbon storage is an unsettled issue in the life cycle assessment (LCA) of buildings. Several researchers (Fouquet et al., 2015; Levasseur et al., 2013; Negishi et al., 2018; Santos et al., 2021) highlighted the importance of considering biogenic carbon, as well as how the choices related to the waste management scenarios of timber products, lead to a significant variation in the LCA results for buildings and could provide useful information for policy-making on the implementation of different solutions for emission reduction. However, the discussion around the effects of different modeling approaches and future scenarios with regard to the waste treatment of biogenic carbon flows of construction products and buildings is getting more attention within the LCA society (Andersen et al., 2022; Petrović et al., 2023).

There have been several studies investigating the strategies to reduce the environmental and resource footprints of buildings. For instance, the application of higher levels of fabric insulation (Lamy-Mendes et al., 2021; Rodrigues et al., 2023); building and service life extension (De Castro et al., 2014; Valencia-Barba et al., 2023); using phase change material (PCM) and Trombe wall (Al-Yasiri and Szabó, 2022; Aranda-Usón et al., 2013); alternative building materials and sustainable management of building waste (Gan et al., 2022; Hossain and Ng, 2020; Zhang et al., 2022); adopting energy-efficient systems and equipment (Smith et al., 2021; Wu et al., 2018); improving the occupant behavior profiles (Fajilla et al., 2020; Lam et al., 2022); and increases in renewable energy sources (RES) (Al-Shetwi, 2022; Zhang et al., 2018). Although these studies have attempted to investigate the various mitigation measures to help reduce the buildings' environmental burdens, most of them did not include the complete life cycle perspective in their case studies of building emissions. In addition, studies investigating emission reduction measures (Alaux et al., 2023; Crawford, 2011; Norouzi et al., 2021b) have focused primarily on building operations and there are few efforts have been placed on measuring and reducing the impact of embodied emissions on the building life cycle.

Moreover, the vast majority of the existing LCA studies have conducted their analysis by applying the static approach which means that, for example in energy modeling, the current UK energy mix is considered to remain constant over the lifetime of the building (Collinge et al., 2013; De Wolf et al., 2017; Kiss et al., 2020). However, neglecting the impact of changes in the electricity mix is one of the most significant drawbacks of the current LCA practices (Negishi et al., 2018), as the decarbonization of electricity generation through increasing the share of renewable sources has a crucial role to decrease GHG emissions (Fouquet et al., 2015; Zhou et al., 2016). Therefore, the LCA of buildings should include temporal aspects to assess tracking the potential changes over a long period and help to make environmental assessment results more robust (Anand and Amor, 2017; Negishi et al., 2018). In this perspective, limited studies have taken this effect to improve their LCA studies. For instance, some studies only considered the time-dependent changes for certain pivotal moments during the use stage of buildings instead of variations over their entire life cycles (Collinge et al., 2014; Roux et al., 2016); some researchers considered only the heating system (Bianco et al., 2017; Neirotti et al., 2020); while others applied the theoretical concepts without a representative building application studies (Negishi et al., 2018; Su et al., 2017; Wang et al., 2021).

To the knowledge of the authors, there is no comprehensive LCA study that addresses the environmental performance of low-energy residential buildings in which the potential contribution of the UK's national strategies, in particular, the impact of the grid decarbonizing and technological changes in waste management treatments of timber materials, for achieving European climate policies and potential improvements to the future electricity systems was investigated. This study intends to fill this gap. Besides this paper investigates: (i) the relative impacts of different building life stages by considering the whole life-carbon emissions and particularly to further study whether the embodied emissions are significantly influenced by the building elements (*i.e.,* choice of materials); (ii) the influence of accounting carbon sequestration in the LCA results; (iii) the impact of widely used HVAC systems on the GHG emissions of the case studies; and (iv) the effect of different levels up of combustion or degradation practices at the end-of-life of timber products on the environmental performance of the buildings. Furthermore, the LCA results will be further compared with the UK benchmark regime for the buildings' carbon targets, aiming to provide insights to policymakers and building designers of the analyzed potential decarbonization solutions.

The remainder of this paper is structured as follows. Section 2 provides an overview of the data and methodology used. First, the LCA methodology is described, followed by the data collection of the case studies, and the different scenarios analyses were undertaken. Section 3 presents the results of the baseline scenario and the effects of future decarbonization of electricity generation and technological progress on the waste management treatments of timber materials. Section 4 discusses the results, limitations, and future work in light of current building decarbonization literature. Section 5 summarizes the results of the work.

2. Materials and methods

2.1. Research methodology

A combination of scenario-based modeling and LCA methodology is used in this study. Fig. 1 summarizes the design framework employed in three main steps. The first step is the collection of building data from relevant databases (*e.g.,* environmental product declarations (EPDs)), and the development of a building information modeling (BIM) model for the case study. Besides, to illustrate different plausible directions, the methodological choices of dynamic aspects and prospective scenarios following government plans and targets are integrated into the results. It is, therefore, required to develop an LCA in accordance with the methodological modular approach of EN 15978 (CEN, 2011), as a baseline scenario, *i.e.,* existing technology and context should be assumed for the calculation (Collinge et al., 2013; Hart et al., 2021). Then, the prospective parameters for data collection and calculation describe a sensitivity analysis based on time-dependent values. In the second step, the changes are integrated using impact categories and environmental indicators into the LCA of the building. Finally, the LCA results of the different scenarios are analyzed and compared with the baseline scenario approach.

2.2. LCA methodological framework

The life cycle assessment (LCA) is a powerful decision support method that can determine the potential environmental impacts, especially the GHG emission, of a process/product through its entire life cycle (cradle-to-grave or cradle-to-cradle).

As shown in Fig. 1, building information modeling (BIM) is oriented to the modeling and communication of both graphic and non-graphic information to organize, store, exchange, and allow access to the building data during its life cycle to increase productivity in building design and construction. The application of BIM in this approach is a significant contribution to improving the processes of building life cycle assessment as it allows managing the semi-automatic calculations of the life cycle assessment through the link of an Excel-based database (Shin and Cho, 2015). The BIM-based LCA approach still has several limitations, such as concerns regarding data interoperability among BIM applications, human-made errors, and lack of database flexibilities (*e.g.,* the possibility to add materials) (Najjar et al., 2019; Santos et al., 2020b, 2020a). Even though some recent studies have focused on improving the inclusion of environmental information in the BIM model to address these limitations, a more regulated approach is required (Santos et al., 2020b).

In this study, the preferred LCA methodology in accordance with ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006), and the European EN 15978 and 15804 framework for the "Sustainability of Construction Works – Assessment of Buildings" (CEN, 2019, 2011) are conducted for assessing the whole life-carbon emissions of buildings according to the following four steps: (i) definition of the goal and scope of LCA; (ii) life cycle inventory analysis (LCI); (iii) life cycle impact assessment (LCIA); and (iv) interpretation.

2.2.1. Application to a real case study

In order to verify the LCA model, a semi-detached dwelling built to satisfy the requirements of the "Passivhaus" standard (Feist, 2011) and evaluated with the Standard Assessment Procedure (SAP) to comply with UK's buildings regulations (UK Government's National Calculation Methodology, 2021) is chosen as a reference case study. Appendix A.1 in Supplementary Materials shows the layout and elevation of the reference case study. The dwelling, which represents the most common characteristics of a British two-story timber-framed structure, is constructed with a

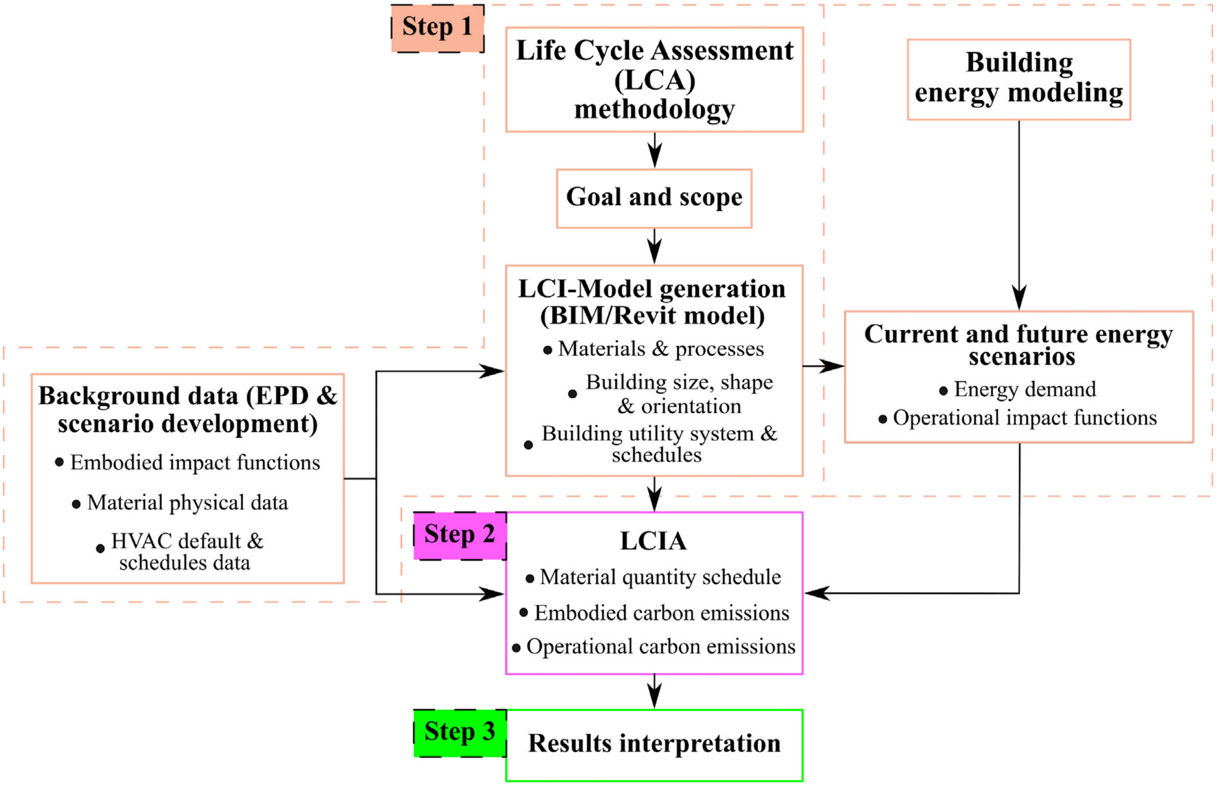

Fig. 1. Framework scheme of the LCA research methodology.

timber frame kit system to external leaf, insulated with the high-performance thermal layer in the wall and the roof, and sheathed with oriented strand board (OSB). The ground floor and foundations are made of a reinforced concrete slab with three layers of expanded polystyrene (EPS) insulation. The internal walls are made of timber stud framework and insulation in between with sheets of plasterboards on both sides. The construction details for the external walls, roofs, internal walls, and foundation of the studied building system are described in Appendix A.2 in Supplementary Materials. The building benefits from the application of argon gas-filled triple glazing with high-performance UPVC framing. In the reference case building model (*i.e.,* BS1), the cooling and heating are provided by a combination of mechanical ventilation with heat recovery (MVHR) and an efficient condensing gas boiler that is directly connected to the storage tank. Based on the target from UK's building regulations, resulting from the implementation of nearly zero-energy buildings (nZEB) targets, the adoption of low-carbon technologies (*e.g.,* electric heat pump) could achieve a substantial reduction in the energy consumption of buildings (D'Agostino, 2015). Moreover, to further reduce energy consumption, the use of heat pumps when combined with the photovoltaic system is a solution of current interest for the UK's building policies which plays a crucial role in the energy balance of an nZEB (De Masi et al., 2021; EASAC, 2021). Therefore, three strategies that are among the widely applicable HVAC systems in UK houses are implemented through efficient energy options: (i) a gas-fired boiler + MVHR (*i.e.,* reference case BS1); (ii) an electric compact heat pump unit as a replacement for condensing gas boiler and MVHR (*i.e.,* BS2); and (iii) a photovoltaic system along with the electric compact heat pump (*i.e.,* BS3).

The compact heat pump unit is an 'All-In-One' Air-to-Water and Air-to-Air system for a complete home climate solution with a seasonal coefficient of performance (SCOP) equal to 5.11. The main thermal characteristics of the building envelope components and integrated technical systems are given in Appendix A.3 in Supplementary Materials.

Based on the real data obtained from the as-built construction drawings, the BIM models were developed by Autodesk Revit (Autodesk, 2021). The embodied environmental impacts are obtained from product-specific EPD data and the scenarios development procedure of the processes in the model (see Section 2.2.3.1). The measurement of operational energy use is performed using DesignBuilder (DB) v6.1 energy simulation software to quantify the annual energy consumption (DesignBuilder, 2021). The DB software calculates the operation phase of the dwelling including energy systems from households' use of heat energy and electricity for space and water heating, and lighting (de Rubeis et al., 2018). These parameters were assessed according to the UK-based building standards and the ASHRAE-approved heat balance method using real hourly data from the EnergyPlus database (EnergyPlus, 2022). The life cycle operational flow used in this LCA study is further elaborated in Section 2.2.3.2. To evaluate the effect of varying the composition of the energy source in building operations, a dynamic dataset is explored to account for the development of future electricity mixes in a sensitivity analysis (see Section 2.4.1). For these scenario predictions, official national statistics of energy mix over the lifespan of the building are combined with data describing these processes from Ecoinvent (Wernet et al., 2016), and analyzed in SimaPro (Pré Consultants, 2022).

The electricity produced from the PV system is injected into the grid displaces, and therefore, according to the UKGBC 'Renewable Energy Procurement & Carbon Offsetting Guidance for net zero carbon buildings' (UKGBC, 2021), it is assumed that offsets produced by exporting on-site produced electricity can be discounted from the operational emissions. The carbon savings are calculated using the same amount of emission intensity of the low-voltage electricity grid for that given year. Fourteen multi-Si PV panels are mounted on the roof with an efficiency of 15.4 % and a total peak power of 3 kW. The solar PV component was simulated using PVsyst (PVsyst SA, 2022), and quantified an average annual electricity generation of ~2630 kWh/y. Appendix A.4 in Supplementary Materials reports the technical specifications of the solar PV panels.

2.2.2. Research goal and scope

The initial part of the model constitutes the goal and scope definition, where the research goal, system boundary, functional unit (FU), and reference study period (RSP) are analyzed. The research goal is to evaluate the

GHG emissions of a representative timber-frame low-energy building based on a standard practice of LCA as a reference point (*i.e.,* baseline scenario). The baseline scenario represents the current LCA practice employed, as suggested by EN 15978 (Bianco et al., 2017; CEN, 2011; RICS, 2017). In this model, we performed the LCA system using static characterization factors and assuming the current technologies and practices remained constant into the calculation, whereas other prospective scenarios are compared with the baseline scenario to discuss the potential changes by parameters describing alternative future developments (Andersen et al., 2022; Fouquet et al., 2015). To initiate this task, the present paper compares three different levels of HVAC strategies, including a gas-fired boiler + mechanical ventilation with heat recovery (MVHR), an electric compact heat pump unit (SCOP: 5.11), and an electric compact heat pump unit (SCOP: 5.11) + 3 kW photovoltaic (PV) panels. More importantly, to better represent the possible development of technological progress to climate change mitigation at the national level, a sensitivity analysis is investigated to assess the influence of future scenarios of the electricity mix pathways and the technological changes in waste management treatments of timber materials.

The FU defines the quantification of the identified function of the studied systems, which is the basis for the quantification of all environmental impacts (de Simone Souza et al., 2021; ISO 14040, 2006). One square meter of gross internal area (GIA) is proposed as a FU to compute the impacts on the buildings; this choice allows further contributions with other studies and building benchmarks (LETI, 2021). According to the Royal Institution of Charted Surveyors (RICS) (RICS, 2017), an average RSP of 60 years was chosen for the service life, which is the standard lifespan of UK buildings and consistent with the Green Guide to Specification standard (BRE, 2021).

The modular structure setup from EN 15978 (CEN, 2011), as shown in Fig. 2, is considered in this study to allow the incorporation of the whole model of the building's life cycle, including the production stage (modules A1–A3); construction process stage (modules A4–A5); use stage, differentiated into modules related to embodied impacts (modules B1–B5) and impacts from operational energy and water use (modules B6–B7); end-of-life (modules C1–C4); additionally, the benefits and loads beyond the system boundary (module D). Building material boundary corresponds to the imported raw materials under study which they characterized in the area, including the building structure, finishing elements, and mechanical systems (such as concrete and cement products, steel and other metals, insulation, plastics, painting, …). Sanitary fittings and installations are excluded from this study. It should be noted that the details pertaining to the goal and scope used for the LCA are consistent with the RICS guidance (RICS, 2017) to enable investigating the whole life carbon assessment of the building case studies and the possibility of comparison with the target values (LETI, 2021).

2.2.3. Inventory analysis

In the LCI, the primary data of resources and energy consumptions are collected for modeling the foreground processes and the datasets for quantification of relevant inputs and outputs throughout the product life cycle are elaborated (Wang et al., 2022a, 2022b). The primary data related to the amount and type of building materials used is performed based on a BIM/Revit model (Autodesk, 2021). The BIM model (*i.e.,* level 2 standard) is generated based on the building design layout and the data about construction products provided by the construction company. The data quantities exported from the BIM model were then post-processed to provide the accurate mining and aggregation of the materials used in the building design (Maierhofer et al., 2022). The materials obtained based on the BIM model are grouped with similar functions in general waste treatment categories, for example, concrete, timber and timber-based, steel and other metals, oil-based (*e.g.,* expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PUR)), inert (gravel, plasterboard, paint, render, and adhesive mortar), composite (windows, and doors), *etc.* The list of quantities of material categories for different building case studies is presented in Appendix A.5 in Supplementary Materials. In the energy simulation, the material information provided by the BIM model has been used as the input for the thermal analysis.

To deliver reliable and consistent results, the data collection process, scenarios development procedure, and cut-off rule are considered in this step (AzariJafari et al., 2021). The cut-off rule, as indicated in EN 15804 (CEN, 2019), is applied to the processes within the system boundaries described in Section 2.2.2. This means that data needs to correspond to the system boundaries set for the assessment. Based on this, the cumulative total of all neglected inputs should not exceed 5 % of energy usage and mass allocated, while it is a maximum of 1 % for each unit process. However, this cut-off rule does not apply to hazardous materials and substances.

2.2.3.1. Life cycle embodied flow. As a data collection and calculation process, the use of product-specific data in the form of third-party verified EPD for each material/product based on the local market could obtain not only consistent and accurate life-cycle inventory and data, but also

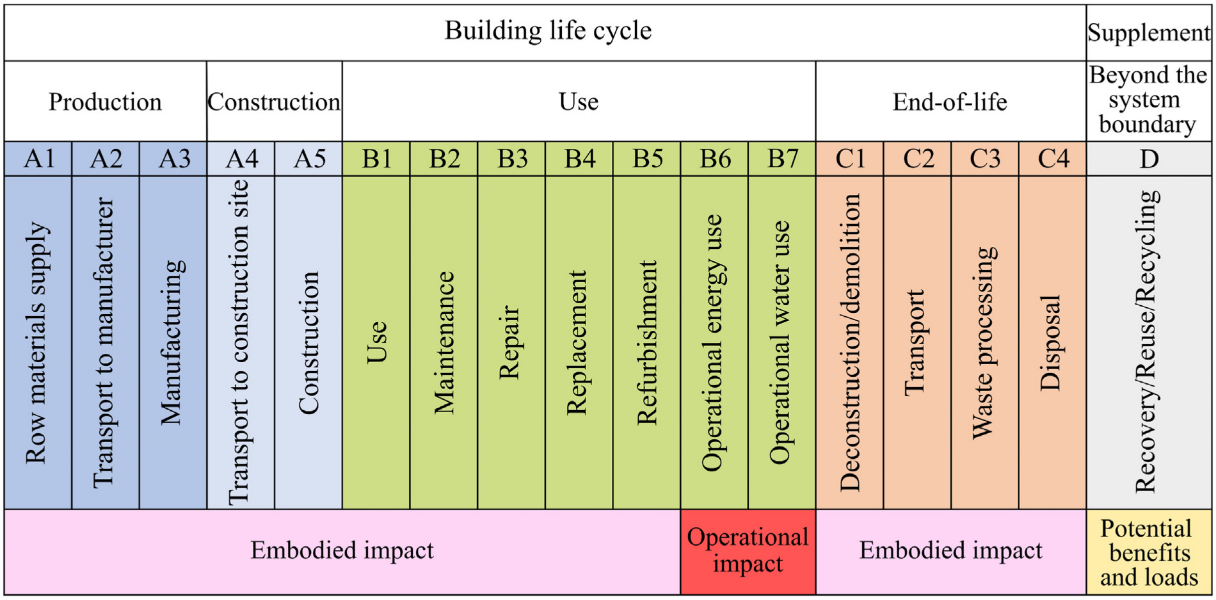

Fig. 2. Building's life cycle stages from EN 15804 and EN 15978 (CEN, 2019, 2011).

provide comparable and transparent LCA results (CEN, 2011). EPDs summarise the description of the product's life-cycle environmental impact that has been developed in accordance with the standardized product category rules, which are transparent and verified documents (Honarvar et al., 2022). As the main source of information used in this environmental assessment, we resorted to several EPD databases to collect nationally published EPDs of materials that exist in the UK market (*e.g.,* The International EPD System (EPD International AB, 2023), Wood for Good Lifecycle Database (Wood for Good, 2023), ECO Platform (EcoPlatform, 2023), and GreenBookLive (BRE Group, 2023)). The shortcomings of the datasets were carefully retrieved from European countries with a similar carrier portfolio to the UK (*e.g.,* Netherlands, Ireland, and Belgium). All EPDs selected in this study were produced to the following requirements of EN 15804 (CEN, 2019), due to EPD standardization, and the comparability of EPDs, as well as inconsistencies in the material denomination. However, the use of EPD data at different stages to conduct a whole building's life cycle presents several challenges, as EPDs are based on one probable scenario and they are not always context-specific (AzariJafari et al., 2021; Fufa et al., 2018). In this study, according to RICS (RICS, 2017) guidance, the most accurate information data for modules (A1–A3), (B1–B3), (C3–C4), and (D) are retrieved from the manufacturers' EPDs. For the remaining life stages and to increase consistency, the background data are obtained based on a project-specific basis (*i.e.,* considering the project location, anticipated operation, and waste management scenarios) (RICS, 2017). In this sense, the scenarios development procedure is employed to clearly identify the appropriate assumptions and estimations for the UK conditions, according to the RICS and IStructE guidance (IStructE, 2022; RICS, 2017), when the data situation is unclear (Wang et al., 2022a).

To estimate the emissions of transportation from the manufacturing facility to the construction site (A4), building elements are classified into three transport categories depending on the product sourcing locations and the default scenarios of the UK's projects specified by RICS (RICS, 2017). These categories are used in combination with the standard transportation distances and applied in the datasets (Appendix A.6 in Supplementary Materials). The impact from the construction energy use (A5) is calculated for the fuel (*i.e.,* electricity, and diesel) consumption of on-site equipment for wood frame buildings using the estimated values of 15 MJ/m^2 of diesel and 2 kWh/m^2 of electricity (Balasbaneh and Sher, 2021). Moreover, the NetWaste (WRAP, 2008) factors are accounted for material wastage of the activities during the construction of the building and then applied to the overall values of inventoried construction materials from the production stage (Appendix A.7 in Supplementary Materials). The UK Government emission conversion factors (BEIS, 2021) are used for the carbon equivalent (CO_2eq) impact of electricity, transport, and fuel consumption.

Any carbon emissions released from building components (*e.g.,* refrigerant leakage by the mechanical systems), and the impact of potential carbon uptake of concrete during the life of the building are accounted for the module B1. Calculation of the emission concerning the refrigerant leakage is based on the manufacture report, while the assessment of carbonation is explained in Section 2.3. To calculate the impacts of materials with lower estimated service life (ESL) than the reference study period (RSP) of the building, the quantity of new items and their end-of-life stage and transportation to the site needed for regular maintenance and replacements are modeled based on the material use percentage and life expectancy of different components and systems (Appendix A.8 in Supplementary Materials).

During the end-of-life (EoL) stage, the most environmentally feasible option is selected, as it is assumed that the actual practices will be the same at the end of the lifespan (Larivière-Lajoie et al., 2022). The carbon emission from any deconstruction and demolition activities (C1) is estimated based on an average value for building demolition of 3.4 kgCO_2eq/m^2 (GIA) (RICS, 2017). The transportation of waste to the disposal facility or intermediate waste processing location (C2) is calculated with a standard distance of 50 km (Hart et al., 2021). In processing and disposal of the waste treatment and any benefit beyond of system boundary (C3–C4, and D), the percentage allocation of waste materials going to different treatments is based on the current practices and facilities of the building sector in the UK for different types of waste materials, as assessed jointly with the construction company based on the representative EPDs of the chosen building context. When the data for the product's end-of-life is not reflected in the same context as the UK waste practices defined in the RICS recommendation (RICS, 2017), the EPDs used can allow the building assessor to choose and calculate the correct scenario based on the assumption that 100 % of the material was disposed of solely *via* one means (Barrett et al., 2019). For those with unavailable data, the default carbon factors according to the IStructE (IStructE, 2022) guidance are considered in the calculation. The default rates for the EoL situation of the building elements are summarized in Appendix A.9 in Supplementary Materials. According to UK practices, 90 % of the general waste mass is recycled or recovered at the end-of-life of the buildings and used for a secondary application (RICS, 2017); however, wool insulation and gypsum board are assumed to be sent to the landfill (Balasbaneh and Sher, 2021). For timber materials, one aspect of the EoL stage is the considerably sensitive results to the inclusion of biogenic carbon (Peñaloza et al., 2016), which has already been discussed in Section 2.3. Another important aspect is how timber materials are treated after demolition. According to the RICS recommendation and in line with the Department for Environment, Food and Rural Affairs (DEFRA) of the UK (DEFRA, 2012), the assumption made for timber waste materials was that 25 % is considered to be landfilled (with no gas recovery) and 75 % incinerated with energy recovery (to generate electricity). It is used for the baseline EoL scenario for timber materials; however, this is a conservative approach, as the implication of landfilling wood in the UK is declining (Symons et al., 2013), and consequently, recycling and biomass recovery of timber is expected to become an increasingly common practice in the upcoming years (Peñaloza et al., 2016). With respect to this advantage from a sustainability perspective, the scenario analysis for modeling different future waste treatments of timber materials is carried out in Section 2.4.2. Concerning timber degradation in landfill, a proportion of carbon contained is released into the atmosphere as CO_2 and methane (CH4) (note that CH4 has a GWP 25 times higher than CO_2 (IPCC, 2007)). In this study, it is assumed that 20 % of the timber is decomposed into carbon, from which 60 % into CH4 and 40 % into CO_2, and none of the landfill gas is recovered, as this is the common practice for timber waste management in the UK (Symons et al., 2013). The key parameters used for the carbon impact of the timber EoL scenarios are shown in Appendix A.10 in Supplementary Materials. It should be noted that the benefits and burdens regarding the reuse, recovery, and recycling of materials after the end-of-life are included to measure the influence on the results but are accounted for separately to the system boundary according to EN 15978 and EN 15804 (CEN, 2019, 2011).

2.2.3.2. Life cycle operational flow. The dynamic building energy simulation is performed using DesignBuilder (DB) for the energy assessment of environmental performance during the operational stage of the case studies (DesignBuilder, 2021). The data exchange from BIM/Revit model was first exported as a gbXML file and then imported into DB. The default DB profiles were applied harmonized with the 'standard user' based on the local climate conditions, and characteristics of the building shell extracted from the models' information, while the energy use pattern and users' behavior parameters are set according to the SAP 2012 (BRE, 2014), and ASHRAE guide (Ben and Steemers, 2014). The DB model was generated according to the analytical model and included the building envelope which they have a significant impact on the overall U-value of the building (Bughio et al., 2021). The weather file used for this study is extracted from the EnergyPlus database (EnergyPlus, 2022) and used in DB simulation software. Operational emissions are calculated by linking final energy results from DB to the specific fuel emissions factors (BEIS, 2021). A summary of the characteristics made in the energy simulations has been provided in Appendix A.11 in Supplementary Materials. As part of the operational use of water stage (B7), it is assumed that the house is occupied by 2.3 people for an average UK household unit with daily water consumption of 150 L per person per day (Cuéllar-Franca and Azapagic, 2012).

2.2.4. Impact assessment

After the data collection for each module, inputs, and outputs listed in LCI are assigned to the corresponding impact indicators of the materials and products throughout their life cycles to be consistent with the goal and scope of the study and then quantified to get the environmental impact results (Rosenbaum et al., 2017). In this study, the environmental indicators in terms of carbon dioxide equivalents (CO_2eq) *via* the Climate Change-Global Warming Potential (GWP100-year) are provided from published literature (*e.g.,* EPDs), and presented in metrics of the environmental impact functions for each life cycle module. The reason for this single indicator is two-fold: (i) it is based on the goal of the study in the response to the current climate crisis and follows the approach for construction types in the Green Guide to Specification (BRE, 2021); and (ii) it is an accurate indicator of the overall impacts and more often used as the sole impact metric on the environmental performance of the buildings, despite the risk of neglecting other environmental impacts such as; resource use, and resource depletion (Anand and Amor, 2017; Balasbaneh and Sher, 2021; Laurent et al., 2012). LCIA could be further developed to quantify environmental impacts through the application of impact factors over time (Röck et al., 2021).

2.3. Carbon sequestration

One of the features of bio-based materials such as timber consists of biogenic carbon. Biogenic carbon absorbs atmospheric CO_2 during plant growth involving photosynthetic processes and is temporarily stored in a bio-based product throughout its service life and then re-emitted CO_2 at its end-of-life through combustion or decay (Hoxha et al., 2020). It is common practice in the current LCIA methods (*e.g.,* EN15978 (CEN, 2011)) that do not account effects of biogenic carbon as a factor of climate change (Fouquet et al., 2015). As highlighted by multiple studies (Peñaloza et al., 2018, 2016; Santos et al., 2021), it is important considering biogenic carbon into account for a building composed of significant amounts of wood as can influence significantly the LCA outcomes of wood-frame buildings for climate change impact. However, there is no consensus on how to deal with biogenic carbon in LCAs, and therefore it can be a source of confusion (Hawkins et al., 2021; Hoxha et al., 2020). To avoid this, the present study assumed that the timber originates from sustainably managed forests consistent with the forestry practice (certified by the Programme for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC)), and the carbon assessment includes the whole of life cycle perspective (RICS, 2017). According to these suppositions, the biogenic carbon emissions from bio-based materials and residues are effectively zero, as the emissions are balanced through the sustainably managed forest on the landscape level. Therefore, according to RICS guidance (RICS, 2017), the biogenic carbon storage figures can be included in the product stage (A1–A3), effectively modeling sequestration as an instantaneous pulse but should be reported separately as a "negative emission" from storing the carbon. Consequently, an equivalent amount of this biogenic carbon is added at the EoL (C) stage of the product system instantaneously as it is re-released into the atmosphere or in the case of new material (*e.g.,* recycling) which is further transferred to a subsequent product system; however, in both cases with a "positive emission" impact (Hoxha et al., 2020). It is worth noting that the treatment of time for carbon emissions and the influence of rotation periods (due to slow forest growth and carbon absorption) of the bio-based material growth are not taken into account in this study, as it is assumed that the calculation of climate change impacts was based on static characterization factors (Lukić et al., 2021). The quantity of biogenic carbon sequestration in the wood products is taken in the material EPD, as this is now required to present separately as additional environmental information for EPDs specified in the latest version of EN 15804:2019 (CEN, 2019). When EPDs were lacking (for the case of EN 15804:2012 (CEN, 2012)), the estimation is calculated according to EN 16449 (EN 16449, 2014). It is assumed that the carbon fraction of woody biomass (dry) is 50 %, while the moisture content of 12 % is taken for timber materials.

In addition, an inherent characteristic of building cementitious materials (*e.g.,* concrete) is their ability to carbon sequestration through the process known as carbonation. The carbonation of concrete in buildings occurs over the lifespan of the products in the use phase (B1) and takes place also in the waste treatment phase (C3–C4), while burdens from replacement are directly accounted for in module B4 (resulting as a negative impact). The CO_2 uptake due to carbonation of the concrete is seldom investigated in LCAs (García-Segura et al., 2014) but is included in this study with the purpose of extracting important design drivers. For carbonation, product-specific EPDs are considered to account for when the information was available. If EPDs do not provide this information, as given in the IStructE guidance (IStructE, 2022), the estimation to take up a 2.5 % re-absorption part of the CO_2eq from the production stage (A1–A3) emissions throughout the use phase (B1) over a 60-year lifespan, and a further 5 % in the waste treatment phase (C3–C4) due to the surface area exposure after the crushing for recycling purposes (Hawkins et al., 2021; MPA The Concrete Centre, 2016).

2.4. Future scenario analysis

In this study, we applied scenario analysis to investigate how the system reacts due to the alteration in the mitigation potential of the environmental impacts. Scenario analysis is a type of sensitivity analysis often used in LCA to obtain robust design decisions (Khan et al., 2021). Therefore, the influence of decarbonization of future electricity mix, and changes in waste treatments of timber materials are analyzed.

2.4.1. Projections of the future electricity mix

After performing a baseline scenario using the current (static) energy modeling following the EN 15978 standard (CEN, 2011), we developed a dynamic energy modeling framework able to describe the sensitivity to some decarbonization scenarios. As shown in Fig. 3, the current electricity mix in the UK still heavily relies on fossil sources, where the share of the mix is 36 % from natural gas, wind 24 %, nuclear 16 %, solar 4 %, and others 20 % (DUKES, 2021). With the tightening regulation, the key climate policy was to drive the decarbonization of the electricity system (Pietzcker et al., 2021).

For the assessment of future decarbonization of the electricity mix, different prospective scenarios depending on the national context defined in Future Energy Scenarios (FES) are used. In this projection, two potential energy pathways are described based on the different speeds of decarbonization for the UK: "Steady Progression", and "Two Degrees" (FES, 2019). The "Two Degrees" can match the 2050 carbon reduction target of the UK and it indicates to reduce the GHG emissions by at least 80 % from the 1990 levels by 2050; while the slowest decarbonization happens in the "Steady Progression" scenario, which doesn't get to reach the target by 2050 (FES, 2019). The "Steady Progression" provides a usual approach to ensuring low costs for consumers and is expected to exhibit approximately half the rate of emissions reduction in 2050 (FES, 2019). Implementing the scenario "Two Degrees" paves the way for the fastest credible decarbonization journey by combining high consumer engagement and more "large-scale" centralized electricity generation. The description for these scenarios which are representative of the UK electricity projection is not detailed here but is reported in (FES, 2019).

The share of each technology used in electricity generation for the current electricity matrix (DUKES, 2021), and for future projections (FES, 2019), are presented in Fig. 3.

To calculate the yearly CO_2 emissions factors for a unit of the low-voltage electricity mix over the building lifespan, the annual average CO_2 coefficient of electricity production in 2020 (BEIS, 2021) is considered for different scenarios, while this CO_2 factor is fixed for the current situation (static) scenario over the lifespan. To compute the carbon factors of the projection scenarios, the future relative shares of electricity sources reported for certain moments (Fig. 3) are modeled with the corresponding energy source-specific unit impacts existent in Ecoinvent 3.8 (Wernet et al., 2016) using Simapro (Pré Consultants, 2022) according to the data

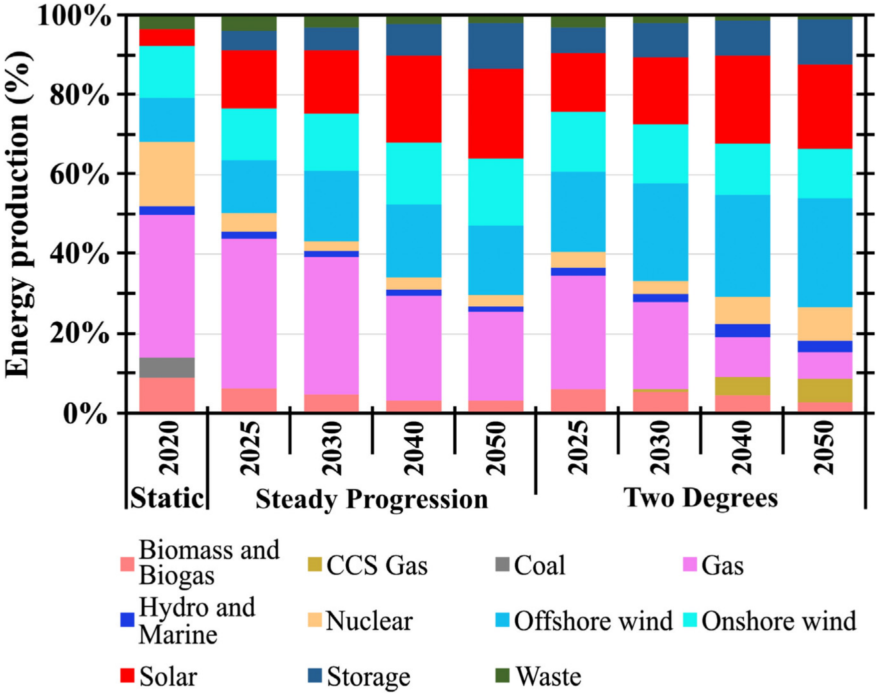

Fig. 3. Mix scenarios of electricity production in the UK (DUKES, 2021; FES, 2019).

described from the FES and the literature studies (Stamford and Azapagic, 2014; Zhao and Baker, 2022). It should be noted that the interconnection network (*i.e.,* import and export of electricity) and technological evolutions in the generation processes are beyond the scope of this study and are not considered (Appendix A.12 in Supplementary Materials). The conversion between different voltage levels and the electricity losses are accounted for in the product system (Itten et al., 2014; World bank, 2018). A gradual annual evolution of the electricity CO_2 factors is considered using linear regression to cover eventual gaps between the values obtained for the key moments over the 60 years of the building service life. As prospective scenarios are provided up to 2050, no further changes are assumed after this year, and thus the impacts of these emission levels are assumed to be identical until the end of the model timeframe. Appendix A.13 in Supplementary Materials shows the CO_2 emission factors in terms of kg/kWh electricity produced from different scenarios.

2.4.2. Additional timber scenarios

Given the long lifespan of buildings, the potential alternative solutions from current waste management practices to future scenarios are considered as it is a significant factor for the embodied carbon reduction of timber materials (Robati and Oldfield, 2022). Two additional scenarios are included to provide different possible results for the end-of-life of timber materials, alongside the initial approach already described. An alternative scenario is proposed in which the current waste management practice of timber materials indicated in the baseline scenario is developed to consider future technologies to achieve higher emissions reduction. An optimistic “BECCS” scenario explores the potential future ability impact of the sequestration of CO_2 at EoL, through a combination of two well-known technologies: bioenergy and carbon capture and storage (CCS) (Jeswani et al., 2022). The latter is particularly important as it plays a significant part in the Climate Change Committee's framework for the UK to help achieve the net-zero emissions target by 2050 (CCC, 2019). Due to the already significant BECCS for the UK plans (20 to 70 Mt. CO_2 annual negative emissions (Smith et al., 2016)), and the arguably greater potential of biomass sources to balance GHG emissions, we focus on quantifying the role of this option that could reduce emissions of biogenic CO_2 back to the atmosphere in a geological formation (Almena et al., 2022). At present, the deployment of BECCS is often described as context-dependent, and it still requires time to be established on a centralized large scale (Almena et al., 2022). According to the UK's strong policy incentives and attractive feedstock of waste wood for future BECCS application (due to appropriate technical characteristics and economics) (Cooper et al., 2019; Hawkins et al., 2021), it has been demonstrated that this technique can capture 90 % of the CO_2 emitted in the combustion of timber waste treatment from the power plant (CCC, 2019; Leonzio et al., 2023). Similar carbon removal from the combustion processing is considered in the BECCS scenario of the present study.

This study also analyzes another deterministic scenario that considers future penetration strategies from existing technologies (Hart and Pomponi, 2020). Based on this vision, the current pressure to minimize climate change impacts is forcing us to keep waste out of landfills and to increase the proportion of recycling rate (Peñaloza et al., 2016), as the recycling process would likely result in a delayed re-release of biogenic carbon (Hawkins et al., 2021). In line with this, Wood for Good (WfG) LCA proposed 55 % recycling of products such as animal bedding or particleboard, 44 % incineration for energy recovery, and 1 % disposal in a landfill (Wood for Good, 2017). Information on the unit processes used for the EoL scenario of timber products is included in Appendix A.10 in Supplementary Materials.

3. Results

The results obtained are interpreted by performing contribution and sensitivity analysis in two aspects: (i) evaluate the GHG emissions of the building's case studies with an LCA in accordance with EN 15978 standard as a baseline scenario and compare the results with UK benchmarks for developing knowledge area; and (ii) the parametric study of the influence of the decarbonization of electricity production and changes in the waste treatment of timber on the GHGs results.

3.1. Life cycle impact assessment of baseline scenario

Fig. 4a presents the variation of the baseline cumulative life cycle (embodied + operational) emissions of the different case studies, including the benefit of the PV system in terms of avoided emissions over the 60-year time horizon, and Fig. 4b makes a distinction between operational and

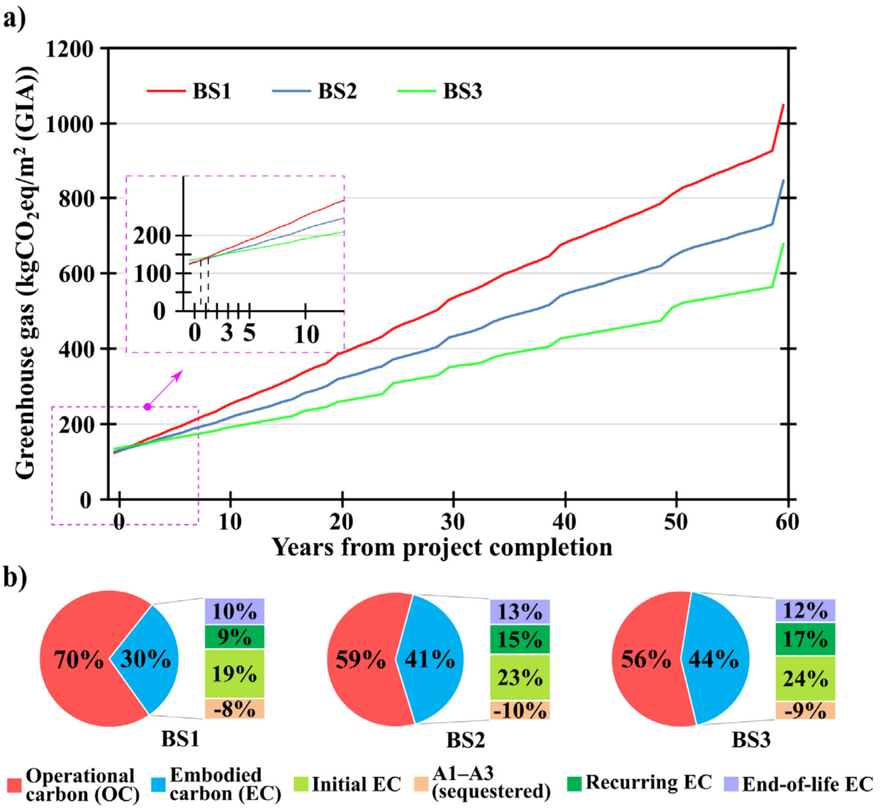

Fig. 4. Building life-cycle emissions for different case studies for (a): Total cumulative GHG emissions over a 60-year; and (b): Contribution of embodied and operational carbon emissions to the whole life-carbon. (Note that this figure considers the baseline scenario, assuming the current electricity mix scenario and RICS scenario for waste treatment of the timber materials.)

embodied impacts of the buildings (detailed results can be found in Appendix A.14 in Supplementary Materials). The initial peak is due to the increase in the emissions of both production (A1–A3), and construction (A4–A5) stages, as we assumed they happen in the same year (see Fig. 4a). The contribution of the production (A1–A3) stage in this figure includes manufacture (fossil) emissions and sequestered (biogenic) emissions. Comparing the life cycle outcomes, it can be noted that they have the same trends while showing an advantage associated with the case studies using the heat pump and/or renewable technologies (*i.e.*, BS2, and BS3), being primary due to their more efficient energy systems and relative to a cleaner combination of energy consumption. As shown in Fig. 4a and Appendix A.14 in Supplementary Materials, the annual saving for the case study using a compact heat pump unit (*i.e.*, BS2), is responsible for ~19 % fewer emissions during the 60-year time horizon with respect to the case study equipped with condensing gas boiler (*i.e.*, BS1). Adding the PV panel to the heat pump (*i.e.*, BS3) significantly reduces the amount of grid electricity, therefore lowering the cumulative emissions by ~20 % compared to the BS2; while the environmental benefits can be also reinforced when the PVs are associated with the heat pump, as ~36 % fewer emissions relative to BS1 are achieved.

From Fig. 4a, the case studies BS2 and BS3 have around ~6 %, and ~17 % higher impacts, respectively, during the first year compared to the reference case study, due to the additional initial embodied emissions related to the production and construction process of those pieces of equipment and PV system (*i.e.*, modules A1–A5). However, due to a lower annual OC emissions rate during the 60-year lifespan of the dwelling, the case studies designed with better (advancements) energy improvement options (*i.e.*, BS2 and BS3) outperform the case study with the installation of a heating condensing gas boiler (*i.e.*, BS1).

As shown in Fig. 4b, the share of operational and embodied emissions to whole life-carbon for the different case studies are represented to 56–70 %, and 30–44 %, respectively. Since the building structure and enclosure were similar in each case study, regardless of the significantly larger effects of OC emissions on the total emissions, the EC of the case study buildings differs at most by ~25 %. The contribution differences associated with the EC in the different life cycle stages can be attributed to two factors: (i) tend to have higher emission-intensive materials of the technical equipment and PV system; and (ii) the relatively high maintenance and replacement of the heat pump-based buildings (due to the direct emissions from refrigerant leakage in BS2 and BS3) than the heating gas boiler-based building (*i.e.*, BS1). These observations are comparable to previous studies of low-energy buildings that discuss how advancements in buildings' operational energy performance led to an increase in embodied loads' contribution (30–60 % of life cycle GHG emissions) (Larivière-Lajoie et al., 2022; RICS, 2017; Röck et al., 2020).

Moreover, the carbon payback period (CPBP) is determined to indicate how long it would take for the operational savings to outweigh the increase of the EC caused by implementing a certain CO$_2$eq mitigation process (Roberts et al., 2020). As shown in Fig. 4a, the CPBP of the increase in the embodied impact emission of the strategy that focuses on the use of heat pumps (*i.e.*, BS2) is 1.7 years. The increased implementation details existing in the building coupled with heat pumps and PV system (*i.e.*, BS3) resulted in a CPBP of 2.2 years.

The contribution analyses of the EC (in kgCO$_2$eq per m^2 (GIA)) are presented in Fig. 5 for the reference case study (*i.e.*, BS1). The contribution analysis is performed to understand the influence of the choices of the different parameters on the EC, including the life cycle modules, the building element families, and the classification of the emissions into the material categories. The first notable part of the Sankey chart is the allocation of the emissions into the distinct life cycle modules according to EN 15978 (CEN, 2011), as presented in Fig. 5b. The A1–A3 (manufacture) represents the most significant single contribution toward the EC emissions of the building due to the extraction of raw materials as well as the transportation and manufacturing of the building materials. Modules A1–A3 (manufacture)

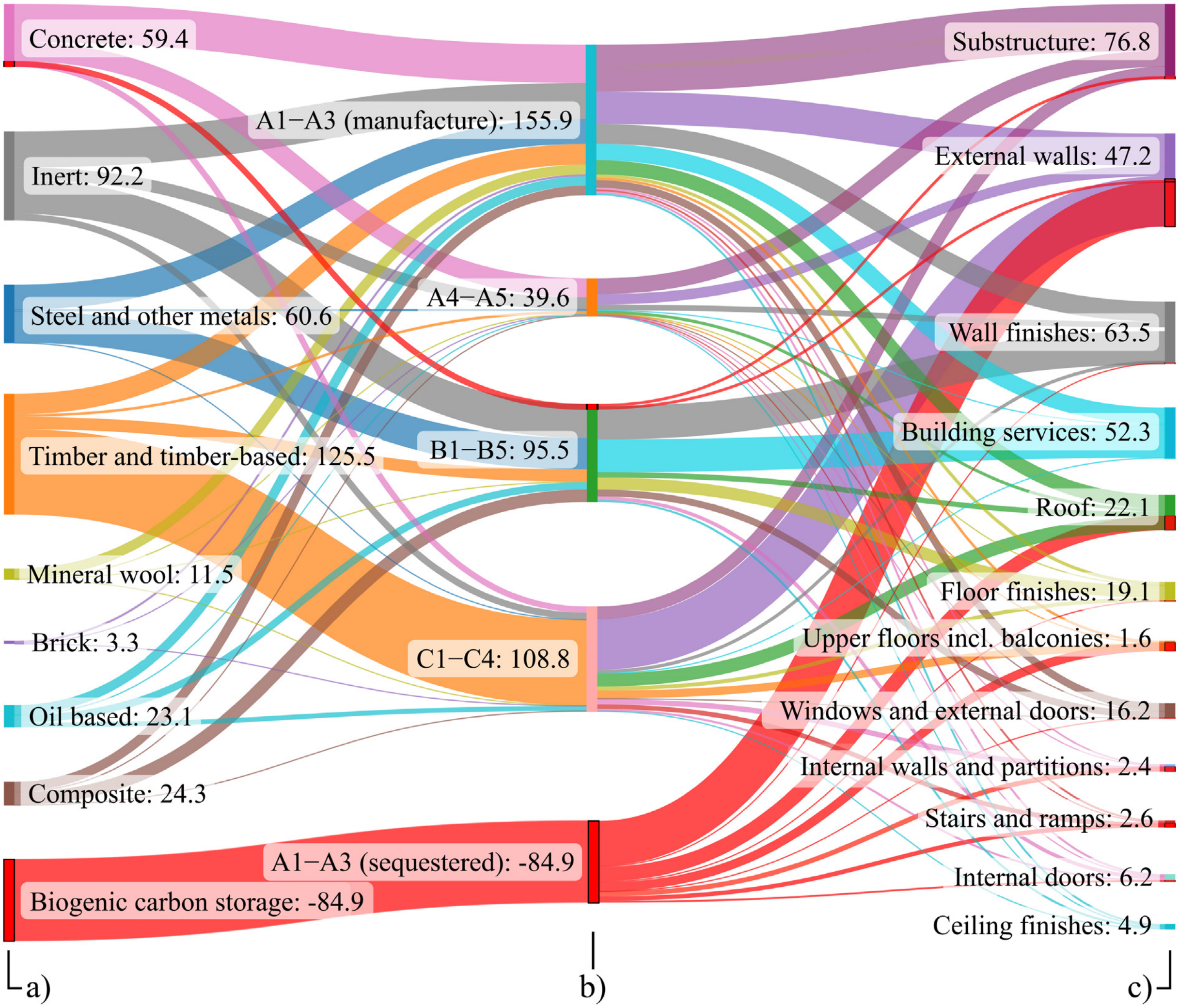

Fig. 5. Embodied carbon emissions of the reference case study in $kgCO_2eq/m^2$ (GIA). It allocates the emissions into three parameters: (a): Material categories based on general waste treatment practices; (b): Distinct life cycle modules according to EN 15978 (CEN, 2011); and (c): Building element families according to the RICS guidance (RICS, 2017).

are responsible for 32 % of the EC calculated (*e.g.,* 155.9 $kgCO_2eq/m^2$). In terms of the in-use stage (B1–B5), GHG emissions have 95.5 $kgCO_2eq/m^2$ (*e.g.,* ~20 % of the EC), mostly because of the contribution of the replacement during the service life of the building (B4), which highlights the importance of recurring EC to the total impacts.

The EoL stage has a considerable contribution to the GHGs emitted by 108.8 $kgCO_2eq/m^2$ emission over the whole building life cycle (*i.e.,* ~22 % of the EC), which is mainly due to impacts from the emissions associated with the incineration of timber materials in waste processing and final disposal (*i.e.,* released back the carbon sequestration into the atmosphere). The scenario for biogenic carbon storage of the timber materials associated with modules A1–A3 (sequestered) is caused by −84.9 $kgCO_2eq/m^2$ emission (*e.g.,* by avoiding 16.55-ton CO_2eq, equal to ~18 % reduction of EC over 60 years), in which a negative sign indicated an environmental gain.

In terms of the construction stage (A4–A5), the transportation of concrete and inert materials resulted in higher carbon emissions, accounting for ~50 % of the total construction stage emissions. However, the results also show that the emissions associated with this stage are not relatively significant compared to other life cycle phases, resulting in ~8 % of the EC emissions.

Another notable result derived from Fig. 5c is the emissions in the distinct life cycle modules in relation to the element contribution, which points to further details of the EC emissions. The higher GHG is induced by the contribution of the "Substructure" system, accounting for ~50 % of the emissions in modules A1–A3 (manufacture) and ~24 % of the EC emissions calculated. The reason for this is that the "Substructure" is comprised almost entirely of concrete and steel, which tend to have significant embodied emissions when it is used in much larger amounts than other building materials. The embodied emission of the exterior enclosure (*i.e.*, clustering "External walls", "Windows and external doors", and "Roof") is responsible for ~27 % of total EC emissions. Due to the use of extensive timber materials in "External walls", and "Roof", their GHG impact are decreased by 50 % and 40 %, respectively.

The third largest contribution to the total embodied impacts is the "Building services", being mainly by "Steel and other metals", which are generally allocated a high fraction of EC emissions and need to be replaced on a regular basis during the use stage. This is assessed by adding 52.3 $kgCO_2eq/m^2$ (*e.g.,* ~10.19-ton CO_2eq) to the overall GHGs.

The results identified architectural finishes as a significant impact contributor (~28 % of the EC emissions), which are mainly driven by the high replacement rates of the building elements associated with the silicone-based render and the paint for the "Wall finishes", as well as the vinyl floor covering for the "Floor finishes". These elements accumulate large amounts of EC over the building lifespan while their recurring embodied contributions can be comparable to or higher than the values of their initial embodied impacts (A1–A5).

Finally, the GHG emissions are also allocated to distinct material categories in Fig. 5a. It can be observed that the "Timber and timber-based" material used in the building envelope components (*e.g.,* "External walls" and "Roof"), stands out as the major contributor to EC emissions (~26 %). The substantial contribution of the "Timber and timber-based" materials is mainly originated from end-of-life treatment (*i.e.,* incineration processing), as they are representing a relative share of 82 % of the demolition EC emissions. Therefore, the choice of changing the waste management treatment of timbers can be identified as a key parameter to reduce the environmental impacts of a timber building, which is further illustrated in Section 3.3.2. The results implied that "Inert" materials (*e.g.,* plasterboard, paint, and render), a component mainly of the finishes, were the second highest contributor to the EC emissions (~19 %), followed by "Biogenic carbon storage" (~ −18 %), "Concrete" (~12 %), and "Steel and other metals" (~12 %). According to Fig. 5a and Appendix A.14 in Supplementary Materials, there is also a substantial contribution from "Oil-based" and "Mineral wool", accounting for ~7 % of the EC emissions in each case study (for both material categories, it is mainly due to having the high-intensity insulation materials embedded in the building envelope components), whereas the quantity of these materials is less than ~1.5 % of the total weight. It is important to point out here that if the concern is to reduce further emissions of the EC emissions, the designer should focus on a careful selection to replace these materials, with an alternative that reduces materials' quantity or emission intensity (these suggestions would serve the same purpose and with similar functionality to the project (Pamenter and Myers, 2021)). For this purpose, the substitution of the cement with supplementary cementitious materials (SCMs) (*e.g.,* ground granulated blast-furnace slag (GGBFS), a by-product of the steel industry) in ordinary Portland cement (OPC) based concrete is the most common method used in the UK cement and concrete industries (Shanks et al., 2019). The average percentage of substitutions could increase to up to 50 % corresponding to a potential reduction in the UK industry that maintains the structural performance (Pamenter and Myers, 2021). By changing the raw materials mix from OPC-based concrete to 50 % GGBFS, the total EC emissions can be reduced by ~2 %. Similarly, insulation is changed to blown cellulose, instead of the rigid polystyrene board within the floor, and of the glass wool within the roof and external walls but with similar thermal performance. With this switch in the case study, the total EC emissions can be reduced by ~3 %, as a result of emission saving of the overall carbon sequestration within the product. Choosing resilient Linoleum floor covering instead of vinyl covering has less impactful alternative materials, as a result of the combination of natural renewable materials and high recycled content. This is assessed by saving ~1 % to the overall embodied impacts. Therefore, focusing on building elements with the greatest potential for improvement in the possible retrofit scenario of existing buildings or designing new buildings with the assessed low environmental impact substitutions can potentially achieve a noticeable reduction in EC emissions.

3.2. Comparison to benchmark

To further interpretation of the results obtained and understand if the analyzed case studies will match the UK's environmental targets, a comparison is made with the benchmark described in the LETI Climate Emergency Design Guide (LETI, 2020b). The LETI, developed by the London Energy Transformation Initiative, is a collaborative network of built environment professionals that proposed voluntary targets for the reduction of EC and OC for residential and non-domestic buildings (*e.g.,* offices and schools). These targets have been incorporated into the policy guidance to push the carbon emissions to become part of legislation to achieve net zero carbon (LETI, 2020b).

Fig. 6a shows the design targets of the LETI for the ambition across various typologies and portfolios of total EC emissions (A1–B5, C1–C4, including sequestration) based on an A++ to a C rating system (LETI, 2021), and the performance of all case studies. The embodied carbon targets are assessed under consideration of the whole life-carbon assessment and the building elements required in RICS while excluding refrigerant leakage and renewable electricity generation (*e.g.,* PVs). From this figure, the LETI provides metrics aligned with the letter banding for residential buildings as follows: LETI 2020 Target, it should be equivalent to letter banding of C (less than 800 $kgCO_2eq/m^2$ (GIA)); and LETI 2030 Target, equivalent with letter banding of A (less than 450 $kgCO_2eq/m^2$ (GIA)) (LETI, 2021). As shown in Fig. 6b in terms of operational energy, this standard also set out performance targets of 35 $kWh/m^2/year$ (GIA) (LETI, 2020b). The comparison of the results obtained in the present study with LETI targets showed that the case studies aligned with band A and meet not only the objectives for the EC of the year 2020 but also for 2030. With respect to operational energy, the case study BS1 does not meet the required performance target, while BS2 and BS3 can match this benchmark.

3.3. CO_2eq emission for different scenarios

3.3.1. Effect of decarbonization on electricity production

To facilitate a detailed comparison of the scenarios, the results for different case studies are displayed for the baseline (current electricity mix) scenario and two future electricity decarbonization scenarios. Fig. 7 shows the contribution of embodied and operational carbon emissions, benefits impact, as well as their relative saving GHG of the different case studies in relation to the baseline's reference case study (*i.e.,* BS1 in the current electricity mix) over a 60-year lifespan of the building. Overall, the total cumulative GHG impact of the case studies decreases significantly (~50 %)

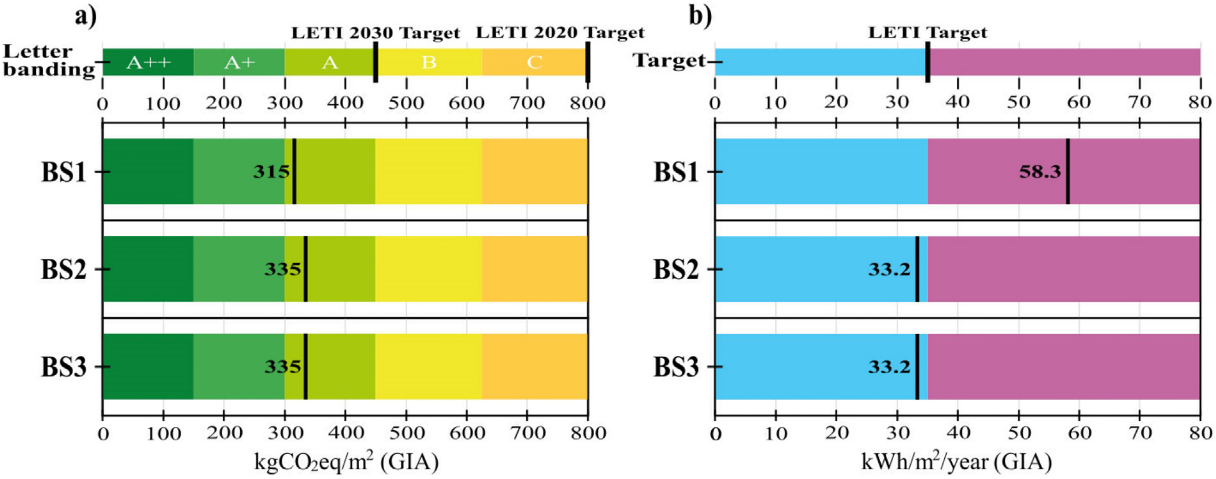

Fig. 6. The performance of the case studies and target values of LETI Climate Emergency Design Guide (LETI, 2020b) for (a): Whole embodied carbon emissions (excl. refrigerant leakage and PV system); and (b): Operational energy.

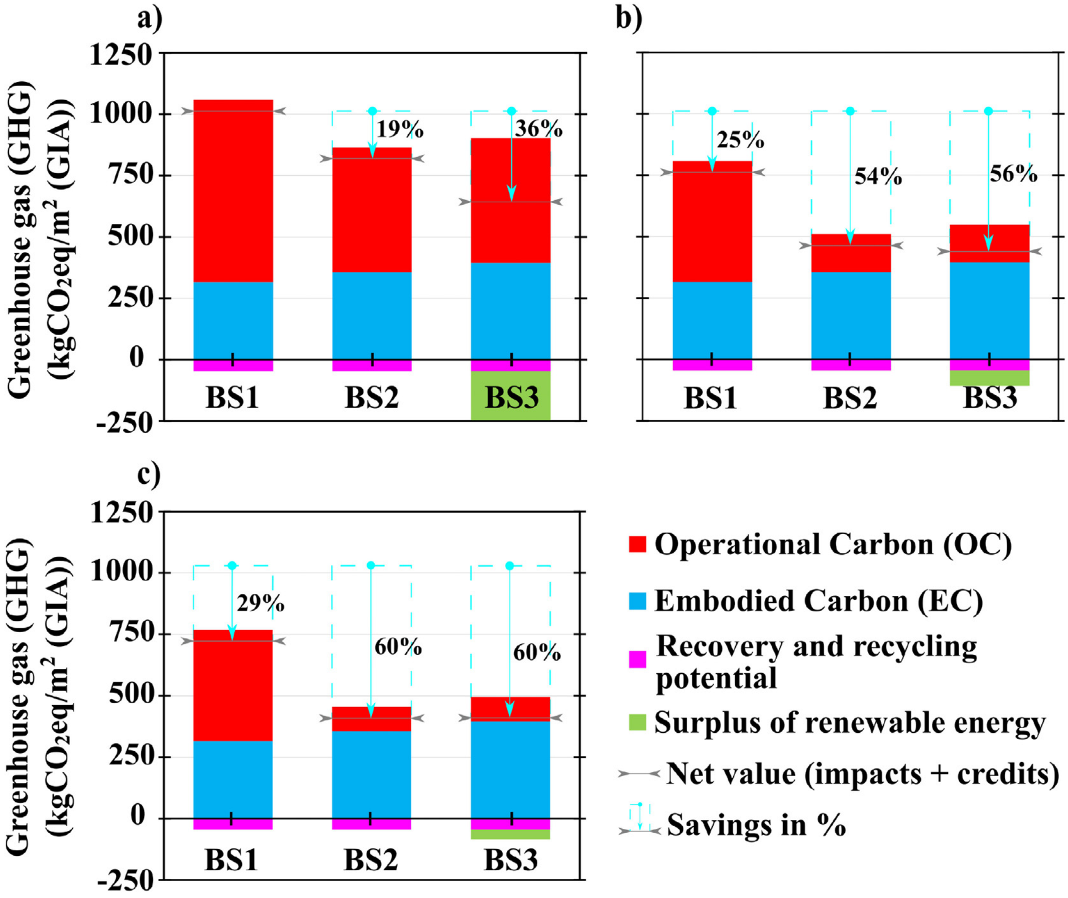

Fig. 7. The effect of decarbonization of electricity mix on greenhouse gas emissions for different case studies over the building lifespan. It includes three scenarios: (a): Static (current) energy mix (Note that panel a considers the same approach as Fig. 4); (b): Steady Progression; and (c): Two Degrees.

when the grid energy is shifting toward increasingly more renewable sources. For example, the two degrees scenario shows the highest improvement in GHG balance emissions, representing ~29 %, ~37 %, and ~50 % reduction in BS1, BS3, and BS2, respectively when scenarios using the same construction techniques are compared.

From the steady progression scenario, the case study BS3 can achieve a 56 % GHG saving over the building's life cycle relative to the baseline's reference case study, being essentially due to a full electricity-based HVAC, and thus, higher energy savings in the use phase and related benefits from an increase in the share of renewables. In this sense, it can be concluded that in order to get the maximum benefits from the electricity production sector and can support the clean energy transition in buildings, it is necessary to: (i) "electrification" the building elements (*e.g.,* from fossil-fuel-based to efficient electricity-based heat pump system); and (ii) improving electricity generation in the cleanest possible way (*e.g.,* two degrees scenario).

Considering the future electricity scenarios (Fig. 7), the benefit from the surplus (PV) electricity production over the building's life cycle is significantly reduced when the electricity grid becomes more decarbonized. This is due to the assumption that the benefit provided by the delivered electricity generation by the PV system is accounted to have the same emission intensity given the evolution of the electricity grid over the lifespan of the building, while the PV modules have the same efficiency of today's perspective. This can be explained by the fact that, if future electricity production is made to more renewable sources, the net performance of PV systems (*i.e.,* impacts + credits) are lowered, while also breaking even; as an example, in certain scenario of the BS3 compared to the BS2 in the two degrees scenario, which this technology produces negative credits to the system during its lifespan, and consequently, the CPBP of PV system exceeds the whole building service life.

From Fig. 7, as the OC impacts of the case studies are reduced significantly, due to improved technological systems and grid decarbonization, the magnitude of EC is increased dramatically. As an example, comparing the baseline's reference case study (*i.e.,* BS1 in Fig. 7a) with the case study equipped with the heat pump and PV panel in a prevalent grid decarbonization scenario (*i.e.,* BS3 in Fig. 7c), it can be seen the ratio between embodied and operational carbon from the current situation and future electricity mix may vary considerably (*e.g.,* ~30 % for BS1 in the current electricity mix, reaching ~500 % for BS3 in two degrees scenario).

3.3.2. Effect of technological progress on the waste treatment of the timber materials

In the previous subsection, a sensitivity of LCA results regarding the energy mix was illustrated. Additionally, the effect of waste management treatments of timbers is explored in a scenario analysis by considering alternative solutions.

Fig. 8 demonstrates the EC emissions differentiated into its modules to the building life cycle for the baseline scenario (as assessed by the RICS scenario) and two technological progress scenarios in the waste treatment of timber materials (*i.e.,* Wood for Good (WfG) and BECCS scenarios). The variation of EoL strategies of timber products has a significant impact on the EC reduction for the case studies by up to 23 %, under sustainable forest management and re-emitted the sequestered carbon at the product's end-of-life. Considering the improvement in the recycling share of waste treatment options (*i.e.,* Wood for Good scenario) for timbers in a cradle-to-grave basis of different case studies, could reduce EC impacts by ~3 % as compared to the same construction technology of the baseline scenario (Fig. 8a and b).

As shown in Fig. 8, the inclusion of environmental credits from the analysis can lead to different overall rankings between scenarios and the

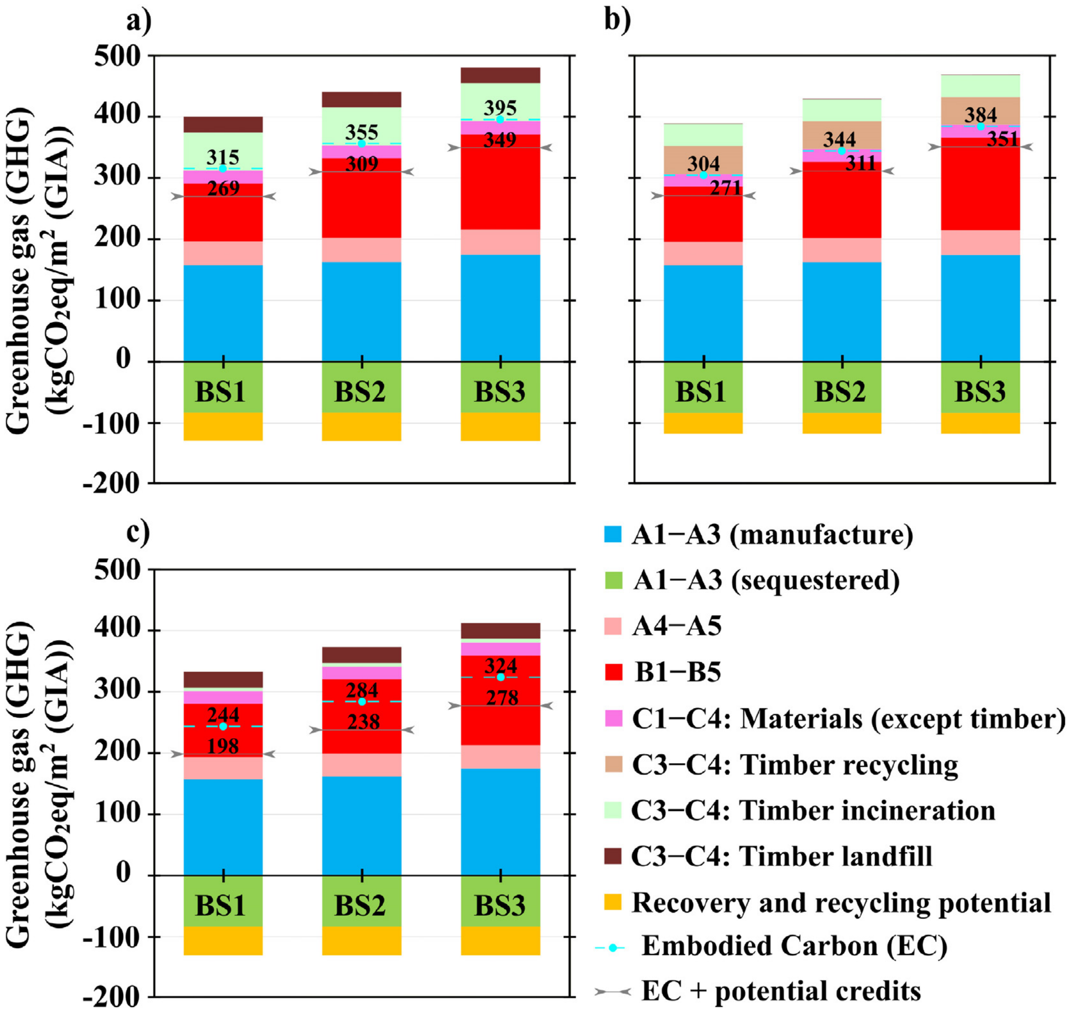

Fig. 8. The effect of technological progress in the waste treatment of timber materials on embodied carbon emissions for different case studies. It includes three scenarios: (a): RICS; (b): Wood for Good (WfG); and (c): Bioenergy with carbon capture and storage (BECCS).

relevance of life cycle stages. The figure shows that the case studies in the WfG scenario have ~2 % higher CO_2eq emissions when using the same construction technology of the baseline scenario are compared. The different result obtained for overall GHG emissions between scenarios, which is a consequence of including credits, is explained by the differences in the higher proportion of timber waste that is used directly for electricity generation treatment from incineration for the RICS scenario compared to the WfG scenario. This implies that considerably higher emission is avoided relative to the lower benefits received for recycling processing (*e.g.,* animal bedding or particleboard).

The results strongly suggested that widespread adoption of the BECCS scenario in timber end-of-life could substantially reduce embodied impacts of BS1, BS2, and BS3 by ~23 %, ~20 %, and ~18 %, respectively, compared with the baseline scenario. This contribution makes up to ~84 % of the waste processing stage (*i.e.,* C3–C4), up to ~20 % of the replacement module (*i.e.,* B4), and up to ~1 % of the construction stage (*i.e.,* A5). In this optimistic scenario, there are substitution benefits associated with the use of future carbon-capture technology (*i.e.,* BECCS) to reduce the emission emitted in the EoL of the timbers, which demonstrates the possibility of using wood products with low long-term climate impacts.

4. Discussion

Addressing the whole life-cycle carbon emissions of buildings is crucial in meeting national and global targets for mitigating climate change in numerous countries. This research focuses on reducing the carbon footprint of a typical low-energy timber-frame residence in the UK, in line with the country's goal of achieving net-zero carbon emissions by 2050, and is intended to inform future construction trends. Currently, the introduction of enhancing building energy efficiency in design and systems can effectively reduce the GHG emissions of buildings over their lifespan, but it passes the load to the electricity mix production, more efficient HVAC systems, or embodied carbon emissions (*e.g.,* material choice and end-of-life measures) (Nematchoua et al., 2022; Rahif et al., 2022).

The findings of this study indicate that installing a compact heat pump unit (*i.e.,* BS2) can reduce total CO_2eq emissions by approximately 19 % when compared to the current electricity mix (*i.e.,* baseline scenario BS1). Furthermore, implementing a coupled PV system with an electric compact heat pump unit (*i.e.,* BS2) may reduce the amount of electricity supply taken from the grid, exhibiting a 36 % reduction of CO_2eq emission. Comparing the results obtained for the analyzed case buildings with other European dwellings (Houlihan Wiberg et al., 2014; Satola et al., 2022) reveals a noticeable contribution of the heat pump and/or PV systems in emission reduction over the building lifespan. This reduction can be particularly attributed to the current situation with a high-carbon electricity emission factor in the UK's grid (~0.25 $kgCO_2eq/kWh$) compared to those countries with cleaner electricity production (*e.g.,* Sweden or Norway). Therefore, the results that identify and implement cleaner energy sources while fostering the use of technologically advanced building systems (*e.g.,* efficient electric compact heat pump unit) play an important role in minimizing energy demand and achieving the target value (Fenner et al., 2018; Ligardo-Herrera et al., 2022).

Due to the high amount of wood used in the studied timber frame dwelling, biogenic carbon accounting in the analyses tends to have a significant contribution to the embodied impact (*i.e.,* ~18 % of EC). However, it should be noted that when biogenic carbon is considered on a cradle-to-gate basis (A1–A3), the EC analysis of timber products might mislead the conclusions, giving an incomplete picture of describing its subsequent release back in the EoL (C) stage. This concluding remark is also highlighted in a few other studies (Morris et al., 2021; Petrović et al., 2023). Indeed, this may also encourage the use of wood products in construction, resulting in possible negative impacts on landscapes. Therefore, it is imperative to consider the entire life-cycle carbon emissions of timber products and buildings to fully comprehend the impact of wood-based materials and make more informed decisions in efficient construction design.

The majority of LCA studies have not assessed the impact of “Building services” mainly because of: (i) the difficulty in quantifying their impacts (*e.g.,* challenging to quantify the life cycle inventory phase of these components) (Rodriguez et al., 2020), and (ii) as their environmental impact appeared to be relatively small in magnitude in earlier studies when compared to operational emissions, thus they are often left outside of the assessment boundaries (Moncaster and Symons, 2013). However, the present study indicates considerably high embodied effects of the “Building services” compared to other building elements, with the latter accounting for ~17 % of EC emissions. This highlights the importance of considering the “Building services” in the embodied carbon assessment of the residential buildings.

Furthermore, the sensitivity analysis of the future electricity mix projections demonstrated an increased share of renewable sources that is reflected in the lower GHG emissions of the case studies, by up to ~50 % when scenarios with the same construction technologies are compared. Additionally, results suggest that the emission saving of the grid decarbonization can be reinforced through implementing the evaluated energy improvement technologies by ~60 % reduction in the building case study of BS2. In this sense, it can be concluded that in order to get the maximum benefits from the electricity production sector and to support the clean energy transition in buildings, it is necessary: (i) to follow “electrification” of the building elements (*e.g.,* from fossil-fuel-based to efficient electricity-based heat pump system); and (ii) to improve the electricity generation in the cleanest possible way (*e.g.,* two degrees scenario). The use of renewable electricity for running heat pumps can be included in any further effort aiming to move toward the complete phasing out of fossil fuels in residential heating (Lin et al., 2021). As a result of these significant operational saving measures, the contribution of embodied to operational carbon emissions can subsequently become more relevant in the environmental balance (*e.g.,* ~30 % for BS1 in the current electricity mix, reaching about ~500 % for BS3 in the prevalent electricity decarbonization scenario). While in agreement with (CCC, 2020; HM Government, 2019a), the results of this study imply that operational savings are large in magnitude to reduce residential UK GHG emissions while achieving a zero-carbon building requires the explicit incorporation of EC emissions. Moreover, the magnitude of the initial emission savings associated with the initial EC is of paramount importance since it can be easily achieved through the implementation of several material efficiency strategies (Azzouz et al., 2017). In this context, the findings also indicated that the use of 50 % ground granulated blast-furnace slag (GGBFS) concrete, blown cellulose insulation, and resilient Linoleum floor covering can attain further savings by ~6 % on embodied carbon emissions. Hence, increasing attention should be placed on the material choice to substantially decrease the initial embodied impacts and immediate contributions to reduce the carbon footprint of buildings.

Moreover, since the compensation of the avoided impacts associated with the surplus (PV) electricity production is sensitive to shifts in the decarbonization of the electricity grid, the benefits from the PV system over the UK building's life cycle are not always feasible. Therefore, both new and retrofit buildings should find a permanent improvement in the net performance of the PV system by developing more environmentally friendly materials and manufacturing techniques. As the possible solutions, the importance of integrating PV panels into building structures such as Building Integrated Photovoltaic (BIPV), and Building Integrated Photovoltaic-Thermal (BIPVT) systems (Lamnatou et al., 2020; Zhang et al., 2018); adopting a photovoltaic system with reused cells in the PV modules (Contreras Lisperguer et al., 2020; Kristjansdottir et al., 2016); and the use of growing waste battery from the automotive sector in the coming years (Cusenza et al., 2019) could be considered.

Additionally, the results illustrated that the adoption of potential technological progress in the waste treatments of timber products and buildings could substantially reduce embodied emissions, by ~3 % through increasing the recycling rate and by ~23 % through introducing carbon capture and storage with bioenergy (BECCS) scenario, as the scenarios with the same construction technology of the baseline end-of-life scenario (landfilling + incineration) are compared. The recycling practice of timber waste materials through secondary uses (*e.g.,* animal bedding or particleboard) does not seem to differ greatly from having landfill and incineration treatments in the baseline scenario. This observation can be explained by the way that biogenic carbon is treated by the EN 15804 standard (CEN, 2019) due to future recirculation options. Through this perspective, as explained in Section 2.3, all the carbon sequestrated in timber products is modeled as being emitted at the end-of-life stage to the atmosphere and is debited accordingly, and a credit is applied reflecting the substitution benefit. However, concerning recycling treatment, the biogenic carbon storage is not actually released into the atmosphere to the first product, but instead transferred in the subsequent products utilizing the recycled biogenic material. It is worth noting that treating carbon transferred to new material as being released is respected based on an accounting convention adopted to avoid double counting the benefits from the biogenic carbon (Morris et al., 2021). Thus, in alignment with the UK path to net-zero carbon (HM Government, 2019b), it is essential to increase the recycling rate of timbers (*e.g.,* WfG scenario) rather than incineration with electricity generation, which can contribute to the long-term carbon storage products, providing the buildings as a temporal carbon sink to slow down climate change (Allen et al., 2022), and consequently, it can allow more time for developing the sustainability transformations of the society envisaged under the Sustainable Development Goals (SDGs) (Andersen et al., 2022).

While modeling benefits outside the system boundary can present methodological challenges (Meex et al., 2018), it is important to note that module D has a significant impact on the overall results, particularly in the case of bio-based products (Häfliger et al., 2017), and it should be taken into account. For instance, in the case of the incineration of timber materials, as shown in Fig. 8a, a large credit is awarded in the recovery and recycling potential stage for the assumed substitution of alternative electricity production. However, as the energy supplied will become more decarbonized, this choice of substitution credits is likely to be very low compared to today's perspective. Therefore, from a climate change perspective, expanding the analysis to include the avoided burdens can lead to different conclusions estimated from LCA studies of timber products and exceed the total debits from other stages. Nonetheless, there is a high uncertainty about the avoided impacts at the time of demolition, particularly considering the relative benefits associated with the current electricity substitution of the recovered energy that might look less favorable option (Hart and Pomponi, 2020).

The temporal perspective of carbon emissions, especially regarding the use phase (*e.g.,* electricity mix) and end-of-life of the building (*e.g.,* waste management treatment) are other topics which are not been covered properly by the previous studies in assessing impacts related to climate change (Cabeza et al., 2014; Meex et al., 2018). It is believed that both technological changes in the electricity mix and the waste management scenarios at the building end-of-life are aspects that should be considered in future GHG emissions calculations, especially for timber products and buildings.

All the results of this study refer to one square meter of gross internal area (GIA) as a functional unit. This choice is in accordance with the RICS guidance to facilitate the incorporation of further contributions with other studies and building benchmarks (LETI, 2021). However, the use of an area-based basis may potentially distort the results, as it attributes both building and occupant-related emissions emitted to the area of the house, thereby wiping out any improvements achieved by increasing the area efficiency (*e.g.,* area per occupant) (Stephan et al., 2013). When the number of occupants in the house is increased, the overall emissions for area per occupant may effectively be reduced. This clearly depicts that a smaller floor area per occupant and the sharing of cars by a higher number of people could contribute considerably to meeting climate targets (Cabrera Serrenho et al., 2019; Roca-Puigròs et al., 2020). Therefore, the area per occupant functional units is judged as a more appropriate metric for comparing buildings with varying floor areas and the number of occupants (Fuller and Crawford, 2011; Stephan et al., 2013).

There are several environmental indicators for quantifying the LCA of buildings. Using only GWP as an environmental impact category has the benefit of increasing clarity for decision-makers, and often correlates with other environmental impacts (Wiik et al., 2018). Moreover, some other studies have found that GWP will be a reasonable proxy for other impact categories, particularly for those categories linked to non-renewable energy consumption, or related emissions (*e.g.,* acidification, photochemical ozone formation, *etc.*) (Häfliger et al., 2017; Lasvaux et al., 2015). However, this sole focus may increase the risk of burden shifting to other impact categories that do not always correlate with GWP, such as resource use and resource depletion (Anand and Amor, 2017; Laurent et al., 2012). Thus, to ensure comparability, it is recommended to conduct further LCA studies considering the broad range of indicators instead of solely focusing on GWP.

Previous studies also suggested that the robustness of LCA results for timber materials in the construction of buildings may be further improved by considering the forest management activities associated with the growth and harvesting of trees as well as the carbon stock changes (Fouquet et al., 2015). Hence, future research steps should address the issue of time differences between the uptake and release of carbon in the timber building sector.

5. Conclusions

This study aimed to address the concerns regarding mitigating the carbon footprint of a representative timber-frame low-energy dwelling in the UK in terms of HVAC GHG emissions through three different energy improvement options, *i.e.,* the reference case BS1: a gas-fired boiler + mechanical ventilation with heat recovery (MVHR); BS2: electrical compact heat pump unit; and BS3: electrical compact heat pump unit + photovoltaic (PV) panels. More particularly, future decarbonization potential from the national perspective concerning the changes in electricity mix production and technological evolution of the waste treatment of timber products used in the building were investigated, aiming at providing a sensitivity analysis of climate change mitigation. The whole life-carbon emissions for a total of eight investigated scenarios were analyzed considering the potential improvements of carbon footprint to fulfill future projections for the new UK building sector, and the results were compared to the LCA results of a baseline scenario, where the existing technology and context were considered fixed over time.

The results of this study show that considering temporal changes in electricity mix production and technological progress in the waste treatment of timber materials significantly alters the predicted climate impacts of the building over its lifespan. For example, the findings indicated that using an efficient electric compact heat pump in parallel with the national decarbonization targets of the electricity mix can significantly reduce the whole life-cycle emissions of long-term climate impact assessment at the UK building by ~60 %. Moreover, the results of this research implied that the adoption of potential technological progress in the waste treatments of timber products and buildings could substantially reduce buildings' embodied emissions, representing by ~3 % through increasing the recycling rate and by ~23 % through introducing carbon capture and storage with bioenergy (BECCS) scenario, as the scenarios with the same construction technology of the baseline end-of-life scenario (landfilling + incineration) are compared.

Results showed that it is of high importance to consider biogenic carbon in evaluating the climate impact of a building composed of significant amounts of wood as it can significantly influence the embodied impact of timber-frame buildings, by ~18 % in the present study, that is expected to support/incentivize the more use of timber-based products in the building sector. Moreover, the inclusion of "Building services" in the climate impact assessment of the residential building is emphasized to obtain a more accurate outcome as it could affect the embodied carbon estimations, *e.g.,* increasing CO_2eq by ~17 % in the current study.

The evaluation of whole life-carbon emissions of the dwellings demonstrates the relative importance of the operations phase in the baseline scenario, compared to the materials, construction, and end-of-life phases. Nonetheless, according to the sensitivity analysis suggest that the decarbonization of electricity mix production and advancements in the treatment of timber waste can considerably reduce the environmental impact of the building's operation and end-of-life phases compared to the material and construction phases. These emission-saving measures highlight the importance of material efficiency strategies for achieving more embodied carbon savings in future construction practices.

CRediT authorship contribution statement

Masoud Norouzi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Assed N. Haddad:** Methodology, Writing – review & editing. **Laureano Jiménez:** Validation, Writing – review & editing, Visualization, Supervision, Project administration. **Siamak Hoseinzadeh:** Conceptualization, Writing – review & editing. **Dieter Boer:** Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163490.

References

Al-Shetwi, A.Q., 2022. Sustainable development of renewable energy integrated power sector: trends, environmental impacts, and recent challenges. Sci. Total Environ. 822, 153645. https://doi.org/10.1016/J.SCITOTENV.2022.153645.

Al-Yasiri, Q., Szabó, M., 2022. Phase change material coupled building envelope for thermal comfort and energy-saving: effect of natural night ventilation under hot climate. J. Clean. Prod. 365, 132839. https://doi.org/10.1016/J.JCLEPRO.2022.132839.

Alaux, N., Ruschi Mendes Saade, M., Hoxha, E., Truger, B., Passer, A., 2023. Future trends in materials manufacturing for low carbon building stocks: a prospective macro-scale analysis at the provincial level. J. Clean. Prod., 382 https://doi.org/10.1016/j.jclepro.2022.135278.

Allen, C., Oldfield, P., Teh, S.H., Wiedmann, T., Langdon, S., Yu, M., Yang, J., 2022. Modelling ambitious climate mitigation pathways for Australia's built environment. Sustain. Cities Soc. 77, 103554. https://doi.org/10.1016/J.SCS.2021.103554.

Almena, A., Thornley, P., Chong, K., Röder, M., 2022. Carbon dioxide removal potential from decentralised bioenergy with carbon capture and storage (BECCS) and the relevance of operational choices. Biomass Bioenergy 159, 106406. https://doi.org/10.1016/J.BIOMBIOE.2022.106406.

Anand, C.K., Amor, B., 2017. Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew. Sust. Energ. Rev. 67, 408–416. https://doi.org/10.1016/J.RSER.2016.09.058.

Andersen, J.H., Rasmussen, N.L., Ryberg, M.W., 2022. Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon. Energy Build. 254, 111604. https://doi.org/10.1016/J.ENBUILD.2021.111604.

Aranda-Usón, A., Ferreira, G., López-Sabirón, A.M., Mainar-Toledo, M.D., Zabalza Bribián, I., 2013. Phase change material applications in buildings: an environmental assessment for some spanish climate severities. Sci. Total Environ. 444, 16–25. https://doi.org/10.1016/J.SCITOTENV.2012.11.012.

Arehart, J.H., Hart, J., Pomponi, F., D'Amico, B., 2021. Carbon sequestration and storage in the built environment. Sustain. Prod. Consum. 27, 1047–1063. https://doi.org/10.1016/J.SPC.2021.02.028.

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G., Guattari, C., 2019. Energy and environmental payback times for an NZEB retrofit. Build. Environ. 147, 461–472. https://doi.org/10.1016/J.BUILDENV.2018.10.047.

Autodesk, 2021. Revit for MEP engineering. Industries. URL https://www.autodesk.com/products/revit/mep. (Accessed 15 July 2022).

AzariJafari, H., Guest, G., Kirchain, R., Gregory, J., Amor, B., 2021. Towards comparable environmental product declarations of construction materials: insights from a probabilistic comparative LCA approach. Build. Environ. 190, 107542. https://doi.org/10.1016/J.BUILDENV.2020.107542.

Azzouz, A., Borchers, M., Moreira, J., Mavrogianni, A., 2017. Life cycle assessment of energy conservation measures during early stage office building design: a case study in London, UK. Energy Build. 139, 547–568. https://doi.org/10.1016/j.enbuild.2016.12.089.

Balasbaneh, A.T., Sher, W., 2021. Comparative sustainability evaluation of two engineered wood-based construction materials: life cycle analysis of CLT versus GLT. Build. Environ. 204, 108112. https://doi.org/10.1016/J.BUILDENV.2021.108112.

Barrett, D.J., Linley, M.D., Best, S.M., Al, Parsi Benehkohal, N., Sussman, M.J., Chiu, H., 2019. The reporting of end of life and module D data and scenarios in EPD for building level life cycle assessment. IOP Conf. Ser. Earth Environ. Sci. 323, 012051. https://doi.org/10.1088/1755-1315/323.

BEIS, 2021. Greenhouse gas reporting: conversion factors 2021. URLDep. Business, Energy Ind. Strateg, London, BEIS. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021. (Accessed 16 September 2022).

Ben, H., Steemers, K., 2014. Energy retrofit and occupant behaviour in protected housing: a case study of the Brunswick Centre in London. Energy Build. 80, 120–130. https://doi.org/10.1016/J.ENBUILD.2014.05.019.

Benato, A., Stoppato, A., 2019. Integrated thermal electricity storage system: energetic and cost performance. Energy Convers. Manag. 197, 111833. https://doi.org/10.1016/J.ENCONMAN.2019.111833.

Bianco, V., Scarpa, F., Tagliafico, L.A., 2017. Estimation of primary energy savings by using heat pumps for heating purposes in the residential sector. Appl. Therm. Eng. 114, 938–947. https://doi.org/10.1016/J.APPLTHERMALENG.2016.12.058.

BRE, 2021. Green guide to specification. URL https://tools.bregroup.com/greenguide/podpage.jsp?id=2126. (Accessed 10 July 2022).

BRE, 2014. SAP 2012 - The Government' s Standard Assessment Proceedure for Energy Rating of Dwellings. Technical Report rev June 2014. Buiding Res. Establ. (on Behalf DECC). Watford. URL.

BRE Group, 2023. GreenBook live. URLBRE Glob. https://www.greenbooklive.com/index.jsp. (Accessed 15 March 2023).

Brooks, M., Abdellatif, M., Alkhaddar, R., 2021. Application of life cycle carbon assessment for a sustainable building design: a case study in the UK. Int. J. Green Energy 18, 351–362. https://doi.org/10.1080/15435075.2020.1865360.

Bughio, M., Khan, M.S., Mahar, W.A., Schuetze, T., 2021. Impact of passive energy efficiency measures on cooling energy demand in an architectural campus building in Karachi, Pakistan. Sustain 13, 7251. https://doi.org/10.3390/SU13137251 2021, Vol. 13, Page 7251.

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2013.08.037.

Cabrera Serrenho, A., Drewniok, M., Dunant, C., Allwood, J.M., 2019. Testing the greenhouse gas emissions reduction potential of alternative strategies for the english housing stock. Resour. Conserv. Recycl. 144, 267–275. https://doi.org/10.1016/J.RESCONREC.2019.02.001.

CCC, 2021. 2021 progress report to parliament. Progress in reducing emissions. URLClim. Chang. Comm. https://www.theccc.org.uk/publication/2021-progress-report-to-parliament/. (Accessed 10 September 2022).

CCC, 2020. The sixth carbon budget: the UK's path to net zero. URLComm. Clim. Chang. https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf. (Accessed 20 March 2023).

CCC, 2019. Net zero: the UK's contribution to stopping global warming. URLComm. Clim. Chang. https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/. (Accessed 10 July 2022).

CCC, 2018. Reducing UK emissions - 2018 progress report to parliament. URLClim. Chang. Comm. https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/. (Accessed 14 August 2022).

CEN, 2019. 15804: 2012 + A2: 2019—Sustainability of Construction. Eur. Comm. Stand URL https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=15804%3A+2012%2B+A2%3A+2019—Sustainability+of+Construction+Works—Environmental+Product+Declarations—Core+Rules+for+the+Product+Category+of+…&btnG= (accessed 9.17.22).

CEN, 2012. EN 15804:2012 - sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. URLEur. Comm. Stand. https://scholar.google.com/scholar_lookup?title=EN15804%3ASustainabilityofConstructionWorks.EnvironmentalProductDeclarations.CoreRulesfortheProductCategoryofConstructionProducts&publication_year=2012&author=EuropeanCommitteeforStandard. (Accessed 2 September 2021).

CEN, 2011. EN 15978:2011 - sustainability of construction works - assessment of environmental performance of buildings - calculation method. URLEur. Comm. Stand. https://scholar.google.com/scholar_lookup?title=EN15978%3A2011-SustainabilityofConstructionWorks-AssessmentofEnvironmentalPerformanceofBuildings-CalculationMethod&publication_year=2011&author=%2FTC350CEN. (Accessed 17 September 2022).

Chen, M., Ma, M., Lin, Y., Ma, Z., Li, K., 2022. Carbon kuznets curve in China's building operations: retrospective and prospective trajectories. Sci. Total Environ. 803, 150104. https://doi.org/10.1016/J.SCITOTENV.2021.150104.

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., 2014. Productivity metrics in dynamic LCA for whole buildings: using a post-occupancy evaluation of energy and indoor environmental quality tradeoffs. Build. Environ. 82, 339–348. https://doi.org/10.1016/J.BUILDENV.2014.08.032.

Collinge, W.O., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., 2013. Dynamic life cycle assessment: framework and application to an institutional building. Int. J. Life Cycle Assess. 18, 538–552. https://doi.org/10.1007/S11367-012-0528-2/FIGURES/6.

Contreras Lisperguer, R., Muñoz Cerón, E., de la Casa Higueras, J., Martín, R.D., 2020. Environmental impact assessment of crystalline solar photovoltaic panels' end-of-life phase: open and closed-loop material flow scenarios. Sustain. Prod. Consum. 23, 157–173. https://doi.org/10.1016/J.SPC.2020.05.008.

Cooper, S., Blanco-Sanchez, P., Welfle, A., McManus, M., 2019. Bioenergy and Waste Gasification in the UK: Barriers and Research Needs. Supergen Bioenergy Hub.

Crawford, R., 2011. Life Cycle Assessment in the Built Environment.

Cuéllar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: life cycle assessment of houses. Build. Environ. 54, 86–99. https://doi.org/10.1016/j.buildenv.2012.02.005.

Cusenza, M.A., Guarino, F., Longo, S., Mistretta, M., Cellura, M., 2019. Reuse of electric vehicle batteries in buildings: an integrated load match analysis and life cycle assessment approach. Energy Build. 186, 339–354. https://doi.org/10.1016/J.ENBUILD.2019.01.032.

D'Agostino, D., 2015. Assessment of the progress towards the establishment of definitions of nearly zero energy buildings (nZEBs) in european member states. J. Build. Eng. 1, 20–32. https://doi.org/10.1016/J.JOBE.2015.01.002.

De Castro, E.B.P., Mequignon, M., Adolphe, L., Koptschitz, P., 2014. Impact of the lifespan of different external walls of buildings on greenhouse gas emissions under tropical climate conditions. Energy Build. 76, 228–237. https://doi.org/10.1016/J.ENBUILD.2014.02.071.

De Masi, R.F., Gigante, A., Vanoli, G.P., 2021. Are nZEB design solutions environmental sustainable? Sensitive analysis for building envelope configurations and photovoltaic integration in different climates. J. Build. Eng. 39, 102292. https://doi.org/10.1016/J.JOBE.2021.102292.

de Rubeis, T., Nardi, I., Ambrosini, D., Paoletti, D., 2018. Is a self-sufficient building energy efficient? Lesson learned from a case study in Mediterranean climate. Appl. Energy 218, 131–145. https://doi.org/10.1016/J.APENERGY.2018.02.166.

de Simone Souza, H.H., de Abreu Evangelista, P.P., Medeiros, D.L., Albertí, J., Fullana-i-Palmer, P., Boncz, M.Á., Kiperstok, A., Gonçalves, J.P., 2021. Functional unit influence on building life cycle assessment. Int. J. Life Cycle Assess. 26, 435–454. https://doi.org/10.1007/S11367-020-01854-1/FIGURES/4.

De Wolf, C., Pomponi, F., Moncaster, A., 2017. Measuring embodied carbon dioxide equivalent of buildings: a review and critique of current industry practice. Energy Build. 140, 68–80. https://doi.org/10.1016/J.ENBUILD.2017.01.075.

DEFRA, 2012. Wood waste: a short review of recent research. URLDep. Environ. Food Rural Aff. http://www.defra.gov.uk/consult/. (Accessed 18 September 2022).

DesignBuilder, 2021. DesignBuilder version 6.1.8.021. URLDes. Softw. Ltd. https://designbuilder.co.uk//. (Accessed 12 September 2022).

Din, A., Brotas, L., 2016. Exploration of life cycle data calculation: lessons from a passivhaus case study. Energy Build. 118, 82–92. https://doi.org/10.1016/J.ENBUILD.2016.02.032.

DUKES, 2021. Digest of UK Energy Statistics (DUKES): electricity. Dep. Business, Energy Ind. Strateg. https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes. (Accessed 20 October 2022).

EASAC, 2021. European Academies' Science AdvisoryCouncil - Decarbonisation of Buildings: for Climate, Health and Jobs : EASAC Policy Report 43.

EcoPlatform, 2023. ECO Portal. ECO Platf. AISBL. URL https://www.eco-platform.org/eco-portal-access-point-to-digital-product-data.html. (Accessed 12 March 2023).

EN 16449, 2014. EN 16449:2014–Wood and wood-based products - Calculation of the Biogenic Carbon Content of wood and Conversion to Carbon Dioxide. URLEur. Stand. https://www.en-standard.eu/csn-en-16449-wood-and-wood-based-products-calculation-of-the-biogenic-carbon-content-of-wood-and-conversion-to-carbon-dioxide/. (Accessed 16 September 2022).

EnergyPlus, 2022. Weather data by region - EnergyPlus. Natl. Renew. Energy Lab. URL https://energyplus.net/weather-region/europe_wmo_region_6/GBR. (Accessed 12 September 2022).

EPD International AB, 2023. The international EPD system. URLInt. EPD Syst. https://www.environdec.com/home. (Accessed 12 March 2023).

European Environment Agency (EEA), 2020. Total greenhouse gas emission trends and projections in Europe. URLEur. Comm. https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-7/assessment. (Accessed 20 September 2022).

European Parliament, 2020. European Parliament Resolution of 15 January 2020 on the European Green Deal (2019/2956 (RSP)). URLEur. Parliam. https://www.europarl.europa.eu/doceo/document/TA-9-2020-0005_EN.html. (Accessed 20 September 2022).

Fajilla, G., Simone, M.De, Cabeza, L.F., Bragança, L., 2020. Assessment of the impact of occupants' behavior and climate change on heating and cooling energy needs of buildings. Energies 13, 6468. https://doi.org/10.3390/EN13236468 2020, Vol. 13, Page 6468.

Feist, W., 2011. Certified passive house—certification criteria for residential passive house buildings. Passiv. House Institute, Darmstadt, Ger. URL https://scholar.google.com/scholar?cluster=13112177155049035575&hl=en&as_sdt=2005&sciodt=0,5. (Accessed 5 September 2022).

Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., Thurairajah, N., 2022. Uncertainties in whole-building life cycle assessment: a systematic review. J. Build. Eng. 50, 104191. https://doi.org/10.1016/J.JOBE.2022.104191.

Fenner, A.E., Kibert, C.J., Woo, J., Morque, S., Razkenari, M., Hakim, H., Lu, X., 2018. The carbon footprint of buildings: a review of methodologies and applications. Renew. Sust. Energ. Rev. 94, 1142–1152. https://doi.org/10.1016/J.RSER.2018.07.012.

FES, 2019. Future energy scenarios resources - National Grid ESO. URLNatl. Grid ESO. https://www.nationalgrideso.com/document/170756/download. (Accessed 2 October 2022).

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., Woloszyn, M., 2015. Methodological challenges and developments in LCA of low energy buildings: application to biogenic carbon and global warming assessment. Build. Environ. 90, 51–59. https://doi.org/10.1016/J.BUILDENV.2015.03.022.

Fufa, S.M., Skaar, C., Gradeci, K., Labonnote, N., 2018. Assessment of greenhouse gas emissions of ventilated timber wall constructions based on parametric LCA. J. Clean. Prod. 197, 34–46. https://doi.org/10.1016/J.JCLEPRO.2018.06.006.

Fuller, R.J., Crawford, R.H., 2011. Impact of past and future residential housing development patterns on energy demand and related emissions. J. Housing Built Environ. 26, 165–183. https://doi.org/10.1007/S10901-011-9212-2/FIGURES/7.

Gan, J., Chen, M., Semple, K., Liu, X., Dai, C., Tu, Q., 2022. Life cycle assessment of bamboo products: review and harmonization. Sci. Total Environ. 849, 157937. https://doi.org/10.1016/J.SCITOTENV.2022.157937.

García-Segura, T., Yepes, V., Alcalá, J., 2014. Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int. J. Life Cycle Assess. 19, 3–12. https://doi.org/10.1007/S11367-013-0614-0/TABLES/8.

Greening, B., Azapagic, A., 2012. Domestic heat pumps: life cycle environmental impacts and potential implications for the UK. Energy 39, 205–217. https://doi.org/10.1016/J.ENERGY.2012.01.028.

Häfliger, I.F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M.R.M., Habert, G., 2017. Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. J. Clean. Prod. 156, 805–816. https://doi.org/10.1016/J.JCLEPRO.2017.04.052.

Hafner, A., Schäfer, S., 2017. Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level. J. Clean. Prod. 167, 630–642. https://doi.org/10.1016/J.JCLEPRO.2017.08.203.

Hart, J., D'Amico, B., Pomponi, F., 2021. Whole-life embodied carbon in multistory buildings: steel, concrete and timber structures. J. Ind. Ecol. 25, 403–418. https://doi.org/10.1111/JIEC.13139.

Hart, J., Pomponi, F., 2020. More timber in construction: unanswered questions and future challenges. Sustain 12, 3473. https://doi.org/10.3390/SU12083473 2020, Vol. 12, Page 3473.

Hawkins, W., Cooper, S., Allen, S., Roynon, J., Ibell, T., 2021. Embodied carbon assessment using a dynamic climate model: case-study comparison of a concrete, steel and timber building structure. Structures 33, 90–98. https://doi.org/10.1016/J.ISTRUC.2020.12.013.

Hertwich, E.G., Ali, S., Ciacci, L., Fishman, T., Heeren, N., Masanet, E., Asghari, F.N., Olivetti, E., Pauliuk, S., Tu, Q., Wolfram, P., 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environ. Res. Lett. 14, 043004. https://doi.org/10.1088/1748-9326/AB0FE3.

HM Government, 2019a. The Future Homes Standard: 2019 Consultation on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations for new dwellings. URLMinist. Housing, Communities Local Gov. https://www.gov.uk/government/consultations/the-future-buildings-standard. (Accessed 23 March 2023).

HM Government, 2019b. The Climate Change Act 2008 (2050 Target Amendment) Order 2019. Queen's Print. Acts Parliam.

Honarvar, S.M.H., Golabchi, M., Ledari, M.B., 2022. Building circularity as a measure of sustainability in the old and modern architecture: a case study of architecture development in the hot and dry climate. Energy Build. 275, 112469. https://doi.org/10.1016/J.ENBUILD.2022.112469.

Hossain, M.U., Ng, S.T., 2020. Strategies for enhancing the accuracy of evaluation and sustainability performance of building. J. Environ. Manag. 261, 110230. https://doi.org/10.1016/J.JENVMAN.2020.110230.

Houlihan Wiberg, A., Georges, L., Dokka, T.H., Haase, M., Time, B., Lien, A.G., Mellegård, S., Maltha, M., 2014. A net zero emission concept analysis of a single-family house. Energy Build. 74, 101–110. https://doi.org/10.1016/J.ENBUILD.2014.01.037.

Hoxha, E., Passer, A., Ruschi, M., Saade, M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: a critical overview of LCA methods. Build. Cities 1, 504–524. https://doi.org/10.5334/BC.46.

Ipcc, 2007. Changes in atmospheric constituents and in radiative forcing. Intergov. Panel Clim. Chang. 19–92.

ISO 14040, 2006. Environmental management — life cycle assessment — principles and framework. URLInt. Organ. Stand. Switz. https://www.iso.org/standard/37456.html. (Accessed 20 August 2022).

ISO 14044, 2006. Environmental management — life cycle assessment — requirements and guidelines. URLInt. Organ. Stand. Switz. https://www.iso.org/standard/72357.html. (Accessed 20 September 2022).

IStructE, 2022. How to calculate embodied carbon (Second edition). URLInst. Struct. Eng. https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/. (Accessed 20 September 2022).

Itten, R., Frischknecht, R., Stucki, M., Scherrer, P., PSI, I., 2014. Life Cycle Inventories of Electricity Mixes and Grid. Version 1.3.

Jeswani, H.K., Saharudin, D.M., Azapagic, A., 2022. Environmental sustainability of negative emissions technologies: a review. Sustain. Prod. Consum. 33, 608–635. https://doi.org/10.1016/J.SPC.2022.06.028.

Khan, M.M.H., Deviatkin, I., Havukainen, J., Horttanainen, M., 2021. Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach. Int. J. Life Cycle Assess. 26, 1607–1622. https://doi.org/10.1007/S11367-021-01953-7/FIGURES/6.

Kiss, B., Kácsor, E., Szalay, Z., 2020. Environmental assessment of future electricity mix – linking an hourly economic model with LCA. J. Clean. Prod. 264, 121536. https://doi.org/10.1016/J.JCLEPRO.2020.121536.

Kristjansdottir, T.F., Good, C.S., Inman, M.R., Schlanbusch, R.D., Andresen, I., 2016. Embodied greenhouse gas emissions from PV systems in norwegian residential zero emission pilot buildings. Sol. Energy 133, 155–171. https://doi.org/10.1016/J.SOLENER.2016.03.063.

Lam, T.W.L., Tsui, Y.C.J., Fok, L., Cheung, L.T.O., Tsang, E.P.K., Lee, J.C.K., 2022. The influences of emotional factors on householders' decarbonizing cooling behaviour in a subtropical Metropolitan City: an application of the extended theory of planned behaviour. Sci. Total Environ. 807, 150826. https://doi.org/10.1016/J.SCITOTENV.2021.150826.

Lamnatou, C., Notton, G., Chemisana, D., Cristofari, C., 2020. Storage systems for building-integrated photovoltaic (BIPV) and building-integrated photovoltaic/thermal (BIPVT) installations: environmental profile and other aspects. Sci. Total Environ. 699, 134269. https://doi.org/10.1016/J.SCITOTENV.2019.134269.

Lamy-Mendes, A., Pontinha, A.D.R., Alves, P., Santos, P., Durães, L., 2021. Progress in silica aerogel-containing materials for buildings' thermal insulation. Constr. Build. Mater. 286, 122815. https://doi.org/10.1016/J.CONBUILDMAT.2021.122815.

Larivière-Lajoie, R., Blanchet, P., Amor, B., 2022. Evaluating the importance of the embodied impacts of wall assemblies in the context of a low environmental impact energy mix. Build. Environ. 207, 108534. https://doi.org/10.1016/J.BUILDENV.2021.108534.

Lasvaux, S., Habert, G., Peuportier, B., Chevalier, J., 2015. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int. J. Life Cycle Assess. 20, 1473–1490. https://doi.org/10.1007/S11367-015-0938-Z 2015 2011.

Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. Environ. Sci. Technol. 46, 4100–4108. https://doi.org/10.1021/ES204163F/SUPPL_FILE/ES204163F_SI_001.PDF.

Lausselet, C., Urrego, J.P.F., Resch, E., Brattebø, H., 2021. Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. J. Ind. Ecol. 25, 419–434. https://doi.org/10.1111/JIEC.13049.

Leonzio, G., Bogle, I.D.L., Ugo Foscolo, P., 2023. Life cycle assessment of a carbon capture utilization and storage supply chain in Italy and Germany: comparison between carbon dioxide storage and utilization systems. Sustainable Energy Technol. Assess. 55, 102743. https://doi.org/10.1016/J.SETA.2022.102743.

LETI, 2021. LETI embodied carbon target alignment. URLLondon Energy Transform. Initiat. https://www.leti.uk/carbonalignment. (Accessed 20 October 2022).

LETI, 2020a. LETI embodied carbon primer, supplementary guidance to the climate emergency design guide. London Energy Transform. Initiat. URL https://www.leti.uk/ecp. (Accessed 20 October 2022).

LETI, 2020b. LETI climate emergency design guide, how new buildings can meet UK climate change targets. URLLondon Energy Transform. Initiat. https://www.leti.uk/cedg. (Accessed 20 October 2022).

Levasseur, A., Lesage, P., Margni, M., Samson, R., 2013. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. J. Ind. Ecol. 17, 117–128. https://doi.org/10.1111/J.1530-9290.2012.00503.X.

Ligardo-Herrera, I., Quintana-Gallardo, A., Stascheit, C.W., Gómez-Navarro, T., 2022. Make your home carbon-free. An open access planning tool to calculate energy-related carbon emissions in districts and dwellings. Energy Rep. 8, 11404–11415. https://doi.org/10.1016/J.EGYR.2022.08.263.

Lin, H., Clavreul, J., Jeandaux, C., Crawley, J., Butnar, I., 2021. Environmental life cycle assessment of heating systems in the UK: comparative assessment of hybrid heat pumps vs. Condensing gas boilers. Energy Build. 240, 110865. https://doi.org/10.1016/J.ENBUILD.2021.110865.

López, L.R., Dessì, P., Cabrera-Codony, A., Rocha-Melogno, L., Kraakman, B., Naddeo, V., Balaguer, M.D., Puig, S., 2023. CO2 in indoor environments: from environmental and health risk to potential renewable carbon source. Sci. Total Environ. 856, 159088. https://doi.org/10.1016/J.SCITOTENV.2022.159088.

Lukić, I., Premrov, M., Passer, A., Žegarac Leskovar, V., 2021. Embodied energy and GHG emissions of residential multi-storey timber buildings by height – a case with structural connectors and mechanical fasteners. Energy Build. 252, 111387. https://doi.org/10.1016/J.ENBUILD.2021.111387.

Mahmoud, S.H., Gan, T.Y., 2018. Impact of anthropogenic climate change and human activities on environment and ecosystem services in arid regions. Sci. Total Environ. 633, 1329–1344. https://doi.org/10.1016/J.SCITOTENV.2018.03.290.

Maierhofer, D., Röck, M., Ruschi Mendes Saade, M., Hoxha, E., Passer, A., 2022. Critical life cycle assessment of the innovative passive nZEB building concept 'be 2226' in view of net-zero carbon targets. Build. Environ. 223, 109476. https://doi.org/10.1016/J.BUILDENV.2022.109476.

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., Verbeeck, G., 2018. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. Build. Environ. 133, 228–236. https://doi.org/10.1016/J.BUILDENV.2018.02.016.

Moncaster, A.M., Symons, K.E., 2013. A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. Energy Build. 66, 514–523. https://doi.org/10.1016/J.ENBUILD.2013.07.046.

Morris, F., Allen, S., Hawkins, W., 2021. On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. Build. Environ. 206, 108285. https://doi.org/10.1016/J.BUILDENV.2021.108285.

MPA The Concrete Centre, 2016. Whole-life carbon and buildings: concrete solutions for reducing embodied and operational CO2. Circ. Econ. 24.

Najjar, M., Figueiredo, K., Hammad, A.W.A., Haddad, A., 2019. Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings. Appl. Energy 250, 1366–1382. https://doi.org/10.1016/J.APENERGY.2019.05.101.

Negishi, K., Tiruta-Barna, L., Schiopu, N., Lebert, A., Chevalier, J., 2018. An operational methodology for applying dynamic life cycle assessment to buildings. Build. Environ. 144, 611–621. https://doi.org/10.1016/J.BUILDENV.2018.09.005.

Neirotti, F., Noussan, M., Simonetti, M., 2020. Towards the electrification of buildings heating - real heat pumps electricity mixes based on high resolution operational profiles. Energy 195, 116974. https://doi.org/10.1016/J.ENERGY.2020.116974.

Nematchoua, M.K., Sendrahasina, R.M., Malmedy, C., Orosa, J.A., Simo, E., Reiter, S., 2022. Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives. J. Clean. Prod. 373, 133834. https://doi.org/10.1016/J.JCLEPRO.2022.133834.

Norouzi, Masoud, Chàfer, M., Cabeza, L.F., Jiménez, L., Boer, D., 2021a. Circular economy in the building and construction sector: a scientific evolution analysis. J. Build. Eng. 44. https://doi.org/10.1016/J.JOBE.2021.102704.

Norouzi, Mohsen, Rafienia, M., Poorazizi, E., Setayeshmehr, M., 2021b. Adipose-derived stem cells growth and proliferation enhancement using poly (lactic-co-glycolic acid) (PLGA)/Fibrin nanofiber mats. J. Appl. Biotechnol. Reports 8, 361–369. https://doi.org/10.30491/JABR.2020.223551.1199.

Pamenter, S., Myers, R.J., 2021. Decarbonizing the cementitious materials cycle: a whole-systems review of measures to decarbonize the cement supply chain in the UK and european contexts. J. Ind. Ecol. 25, 359–376. https://doi.org/10.1111/JIEC.13105.

Peñaloza, D., Erlandsson, M., Berlin, J., Wålinder, M., Falk, A., 2018. Future scenarios for climate mitigation of new construction in Sweden: effects of different technological pathways. J. Clean. Prod. 187, 1025–1035. https://doi.org/10.1016/J.JCLEPRO.2018.03.285.

Peñaloza, D., Erlandsson, M., Falk, A., 2016. Exploring the climate impact effects of increased use of bio-based materials in buildings. Constr. Build. Mater. 125, 219–226. https://doi.org/10.1016/J.CONBUILDMAT.2016.08.041.

Petrović, B., Eriksson, O., Zhang, X., 2023. Carbon assessment of a wooden single-family building – a novel deep green design and elaborating on assessment parameters. Build. Environ. 233, 110093. https://doi.org/10.1016/J.BUILDENV.2023.110093.

Pietzcker, R.C., Osorio, S., Rodrigues, R., 2021. Tightening EU ETS targets in line with the european green Deal: impacts on the decarbonization of the EU power sector. Appl. Energy 293, 116914. https://doi.org/10.1016/J.APENERGY.2021.116914.

Pomponi, F., Moncaster, A., 2016. Embodied carbon mitigation and reduction in the built environment – what does the evidence say? J. Environ. Manag. 181, 687–700. https://doi.org/10.1016/J.JENVMAN.2016.08.036.

POST, 2021. Reducing the whole life carbon impact of buildings. URLParliam. Off. Sci. Technol. UK Parliam. Postbr , p. 44.. https://researchbriefings.files.parliament.uk/documents/POST-PB-0044/POST-PB-0044.pdf. (Accessed 10 September 2022).

Pré Consultants, 2022. SimaPro. PRé Sustain. B.V. URL https://simapro.com/. (Accessed 20 September 2022).

PVsyst SA, 2022. PV-syst 7.2, Photovoltaic system software 7.2. URL https://www.pvsyst.com/. (Accessed 14 September 2022).

Rahif, R., Norouziasas, A., Elnagar, E., Doutreloup, S., Pourkiaei, S.M., Amaripadath, D., Romain, A.C., Fettweis, X., Attia, S., 2022. Impact of climate change on nearly zero-energy dwelling in temperate climate: time-integrated discomfort, HVAC energy performance, and GHG emissions. Build. Environ. 223, 109397. https://doi.org/10.1016/J.BUILDENV.2022.109397.

RICS, 2017. Whole life carbon assessment for the built environment. URLR. Inst. Chart. Surv. Parliam. Sq. London SW1P 3AD. https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the–built-environment-november-2017.pdf. (Accessed 14 September 2022).

Robati, M., Oldfield, P., 2022. The embodied carbon of mass timber and concrete buildings in Australia: an uncertainty analysis. Build. Environ. 214, 108944. https://doi.org/10.1016/J.BUILDENV.2022.108944.

Roberts, M., Allen, S., Coley, D., 2020. Life cycle assessment in the building design process – a systematic literature review. Build. Environ. 185, 107274. https://doi.org/10.1016/J.BUILDENV.2020.107274.

Roca-Puigròs, M., Billy, R.G., Gerber, A., Wäger, P., Müller, D.B., 2020. Pathways toward a carbon-neutral swiss residential building stock. Build. Cities 1, 579–593. https://doi.org/10.5334/BC.61.

Röck, M., Baldereschi, E., Verellen, E., Passer, A., Sala, S., Allacker, K., 2021. Environmental modelling of building stocks – an integrated review of life cycle-based assessment models to support EU policy making. Renew. Sust. Energ. Rev. 151, 111550. https://doi.org/10.1016/J.RSER.2021.111550.

Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – the hidden challenge for effective climate change mitigation. Appl. Energy 258, 114107. https://doi.org/10.1016/J.APENERGY.2019.114107.

Rodrigues, C., König, J., Freire, F., 2023. Prospective life cycle assessment of a novel building system with improved foam glass incorporating high recycled content. Sustain. Prod. Consum. 36, 161–170. https://doi.org/10.1016/J.SPC.2023.01.002.

Rodriguez, B.X., Huang, M., Lee, H.W., Simonen, K., Ditto, J., 2020. Mechanical, electrical, plumbing and tenant improvements over the building lifetime: estimating material quantities and embodied carbon for climate change mitigation. Energy Build. 226, 110324. https://doi.org/10.1016/J.ENBUILD.2020.110324.

Rosenbaum, R.K., Hauschild, M.Z., Boulay, A.M., Fantke, P., Laurent, A., Núñez, M., Vieira, M., 2017. Life cycle impact assessment. Life Cycle Assess. Theory Pract., 167–270 https://doi.org/10.1007/978-3-319-56475-3_10/FIGURES/28.

Roux, C., Schalbart, P., Peuportier, B., 2016. Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. J. Clean. Prod. 113, 532–540. https://doi.org/10.1016/J.JCLEPRO.2015.11.052.

Saade, M.R.M., Guest, G., Amor, B., 2020. Comparative whole building LCAs: how far are our expectations from the documented evidence? Build. Environ. 167, 106449. https://doi.org/10.1016/J.BUILDENV.2019.106449.

Santos, P., Correia, J.R., Godinho, L., Dias, A.M.P.G., Dias, A., 2021. Life cycle analysis of cross-insulated timber panels. Structures 31, 1311–1324. https://doi.org/10.1016/J.ISTRUC.2020.12.008.

Santos, R., Aguiar Costa, A., Silvestre, J.D., Pyl, L., 2020a. Development of a BIM-based environmental and economic life cycle assessment tool. J. Clean. Prod. 265, 121705. https://doi.org/10.1016/J.JCLEPRO.2020.121705.

Santos, R., Costa, A.A., Silvestre, J.D., Vandenbergh, T., Pyl, L., 2020b. BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. Build. Environ. 169, 106568. https://doi.org/10.1016/J.BUILDENV.2019.106568.

Satola, D., Wiberg, A.H., Singh, M., Babu, S., James, B., Dixit, M., Sharston, R., Grynberg, Y., Gustavsen, A., 2022. Comparative review of international approaches to net-zero buildings: knowledge-sharing initiative to develop design strategies for greenhouse gas emissions reduction. Energy Sustain. Dev. 71, 291–306. https://doi.org/10.1016/J.ESD.2022.10.005.

Scamman, D., Solano-Rodríguez, B., Pye, S., Chiu, L.F., Smith, A.Z.P., Cassarino, T.G., Barrett, M., Lowe, R., 2020. Heat decarbonisation modelling approaches in the UK: an energy system architecture perspective. Energies 13, 1869. https://doi.org/10.3390/EN13081869 2020, Vol. 13, Page 1869.

Shanks, W., Dunant, C.F., Drewniok, M.P., Lupton, R.C., Serrenho, A., Allwood, J.M., 2019. How much cement can we do without? Lessons from cement material flows in the UK. Resour. Conserv. Recycl. 141, 441–454. https://doi.org/10.1016/J.RESCONREC.2018.11.002.

Shin, Y.S., Cho, K., 2015. BIM application to select appropriate design alternative with consideration of LCA and LCCA. Math. Probl. Eng. 2015. https://doi.org/10.1155/2015/281640.

Smith, M., Bevacqua, A., Tembe, S., Lal, P., 2021. Life cycle analysis (LCA) of residential ground source heat pump systems: a comparative analysis of energy efficiency in New Jersey. Sustain. Energy Technol. Assessments 47, 101364. https://doi.org/10.1016/J.SETA.2021.101364.

Smith, P., Haszeldine, R.S., Smith, S.M., 2016. Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK. Environ. Sci. Process. Impacts 18, 1400–1405. https://doi.org/10.1039/C6EM00386A.

STA, 2016. STA annual survey of UK structural timber markets. Struct. Timber. URL https://www.structuraltimbermagazine.co.uk/news/sta-annual-survey-of-uk-structural-timber-markets/. (Accessed 25 March 2023).

Stamford, L., Azapagic, A., 2014. Life cycle sustainability assessment of UK electricity scenarios to 2070. Energy Sustain. Dev. 23, 194–211. https://doi.org/10.1016/J.ESD.2014.09.008.

Stephan, A., Crawford, R.H., de Myttenaere, K., 2013. A comprehensive assessment of the life cycle energy demand of passive houses. Appl. Energy 112, 23–34. https://doi.org/10.1016/j.apenergy.2013.05.076.

Su, S., Li, X., Zhu, Y., Lin, B., 2017. Dynamic LCA framework for environmental impact assessment of buildings. Energy Build. 149, 310–320. https://doi.org/10.1016/J.ENBUILD.2017.05.042.

Symons, K., Moncaster, A., Symons, D., 2013. An application of the CEN/TC350 standards to an Energy and Carbon LCA of timber used in construction, and the effect of end-of-life scenarios. Aust. Life Cycle Assess. Soc. Conf. Sydney, Aust.

UK Government's National Calculation Methodology, 2021. Standard assessment procedure. Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/guidance/standard-assessment-procedure. (Accessed 25 December 2021).

UKGBC, 2021. Renewable energy procurement & carbon offsetting - guidance for net zero carbon buildings. URLUK Green Build. Counc, London, UK. https://www.ukgbc.org/ukgbc-work/renewable-energy-procurement-carbon-offsetting-guidance-for-net-zero-carbon-buildings/. (Accessed 20 September 2022).

UKGBC, 2019. Net zero carbon buildings: a framework definition. URLUK Green Build. Counc. london. https://www.ukgbc.org/ukgbc-work/net-zero-carbon-buildings-a-framework-definition/. (Accessed 10 September 2022).

Valencia-Barba, Y.E., Gómez-Soberón, J.M., Gómez-Soberón, M.C., 2023. Dynamic life cycle assessment of the recurring embodied emissions from interior walls: cradle to grave assessment. J. Build. Eng. 65, 105794. https://doi.org/10.1016/J.JOBE.2022.105794.

Wang, J., Song, C., Yuan, R., 2021. CO2 emissions from electricity generation in China during 1997–2040: the roles of energy transition and thermal power generation efficiency. Sci. Total Environ. 773, 145026. https://doi.org/10.1016/J.SCITOTENV.2021.145026.

Wang, Yan, Pan, Z., Zhang, W., Borhani, T.N., Li, R., Zhang, Z., 2022. Life cycle assessment of combustion-based electricity generation technologies integrated with carbon capture and storage: a review. Environ. Res. 207, 112219. https://doi.org/10.1016/J.ENVRES.2021.112219.

Wang, Yongzhen, Wang, J., He, W., 2022. Development of efficient, flexible and affordable heat pumps for supporting heat and power decarbonisation in the UK and beyond: review and perspectives. Renew. Sust. Energ. Rev. 154, 111747. https://doi.org/10.1016/j.rser.2021.111747.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Wiik, M.K., Fufa, S.M., Kristjansdottir, T., Andresen, I., 2018. Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the norwegian ZEB research Centre. Energy Build. 165, 25–34. https://doi.org/10.1016/J.ENBUILD.2018.01.025.

Wood for Good, 2023. Wood for good lifecycle database. BRE. URL https://woodforgood.com/lifecycle-database/. (Accessed 15 March 2023).

Wood for Good, 2017. Environmental Product Declaration: 1m3 of kiln dried planed or machined sawn timber used as structural timber. BRE. URL https://woodforgood.com/assets/Downloads/EPD/BREGENEPD000124.pdf. (Accessed 20 September 2022).

World Bank, 2018. Electric power transmission and distribution losses. URLIEA Stat. https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS. (Accessed 27 September 2022).

WRAP, 2008. Net waste tool - guide to reference data. WRAP's built environ. Program. URL https://wrap.org.uk/wraps-built-environment-programme. (Accessed 15 September 2022).

Wu, W., Skye, H.M., Domanski, P.A., 2018. Selecting HVAC systems to achieve comfortable and cost-effective residential net-zero energy buildings. Appl. Energy 212, 577–591. https://doi.org/10.1016/J.APENERGY.2017.12.046.

Zhang, T., Wang, M., Yang, H., 2018. A review of the energy performance and life-cycle assessment of building-integrated photovoltaic (BIPV) systems. Energies 11, 3157. https://doi.org/10.3390/EN11113157 2018, Vol. 11, Page 3157.

Zhang, Z., Malik, M.Z., Khan, A., Ali, N., Malik, S., Bilal, M., 2022. Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco-sustainability. Sci. Total Environ. 807, 150856. https://doi.org/10.1016/J.SCITOTENV.2021.150856.

Zhao, G., Baker, J., 2022. Effects on environmental impacts of introducing electric vehicle batteries as storage - a case study of the United Kingdom. Energy Strateg. Rev. 40, 100819. https://doi.org/10.1016/J.ESR.2022.100819.

Zhou, Z., Feng, L., Zhang, S., Wang, C., Chen, G., Du, T., Li, Y., Zuo, J., 2016. The operational performance of "net zero energy building": a study in China. Appl. Energy 177, 716–728. https://doi.org/10.1016/J.APENERGY.2016.05.093.