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Long-term decarbonization prediction of buildings accounting for temporal variations in grid and material emission factors: A case study of timber-framed passive houses in the United Kingdom

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ABSTRACT

Most studies have conducted life cycle assessment (LCA) in evaluating the carbon footprint of buildings to be independent of temporality in emissions accounting, which often overlooks the mitigation strategies to meet long-term emission reduction targets. This paper aims to investigate the whole-life carbon (WLC) emissions of a UK low-energy dwelling and examine how potential modeling approaches on low-carbon development will impact the LCA results. Particularly, the variations of future decarbonization of both grid and materials, as well as the photovoltaic (PV) allocation with and without batteries, are employed in the building's environmental performance analysis. The results demonstrated that considering the temporal perspectives can drastically reduce the WLC of buildings, representing up to 51 % compared to baseline calculations. With grid decarbonization, implementing a 4kWp grid-connected PV system can offset the building's operational emissions by 76 % compared to the existing 2kWp PV reference over a 60-year perspective. Our findings also revealed that adding batteries to grid-connected PV systems does not necessarily increase the emission savings achieved by system configuration for buildings when the decarbonization of both grid and materials is considered. Overall, this study highlights the importance of low-impact strategies that focus on upfront embodied carbon for policymaking in the building sector.

Nomenclature

Abbreviations	
ASHRAE	The American society of heating, refrigerating and air-conditioning engineers
BECCS	Bioenergy with Carbon Capture and Storage
BECD	Built Environment Carbon Database
BEM	Building Energy Modeling
BIM	Building Information Modeling
BIPV	Building-Integrated Photovoltaic
BIPVT	Building-Integrated Photovoltaic-Thermal
BOQ	Bill of Quantity
CCC	Climate Change Committee
CCUS	Carbon Capture, Utilization, and Storage
CIBSE	Chartered Institution of Building Services Engineers
CLT	Cross Laminated Timber
BEIS	Department for Business, Energy and Industrial Strategy
DEFRA	Department for Environment, Food and Rural Affairs
DHW	Domestic Hot Water
EAF	Electric Arc Furnace
EEC	End-of-life Embodied Carbon
EoL	End-of-life
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene Insulation
EPW	EnergyPlus Weather
FES	Future Energy Scenarios

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Abbreviations	
F-gases	Fluorinated Greenhouse Gases
FU	Functional Unit
gbXML	Green Building Extensible Markup Language
GHG	Greenhouse Gas [kg CO_2eq]
HFC	Hydrofluorocarbon
HVAC	Heating, Ventilation and Air Conditioning
IEQ	Indoor Environmental Quality
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LOD	Level of Development
MEP	Mechanical, Electrical, and Plumbing
MVHR	Mechanical Ventilation with Heat Recovery
nZEBs	nearly-Zero Energy Buildings
PCRs	Product Category Rules
PEFC	Programme for the Endorsement of Forest Certification
PV	Photovoltaic
REC	Recurring Embodied Carbon
RICS	Royal Institution of Chartered Surveyors
RSP	Reference Service Period [year]
T&D	Transmission and Distribution
UKGBC	UK Green Building Council
UEC	Upfront Embodied Carbon
WBCSD	World Business Council for Sustainable Development
WLC	Whole-Life Carbon
WRAP	Waste and Resources Action Programme, a UK organisation
WTT	Well-to-Tank
Symbols	
$CF_{PV-gridreimp}$	Carbon conversion factor of photovoltaic electricity injected into the grid and reimported later [kg CO_2eq/kWh]
$CF_{ovr,i}$	Overall carbon conversion factor of electricity generated by the energy source type *i* [kg CO_2eq/kWh]
CO_2eq	Carbon Dioxide Equivalent [kg CO_2eq]
EC	Embodied Carbon [kg CO_2eq]
$EF_{el-T\&D,i}$	Carbon emission factor associated with electricity transmission and distribution loss of the purchased power for the energy source type *i* [kg CO_2eq/kWh]
$EF_{gen,i}$	Carbon emission factor associated with the national electricity generated by the power industry for the energy source type *i* [kg CO_2eq/kWh]
$EF_{inf,i}$	Carbon emission factor associated with the embodied emissions of energy infrastructure for the energy source type *i* [kg CO_2eq/kWh]
$E_{PV-gridreimp,t}$	Annual photovoltaic electricity generation injected into the grid and reimported in year *t* [kWh/year]
$E_{load,i,t}$	Annual electricity needed to feed the building load type *i* in year *t* [kWh/year]
$E_{on-site,t}$	Annual photovoltaic electricity generated on-site and directly consumed by the building in year *t* [kWh/year]
ESL	Estimated Service Life [year]
$f_{T\&D,t}$	Decarbonization factor associated with the energy distribution and storage in year *t* [%]
$f_{WTT-gen,i,t}$	Decarbonization factor of the extraction, refining, and transportation of raw fuel sources in year *t* [%]
$f_{gen,t}$	Decarbonization factor of the national electricity generated by the power industry in year *t* [%]
$f_{inf,t}$	Decarbonization factor of the embodied emissions of energy infrastructure in year *t* [%]
GIA	Gross Internal Area [m^2]
GWP	Global Warming Potential [kg CO_2eq]
$IMP_{BL,t}$	Impact value of the evolving future scenario at the time *t* [kg CO_2eq]
$IMP_{EF,t}$	Impact value of the baseline scenario at the time *t* [kg CO_2eq]
IMP_{ope}	Total operational carbon impact [kg CO_2eq]
OC	Operational Carbon [kg CO_2eq]
PRD_t	Percentage of relative differences at the time *t* [%]
U-value	Thermal Transmittance [W/(m^2K)]
$WTT_{Gen,i}$	Carbon emission factor associated with the extraction, refining, and transportation of raw fuel sources for energy source type *i* [kg CO_2eq/kWh]
$WTT_{T\&D,i}$	Carbon emission factor associated with energy consumption to store and distribute the energy to the building for energy source type *i* [kg CO_2eq/kWh]

1. Introduction

Climate change mitigation of the adverse impacts on ecosystem health and human well-being is one of the foremost global concerns in the twenty-first century [1]. The levels of greenhouse gas (GHG) emissions resulting from human activities are out of balance, which poses substantial risks of extreme weather events such as droughts, floods, tropical cyclones, and heat waves [2]. The International Panel on Climate Change (IPCC) (AR6) warns that all anthropogenic activities must reach a level of net-zero GHG emissions by 2050 to maintain the global average temperature increase within the 1.5 °C threshold [3,4]. The building sector plays a relevant role in achieving sustainable and circular economic development as well as in mitigating its contribution to climate and environmental emergencies (about 40 % of the global energy and process emissions) [5,6]. With rapid and continuing growth in both human population and urbanization, the need for new construction is expected to grow with more than 100 % of global floor area and material usage by 2060, while simultaneously further increasing carbon emissions [7]. To address these pressing issues, the building sector could have a fundamental role in the transition to cleaner energy models and in achieving a low-carbon economy on the local and global scale.

The challenge for decarbonization of buildings can be achieved through whole-life carbon (WLC) declarations into two domains: (i) by reducing the impacts attributed to the energy consumption during its occupancy (*e.g.,* heating, ventilation, etc.); and (ii) by ensuring low or zero embodied impacts stemming from materials and components (*e.g.,* production, transport, etc.). At present, one-fifth of the United Kingdom's (UK) annual territorial GHG emissions (454 MtCO) are emitted from building operations, 90 % of which are from the residential sector [8]. As a consequence, the current plan for the UK is reliant on decarbonizing the electricity mix and the transition to electrically driven heat pumps by 2050 as a result of the Future Homes Standard (FHS) on a national scale [9,10]. With respect to electricity decarbonization, the UK government in line with the EU Green Deal call is legally committed to a substantial tightening of the EU emissions trading system target for ensuring at least 74 % of electricity from renewable sources by 2030, as well as zero electricity generation emissions by 2040 [11].

To further reduce the demand for grid energy and accelerate the decarbonization of the housing sector, the use of renewable energy sources such as passive solar building design, solar thermal systems, photovoltaic (PV) technologies, or green roofs have great development prospects [12–14]. Solar PV systems, as the most promising renewable energy technology [15], could be exploited on fixed structures such as rooftops, ground-mounted systems, or façades integrated into a building (*i.e.,* building-integrated PV (BIPV) and building-integrated PV-thermal (BIPVT) systems) [16,17]. Essentially BIPV/BIPVT systems are showing an increasing utilization trend because of their efficient installation and positive contribution to the nearly zero-energy buildings [18]. These systems have double function by generating electricity and using the building envelope (and also utilizing the thermal energy from the back of the PV panels for domestic hot water of the building in the case of BIPVT) [19]. On the other hand, due the unstable weather conditions, PV systems combined with energy storage systems are adopted to increase self-consumption and improve the overall performance of systems, especially in grid-connected mode [20]. Therefore, with continuous technical improvement and cost reduction, the grid-connected PV-battery energy storage system is expected to enable the transition toward more renewable and sustainable options in the building area [21,22]. From a life cycle perspective, as the operational impacts of buildings decrease, the relative importance of embodied emissions to the building's whole life cycle becomes increasingly significant. More recent studies have indicated that the impacts of the embodied emissions of new buildings can exceed those of operational impacts [23–26]. At a national level, emerging voluntary frameworks, such as the UK Green Building Council (UKGBC), have set out targets of 40 % less embodied carbon by 2030, followed by a whole-life carbon roadmap in achieving net zero carbon by 2050 [24,27]. Therefore, effective emission reduction strategies within the building sector should be placed, particularly in the decarbonization of embodied emissions by addressing the WLC assessments of a building [28,29].

Mitigation strategies to address the environmental and resource footprint of a building can be implemented by promoting technological innovations and process optimization [30,31], embracing renewable and low-carbon alternatives, such as wood-based products [32–34], applying renewable energy technologies [35,36], or incorporating circular economy principles to minimize waste and improve resource efficiency [37,38]. However, the reported results of life cycle assessment (LCA) studies in the literature may vary depending on system boundary definition (*i.e.,* whether whole-life embodied carbon is included in the boundary scoping), and physical characteristics of a building (*i.e.,* inclusion or exclusion of finishes and mechanical systems) [39,40], as well as biogenic carbon accounting at the end-of-life (EoL) stage [41]. In this perspective, the mitigation strategies from the building sector have rarely been considered in the literature from the full life cycle stages [42]. For instance, some studies have limited their system boundary scoping to cradle-to-gate emissions, which only determine the embodied impacts of building materials that end when the product leaves the factory [43,44]. Moreover, there is a rapid growth in timber demand in the UK market (an anticipated increase of 40 % by 2050 [45]), thereby considering the mitigation potential of wooden construction becoming more attention within the LCA society [46]. The Climate Change Committee (CCC), for example, has recommended the UK construction industry for the continuing shift away from concrete, masonry, and steel to timber houses [45,47]. Although several standards and industrial practices give an insight into the quantification of the environmental performance of bio-based materials, there is no clear methodology for allocating biogenic carbon (*i.e.,* atmospheric carbon that is captured via biomass in the carbon cycle), leading to substantial differences in the GHG results [41,48]. From this point of view, future efforts to shift from the current paradigm toward the co-benefits of a timber-based construction product should be considered from a whole-life cycle perspective of the construction industry.

Nonetheless, the vast majority of the existing LCA studies have employed deterministic models with a static approach and ignore potential future variations at different levels of systems, *e.g.,* increased renewable energy penetration [49,50]. However, this limited-time perspective of emissions potentially leads to flawed LCA outcomes when considering a building's long lifespan [51]. As a result, there is a growing need for further investigations focused on adopting temporal parameters into the assessment of electricity production, as well as construction material manufacturing. It further aims not only to evaluate possible LCA outcome fluctuations over the building lifespan but also to increase the practice and applicability of environmental behavior at the national level, thereby ensuring the ability to guide long-term decision-making [52,53]. In this context, the domain still presents several limitations. First, its application typically focuses on certain materials or technology types and is not being applied in representative building case studies. As an example of the cement sector, the use of supplementary cementitious materials and optimizing the clinker content in cement [54], as well as low-carbon production alternatives and the adoption of carbon capture, utilization, and storage (CCUS) technologies [55], are identified to ongoing changes and anticipated future shifts. Other studies have also estimated the potential of similar cleaner strategies to get future environmental impacts for steel [56–58], foam glass [59], and bricks, wood-based materials, or plastics [60]. As for renewable energy, Brodnicke et al. [61] highlighted the significance of factoring in grid emission intensity when assessing the emissions-saving potential of PV and battery systems.

Further, while prospective scenarios of building energy and its environmental performance have been investigated in previous studies [62–66], the stages corresponding to recurrent embodied emission (*e.g.,* impacts associated with material maintenance, and replacement) and EoL have been omitted or developed in less detail. For example, Su et al. [64] enhanced the precision of calculating the carbon emissions of a passive building by considering the dynamic carbon emissions of energy systems in different scenarios. Hiyama and Srisamranrungruang [65] utilized the time-varying CO_2 intensity of electricity to evaluate the impact of energy-saving considerations in the façade design of a generic office model in Japan.

Upon conducting the literature review in addressing the environmental footprint of buildings, it is essential to further investigate the state of decarbonization strategies from a life cycle perspective, particularly taking the assessment of both current and future development scenarios on a national level. Yet, to our knowledge, there has been no study investigation of the environmental performance of timber-frame dwellings in which the impact of the UK's long-term changes in GHG emission intensities of materials and energy-carrier inputs has been undertaken. Therefore, the novelty of this study lies in filling this gap by assessing the relevant detailed time-step evaluation of the future reduction of building emissions by considering both the operational and embodied impacts. This article also contributes to examining the future role that solar PV with and without battery systems can play in conjunction with the building scale within the context of a decarbonizing electricity sector. The findings of this study provide professionals and stakeholders with insights into the long-term prediction of environmental impacts to support policy experts, thereby analyzing and identifying potential solutions for more sustainable development. Nevertheless, the LCA results can be extrapolated to many countries (*e.g.,* Northern European context) that build similar styles and techniques with useful knowledge for carbon mitigation in building design and construction.

The remainder of this article is structured as follows. Section 2 introduces the research methodology adopted in this study, and demonstrates the modeling data sources of different future scenarios using a case study. Section 3 presents the results of the baseline scenario and the predicted long-term emission reduction potential of building mitigation strategies. The carbon-saving perspective, limitations, and prospects for future research are discussed in Section 4. Finally, Section 5 concludes the main findings of the work.

2. Material and methods

2.1. Research model

To evaluate trade-offs and identify opportunities for improvement of modeling assumptions on building mitigation decisions, an LCA-based GHG assessment and scenario-based approach are developed in this study. Fig. 1 illustrates the proposed methodological approach followed within building information modeling (BIM) in three main steps. The first step provides the inventory background data used, followed by the scenario definition and development, and building energy model preparation for the case studies. Future scenarios are defined considering sensitive temporal perspectives by looking at targeted policies that can impact the environmental performance of a building over its lifespan. The time-dependent characteristics of the building system are then integrated into the LCA model according to the chosen impact assessment to be compared with the baseline (constant) scenario. The baseline evaluation corresponds to the standard LCA framework within the context of sustainability assessment [67] and assumes that the input parameters applied are existing sources of technical data over the whole analysis period [48,68]. Finally, the results of the different scenarios are analyzed and interpreted as explorative decarbonization pathways for future development.

In the subsequent sections, we describe how the framework was conducted to model the investigated mitigation measures, followed by LCA methodology to calculate the GHG emissions, and the description of the case study (Sections 2.2, and 2.3, respectively).

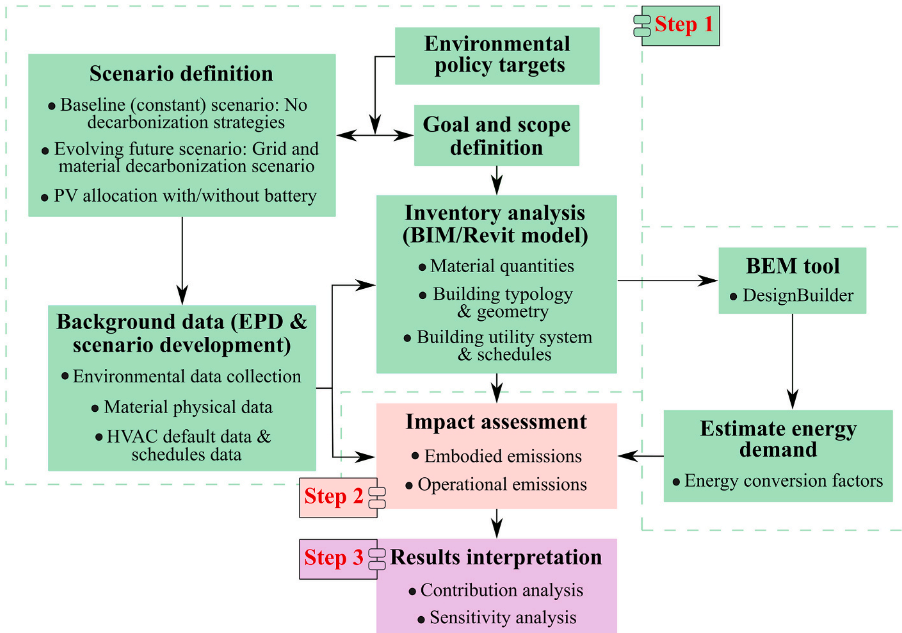

Fig. 1. Framework scheme of the LCA research methodology. BIM: Building information modeling, BEM: Building energy modeling, and EPD: Environmental product declaration.

2.2. Modelling technological mitigation scenarios

To understand the influence of variable characteristics on the LCA results and make a robustness assessment, several assumptions are defined in the system dynamics model. The relevance of the LCA results is highly reliant on these defined sensitivity scenarios [69]. In this context, it is crucial to consistently consider the investigated scenarios of the construction sector at a national level, thus identifying the most critical areas for future decarbonization strategies. This study incorporates electricity mix evolution and material decarbonization as the essential sets of boundary conditions to predict long-term carbon emissions and thereby examines this evolving scenario with the current state scenario by employing the percentage of relative differences (PRD) indicator. The PRD can be used to determine the relative variation between the impact results of a given strategy at baseline and evolving future scenarios, which is calculated following Equation (1):

$$PRD_t = \left(IMP_{EF,t} - IMP_{BL,t}\right) / IMP_{BL,t}.100 \tag{1}$$

where PRD_t is variation percentage at the time t under baseline assessment result (%), while $IMP_{EF,t}$ and $IMP_{BL,t}$ indicate the impact value at the time t for the baseline scenario, and evolving future scenario (kg CO_2eq), respectively.

2.2.1. Grid decarbonization

The UK's decarbonization targets are forcing the power sector to a rapid change in response to national net zero commitment and international climate change mitigation policies [70]. As the grid mix is sensitive driven by the reduction in fossil-based electricity generation and the promotion of renewable resources, expected time-dependent effects in background energy systems will change the carbon intensity of electricity delivered to buildings [71]. In this sense, the modest future projection of the energy system excluding the negative emissions from bioenergy with carbon capture and storage (BECCS) was utilized in the present study as a conservative approach to the model grid and water decarbonization based on the political targets suggested by authority organizations [72,73]. The key features of this scenario are characterized by gradual decarbonization of the power sector under assumptions of future economic growth and increased demand for electricity based on the UK population, followed by advanced technological development in the mid-2030s, while natural gas maintains a significant role [72]. The non-consideration of the negative emissions from the BECCS systems in this study is attributed to complying with current LCA standards [67], which do not permit permanent carbon storage to be factored into an assessment.

The carbon intensity of the electricity mix was modeled following the projected year-by-year decarbonization factor of the respective moment within the lifespan considered. The potential benefits of using on-site electricity at the time of generation by PV systems are assigned as the avoided electricity from the grid. However, the impacts associated with electricity transmission in the transport network, losses in the distribution network, and embodied emissions of distribution were also accounted for in PV systems when electricity generation is exported to the grid and then reimported at different times. The environmental impacts of building operations are calculated following Equations (2)–(4) (Figure A.1 in supplementary material A.1):

$$IMP_{ope} = \sum_{i}^{n} \sum_{t}^{T} \left(E_{load,i,t} - E_{on-site,t}\right).CF_{ovr,i} + \sum_{t}^{T} E_{PV-gridreimp,t}.CF_{PV-gridreimp} \tag{2}$$

with

$$CF_{ovr,i} = \sum_{t}^{T} \left(\left(EF_{gen,i}.f_{gen,t}\right) + \left(WTT_{gen,i}.f_{WTT-gen,t}\right) + \left(EF_{el-T\&D,i} + WTT_{T\&D,i}\right).f_{T\&D,t} + \left(EF_{inf,i}.f_{inf,t}\right) \right) \tag{3}$$

and

$$CF_{PV-gridreimp} = \sum_{t}^{T} \left(\left(EF_{el-T\&D} + WTT_{T\&D} \right) . f_{T\&D,t} + \left(EF_{inf,i} . f_{inf,t} \right) \right) \tag{4}$$

where IMP_{ope} is the total operational carbon impact (kg CO_2eq), T is the lifespan of a building (year), $E_{load,i,t}$ is the annual electricity needed to feed the building load type i in year t (kWh/year), $E_{on-site,t}$ is the PV electricity generated on-site and directly consumed by the building in year t (kWh/year), $CF_{ovr,i}$ is the respective overall conversion factor of electricity generated by the energy source type i (kg CO_2eq/kWh). Additionally, $E_{PV-gridreimp,t}$ is the PV electricity injected into the grid and reimported in year t (kWh/year), and $CF_{PV-gridreimp}$ is the respective conversion factor of PV electricity injected into the grid and reimported later (kg CO_2eq/kWh).

In equations (3) and (4), $EF_{gen,i}$ and $f_{gen,t}$ represent the carbon emission factor associated with the national electricity generated by the power industry for the energy source type i (kg CO_2eq/kWh), and its decarbonization factor in year t (%). Moreover, $WTT_{Gen,i}$ and $f_{WTT-gen,i,t}$ refer to the carbon emission factor associated with the extraction, refining, and transportation of raw fuel sources for the energy source type i (kg CO_2eq/kWh), and its decarbonization factor in year t (%), respectively. $EF_{el-T\&D,i}$ and $WTT_{T\&D,i}$ indicate the carbon emission factor associated with electricity transmission and distribution loss of the purchased power for the energy source type i (kg CO_2eq/kWh), and the carbon emission factor associated with energy consumption to store and distribute the energy to the building for the energy source type i (kg CO_2eq/kWh), respectively. $f_{T\&D,t}$ is the decarbonization factor associated with the energy distribution and storage in year t (%). Additionally, $EF_{inf,i}$ and $f_{inf,t}$ are carbon emission factor associated with the embodied emissions of energy infrastructure for the energy source type i (kg CO_2eq/kWh), and its decarbonization factor in year t (%), respectively.

2.2.2. Technological evolution of replacement and improvement of components

Alongside grid decarbonization, evolving embodied emissions of construction materials (especially, producing new construction materials when making replacements in the future) can be expected to need less energy and materials in the background system for manufacturing, leading to a decrease in environmental performance concerning the initial impact. This essence is a parameter from the hierarchies perspective of environmental impact analysis, which reflects the possible future evolution of the market and practicality when dealing with the analysis of long-term environmental impacts [74]. For these reasons, the assessment should take a prospective modeling approach to define proper and realistic scenarios for potential improvements in initial emissions from replacement measures. The implementing calculation of this module would therefore depend on performance-based regulations for the respective national context as an additional part of the 'like-for-like' assumption based on the EN 15978 standard [75]. To address this, the UK Green Building Council [76] published the industry's pathway to net zero by 2050 for an input-output top-down approach calculated on consumption-based emissions of several construction materials (*i.e.,* bricks and ceramic, cement and concrete, steel and other metals, timber, plastic and chemicals, glass, and other materials). The embodied impacts on the future replacements of materials are calculated over time using the expected decarbonization trajectory as well as considering the components' lifespan (see Figure A.2 in supplementary material A.2). The formula for computing the embodied carbon emissions is presented in Equation (5):

$$IMP_{emb} = \sum_{i}^{n} \sum_{t}^{T} Q_{i,t} . EF_i \ . f_t \tag{5}$$

where IMP_{emb} is the total embodied impact (kg CO_2eq), $Q_{i,t}$ is the amount of each material/activity installed or disposed of i in the given year t (unit), EF_i is the specific carbon emission factor per material/activity for production and disposal of i (kgCO_2eq/unit), and f_t is the decarbonization factor for the given year t (%). Following a conservative perspective of technological learning aligned with the Royal Institute of Chartered Surveyors (RICS) [73], a default decarbonization factor is assumed for some of the embodied impacts occurring over the building life cycle, such as building maintenance, repair, demolition, and transportation to waste processing.

2.3. LCA methodological framework

Life cycle assessment (LCA) is a systematic methodology used to evaluate the environmental performance and potential impacts of a product, process, or activity throughout its entire life cycle. The GHG emissions of the scenarios are assessed using the LCA methodology as follows by the ISO 14040/14044 standards [77,78] and EN 15978 [75], and consists of four steps: definition of goal and scope, life cycle inventory, life cycle impact assessment, and interpretation of the results. The methodology integration with BIM has facilitated the flow of information within the LCA application across the project life cycle, from design to demolition [79]. As depicted in Fig. 1, the process developed to extract material properties and the integrated energy calculations are the cornerstones of the framework. The case study is modeled in BIM/Revit and then material demand is incorporated into the use of environmental impacts (*e.g.,* environmental product declarations (EPDs)). As the degree of detail is significant in the creation of a BIM life-cycle inventory, the BIM model developed in this study was at the level of development (LOD) 300 [80]. This classification system establishes rapid modeling while recognizing an exhaustive definition of the layer of building materials (*i.e.,* specific materials, amounts, and densities) supplied in the structural modeling [81]. For energy analysis, the interoperability between BIM-based building energy modeling (BIM-based BEM) is explored to offer an efficient approach to data transfer and enable the advantages of a user-friendly and replicable model [82].

2.3.1. Aim and scope of the LCA study

The goal of this research is to investigate the GHG emission impacts of typical timber buildings from a life cycle perspective based on a standard approach of the LCA framework adhered to EN 15978 [75]. This LCA approach (*i.e.,* baseline scenario) was modeled with the current environmental impacts and technological capabilities of inventory analysis [83,84]. However, the construction industry is dynamic, and markets for materials, construction practices, and building systems may differ over time. More particularly, to provide insights into the robustness and reliability of the assessment, the initial analysis of the baseline scenario is compared with the different potential impacts of the investigated modeling assumptions: (i) the decarbonization opportunity of both the electricity mix and the embodied emissions of construction materials (especially considering their future development driven during replacement); and (ii) examining the GHG emission benefits gained by PV solar with and without batteries within the current and decarbonized electricity grid by analyzing the GHG payback time (GPBT), which refers to the time required for a system or a certain CO_2eq mitigation strategy to pay back for the initial embodied emissions emitted through renewable energy generation.

The functional unit (FU) of this study is established as a one-square-meter gross internal area (GIA) of the building. This reference flow facilitates accurate and meaningful comparisons during the life cycle assessment process with other studies [73]. A 60-year reference study period is assumed to be consistent with the typical design life of a UK building [73]. To translate inventory results into impact scores, this study focused on a WLC assessment according to the 100-year global warming potential (GWP100) indicator. This choice pursues the goal of mitigating the climate change impact associated with the assessed system to avoid potentially catastrophic consequences [85], and also it reflects as a leading indicator for translating various environmental

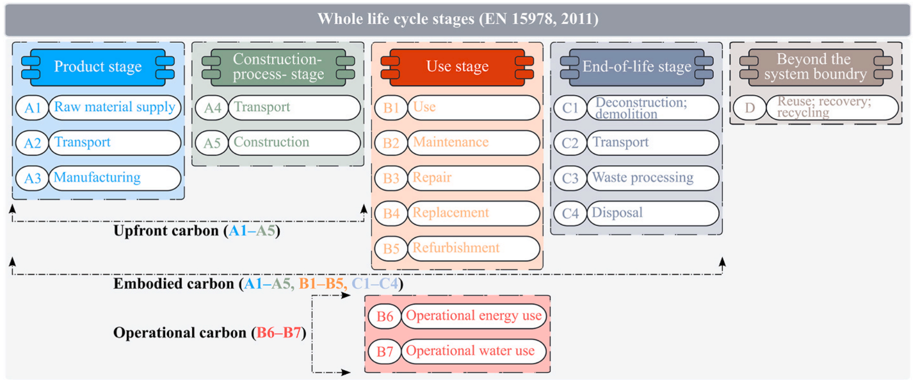

Fig. 2. Building life cycle stage from EN 15978 [75].

impacts into a single comparable unit in the construction industry and promoting sustainability [83,86].

The research scope covered the whole life cycle stages of the building in line with standard EN 15978 [75]. The considered life cycle modules are illustrated in Fig. 2 and consist of the product stage (A1–A3, cradle-to-gate); construction process stage (A4–A5, handover); use stage – building fabric (B1–B5); use stage – operation of the building (B6–B7); end-of-life stage (C1–C4, grave); and beyond building life cycle (D, benefits and loads beyond the system boundary). According to EN 15978 [75], the burdens and credits (negative emission values) of material recirculation are reported in a separate module as net impacts (*i.e.,* Module D). The inventory for building parts included encompasses the substructure, the ground floor slab, external walls, roofs, windows and doors, internal walls and partitions, finishes, floor decks, stairs and balconies, and building services (water, ventilation, heating, and cooling).

2.3.2. Application of the framework to a case study

According to the Directive (2010/31/EU [87]) only nearly-zero energy buildings (nZEBs) may be built in the EU starting in 2021 [88]. Among the various strategies for designing and constructing low-energy or nZEB housing, the passive house methodology stands out as a well-established and clearly defined approach aimed at achieving sustainable construction solutions and systems [89–91]. This methodology not only promotes energy savings through controlling the envelope with high levels of insulation and airtightness but also simultaneously improves the basis of thermal comfort and indoor environmental quality (IEQ), cost reductions, resource efficiency, and resilient to climate change [92,93].

In this study, the proposed methodology has been applied to a semi-detached dwelling situated in the UK as a bespoke house under current nZEBs regulations to qualify for the passive house standard [94]. The building block is a two-story timber-framed structure with a gross internal floor area of 104 m^2 constructed in 2020. Fig. 3 shows the

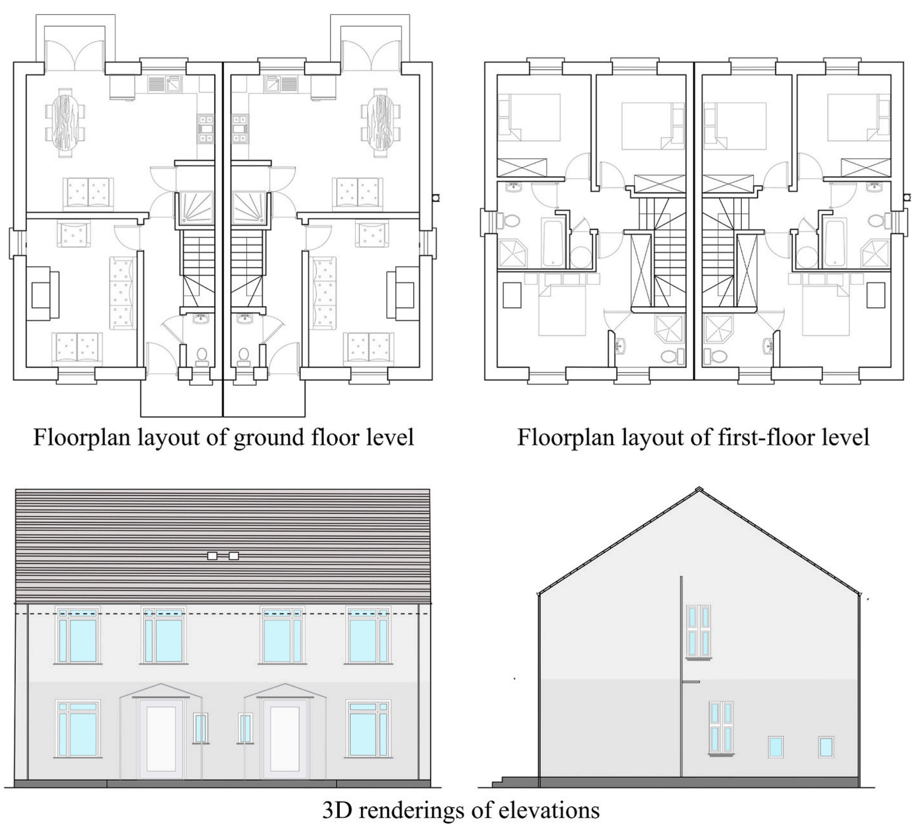

Fig. 3. Design plans and 3D renderings of the elevations for the reference case study.

building layout and the 3D renderings of the elevations in the reference house. The façade of the building is constituted by a timber frame with high-performance insulation, and its outer face is overlaid with a low e-breather membrane. The building element system is composed of an insulated concrete strip foundation, covered by the concrete screed with vinyl floor finish in the substructure, and a timber truss structure with concrete tiles in the roof (for the construction details, see Figure A.3 in supplementary material A.3).

The HVAC system was designed to run on a compact solution for heating, hot water production, and ventilation based on an electric heat pump. The seasonal coefficient of performance (SCOP) of the system is equal to 5.1 using R-134a as the refrigerant. A storage tank of 180 L with supplementary electrical heating of 1.5 kW capacity is used in this study. The building benefits from the implementation of high-performance UPVC framing windows combined with triple-glazed filling with argon gas. Coupled with the information provided in the architectural and engineering design plans, the detailed BIM model was developed using Autodesk Revit 2023 [95]. Detailed information related to the quantities of materials employed in each element in the building typology and the performance parameters of the thermal properties are listed in Table A.1 in supplementary material A.4.

The data source for building material emissions is taken from product-specific datasets, *e.g.,* EPDs, while it is supplemented by national default values for processes related to transportation, construction, and demolition for the UK context as explained in Section 2.3.4.

The reference case building model (*i.e.,* CS1) is supplied by the grid and the 2kWp site-generated solar PV system. Since solar radiation fluctuates during the day, energy-storage batteries are used to take maximum advantage of the PV surplus and reduce the building's import of grid electricity [12]. Hence, maximizing the use of on-site PV systems coupled with lithium-ion battery storage could be a promising solution for cleaner power production [96], thereby accelerating the decarbonization of the UK's residential sector aiming to achieve net-zero emissions [97,98]. Thus, according to the RIBA 2030 target [99] and taking into consideration the net conditioned area and the maximum available roof space, the reference case (*i.e.,* CS1) is to be compared with the impact of the building under two existing advanced system configurations: (i) 4kWp rooftop's solar PV system (*i.e.,* CS2); and (ii) 4kWp PV with battery storage (*i.e.,* CS3).

System sizing and simulation of both grid-connected photovoltaic systems with and without battery technologies were performed using PVsyst v7.4 [100,101], and power generations were quantified. PVsyst was selected as it is a widely used software for the purpose of designing and configuring solar PV systems at a specific location [102]. Further, numerous studies have also showcased that the result accuracy of this tool is very close to actual measured data [103–105]. During the simulation, the detailed meteorological data, such as monthly global radiation, diffuse reflection, and temperature was taken into account based on the analytical solution using well-defined variables [100], while some additional technical parameters, such as surface reflection rate, and the tilt angle were inserted according to the system-dependent utilized in the study. The specifications of the PV panel and battery systems as well as their respective country of production and transportation scenarios are summarized in Table A.2 in supplementary material A.5.

2.3.3. Building energy modeling (BEM)

The measurement of operational energy demand is undertaken based on the thermal dynamic simulation method through baseline model generation proposed in the Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum 54 (TM54) guideline [106]. The modeling approach is followed in a step-by-step methodology to include building operation and user behavior by considering the energy use of heating, electric appliances, lighting appliances, ventilation, and domestic hot water according to national regulations.

After generating the building-physics model in Revit [95], the analytical energy models were exported as pre-exported settings for the green building extensible markup language (gbXML) data schema and then imported into Designbuilder v7.2.0.032 [107] for energy simulation. It should be noted that the exported gbXML file preserves technical data regarding the building characteristics, such as its orientation and the properties of the envelope materials, while the building simulation model settings, including occupancy and energy use patterns, were inserted to reflect its typical occupying hours and operating based on CIBSE TM54 [106] and the ASHRAE guide [108]. Moreover, the standard energy plus weather (EPW) data files containing meteorological data were used for the simulation [109]. The main assumptions performed in the study are listed in Table A.3 in supplementary material A.6.

2.3.4. Data collection and GHG emission calculation

The inventory analysis of the IFC model in Revit was selected as the basis for the LCA calculation and was linked to products or processes associated with EPDs (see Table A.4 in supplementary material A.7). The basic LCA calculation procedures of embodied emissions are retrieved from building-specific EPDs, which serve as standardized documents for quantifying the environmental impacts of manufacturing products and consequently guarantees the reliability of environmental information [110]. The EPDs were ISO-compliant Type III environmental declarations in accordance with EN 15804 [67]. The reason for this is to ensure that project-relevant material data are used wherever possible covering all the building systems and aligned with the RICS guidance [73]. The datasets employed in the analysis are also geographically adjusted to the current UK market to reflect industry-wide national averages of manufacturing technology, transportation requirements, and energy mix context, which are obtained from the Built Environment Carbon Database (BECD) [111]. To ensure the consistency and comparability of assessment, EPDs should undergo revision in accordance with building-level scenarios [112], as suggested by EN 15978. When the data situation is unclear, the scenario development procedure is used to provide valuable insight for critical modeling parameters, such as the treatment of biogenic carbon emissions, viable forms of material transportation, and material recycling and disposal rates of the asset [113]. For specific factors, such as transportation to the building site, and on-site activities, the UK's Department for Business, Energy and Industrial Strategy (BEIS) [114] and the guidelines of the RICS [73] provided default emission values in the cases where values for certain materials are not available. It was also recommended to refer to the Chartered Institution of Building Services Engineers (CIBSE) calculations [115] to estimate the embodied carbon (EC) of mechanical, electrical, and plumbing (MEP) systems based on manufacturer information when EPDs are not available. For the included material and energy input flows, the cut-off criteria were aligned with the EN 15804 standard [67] to facilitate an efficient calculation procedure and avoid environmental discounting [116]. In the case of insufficient input data, the cut-off criteria were set at 1 % in terms of total mass input of its unit process and 1 % of environmental impacts, while no more than 5 % for the total of neglected input flows per module cannot be exceeded [67]. However, this cut-off rule does not apply to hazardous materials and substances. In this study, biogenic carbon of bio-based materials is considered by applying the $-1/+1$ approach (see supplementary material A.8 for details), following the current version of the EN 15804 standard [67]. The main sources of the LCA data used and the approach to the temporal emissions accounting in the impact assessment for different life cycle stages are given in Table 1.

In line with RICS guidance, all life cycle impacts associated with the production and construction stages for the PV and battery systems are allocated to the upfront emissions of the buildings, while emissions for the replacement and end-of-life stages of these technologies are considered in recurring and end-of-life embodied impacts, respectively. Besides, the electricity delivered from grid-connected PV systems with battery was modeled using the approach described by Cusenza et al.

Table 1
Source of LCA data used and approach to the decarbonization scenario in the impact assessment for different life cycle stages of the case study assessment.

Building life cycle stages	Main source of LCA data for product	Approach to temporal emissions accounting
Product stage (A1–A3)	Inventory sourced from tendered quantities; and EPDs declarations (which are specific EPDs following EN 15804 standard, and verified), are referred to. When this is not practicable, the use of Ireland and the Netherlands can be employed, given their geographical proximity, similar context, and market mechanisms [117].	No decarbonization.
Transportation in construction (A4)	Use default values developed for the UK context based upon the manufacturing location connected to each product type and various modes of transportation to enhance representativeness (see Table A.5 in supplementary material A.9); and include a 43 % empty running factor for the return journey (except for concrete ready mix which is 100 %) [73]. To inform the transport scenarios, the products and components are classified into five transport categories depending on their sourcing locations and the default scenarios of the UK's projects specified by RICS (*i.e.,* locally, regionally, nationally, European, and globally manufactured) [73].	No decarbonization.
Construction process (A5)	Include impacts arising from three distinct processes: Preconstruction demolition based on a standard assumption from RICS default values [73]; emissions due to construction activities for the baseline building-specific impacts of UK projects [73]; and on-site construction waste and waste management for each building material type from the national database (see Table A.5 in supplementary material A.9).	No decarbonization.
Use (B1)	Estimate impacts of refrigerant leakage and cementitious carbonation based on data from EPDs, where available. In the absence of specific information, use equivalent sources as detailed in CIBSE TM65 [115] for refrigerants, while guidance on calculating the carbon uptake from carbonation is given in EN 16757 [118].	50 % decarbonization of predicted fugitive refrigerant impacts [73].
Maintenance and repair (B2–B3)	Use relevant carbon data from EPDs when available. If no data is available, assume the default national equivalent [73,119].	50 % decarbonization of predicted impacts [73].
Replacement and refurbishment (B4–B5)	As modules A and C for each replacement; and using reference service lifetimes (RSLs) reported in EPDs and RICS default values for each building material and component [73]. Given a building reference study period of 60 years, it is assumed that no radical refurbishment activities (B5) were planned during the use phase, and this does not apply to this investigation.	Decarbonization pathway for replacement materials based on the UK Green Building Council [76].
Energy use in operation (B6)	Energy use is quantified through the dynamic simulation method according to technical standards and typical values for the UK context [106] and matched with conversion indicators from the national energy environmental profile [72]. The conversion factors also include the supply chain impacts for the well-to-tank (WTT)[a], the embodied carbon of energy infrastructure, and emissions from transmission and distribution losses (T&D) in the production mixes [73,114].	Use decarbonized emission factors from the national government [72], and select the conservative scenario.
Water use in operation (B7)	Assumed the mid-range benchmark levels of water consumption in the national households [120,121] and carbon intensity for both water supply and wastewater treatment [122].	The same decarbonization rate that is used in B6 is applied to the predicted impacts [73].
Demolition (C1)	Assumed the standard proportion value derived from the default business-as-usual (BAU) scenario of impacts from construction activities based on the national database [73].	50 % decarbonization of predicted impacts [73].
Transportation in EoL (C2)	Assumed a transport distance to the processing facility of 50 km; and the mode of transport to be a heavy-duty diesel truck with a 50 % load to account for the empty running factor for vehicles returning to the site and leaving with a 100 % load [73].	50 % decarbonization of predicted impacts [73].
Waste processing and disposal (C3–C4)	Where product and design details allow, use bespoke EoL scenarios obtained from EPDs. Where data are unattainable, the default share per treatment process from the BAU scenario (see Figure A.4 in supplementary material A.10), and emission factors are assumed [73]. To support the assessment in selecting and formulating the relevant EoL scenarios, the information for "100 % scenarios" is provided as this allows to use of composed scenarios evaluated at the building level [123].	No decarbonization [73].
Benefits and loads beyond the system boundaries (D)	Use EPD data when available. Refer to the RICS methodology for how to estimate module D impacts; and use default emission factors for those that do not have existing EPD reports, which should be based on waste processing and disposal treatments [73,75, 124].	50 % decarbonization of predicted reuse, recycling, and energy recovery impacts [73].

[a] Well-to-Tank (WTT) impacts represent the upstream emissions of extraction, refining, and transportation of raw fuel sources.

[125]. It accounts that the battery storage cannot feed the grid and vice versa. The environmental factors for lithium-ion battery storage were collected from Stevenson [126]. Life cycle carbon emissions from the replacement and maintenance stage (modules B1–B5) were modeled in the inventory analysis based on the assuming standard service lifetimes of the building materials obtained from product-specific data by the EPDs. The carbon intensity of the electricity mix used in building utilities (*e.g.,* HVAC systems) was based on the country-specific electricity data provided by UK national statistics [72].

As shown in Table 1, a default factor of 50 % emissions reduction over the building lifespan is implemented for some modules pertaining to embodied impacts, including fugitive refrigerant, maintenance, repair, demolition, transportation of waste processing, and benefits and loads beyond the system boundaries. These scenarios for embodied carbon decarbonization are uncertain due to sensitivity to the characteristic factor of different material categories and sources (*e.g.,* grid mix in the country of production for the material); however, this analysis supports continuous improvement in the background model by following a conservative perspective of technological learning [73].

3. Results and discussion

The results are interpreted using contribution and sensitivity analysis to identify influential parameters and potential areas for improvement. As a first step, baseline assessment results are presented, where the GHG emission factors of the case study are followed in accordance with their current state. Subsequently, the emissions from building mitigation measures and the associated emission savings are assessed for different future technological progress.

3.1. Life cycle emissions of baseline assessment

Fig. 4a presents the results of the cumulative carbon footprint of the building's baseline (current state) scenario for the three system configurations over time. The highest positive peak at the beginning is due to the increase of upfront embodied carbon (UEC) impacts allocated to the material production (A1–A3), and construction (A4–A5) stages, while the final peak occurs at the EoL stage (year 60) to distinct end-of-life embodied carbon (EEC) emissions (*i.e.,* C1–C4). In year 0, the inclusion of biogenic carbon gives an initial credit (negative emission), which advantages the permanently sequestered carbon by showing lower emissions until the EoL stage. Additional spikes occur over the project's lifetime, resulting from the recurrent embodied carbon (REC) emissions (*i.e.,* B1–B5) of those materials and components that need to be replaced at the end of their service lifespan. There is also a constant emission emitted due to the OC impacts (B6–B7) which take place over 60 years.

As shown in the life cycle results, the case studies follow the same trends due to the similar building structure and enclosure, while resulting in significant opportunities attributed to those using renewable technologies with and without battery storage (*i.e.,* CS2, and CS3). The case studies CS2 and CS3 tend to have around ~6 %, and ~11 % higher emissions in the initial impacts, respectively, compared to the reference case study (*i.e.,* CS1). This is due to the additional embodied impacts that may be emitted during the production stage (modules A1–A3) of these renewable energy system components (*e.g.,* PV panels and battery systems). Manufacturing of PV cells and associated components contains several carbon-intensive processes, generally for heating processes, and substantial electricity inputs [127], which are leading to noteworthy impact contributions. However, when the benefits from annual surplus (PV) electricity production are obtained during building operations, case studies incorporating advancement system configuration (*i.e.,* CS2 and CS3) can outperform the standard practice with the installation of a 2kWp PV system (*i.e.,* CS1) and bring to a GPBT lower than 6 years. In other words, even if the initial impacts of solar energy systems and batteries are high levels, the renewable energy produced on-site injected into the grid using the assessed technologies can compensate for substantial CO_2eq emissions and thereby would significantly affect their payback time. This noticeable positive return is mainly due to the current high carbon-intensive electricity mix in the UK (~0.207 kg CO_2eq/kWh [72]) in comparison to those studies in regions characterized by relatively similar solar irradiation while in cleaner energy sources (*e.g.,* a GPBT up to 18 years in zero-emissions pilot buildings in Norway [128], and even the GPBT exceeds the service lifespan in the case study in northern France and southern Sweden [129]).

Fig. 4b illustrates the contribution of the embodied and operational impacts on the WLC emissions of the case studies. The footprint reference case study (*i.e.,* CS1) is 1065 kg CO_2eq/m^2, while the footprints of the case studies with installing 4kWp PV system are 960 kg CO_2eq/m^2 and 940 kg CO_2eq/m^2 with and without batteries, respectively. Based on Fig. 4b, the proportions of embodied impact on the WLC of CS1, CS2, and CS3 account for 46 %, 53 %, and 58 %, respectively. Since the case studies have the same structural parts and energy classes, these outcomes point out how PV system configurations (with and without storage) allocated to the building could lead to an increase in the contribution of embodied flows (40–60 % of life cycle GHG emissions) [130].

A hotspot analysis of the EC for the reference case study (*i.e.,* CS1), allocating the emissions into different life cycle modules and building material categories is shown in the chord diagram in Fig. 5. The hotspot analysis is performed to assist in making informed decisions about material substitutions that can contribute to the reduction of embodied impacts. The REC emissions (modules B1–B5) have surprisingly the most substantial influence (*i.e.,* ~27 % of the EC emissions), being mainly due to replacing those materials, as their functionality is potentially compromised past their estimated technical lifespan. The second-largest contribution is modules A1–A3 (manufacture), accounting for ~26 % of the EC emissions of the building (*i.e.,* 183.2 kg CO_2eq/m^2). The EoL stage significantly contributes to the EC impact (~18 % of embodied emissions) as a result of mostly incineration processing of timber materials. Another notable result derived from Fig. 5 is the substantial contribution of modules A1–A3 (sequestered) attributed to biogenic carbon storage to the embodied impact of the assessed timber building (~16 % of embodied emissions). However, this carbon stored in timber materials is temporary (although often long-term), and they are shifted to the end of their life.

The results also showed that "*Steel and other metals*" materials, such as reinforcing steel, "*Timber and timber-based*" materials, such as softwood timber products, and "*Oil-based*" materials, such as polystyrene insulation foam and PVC floor vinyl, are recognized as the most significant CO_2eq emissions at the material level, which they are mainly contributed by both UEC and REC emissions. This indicates that the replacement of these carbon-intensive emitters (hotspots) with relevant measures should be considered as more effective mitigation strategies. Notably, these suggestions would be addressed by reducing materials' quantity or emission intensity while serving the same purpose and with similar functionality [131]. As the possible solutions, carbon emissions can be reduced through various mitigation strategies by material substitution (*e.g.,* 50 % per mass of produced cement by using supplementary cementitious materials and optimizing the clinker content in cement production [54]), improved material efficiency (*e.g.,* 35 % in

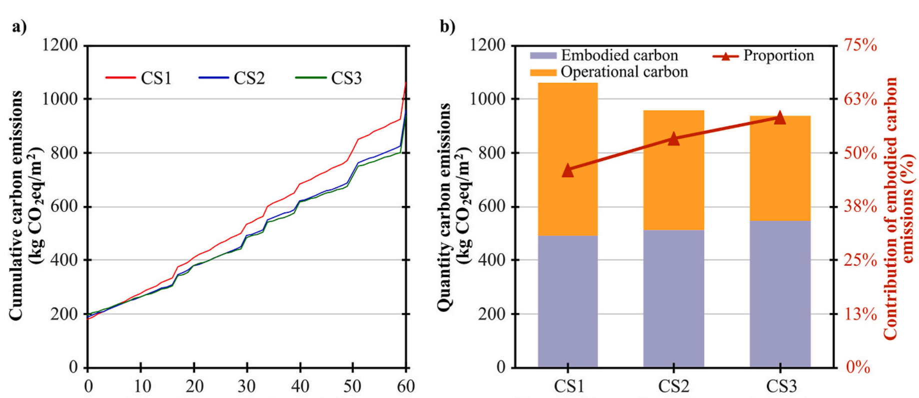

Fig. 4. Building life-cycle emissions for (a): Cumulative whole-life cycle (embodied + operational) impacts over time; and (b): Contribution of operational and embodied carbon emissions to the whole-life carbon (WLC) emissions, as well as the proportion of embodied carbon related to WLC. (Note that this figure considers the baseline scenario, which assumes the current situation of available technology and practices over time for the production of the electricity mix and future replacement materials, as well as where carbon sequestration is accounted for.)

quantities for concrete in slabs and 40 % per mass for slab reinforcement by optimizing the material use in structural design methods [132]), and increased circular material use (*e.g.,* 50 % for paint by use of materials with high recycled content [133]).

It is also important to note that "*Refrigerant leakage*" tends to have the highest rates of CO_2eq/m^2 (~21 % of REC). The refrigerant type in the case study is R-134a, which is also widely employed for residential heat pumps in the current UK community [134]. However, it contributes significantly to climate change because of its losses and a high GWP of 1430 kg CO_2eq/kg [115]. The UK government aims to gradually reduce the use of fluorinated greenhouse gases (F-gases) by 79 % below the average levels used for 2009–2012 by 2030 [134], and the pure propane refrigerant (R-290) is an appropriate alternative due to the smaller charge amount and promising low-GWP substitutes while improving the system performance of heat pump units [135]. Replacing the default working fluid for utilization in the heat pump with R-290 results in 8 % reductions in EC, which is equivalent to a net 4 % reduction in a 60-year whole-life cycle carbon emissions.

3.2. Temporal scenarios for life cycle GHG emissions of building

To understand how temporal emissions accounting affects building practices, Fig. 6 depicts the contribution of carbon emissions for two different pathways: the baseline (constant) scenario and the evolving future scenario. The former does not assume decarbonization strategies and follows the current situation of the life cycle inventory over the building lifespan (see Fig. 6a), while the latter considers the future variations in the carbon intensities of electricity generation and materials (see Fig. 6b). As shown in Fig. 6a, the main contributor from the WLC in the current scenario is "*Building services*", representing 748 kg CO_2eq/m^2. This noticeable contribution from the "*Building services*" (*i.e.,* ~70 % of the overall emission) can be further separated into sub-elements, which are mostly dominated by emission-driven in operations (*i.e.,* ~54 % of the WLC). Non-operational emissions from "*Building services*" are mainly caused by the services (mechanical, electrical, and plumbing), as a result of having for ~23 % of the EC calculated. As also illustrated in Fig. 6a, the building layer "*Finishes*" tends to have a significant contribution to the embodied impact (~16 % of the EC).

When considering a grid decarbonization strategy along the operation of the building (see Fig. 6b), the reference building system case study demonstrates the potential for reducing to ~64 % the OC associated with the baseline result assessment. The results also show no significant difference between baseline and evolving future scenarios for "*Substructure*" and "*Structure (frame, floors, roofs, and stairs)*", where the future variations results are ~3 % lower than the current state results. However, there is a considerable difference between the impacts obtained by baseline and temporal emissions accounting for three building layers; "*Building services*", "*Stuff (fittings, furnishings, and equipment)*", and "*Finishes*". This higher difference is because these layers have significant quantities, emission factors, and replacement rates throughout the entire building. For example, the EC emissions of "*Finishes*" in the baseline scenario associated with modules A1–A3 (manufacture + sequestered) and modules B1–B5 are being relatively similar counted (*i.e.,* from 28.7 to 30.1 $kgCO_2eq/m^2$, respectively), while in evolving future scenario being one-third counted attributed to the impact assessment (*i.e.,* from 28.7 to 8.6 $kgCO_2eq/m^2$, respectively). This is why when recurring emissions of "*Finishes*" begin to accumulate, the combined impacts in evolving scenarios can significantly lower the initial construction impacts depending on the baseline level across multiple life cycles (mainly because of interior finishing, and replacement of the gypsum walls). The contribution of modules B1–B5 to the whole life-carbon of the "*Skin/Façade (external walls, windows, and doors)*" for bassline and evolving scenarios are represented to 20.5 to 8.6 $kgCO_2eq/m^2$, respectively. This shift specifically pertains to lower emission factors for the replacement of windows and doors with shorter lifespans compared to the building itself. In a consistent manner for "*Building services*", the EC emissions of modules B1–B5 decreased from 124.7 in the baseline scenario compared to 42.6 $kgCO_2eq/m^2$ in the evolving

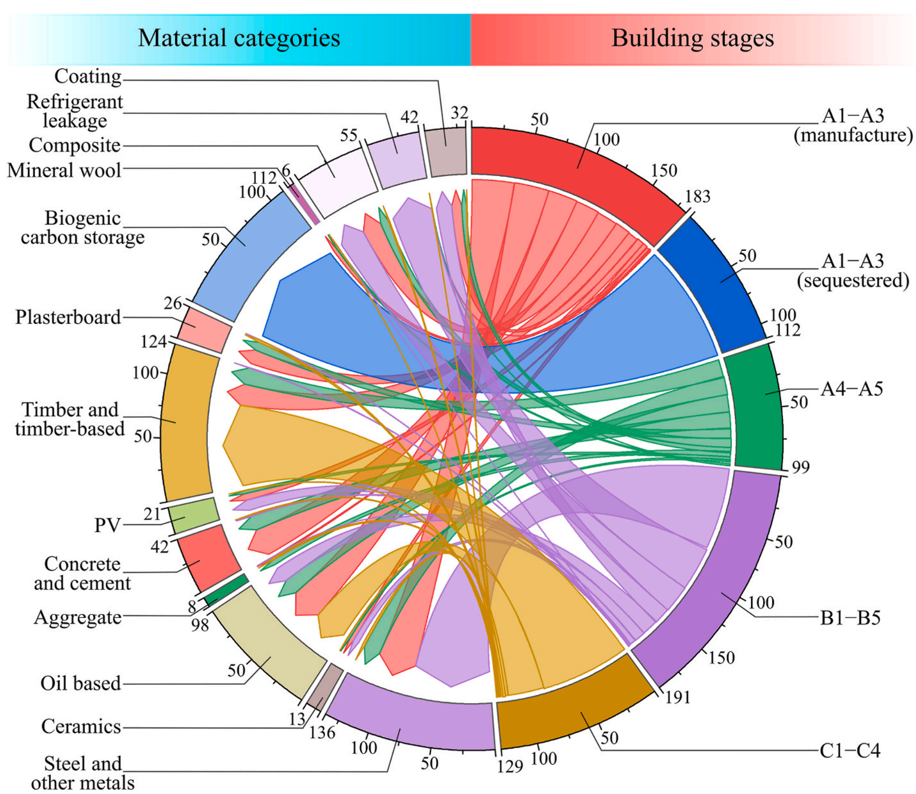

Fig. 5. Distribution of embodied carbon (EC) emissions from the building stages according to EN 15978 [75] and material categories according to a set of predefined material and product groups.

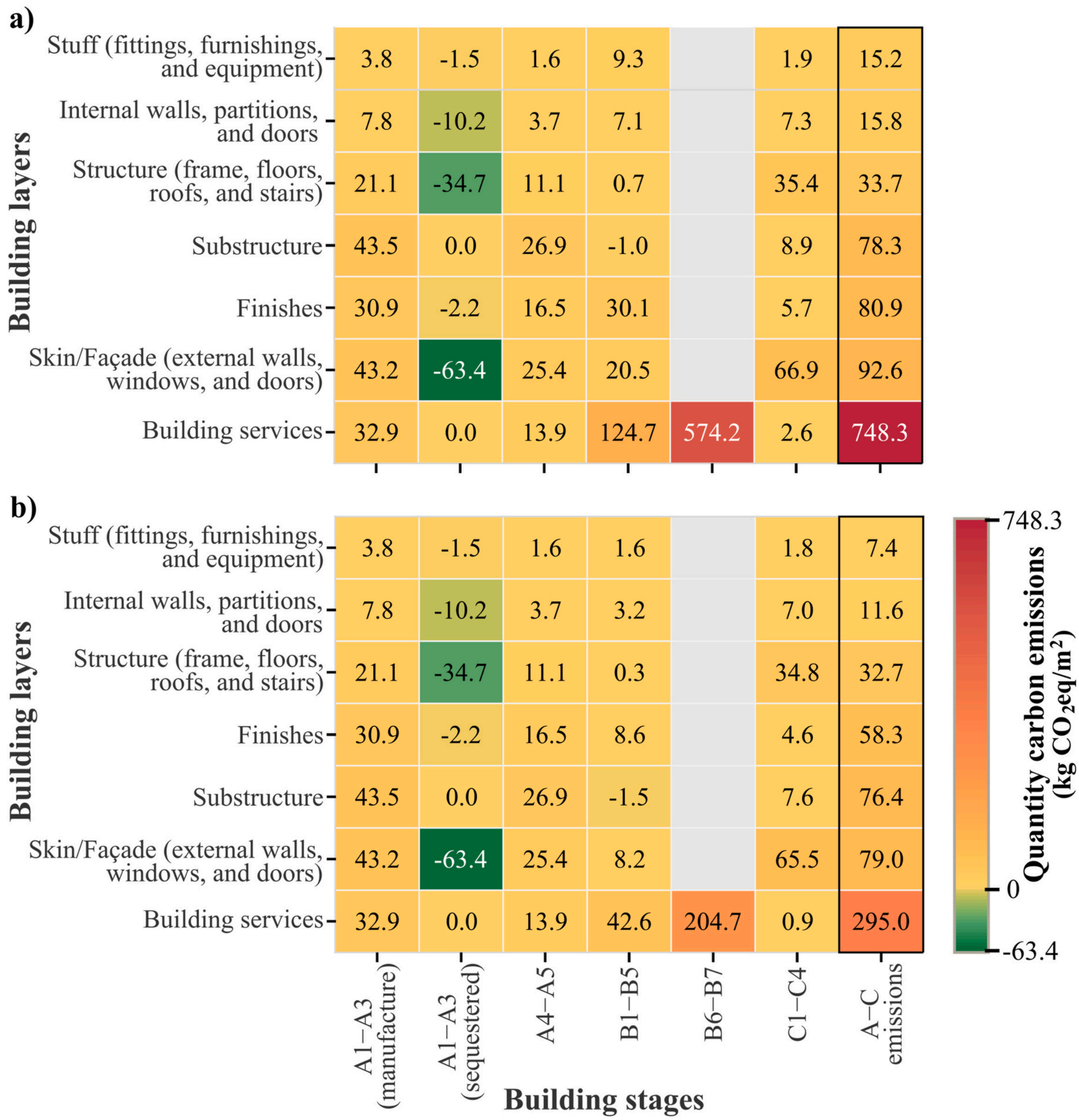

Fig. 6. Calculated carbon emissions of the reference case study for different future-oriented assumptions in terms of: (a) Baseline (current state) scenario, and (b) Evolving future scenario (*i.e.,* electricity mix evolution and material decarbonization). It allocates the emissions into building stages according to EN 15978 [75] and building layers according to WBCSD guidance [136]. (Note that embodied emissions of renewable electricity generation (*e.g.,* PV and battery storage) are allocated to the "*Building services*" category.)

scenario. Notably, the expected decarbonization of the electricity mix leads to a substantial reduction in carbon footprint attributed to the modules B6–B7 by ~65 % (*i.e.,* from 574.2 to 204.7 $kgCO_2eq/m^2$, for baseline and evolving future scenarios, respectively).

The LCA results for the baseline and evolving future scenarios over the building life cycle phases for different case studies are shown in Fig. 7. The PRD values indicate the extent to which the evolving future results are lower than their corresponding baseline counterparts. There are no differences between baseline and evolving future impacts in UEC and biogenic carbon storage for the case studies as no temporal variations exist during this period. The impacts from the future-oriented perspective resulted in considerable differences for the use stage flow (up to −67 % and −64 % for REC and OC, respectively), while little difference is observed for the EOL impact (up to −7% for EEC). Overall, the PRD ratio of the WLC impact indicates a significant potential reduction in GHG emissions of 47 % when the evolving future scenario is considered for the case of $CS1_{BL}$.

Fig. 7 shows that even in a certain scenario considering a dynamic grid and material decarbonization scenario, adding more large-scale implementation of solar PV systems without battery storage (*i.e.,* $CS2_{EF}$) can achieve CO_2eq savings for buildings, representing a 6 % reduction against a 2kWp grid-connected PV system (*i.e.,* $CS1_{EF}$). Comparing the effect of battery storage; the carbon emissions are increased slightly with storage, leading to a 1 % higher emission. This implies that when considering the evolving future scenario for the GPBT calculations, the grid-connected PV battery system does not pay back its additional emissions within the building lifespan, resulting in a possible negative carbon reduction efficiency for the system configuration examined in the building case study. This negative carbon balance for the system during the building lifespan is even more apparent when an incredibly optimistic grid decarbonization scenario (*e.g.,* holistic transition scenario [72]) in line with climate change targets is taken into account. In this sense, it can be concluded that in order to support low-carbon decision-making in UK buildings, it is necessary to: (i) adopt a large-coverage possible of the available rooftop area with a solar PV system; and (ii) significantly improve the environmental performance for future replacement of its components, notably batteries and panels, over time.

As shown also in Fig. 7, in applying a grid decarbonization strategy along the operation phase, the emission savings increases to ~73 % by a 4kWp PV system (*i.e.,* $CS2_{EF}$), with even greater potential reductions of ~76 % by a 4kWp PV + battery system (*i.e.,* $CS3_{EF}$) compared with the baseline's reference case study (*i.e.,* $CS1_{BL}$). Moreover, with a discounting of future emissions, the magnitude of OC and REC emissions is correspondingly substantially decreased due to on-site energy-generated measures (*e.g.,* rooftop PV), electricity mix evolution, and material decarbonization, thus emphasizing keeping a stronger focus set on UEC emissions from material production. As an example, comparing the baseline's reference case study (*i.e.,* $CS1_{BL}$) with the building case study integrated with a 4kWp PV + battery in the evolving future scenario (*i. e.,* $CS3_{EF}$), it can be seen that the proportion of UEC impacts on the WLC emissions may vary considerably (*e.g.,* ~27 % for $CS1_{BL}$, reaching ~57 % for $CS3_{EF}$).

4. Discussion

Addressing the potential for deeper decarbonization of buildings is crucial for several countries around the world as part of their national and global challenges in climate change. Given the UK government's target to build ~355,000 homes per year by the mid-2020s [8], there is a pressing need for a comprehensive understanding of the associated carbon footprint that considers pathways in line with current states and long-term climate impact developments [137].

Even though OC impacts represent the largest fraction of emissions from buildings, the EC impacts (particularly the UEC emissions) also contribute significantly under the current scenario. For instance, the results illustrated that the UEC (emissions released in materials and construction processes up to practical completion, modules A1–A5) represent ~27 % of WLC emissions in the baseline scenario. However, when considering the effect of future electricity mix change and the decarbonization opportunity of embodied impact (*e.g.,* low-carbon production for future replacement), the relative share of UEC to the total attributable is considerable for the building case studies, representing as high as 57 % of WLC emissions. This increase in the relative contribution of upfront embodied impact from 27 % to 57 % to the carbon footprint suggests that in the future, building assessors should place more importance on their material choices and design in energy-reduction actions. A similar conclusion was also reached by other studies [26,138,139], highlighting a paradigm shift to the production and construction phases in terms of energy consumption and/or GHG emissions. The other reason for the critical role of upfront carbon is that this emission occurs irreversibly to the global environment before construction, and it remains invisible as new buildings will not be demolished by 2050 [140]. Correspondingly, the findings also demonstrated that, when considering the temporal emissions perspective, the relative contribution of the avoided emissions achieved by biogenic carbon in products (−112 kg CO_2eq/m^2) could increase by ~11 % compared to baseline result calculations. Hence, to meet the mid-century carbon targets, it is therefore essential that upfront emissions and biogenic carbon are always considered as a matter of urgency in sustainable architecture and building design.

The results showed that when taking into account an evolving future scenario and incorporating advancement system configuration along the WLC, the potential emissions reduction using the comparison of the baseline's reference case study (*i.e.,* $CS1_{BL}$) represents 47–51 %, with a higher saving for the 4kWp PV without battery storage (*i.e.,* $CS2_{EF}$). This reduction is mainly because the building case study is situated in the UK, where the grid already has a relatively high carbon intensity and consequently a larger relative emission saving obtained from the energy generated from PV panels (with and without battery) in the short term. However, surplus (PV) electricity production for future scenarios when the UK's national electricity mix is quickly and strongly decarbonized, does not pay back the corresponding life cycle embodied emission investment of PV and/or battery systems. This remark is supported by the findings of a few other studies in the field [128,141]. Conversely, this leads to the conclusion that the embodied impact of PV systems (particularly integrated with battery storage) has a large magnitude influence on their net environmental life-cycle performance. Thus, as this paper shows, even with considering a 50 % embodied emissions reduction of the future replacement for existing PV and battery technologies, it may be possible that the on-site energy generation with battery systems cannot be considered a meaningful sustainable and environmentally friendly solution in the long term in the UK. As a response to this challenge, the secondary utilization of batteries from the end-of-life electric automotive sector for storage systems in buildings [125], advancements in PV hybrid systems [142,143], looking at emerging PV technologies, such as organic solar cells [144], adoption of BIPVT systems [145], as well as recovery of materials composing the PV modules [146,147] should be considered in importance to attaining both net-zero energy and carbon balance in buildings. In similar concern, the results also indicated that with the substitution of high-GWP working fluids R-134a with propane (R-290), as an eco-friendlier alternative in heat pump systems, the building case study can attain further savings by ~8 % in EC, which is equivalent to a net 4 % reduction in 60-year whole-life cycle carbon emissions. Despite this drastic contribution compared to other building elements in the present

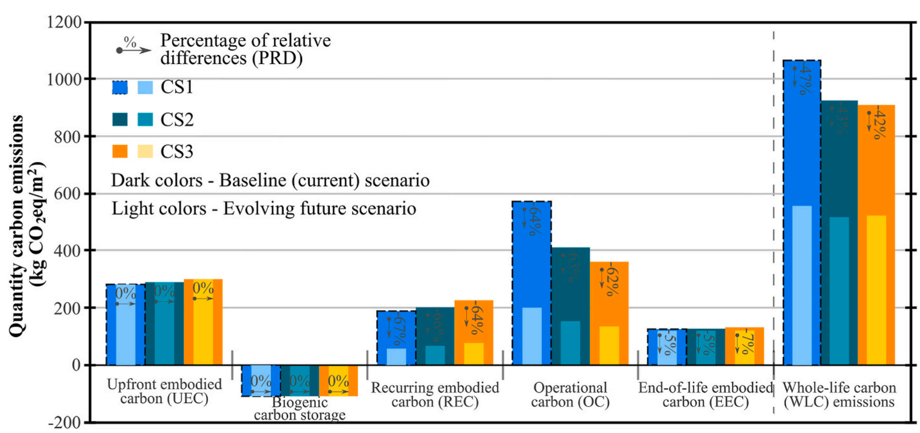

Fig. 7. The carbon footprint of baseline (current) and evolving future scenarios in different life cycle stages. The chart includes a distinction between operational and embodied emissions, and the percentage of relative difference (PRD) ratios to demonstrate how the LCA result varies across its relevant building stages.

study, refrigerant emissions have been neglected for years by country policies and previous studies mainly because of: (i) as often summarized as the balance of the system and neglected for the use phase due to lack of data [148], and (ii) as assuming all systems to be maintenance-free, thus refrigerants left outside of the assessment boundary [149]. Hence, the increasing attention of the design and research communities should be placed on a careful selection of all the building's envelope materials and components to initially decrease the embodied impacts, and thus eventually contribute to further reduction of the WLC impacts of the building.

It is crucial to note that the decarbonization of the electricity mix will significantly influence the environmental performance of material production [150], indicating that the replacement of construction products will cause less GHG emissions. As a result, following a dynamic approach to the operational aspect while maintaining a static approach to the embodied part can lead to biased results in the estimated performance throughout the building's lifespan [86,151]. It is therefore necessary to implement a dynamic approach that will take into account simultaneously grid variations in carbon emission intensity correspondingly, and also adapt the influence of the substitution potential of replacement materials for being followed in future construction practices. Using the life cycle environmental workflow implemented in this study, emission-saving potential through both operational and embodied measures can be extrapolated to other countries for testing their long-term low-carbon development targets in the construction sector.

Despite the interest and the expected future role of introducing the BECCS supply chain as a negative emissions technology to mitigate carbon emissions [152,153], the progress of its potential has been marginal in the UK industry [154], and it will take time to be implemented commercially, due to its high costs, governance issues, and environmental considerations [155]. With respect to the latter, this article thus did not include consideration of permanent carbon storage of BECCS technologies in the assessment in compliance with the current LCA standard [67]. It is important to point out that deployment of BECCS could potentially capture close to 90 % or above of CO2 emission in the flue gas (or syngas) [153,156]. However, even though emission savings derived from the future potential of the BECCS supply chain do not guarantee that a subsequent life will take place, this would effectively reflect how keeping its long-term sequestration emissions out of the atmosphere [157], and thereby may buy time for advancements to be made in the climate transformative technologies. Hence, in line with the UK climate change mitigation framework, performing an optimistic future mix of BECCS applications, where potentially it supports the expansion of low-carbon electricity supply [154], can achieve a significant potential reduction within the UK's wider net-zero strategy.

Given the current urgency of mitigating GHG emissions from the built environment [85], this study focused on the GWP indicator as a priority performance evaluation for the construction industry [158, 159]. The selection of this investigated impact category is also justified through previous studies, demonstrating as a proxy indicator that has the benefit of reducing the complexity of multiple impacts to facilitate effective communication to policymakers [160], and further, stating a high correlation of the GWP with many other impact categories [161, 162]. However, there is a risk of potentially overlooking new insights in the evaluation of future dynamic situations if only a single environmental impact (*e.g.,* the GWP) is considered, where it may introduce shifts in environmental considerations [163,164]. Thus, to avoid burden-shifting by solely focusing on the GWP indicator, it is essential to analyze how the evolving future scenarios will change the importance of the different impact categories by investigating a broader set of environmental indicators in the assessments.

This article assessed the mitigation climate strategies of a British timber-framed building sector aiming to support further policy development in the UK and similar Northern European contexts as a priority to increase the sustainability performance of the construction industry. Further analysis could be extended to examine different building types (*e.g.,* multi-unit residential buildings) and structural materials (*e.g.,* steel frame), as well as to cover other geographic locations to gain a more comprehensive understanding of features relevant to building carbon footprint.

5. Conclusions

The objective of this study was to evaluate the whole-life carbon (WLC) impacts of timber low-energy buildings from a future-oriented perspective. The methodological approach combines life cycle assessment (LCA) and scenario-based model with the consideration of different decarbonization strategies, aiming to look at the effect of introducing temporal factors of (i) future evolution of building material replacement and decarbonization of the electricity mix; and (ii) grid-connected photovoltaic (PV) systems with and without battery utilization.

The analysis shows that a temporal emission accounting for the grid and materials reveal substantial differences in the LCA results compared with the standard consideration (up to ~60 % reduction in the case study equipped with 4kWp PV). In future research, a dynamic assessment of operational and embodied impacts (particularly including the significant influence of electricity mix evolution and decarbonization of future replacement materials) should be implemented whenever addressing emission savings for different low-carbon targets of the building industry or in the case of other long-time sector developments. This system dynamic approach may also add higher accuracy to the accounting of the environmental savings achieved by photovoltaic systems toward a decarbonized and sustainable residential sector. When considering the decarbonization of both grid and materials, the findings reveal that adding battery storage to the grid-connected PV systems is not necessarily a net environmental positive for the building, with the latter increasing CO_2eq by ~2 % of WLC impacts in this work. Furthermore, although in many studies the impact of "*Refrigerant leakage*" is disregarded in the assessment boundary of residential buildings as it is considered negligible, this study highlights the relatively significant contribution to the embodied impact of the non-natural refrigerant fluid used in heat pump systems compared to other building elements for both at the current state and especially in the evolving future scenarios.

Moreover, we have highlighted that although the implemented strategies of the integrated PV system configurations, electricity mix evolution, and decarbonization of materials could achieve a substantial reduction of the carbon footprint of the building case study, the actions aimed at achieving a more low-carbon building sector cannot be focused only on these emission-saving measures. It is also believed that the materials production and end-of-life stages can potentially become more relevant in low-energy buildings as a result of future considerations of the temporal perspective included in this study (*e.g.,* the relative contribution of upfront embodied impacts to the WLC of buildings increases from ~27 % in the baseline's reference case study to ~57 % in a case study integrated with a 4kWp PV + battery system under the evolving future scenario). This proves the importance of low-impact strategies focusing on the material level (*e.g.,* utilization of more eco-friendly materials) and also the potential benefits of circular economy concepts in new building projects. Thus, for any future effort aiming to contribute to the national decarbonization targets, the increasing attention of practitioners should be placed on the material market to substantially decrease the upfront embodied impacts and technological progress in the waste management treatment of materials to reduce end-of-life embodied emissions.

CRediT authorship contribution statement

Masoud Norouzi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Assed N. Haddad:** Writing –

review & editing, Resources, Methodology. **Laureano Jiménez:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition. **Mostafa Mohajerani:** Writing – review & editing, Visualization, Methodology. **Dieter Boer:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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

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