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Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland

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A B S T R A C T

This paper implements a Life Cycle Assessment of several low-energy/passive house buildings located in Northern Ireland. This work aims (i) to assess the environmental performance of the buildings and (ii) to evaluate the effect of electricity decarbonization on the dwellings' global warming potential (GWP). Three different future electricity mix scenarios have been used and compared to a static scenario where the current electricity mix remains constant. The LCA results of the static scenario reveal that applying passive-house standards could reduce the impact of dwellings while it does not necessarily provide a positive environmental outcome. The building operation phase contributed the most to the environmental impact, while negligible impact comes from the end-of-life stage. The electricity decarbonization leads to a significant reduction of GWP in all cases, with the highest value achieved for the passive house using the highest share of electricity, 58%-70% GWP reduction compared to the static scenario. Moreover, electricity decarbonization increases the relative share of the production stage to the overall building emission. Therefore, close attention should be paid to construction material selection in any effort aiming to achieve further environmental benefits. The buildings' environmental and operational energy performances were also compared to the RIBA 2030 Climate Challenge.

1. Introduction

In recent years, the world has been facing major environmental challenges such as global warming, ozone depletion, and the destruction of natural habitats, mainly arising from human activities. Therefore, there is an urgent need for worldwide commitments to prevent and reduce these consequences [1,2]. Among different sectors, the building sector is a significant consumer of energy and natural resources, and it potentially damages the environment [3]. For instance, in Europe, the impact on the buildings' life cycle is around 50% of all energy use, 33% of all water use, 50% of all raw material extraction, and 40% of all greenhouse gas emissions [4]. According to the UN Sustainable Development Goals (SDGs), the construction sector has unique opportunities for addressing local and global environmental objectives [5]. From this perspective, any effort towards increasing sustainability and cleaner construction must include this sector as a critical element in decreasing the total energy usage and greenhouse gases.

Concerning the desire to reduce building energy use and greenhouse gases, the operational stage of a building is critically important as it typically contributes to 60–90% of the total building environmental impacts [6–10]. Several strategies may help to achieve a significant reduction of energy use in the building operation phase: (i) minimizing the need for energy inputs (*e.g.,* increasing levels of insulation, glazing with better thermal performance, and using airtightness); (ii) adopting buildings with energy-efficient and low-carbon technologies (*e.g.,* electrical heat pumps); (iii) decarbonize of the electricity mix production and use on-site electricity production (*e.g.,* photovoltaics, wind, hydro, and biomass); and (iv) variation of occupant behaviors (*e.g.,* thermal management, and typology of the family) [11–13]. Several studies have been conducted to address these strategies, for example, using different insulation materials for the building envelope [14–16]; choosing more efficient heating, ventilation, and air-conditioning (HVAC) equipment [17–19]; using building automation and control system (BACS) [20,21]; encouraging energy-saving measures within occupant behaviors [22–25]; and applying renewable energy technologies [26–29].

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Nomenclature

Abbreviations

AA	Accelerated Ambition [-]
ACC	Addressing Climate Change [-]
ADP	Abiotic Depletion Potential [kg Sb eq]
AP	Acidification Potential [kg SO_2 eq]
BIPV	Building-integrated photovoltaic [-]
BIPVT	Building-integrated photovoltaic with thermal [-]
BIM	Building Information Modelling [-]
BRE	Environmental Assessment Method
CED	Cumulative Energy Demand [GJ eq]
CML	Institute of Environmental Sciences (Faculty of Science University of Leiden, Netherlands) [-]
CO_2	Carbon dioxide [kg CO_2]
CO_2 eq	Carbon dioxide equivalent [kg CO_2 eq]
ELCD	European Life Cycle Database [-]
EoL	End-of-life [-]
EP	Eutrophication Potential [kg N eq]
EPD	Environmental Product Declaration [-]
FSC	Forest Stewardship Council [-]
ESL	Estimated Service Life [year]
FU	Functional Unit [-]
GHG	Greenhouse Gases [kg CO_2]
GIA	Gross Internal Area [m^2]
GSHP	Ground source heat pump [-]
GWP	Global Warming Potential [kg CO_2 eq]
HRE	Heat Recovery Efficiency [%]
HVAC	Heating, Ventilation and Air Conditioning [-]
ISO	International Organization for Standardization [-]
LCA	Life Cycle Assessment [-]
LCI	Life Cycle Inventory [-]
LCIA	Life Cycle Impact Assessment [-]
multi-Si PV	Multi-crystalline Silicon photovoltaics [-]
MP	Modest Progress [-]
MV	Mechanical ventilation [-]
MVHR	Mechanical ventilation with heat recovery [-]
NV	Natural Ventilation [-]
NZEB	Net or Nearly Zero Energy Building [-]
OLD	Ozone Layer Deplation [mg CFC-11 eq]
PH	Passive House [-]
PHPP	Passive house planning package [-]
PEFC	Programme for the Endorsement of Forest Certification [-]
POP	Photochemical Oxidation Potential [kg NMVOC eq]
PV	Photovoltaic [-]
RE	Renewable Energy [-]
RES-E	Electricity produced from renewable energy sources [-]
RIBA	Royal Institute of British Architects [-]
RICS	Royal Institute of Chartered Surveyors [-]
SAP	Standard Assessment Procedure [-]
SPF	Seasonal Performance Factor [%]
SDGs	Sustainable Development Goals [-]
TESNI	Tomorrow's Energy Scenarios Northern Ireland [-]
U-value	Thermal Transmittance [W/(m^2K)]
UN	United Nation [-]

With regard to solar energy technologies, the benefits of implementing innovative practices of Building Integrated Photovoltaic (BIPV), Building Integrated Photovoltaic-Thermal (BIPVT) systems, and passive solar building technologies should be highlighted. Essentially BIPV/BIPVT systems are the integration of the PV module into the building structure so that the conventional building materials are replaced by PV cells. These systems not only can act as a standard exterior building envelope but also provide the opportunity for on-site electricity production (and thermal energy via an absorption process in the case of BIPVT). This would pave the way for net-zero energy constructions, whose potential in terms of energy consumption and reduction of global warming is commonly recognized [30]. In addition, using BIPV/BIPVT can significantly improve the building aesthetic, natural lighting, and thermal comfort [31]. The main advantage of using BIPV/BIPVT systems over non-integrated PV systems is that they carry out multi-functions, for example, by providing thermal insulation, noise prevention, being weatherproof, as well as offsetting the system initial costs [30]. In passive solar building technologies, the windows, walls, and floors are made in a way to collect, store, reflect, and distribute solar energy in the building without using mechanical and electrical devices (unlike active solar techniques, *e.g.,* PV). These techniques not only convert sunlight into heat (in water, air, and thermal mass), but they cause air-movement for the purpose of ventilation, with a small share of using other energy sources [32]. An example of a passive solar heating system is the Trombe wall that is a massive wall located behind glass; it absorbs solar energy and releases it towards the building interior at night. The hot air between the wall and the window can be introduced into interior spaces by incorporating heat-distributing vents at the top of the wall [33].

Northern Ireland, the region studied in this work, follows the UK's commitment to Paris Climate Agreement [34] to reach net-zero greenhouse gas (GHG) emissions by 2050. The Northern Ireland region has a number of challenges, including high levels of fuel poverty, lack of natural resources, high dependence on imported fossil fuels, and building regulations which are the lowest in the UK. According to the 2016 House Condition Survey [35], 99% of dwellings in Northern Ireland had central heating, where 68% of them are oil-fired, 24% with central gas heating, and 8% including solid fuel, electric, and fuel systems. However, the potential for the deployment of low-energy buildings is considerable. Previous studies have shown that the net additional cost of a three-bedroomed passive house can be as low as £5,088 [36]. Moreover, passive houses combined with electric heat pumps can simultaneously reduce the operational energy demand, remove the dependence on imported fossil fuels, improve comfort levels, and realize multiple financial benefits [37]. In particular, the construction of new buildings based on passive house standards is in line with the demand of UN energy efficiency standard as well as the findings of the UK Climate Change Committee (CCC) for new buildings to be built with a space heating demand of 15 to 20 kWh/m^2/year [38].

As shown previously in [36,37], the use of three-bedroomed passive houses can provide economic, logistic, and energy benefits, along with improvement in inhabitant comfort level. Moreover, a vast majority of existing Life Cycle Assessment (LCA) practices do not consider the influence of future decarbonization in the electricity mix on LCA results, and frequently, the practitioners use current energy mixes for future scenarios [39]. To the best of the authors' knowledge, there is no work published to address the environmental performance of semi-detached passive house dwellings in which Northern Ireland's electricity decarbonization is evaluated. Therefore, this study looks at how this approach can contribute to meeting the UK's environmental commitments by considering not only the operational carbon emissions of the case study passive house dwelling with integrated heat pump, but also in particular, the impact of the decarbonizing grid on the typology which shows such potentials. For doing so, the relevance of considering future electricity mix according to the Tomorrow's Energy Scenarios Northern Ireland (2020) [40] on the environmental impact of case studies is evaluated. Furthermore, to improve the understanding of decision-makers on the buildings' environmental performance, the LCA results of the present study will be further compared to an existing UK's benchmark regime for the buildings.

The paper is organized as follows: a general outline of the environmental assessment methodology and tools is explained in Section 2. It also describes the future electricity mix scenarios considered. Section 3 describes the case studies, and Section 4 reports the LCA results and discusses the effects of decarbonization in the case studies. The conclusion and insights for future research are provided in Section 5.

2. Materials and methods

In this section, the framework employed to model and analyze the effect of decarbonization is described. The first step of this analysis is to collect the data, and to perform a traditional LCA on the four single-family houses. Besides, the energy scenarios are defined to model the current and future electricity mix's decarbonization pathways, and the life cycle inventory datasets are modeled using the defined electricity mixes. In the next step, the impact of decarbonization of the electricity generation is integrated into the LCA of the case studies. Finally, the environmental impact (embodied carbon) and the operational energy of the dwellings are compared to the existing national benchmark to assess the contribution of the building sector in achieving the UK's environmental targets.

2.1. Environmental impact assessment

The Life Cycle Assessment (LCA) is a broadly accepted tool to carry out the environmental impact assessment associated with a process/product through its whole life cycle. This study follows the standardized ISO norms 14,040 and 14,044 [41,42], in which the framework of an LCA includes four steps: (1) Goal and scope definition: outlines the envisioned application, the motivations for conducting a study, define the methodological framework to satisfy the intended goals, outlines the boundary of the system, and defines the functional unit; (2) Life cycle inventory (LCI): compiles and quantifies inputs (*e.g.,* materials, and energy) and outputs (*e.g.,* emissions to air, water, and soil) that cross the system boundary; (3) Life cycle impact assessment (LCIA): uses environmental impact indicators to predict the extent and importance of the impacts to human health and the environment; (4) Interpretation phase: depicts the results and derives conclusions [42].

2.1.1. Goal and scope of the LCA

This study aims to evaluate the environmental impact of four different residential buildings located in Northern Ireland, including two low-energy buildings complying with functional requirements of SAP (2009) and SAP (2012) [43,44], and two dwellings meeting the requirements of Passivhaus standard. In particular, the environmental performance of the case studies is evaluated based on both construction materials and elements breakdowns, related to the production phase, in-use, and end-of-life phases, which highlight the co-benefits of low-energy/passive houses. Additionally, we study the influence of future electricity mix on the LCA results of the aforementioned case studies, see section 2.2.

In the present study, the functional unit in the inventory analysis is one square meter gross internal area (GIA) of the building. The lifespan of 60 years was assumed for the operational stage, which is consistent with RICS as the buildings' lifetime in the UK [45].

2.1.2. System boundaries

The overall LCA of a building, using the cradle to grave approach, covers from raw material to demolition. According to the European standard EN 15978 standard [46], as shown in Fig. 1, the life cycle stages of a building are (i) product stage (A1–A3); (ii) construction stage (A4–A5); (iii) use stage (B1–B7); (iv) end-of-life stage (C1–C4); and (v) benefit and loads beyond building life cycle (D).

According to EN 15,978 standard, as shown in Fig. 1, the LCA study includes (i) materials production phase (modules A1–A3); (ii) transport to the building site (module A4); (iii) in-use phase, including ordinary maintenance, *i.e.,* the combination of maintenance and replacement (modules B2 and B4), and operational energy use (module B6), which covers all the processes occurring during the building service, such as heating, cooling, and energy usage by electrical appliances; (iv) end-of-life, including transport from construction site to waste processing/disposal, and processes for waste processing and disposal (modules C2–C4); and (v) beyond the system boundary, including resource recovery of building materials and components, and in particular the benefits deriving from the surplus of renewable energy exported to the grid (module D). The modules use (B1), repair (B3), refurbishment (B5), and operational water use (B7) were not considered due to the lack of data, and in the present LCA comparison would be assumed to be similar for all dwellings, so they were omitted from the LCA boundary. The construction (A5), and deconstruction (C1) modules were also excluded since these modules typically have a negligible impact [47,48]. The system boundaries included in this study contribute to the majority of building life cycle impacts (82–98%) [49]. The analysis covered the materials utilized in the structure and the building envelope, including the foundation, beams and columns, floor slabs, exterior, and interior walls, roofs, windows, surface materials, electrical and heating systems, and paints. However, fixtures, fittings, lighting, and plumbing were not included in this study.

One of the features of the wood-based buildings is the biogenic carbon contained in the bio-based materials. Biogenic carbon is the sequestration of carbon dioxide from the atmosphere during plant growth involving photosynthetic processes. When these materials ultimately decompose or are incinerated at the end-of-life stage, the sequestered carbon is re-emitted to the air [50]. According to RICS [45], this study assumes that the timber originates from a sustainably managed forest (certified by FSC/PEFC or equivalent). Therefore, the two main approaches can be distinguished when assessing the impact of biogenic carbon: (i) according to the product environmental footprint (PEF) standard [51], it can be omitted since any carbon sequestered initially will be released back into the atmosphere (the '0/0' approach); (ii) based on EN 15804 standard [52], it can be taken into account as a negative emission during materials production stage (A1-A3), and an equivalent positive emission at the end-of-life (C) stage (the '–1/+1' approach; –1 for CO_2 uptake; +1 for CO_2 emission) [50]. The amount of sequestered carbon in wood products is calculated according to EN 16449 [53]. It is worth noting that absorption of CO_2 by carbonation of the cement-based products is not accounted as the use phase (module B1) was out of the system boundary included.

2.1.3. Life cycle inventory (LCI)

The LCI of the primary data, including building drawings and the data about building products, electricity, fuel consumption for plants and equipment, and wastes, were provided by the construction company (Tables A.1 and A.2 in Supplementary Materi-

Life cycle of buildings																Supplement
Production			Construction		Use							End-of-life				Beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Row materials supply	Transport to manufacturer	Manufacturing	Transport to construction site	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse/recycling
✓	✓	✓	✓	-	-	✓	-	✓	-	✓	-	-	✓	✓	✓	(✓)

Fig. 1. Life cycle stages of buildings [46], Note: [✓] indicates if processes in a life cycle stage are included, [-] indicates if the processes of a life cycle stage are omitted, and [(✓)] indicates that the processes of a life cycle stage are partially included.

als). These documentations contain a building information modeling (BIM) object (products' details and technical specifications), spillage, and maintenance instructions. Other required data, such as equipment, was gathered through questionnaires and interviews with experts. If the data was unavailable, it was retrieved from environmental product declarations (EPDs), the information from manufacturers, and scientific papers. Quantity information (*e.g.,* length, area, and volume) of different materials and components were exported from Revit/BIM [54]. In this study, the cut-off criteria of the EN 15804 [55] were followed. According to this standard, the inputs with less than 1% contribution to the mass or primary energy demand may be neglected, while the cumulative total of these neglected inputs should not exceed 5%. However, this cut-off rule was not applied to hazardous materials and substances. The inventory data for pellet fuel production was taken from [56], and data for pellet combustion were taken from [57,58]. In addition, the physical properties of the heating oil were taken from the digest of UK energy statistics (DUKES) report [59].

Domestic consumptions and ordinary maintenance have been calculated with the assumption of a lifespan of 60 years. The estimated service life (ESL) of different inputs is mainly based on information of the manufacturer from the EPDs, and the durability of fabric components taken from RISC default service life [45] (Table A.3 in Supplementary Materials). The values given within the ESL are considered for each building component to calculate the materials and energy consumption. The consumption of wood pellet, oil, and electric energy needed for heating and cooling was assessed considering the local climate conditions, characteristics of the building shell, heating and cooling mode and the form of energy systems, and users' behaviors. The operational energy for various case studies was evaluated by thermal energy performance in the Passive House Planning Package (PHPP) [60].

For transportation (modules A4 and C2), a combination of average values specified by RICS was used [45]. These default values consider the transportation from the manufacturing companies of materials and components to the UK project site, and from the building to the recycling plants and/or disposal sites (Table A.4 in Supplementary Materials). The transportation data emissions were taken from the Ecoinvent database [61].

Concerning the end-of-life stage, for all built-in products, a waste treatment scenario was implemented for different processing options (*i.e.,* recycling, landfill, and incineration), based on the data obtained from EPDs, and the RICS recommendation [45] (Table A.5 in Supplementary Materials). The present work adopts the method proposed by the PEF4Buildings project assumptions [62] to quantify the avoided impacts related to recycling processes for various materials [63]. In particular, according to the PEFCR Guidance [51], the default recycled content values on the EU market were used for inert materials, metals, plastics, and wood products.

2.1.4. Life cycle impact assessment (LCIA)

The LCI data was employed to calculate the environmental impact of the materials and products throughout their life cycles. According to EN 15,978 [46], the most relevant data for environmental analysis is specific information from each product collected from EPDs defined in EN 15,804 [55]. However, due to lack of sufficient open access EPDs for all materials, in the case of those materials where no relevant data were available, use the generic data available at Ecoinvent v3.7.1 [61] and the European Life Cycle Database (ELCD) v3.2 [64] are proposed.

In this study, the two well-known LCIA methods of (i) Cumulative Energy Demand (CED) method [65], and (ii) the CML-IA baseline V3.01 method [66] were employed [67]. The CED is a commonly-used method to measure direct and indirect energy use throughout the entire life cycle of a product or a system [68], and it serves as an indicator for choosing a more environmentally friendly alternative [69]. CML is an impact assessment method to evaluate midpoint impact categories through focusing on quantitative modeling to early stages in the cause-effect chain to limit uncertainties [66]. This method is most widely used in building LCA studies from the environmental and political point of view [46,70,71]. CML includes a set of 11 environmental, resource-depletion, and toxicology midpoint impact categories. In this study, CML was used to account for the major environmental concerns using the following impact categories: Global Warming Potential (GWP), Abiotic Depletion Potential for elements (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidation Potential (POP), and Ozone Layer Depletion (OLD) [72,73]. The SimaPro v9.2 software [74] was used to estimate environmental impacts. Results for those items that come from the EPDs were modified and were added in LCA calculations.

2.2. Electricity mix scenario design

A parameter that has a significant hotspot impact on the LCA results is the electricity mix, as it is broadly assigned to the energy-consuming phase of many products. This is particularly true for buildings, as highlighted in multiple studies [75,76].

In this study, the LCA is implemented for the current, and three future electricity mix scenarios as defined in Tomorrow's Energy Scenarios Northern Ireland 2020 (TESNI 2020). As illustrated in Fig. 2, current Northern Ireland's electricity mix is still heavily dependent on fossil fuels, with an energy mix of 43% natural gas, coal 14%, oil 2%, wind 35%, solar, and others 6% [77,78]. For the baseline analysis, the current electricity mix in 2018 is considered, and it is assumed to remain constant over the life cycle of the building. This type of modeling, *i.e.,* taking a static (current) electricity supply mix of a specific year in the product's life cycle, has been employed in many LCA studies [67,79]. However, since new renewable energy plants will be installed in the coming years, the substantial decarbonization of the electricity used is expected [80]. Therefore, the reliability of the environmental impact analysis may be significantly improved if the time-related changes in the electricity mix are considered [81,82]. Additionally, the uncertainties can be addressed by comparing potential scenarios in a sensitivity analysis.

TESNI 2020 reports the three future electricity mix scenarios, that exhibit potential energy pathways to achieve various degrees of decarbonization for Northern Ireland, respectively named: "Modest Progress", "Addressing Climate Change", and "Accelerated Ambition" [40]. All these scenarios deliver Northern Ireland's contribution to the UK target emission reduction of 80% by 2050 compared to 1990, based on the 2008 Climate Change Act [40].

The "Modest Progress", corresponding to the "MP" scenario in this study, represents a situation in which decarbonization progress is made compared to the present day; however, it is slower than in the other scenarios. In this scenario, 60% of electricity is generated from renewables (60% RES-E) by 2030, and GHG reduction of more than 35% by 2030; little economic growth is expected over the next decade; new homes from 2025 and existing properties from 2035 must adopt the Future Homes Standard while a ban on new petrol and diesel cars will be proposed by 2040 [40].

In "Addressing Climate Change", named as "ACC" scenario in the present study, a situation is assumed in which Northern Ireland achieves a low carbon future while 70% RES-E target for 2030 is met, and GHG reduction is more than 35% by 2030. The adoption of Future Homes Standard to new homes from 2025 and existing properties from 2035 is planned whilst new petrol and diesel cars will be banned by 2040. This scenario achieves UK net zero emissions reduction contribution for Northern Ireland by 2050, set out by the Committee on Climate Change [40].

The fastest decarbonization progress is achieved through "Accelerated Ambition", corresponding to the scenario "AA" in this work. In this scenario, Northern Ireland reaches the very ambitious target of 80% RES-E by 2030 through continued development of onshore wind and a large increase in solar generation, including also a significant uptake by consumers through the use of rooftop PV. This scenario reaches the UK net zero emissions reduction contribution for Northern Ireland by 2040, 10 years sooner than ACC [40].

Information about future projections is available in the TESNI 2020 [40] for certain pivotal moments (*i.e.,* 2025, 2030, 2040, 2050). The electricity mixes used in this study for the current situation, and for the future scenarios (as reported in TESNI 2020 [40]) are presented in Fig. 2.

In this study, in order to calculate the yearly CO_2 emission factors of the current situation and future scenarios for a unit of the low-voltage electricity mix, the contribution of all generation technologies reported for the available moments are modeled with Ecoinvent 3.7.1 [61] using Simapro (Tables A.1–A.8 in Supplementary Materials) (*e.g.,* Ref. [79]). In this study, technological evolutions in the generation processes are beyond the scope of the current study and, therefore, not taken into account. The electricity imported and the losses due to the transmission and distribution are taken into account in the product system. The M2 model described in [79] was used to model the imported electricity. A gradual annual evolution of the electricity CO_2 factors is considered

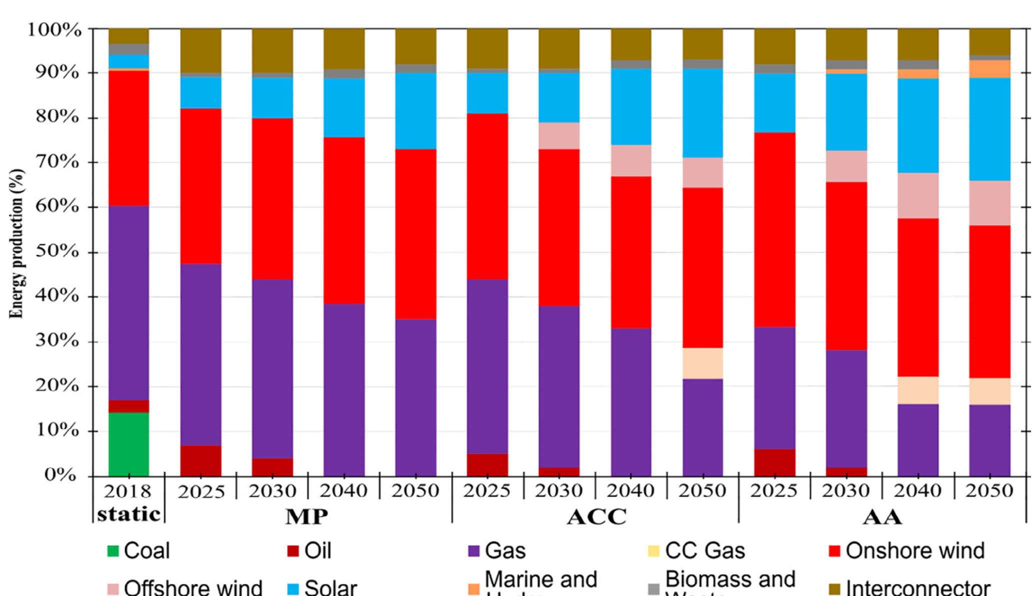

Fig. 2. Electrical energy production shares in Northern Ireland.

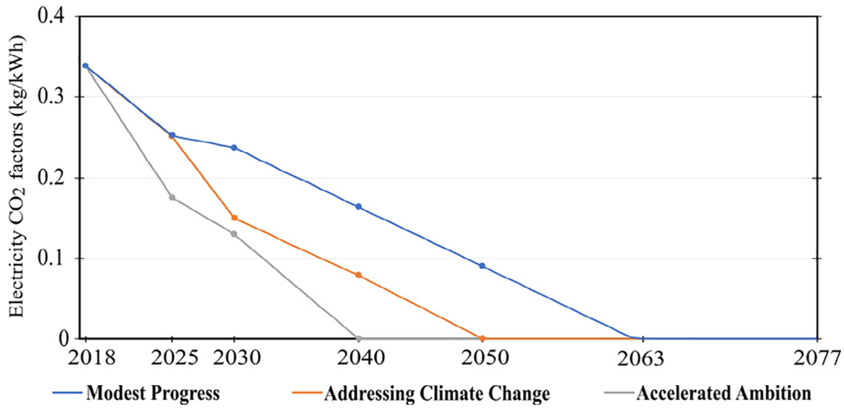

Fig. 3. Electricity CO_2 emission factors of the scenarios.

using a linear interpolation between the values obtained for the key moments. For the scenarios ACC and AA, it is considered that the value of the carbon emission factors remains stable at zero for the levels after 2050, while it decreases with a fixed slope to 2050 in the scenario MP. Fig. 3 shows the CO_2 emission factors in terms of kg/kWh electricity produced from different scenarios.

2.3. Benchmark

The benchmark used in this study for comparing the environmental performance of the analyzed case studies is the RIBA 2030 Climate Challenge. The RIBA 2030, developed by the Royal Institute of British Architects, proposes well-established voluntary target values for operational energy use, water use, and embodied carbon for domestic/residential and non-domestic buildings [83]. These performance targets set out a trajectory to realize the reductions necessary by 2030 in order to have a realistic prospect to achieve the net-zero carbon for the UK building stock by 2050 [83]. Based on these targets, an intermediate target by 2025 is established. These target values serve as the benchmark that does not necessarily need to be met, but they can be helpful in the building design process to identify where to act to improve the environmental performance of a building, and to understand if the building will contribute to achieving the UK environmental targets [83]. In this study, the operational energy and embodied carbon of the case studies were compared to the benchmark target values.

3. Application to the building case study

In this study, a reference house built based on the most common characteristics of typical semi-detached dwellings is considered. The building block has a two-story timber frame south-orientated (187.1 m^2 heated floor area) and is located in Northern Ireland. The house was designed in 2018, according to a project described by a local building company. The building envelope is constructed on a strip foundation of concrete, with a wooden frame insulated by mineral wool in the walls and roof. The ground-level floor is made from reinforced concrete cast over a layer of expanded polystyrene (EPS). Fig. 4 shows the 2D and 3D models of the reference house.

Four different actual types of semi-detached buildings built based on the reference house are considered in this study. Table 1 and Table 2 give an overview of the existing differences between case studies regarding their thermal properties, ventilation method, space heating systems, and installation of renewable technologies. Each of the different case studies uses a combination of different technologies to deliver energy.

In this work, the dwellings were modeled in Standard Assessment Procedure (SAP) 2009 and (2012) [43,44], and in Passive House Planning Package (PHPP). SAP was considered as it is the UK Government's National Calculation Methodology (NCM) [84]. It is based on the BRE Domestic Energy Model (BREDEM), and it provides accurate and reliable assessments for calculating dwellings' energy performance to comply with UK building regulations [85]. SAP is a steady-state model for assessing how much annual energy (*e.g.,* space heating, domestic hot water, and electric lighting) a dwelling will consume when delivering a defined level of comfort and service provision [85]. PHHP incorporates the Passivhaus methodology for assessing the energy performance of a building, and it consists of systematically developed calculations by comparing dynamic simulations to validated measurements in completed Passive House projects [84].

The first case study (BS1) achieves compliance performance criteria that pass current minimum building regulations requirements on SAP (2009) [43]. The second case study (BS2) focuses on using renewable technologies and using thicker insulation in the floor to meet the SAP (2012) regulation requirements [44]. The BS1 and BS2 benefit from double glazing windows and doors, a wood pellet stove, and high efficiency condensing oil boiler supplied to the water tank for domestic hot water and space heating. The generated electricity by 2 kW photovoltaics is fully exported to the grid, and it is considered to be substituted for the low-voltage electricity from the Northern Ireland-country mix, which consequently brings environmental benefits to the system. Its configuration has been analyzed using a polycrystalline cell type. Based on the manufacturer specifications, the Terreal Solutions PV3-1S (82 Wp) modules with a 15.4% nominal efficiency have been considered. The installation performance was simulated using PVsyst [86], and the average annual electricity production was estimated to be 1,748 kWh/y. Solar PV technical specifications are listed in Table A.10 in Supplementary Materials.

Case studies 3 and 4 (*i.e.,* PH1 and PH2) comply with the international Passive House standard and also the Irish buildings regulations. The case study PH1 benefits from its advanced building fabric design (*e.g.,* the application of triple glazing and advanced insulations), superior airtightness performance, in combination with mechanical ventilation with heat recovery (MVHR), and an efficient condensing oil boiler that is supplied to the water tank. The same design strategy as PH1 is used in PH2 but with a Heat Pump compact P unit instead of MVHR and oil boiler.

The materials inventory of the four case study types resulted in 252 processes, each characterized by the materials quantity, and

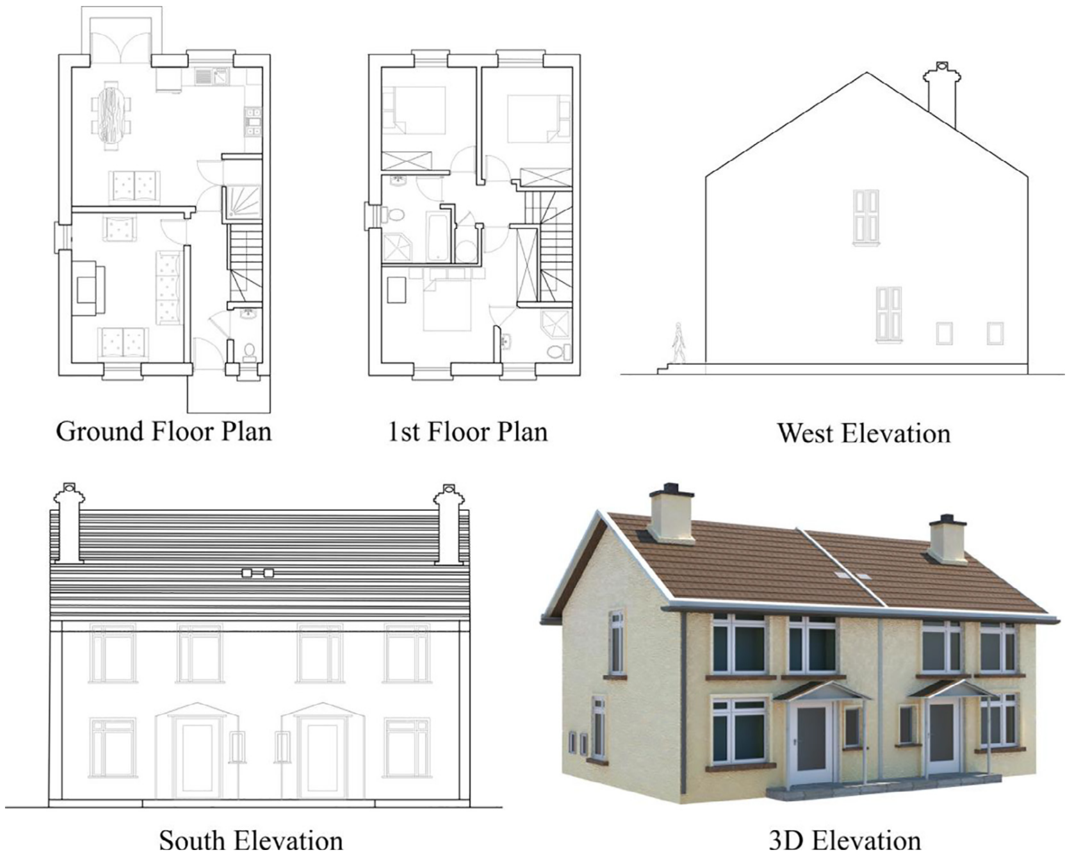

Fig. 4. 2D and 3D model of the reference house.

Table 1
Characteristics of the building envelope and ventilation systems for the case studies.

Energy-standard		Building case study BS1 Low energy	BS2 Low energy	PH1 Passive house	PH2 Passive house
U-Value (W/ (m^2 K))	External wall	0.20	0.20	0.148	0.148
	Roof	0.15	0.15	0.085	0.85
	Floor	0.258	0.175	0.209	0.209
	Window	1.80	1.80	0.75	0.75
Airtightness	(ac/h @ 50 Pa)	5	5	0.4	0.4
Ventilation		NV and MV	NV and MV	MVHR	MVHR (Compact P unit)
Mechanical ventilation system	HRE (%)	N/A	N/A	83	80

NV = Natural Ventilation (Purge ventilation via windows in the habitable room and open flue in the living room); MV = Mechanical Ventilation (Mechanical extract fan of 10 m^3/h in kitchen and bathrooms); MVHR = Mechanical Ventilation with Heat Recovery; HRE = Heat Recovery Efficiency; N/A = Not Available.

Table 2
Characteristics of the heating systems and renewable technologies of each case study.

	Building case study			
	BS1	BS2	PH1	PH2
Heated Floor Area (m^2)	187.1	187.1	187.1	187.1
Primary heat generator	Heating oil boiler	Heating oil boiler	Heating oil boiler	HP compact P unit
[a]Secondary heat generator	Wood pellet stove	Wood pellet stove	N/A	Direct electrical (heating resistance)
Passive house compact unit with exhaust air heat pump	N/A	N/A	N/A	Compact P unit
Efficiency Heating System	Main: 93%, Sec: 84%	Main: 93%, Sec: 84%	Main: 93%	Main: SPF 300%, Sec: 70%
Renewable technology- multi-Si PV (m^2)	N/A	12	N/A	N/A

multi-Si PV = Multi-crystalline Silicon photovoltaics panels; SPF = Seasonal Performance Factor; N/A = Not Available.
a: Secondary heating systems account for 40% of space heating requirements.

Table 3
Mass of different materials utilized in the reference building case studies (in ton).

Material	Case study			
	BS1	BS2	PH1	PH2
Ceramics	2.7	2.7	2.3	2.3
Concrete and cement product	66.9	66.9	63.8	63.8
Glass	0.7	0.8	1.1	1.1
Gravel and sand	23.2	23.2	23.2	23.2
Insulation	4.0	4.0	4.5	4.5
Paint	1.6	1.6	1.6	1.6
Plasterboard	8.3	8.3	8.7	8.7
Plastics	8.6	8.6	8.6	8.6
Steel and other metals	3.3	3.5	3.3	3.2
Timber	9.0	9.0	9.1	9.1

their corresponding construction waste factors (Table A.1 in Supplementary Materials). The building materials were grouped into ten main categories: concrete and cement product, timber, plastics, gravel and sands, glass, etc. Table 3 reports the amounts used in the construction of the building.

4. Results and discussion

4.1. Life cycle impact assessment

Table 4 shows the overall LCA results balance (impacts + cred its), including cumulative energy demand and six mid-point impact categories of the case studies. The BS1 (*i.e.,* low-energy building with wood pellet stove and oil boiler) is regarded as the base case. The relative performance of the remaining case studies is reported with respect to this base case study for a fixed building lifetime of 60 years. Table 4 shows the passive house design reduces midpoint indicator of all impact categories with an average of 30% (and up to 50%) compared to the base case BS1, except the abiotic depletion potential category where the PH2 (*i.e.,* passive house with an electric heat pump compact unit) has relatively similar environmental impacts. Between the two PH case studies, the case of PH2 exhibits much better energy-saving and environmental benefits with an average of 18% compared to the passive house equipped with condensing oil boiler (*i.e.,* PH1).

Table 4 also shows an advantages associated with passive house design, which is their more efficient energy systems. With regard to CED, the residential timber frame dwelling built in accordance with the passive house standard provides a consistent reduction of the energy demand (38– 53%) compared to the wood and oil-based heating system in low energy building standard of BS1. The better energy performance is due to upgrades to the insulation, windows/doors, airtightness, and heating systems (*e.g.,* boilers/HP).

The global warming potential (GWP) has a 30–43% lower environmental impact of PHs compared to BS1. This is mainly due to better efficient heating technology used in the PHs; these types of dwellings follow a similar pattern as the energy consumption of an energy source with minor fossil fuel contribution compared to the low-energy buildings. In both approaches of the −1/+1 and the 0/0, the biogenic carbon is assumed to be carbon neutral throughout the building life cycle; therefore, considering any of these approaches would lead to the same results. According to Table 4, a similar consideration for the GWP indicator can be made for the ozone layer depletion (OLD) and photochemical oxidation potential (POP). Concerning the OLD, the environmental performance of PHs is distinct compared to BS1. This is basically because of fossil fuel burning (using pellet in stove heating system) in the latter case studies. An evaluation of the EP indicator results shows a 48–56% reduction of environmental impacts in PHs.

Fig. 5 illustrates the environmental impact of each case study over the building life cycle, including GWP (from both '–1/+1′ and '0/0′ approaches), AP, ADP, OLD, POP, EP, and CED. With regard to the GWP, although the overall impact calculated with the approaches 0/0 and –1/+1 would be the same, they exhibit different impacts from their materials production and end-of-life stages. As shown in Fig. 5, with the 0/0 approach, the contribution of the materials production stage is 7–12% for case studies, while with the –1/+1 approach, it is 3–6%, which is basically due to the differences associated with the biogenic carbon uptake in the timber-based components. No benefit of sequestered biogenic carbon is considered with the 0/0 approach, while the –1/+1 approach includes biogenic carbon within the materials production stages; hence, the latter approach exhibits lower carbon emissions from the materials production stage. Fig. 5 shows that the impact from

Table 4
Impact assessment results balance for the case studies. Absolute emission per m^2 (GIA) for a 60-year lifetime is given for BS1 (low-energy building with oil boiler and wood stove), while corresponding relative values for comparison are given for the BS2 (low-energy building with oil boiler, wood stove, and MCPV), and PH1– PH2 (passive house with oil boiler, and heat pump, respectively).

Impact indicator	Unit	Absolute (unit/m^2 (GIA))	Difference (%)		
		Base case-BS1	BS2	PH1	PH2
GWP ('0/0′ approach)	kg CO_2 eq	2431	−10	−30	−43
GWP ('-1/+1′ approach)	kg CO_2 eq	2431	−10	−30	−43
AP	kg SO_2 eq	9.38	−8	−30	−40
ADP	kg Sb eq	0.0271	10	−7	0
OLD	mg CFC-11 eq	0.00052	−3	−35	−57
POP	kg NMVOC	0.52	−6	−38	−48
EP	kg N eq	2.51	−8	−48	−56
CED	GJ eq	64.0	−6	−38	−53

GWP = Global warming potential; AP = Acidification potential; ADP = Abiotic depletion potential; OLD = Ozone layer depletion; POP = Photochemical oxidation potential; EP = Eutrophication potential; CED = Cumulative energy demand.

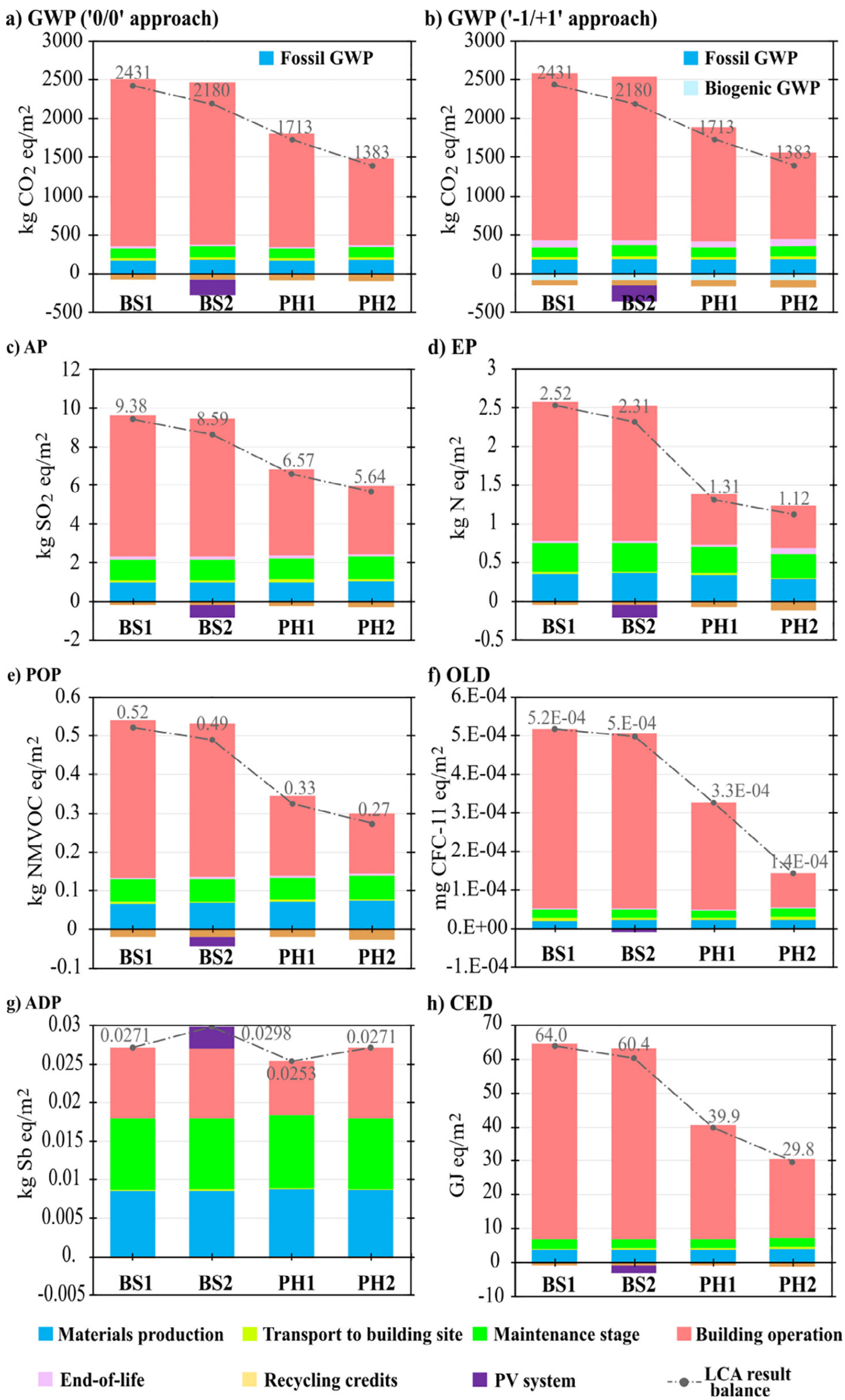

Fig. 5. Life-cycle environmental damage generated by each stage.

the EOL stage calculated with the −1/+1 approach is about 4% higher than the 0/0 approach. The reason behind this is that the timber-based components are assumed to be incinerated in the EOL stage, and the biogenic carbon is released accordingly.

The building operation, materials production, and maintenance stages are responsible for most environmental damages generated in most impact categories, while only a minor portion is generated during the end-of-life phase. The building operation dominates the overall indicator results in primary energy use (greater than70% on indicator CED), and all of the environmental categories (except abiotic depletion), whereas the ratio between building operation and other phases may vary strongly (*e.g.*, 45/55 % for PH1 in EP, reach-

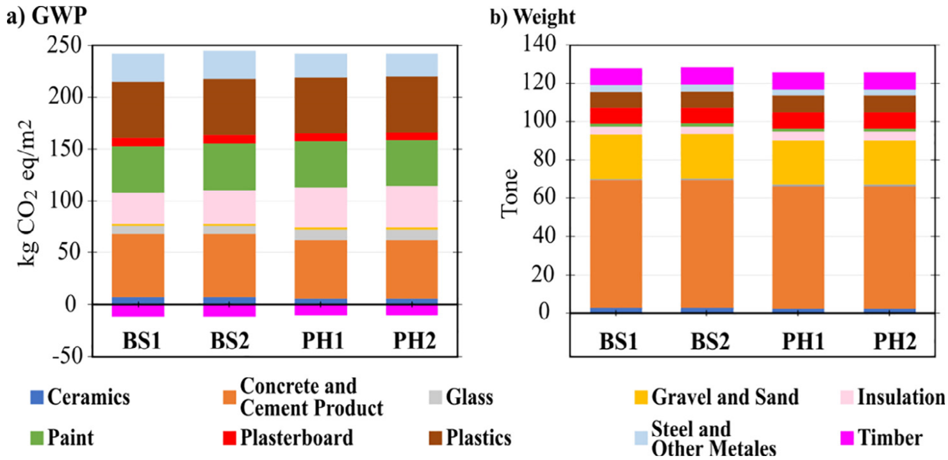

Fig. 6. The composition of house construction materials (a) in terms of greenhouse gas emission, and (b) in terms of weight.

ing about 90/10 % for BS1 in indicator OLD). This dominating factor influencing the results is mainly caused by the fact that the requirement for operating energy used for household services in BS1 and BS2 is significantly higher than for passive houses.

As shown in Fig. 5, the second-largest contribution is followed by the materials production phase, basically due to the amount of materials used in the building elements during this stage, especially the cement in concrete-based components and silicone-based product on indicator GWP, ADP, and OLD. The high environmental indicator results for EP and AP are mainly due to construction products used for the building equipment, *e.g.*, the heating systems and electrical installations. The high value derives from metals, especially from copper products resulting from the use of primary copper. In contrast to that, the impacts in the category POP are influenced by other construction products, mainly plastic materials.

During the maintenance phase, the replacement of the equipment, the silicone-based product and painting in finishes, and PVC used on door and windows are the highest environmental impact contributors. The maintenance phase is the most significant contributor to the ADP indicator, essentially due to replacing the door and windows and steel production in new equipment.

As shown in Fig. 5, the possible environmental benefit coming with the application of renewable energies can be highlighted here: interestingly, the use of solar PV panels in BS2 results in a 7% reduction in the GWP, as is shown an offset for the displaced grid electricity. With technological advances and the cost reduction of PV materials, mass adoption of BIPV/BIPVT is expected that can lead to further reduction of energy consumption and global warming in net-zero energy constructions [87]. Additionally, while the operation phase dominates other phases with respect to primary energy use (*i.e.*, CED) and emissions in all case studies, the production and maintenance phases cannot be ignored, particularly for passive houses.

Fig. 5 also depicts that in most cases, the emissions from the end-of-life do not exceed 2% of the impacts from the use phase of existing buildings. In the recycling treatment phase, the benefits (negative values) and the loads beyond the system boundary are declared for the recycling potential of the materials. These recycling credits contribute by about 4% of the emissions balance from GWP, POP, AP, EP, and CED.

From Fig. 5, it can be concluded that as the dwellings become more energy-efficient, the environmental impacts stemming from the production, maintenance, and end-of-life of the building materials will represent a higher share of the buildings' total environmental burden and, consequently, the relevance of energy production decreases [88].

Fig. 6 shows the share of weight and GWP presented by various materials in each case study. As shown, concrete and cement products, insulation, and plastics contribute the most to the overall emission outputs of the constructions, while the highest portion of the construction's weight comes from the concrete and cement products (51%-53%), gravel and sand (18%-19%), and timber (7%). According to Fig. 6, there is a substantial contribution from the insulation (EPS, XPS, and mineral wool) and paint affecting the GHG (about 35% of the overall impact coming from the material level). Therefore, these materials should be considered among the main contributors to the environmental impact.

From Fig. 6 (panel a), timber has negative values in environmental impacts compared to other construction materials involved. As recovered wood is increasingly used for energy purposes in the UK [89], we assumed that wood is recovered and used as bioenergy. In addition, since concrete is used in a substantial quantity proportion in the construction, it becomes responsible for a large share of greenhouse gases.

Fig. 7 shows the breakdown of greenhouse gas emissions of each construction element for different scenarios. The finishes, mechanical works, and substructure are the top three elements with the highest GWP in all case studies. This is essentially due to silicon-based products and paints in finishes, insulation and steel in mechanical works, whereas concrete (which accounts for 50% of the total construction weight) in substructure shows relatively low GWP. The PV system significantly contributes to greenhouse gas emissions, as this dominant role is due to the significant amount of glass, steel, and aluminum in the production stage.

Due to the specific nature of any LCA study (*i.e.*, the specific system under analysis, the specific assumptions, functional unit, system boundaries, quality of data, and allocation procedure), it is complicated to compare the results of this LCA analysis to other studies [90,91]. Anyway, the results obtained for global warming potential, as the most utilized impact category, are in general agreement with those reporting the LCA results for passive houses [75,92,93].

4.2. Effect of decarbonization of electricity production

After performing a traditional LCA in accordance with the baseline electricity mix, we analyzed the sensitivity to the decarbonization scenarios and their effects on LCA results.

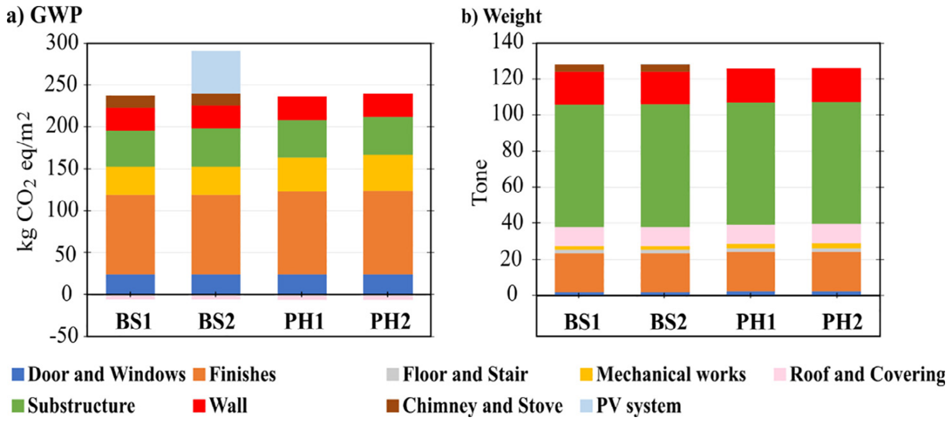

Fig. 7. The composition of house construction elements (a) in terms of greenhouse gas emission, and (b) in terms of weight.

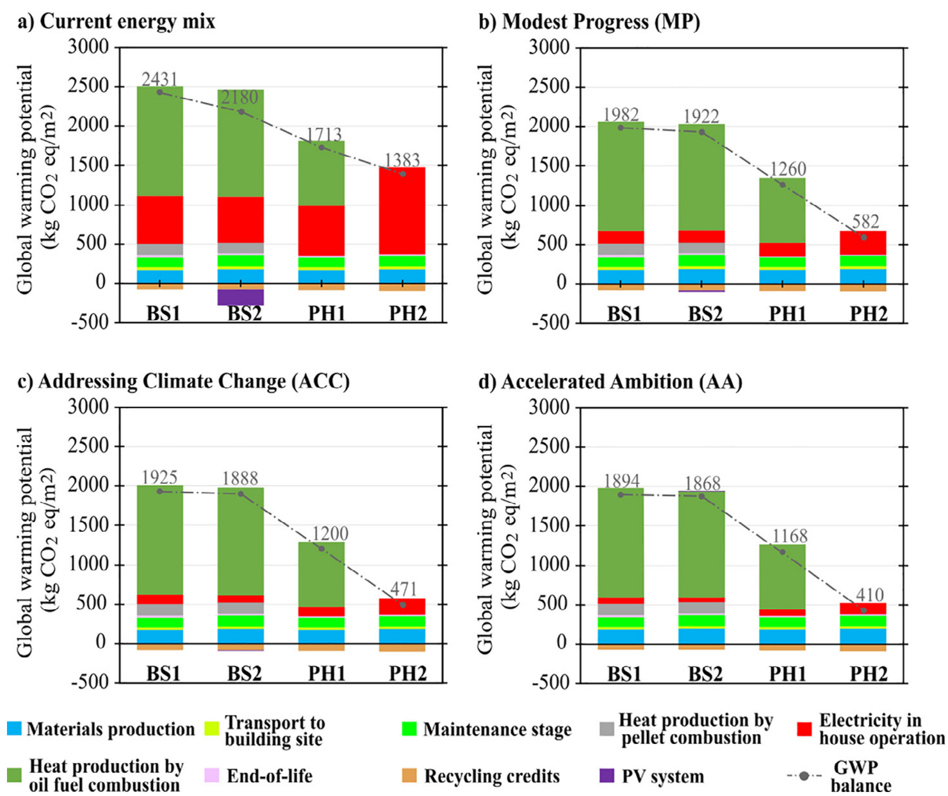

Fig. 8. Global warming potential associated with current energy mix and three future electricity mix scenarios for different case studies for the lifespan of 60 years.

Fig. 8 shows the life cycle GWP emissions over a 60-year building operation for the baseline (current energy mix of 2018) and three different electricity mix scenarios defined in TESNI (2020). Generally speaking, decarbonizing the electricity grid significantly impacts the hierarchy of case studies' life cycle GWP emissions and decreases the total environmental impact of the case studies by 70%.

The case study PH2 (*i.e.,* using the heat pump compact unit) shows the highest reduction in cumulative GWP emissions, representing 58%, 66%, and 70% reduction in the scenarios MP, ACC, and AA, respectively, in 2050, compared with current electricity mix scenario. This is due to the use of electricity as the only building energy source in this case, and therefore, a higher reduction in environmental impacts with an increase in the share of renewables. A similar consideration can be made for the low-energy case studies where a relatively low difference in GWP reduction is obtained (*e.g.,* 12% for the scenario MP, reaching about 22% for the scenario AA). This is due to the highest share of fossil fuels in its building operation among other case studies. Decarbonization of electricity is one of the key steps in order to meet the UK's target of 80% carbon reduction by 2050 [80], due to three reasons: (i) electricity generation is still one of the highest contributors to UK GHG emissions, 10% of the total national emissions in 2019 [94], followed by (ii) it is expected that the electricity demand grows significantly in the future, as heating systems are electrified, and as climate change increases the demand for thermal comfort and HVAC systems [11,40]; (iii) it is expected that the decarbonization of electricity becomes relatively more straightforward than of other sectors in the near future [95]. Therefore, it is necessary to "electrify" the building as much as possible to get the maximum benefits from the decarbonization scenario of electricity production.

This study assumes that production processes and emissions released by using the unit of energy generated from fossil-derived fuels energy carriers remain almost constant over time. As shown in Fig. 8, when electricity decarbonization is implemented, the ratio between the emission from the materials production stage to the emission from electricity-derived in the use-phase is increased significantly. For example, the ratio between building operation and other phases from the current situation and future electricity mix may vary considerably (*e.g.,* 86/14 % for BS1 in the current electricity mix, reaching about 23/77 % for PH2 in AA). This implies an increasing significance of materials production in the building's life cycle because of the decarbonization of electricity production. Therefore, close attention should be paid to the material market in any effort aiming to meet further environmental benefits.

Comparing panels a and b of Fig. 8, it can be concluded that for the case of PH2, 76% carbon emission reduction can be achieved even if modest progress is made in decarbonizing the electricity grid. Further emission reductions, up to 83%, can then be achieved as grid decarbonization becomes more prevalent.

4.3. Comparison to benchmark

Benchmark values from the RIBA 2030 Climate Challenge are used to assess the environmental performance and operational energy of the assessed buildings. At the time of this publication, the RIBA 2030 Climate Challenge provides metrics for embodied CO_2e benchmarking based on incremental goals for residential buildings as follows: for business as usual, it should be less than 1200 kg CO_2e/m^2 (GIA); for the year 2025, less than 800 kg CO_2e/m^2 (GIA); and for 2030, less than 625 kg CO_2e/m^2 (GIA) [83]. For the case of operational energy, this standard also set out the performance targets of 120 kWh/m^2 (GIA)/year, 60 kWh/m^2 (GIA)/year, and 35 kWh/m^2 (GIA)/year for business as usual, the years 2025, and 2030, respectively [83].

Fig. 9 illustrates the target values of the RIBA 2030 Climate Challenge and the performance of all case studies. As shown in this figure, the case studies BS1, BS2, PH1, and PH2 emit 354 kg CO_2e/m^2, 430 kg CO_2e/m^2, 351 kg CO_2e/m^2, and 366 kg CO_2e/m^2, respectively, in which they meet not only the target values for the embodied carbon of the intermediate year 2025 (800 kg CO_2e/m^2) but also do for the targets of the year 2030 properly (625 kg CO_2e/m^2). However, with regard to operational energy, not any of the case studies can achieve the required RIBA 2030 performance target for the year 2030. As it can be seen in Fig. 9, case study PH2 (*i.e.*, the passive house that uses a heat pump compact unit) is the only dwelling that can meet the RIBA 2030 target for operational energy by the year 2025. Therefore, as a general concluding remark, the performance of the buildings with respect to their operational energy should be improved. Here the importance of employing potential technologies such as BIPV/BIPVT systems and passive heating techniques (*e.g.*, Trombe wall) should be highlighted.

5. Conclusion

Previous studies have demonstrated a significant potential in Northern Ireland (NI) to combine low energy standards(*e.g.*, passive houses) with electrical heat pumps in order to achieve simultaneously reduction of operational energy, and to substitute fossil fuels with renewable electricity [37]. The purpose of this life cycle approach is two-fold: to provide an estimation of the environmental impact of case study buildings designed to meet the current NI Building Regulations (as assessed by SAP 2009) and the Passivhaus standard in Northern Ireland; and to investigate the overall effect of the electricity decarbonization on the global warming potential (GWP) of the dwellings via an LCA.

The building's environmental performance was evaluated using seven environmental impact categories related to materials production, in use, and end-of-life phases. Within this study, three decarbonization scenarios, concerned with future electricity-mix scenarios according to Northern Ireland TESNI 2020, were defined, and their GWP was compared with the LCA results of the traditional static approach, *i.e.*, assuming the current electricity mix remains constant during the buildings life cycle of 60 years. All three future scenarios approach the target emission reduction of 80% for 2050 compared to 1990.

The results of the traditional LCA indicated that the building's operation phase contributed the most to the environmental impacts in all types of buildings. This is followed by the materials production phase, while the end-of-life stage shows negligible environmental impact. Additionally, in all environmental categories (except for abiotic depletion potential), the emission generated in the operation phase were dramatically higher than the corresponding amount in other building life phases. The findings also showed that implementing the passive-house standard may significantly decrease the environmental impacts with an average of 30% (and up to 50%) compared to low-energy buildings in all cat-

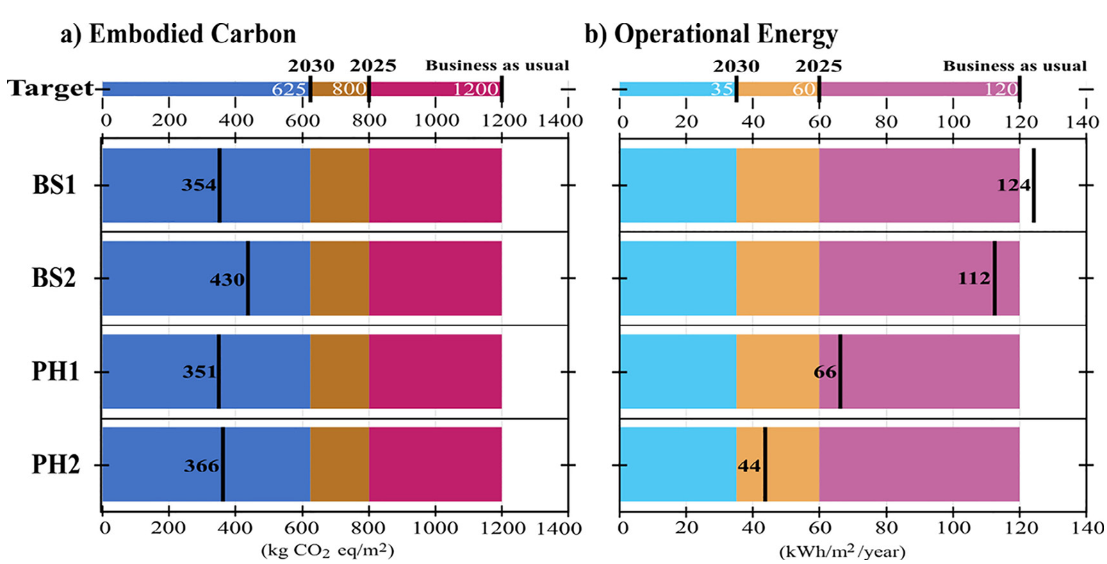

Fig. 9. Environmental and operational energy performance of the case studies and the performance targets of RIBA 2030 Climate Challenge.

egories, except in abiotic depletion where low-energy buildings showed a better performance. At the material level, concrete is the main contributor to emissions across all environmental impact categories except in the adiabatic depletion category, where the insulation material is responsible for the highest environmental damages.

The findings showed that implementing any of the TESNI 2020 scenarios significantly reduced the GWP of any case study. The highest GWP reduction was corresponding to the passive house case study with the highest share of electricity demand and is as high as 58%, 66%, and 70% for the scenarios modest progress (MP), addressing climate change (ACC), and accelerated ambition (AA), respectively, when compared to the GWP reduction of the cases in traditional LCA.

Comparing the GWP of the static and the three future electricity decarbonization scenarios reveal that the highest emission reduction is related to the energy use in the "Accelerated Ambition" scenario. However, for the buildings with better thermal performance (*i.e.,* passive houses using the heat pump compact unit), the relative importance of the use phase will become smaller. In summary, it can be concluded that considering the future electricity mix over a building life cycle significantly influences the results. The results demonstrated that the passive house dwellings equipped with electric heat pump compact units represent 76% carbon emission reduction in case of modest decarbonization progress. The emission can be further reduced if the grid decarbonization becomes more prevalent (*e.g.,* up to 83% in AA).

Analyzing the carbon emission of future electricity-mix scenarios showed an increase in the relative share of the production stage in the total building emission due to the decarbonization of electricity production. Therefore, close attention should be paid to the material market in any effort aiming to meet further environmental benefits.

Comparing the environmental performance of the case studies with the target values proposed in the RIBA 2030 Climate Challenge showed that all case studies perform well with respect to the embodied carbon, and they all meet the target levels set out for the intermediate year of 2025, and 2030. However, concerning operational energy, not any of them can meet the levels proposed for 2030. Among the dwellings studied, only the case study PH2 (*i.e.,* the passive house that uses heat pump compact unit) which has represented the best performance, can meet the benchmark target value of operational energy for 2025. In this regard, the potential of employing innovative technologies, particularly BIPV/BIPVT systems and passive heating techniques (*e.g.,* Trombe wall) should be highlighted for both new and retrofit buildings, aiming to improve the building's operational energy performance.

CRediT authorship contribution statement

Masoud Norouzi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Shane Colclough:** Methodology, Formal analysis, Visualization, Writing – review & editing. **Laureano Jiménez:** Validation, Visualization, Supervision, Funding acquisition, Writing – review & editing. **Jordi Gavaldà:** Data curation, Writing – review & editing. **Dieter Boer:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing – review & editing.

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.enbuild.2022.111936.

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