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Life cycle carbon assessment of decarbonising UK's hard-to-treat homes: A comparative study of conventional retrofit vs EnerPHit, heat pump first vs fabric first and ecological vs petrochemical retrofit approaches

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ABSTRACT

In order to achieve its 2050 net-zero emissions goal, the UK government must significantly improve the energy performance of millions of hard-to-treat homes through retrofitting. However, questions over the embodied carbon emissions of retrofit projects arise, specifically deep retrofits, when the embodied carbon emissions of the retrofit are compared to a shallow retrofit or demolition. This study evaluates the carbon footprints of various retrofit interventions by comparing the impact of a deep retrofit based on the Passivhaus retrofit standard (EnerPHit) to a shallow or conventional retrofit following UK building regulations. The research also assesses the whole-life carbon impact of a 'heat-pump first' compared to a 'fabric-first' approach using natural insulation materials versus standard petrochemical-derived insulation. Finally, the study presents the carbon avoidance achieved through retrofitting compared to the carbon emissions from demolition and building new homes. The findings reveal that retrofitting buildings can reduce operational carbon emissions by 59% to 94%. Conventional retrofit scenarios generate 37% fewer energy savings than the EnerPHit standard with petrochemical materials but only result in 1% less embodied carbon. Low carbon technologies, such as photovoltaic panels or heat pumps, increase the embodied carbon by 38% to 117% but did significantly decrease operational carbon emissions by 71% (photovoltaics) and 61% (heat pumps). Using natural materials in both deep and shallow retrofits can reduce total embodied carbon by 7% to 14%. The study also found that the embodied carbon of the brick and timber, saved as a result of the refurbishment, is much greater than the product stage embodied carbon of deep or shallow retrofits.

1. Introduction

The climate change emergency and the need to reduce anthropogenic greenhouse gas (GHG) emissions are highlighted within the framework of the United Nations Climate Change Conference of the Parties (COP) [1] and in globally recognised reports and blueprints such as the Intergovernmental Panel on Climate Change (IPCC) [2] and Sustainable Development Goals (SDGs) [3].

In 2021, the buildings and construction sector accounted for around 37% of energy and process-related CO2 emissions and over 34% of energy demand globally [4]. To achieve the goals of the Paris Agreement, the United Nations Framework Convention on Climate Change (UNFCCC) has set a goal for the built environment to halve its emissions by 2030. This means that operational emissions must be reduced to net zero in both new buildings and, through extensive retrofitting, the existing stock. Additionally, a 40–50% reduction in embodied carbon must be achieved in all projects. To achieve the embodied carbon reductions, a life cycle approach is necessary for new and retrofitted buildings [5].

As it is estimated that about 60% and 70% of the building stock in the US and EU in 2050, respectively, will be buildings that exist now, then the energy retrofitting of existing buildings is essential to meet the zero carbon targets [6]. When compared to EU member states, the UK has the highest proportion of homes constructed before 1946, accounting for around 38% of the total. In contrast, Germany and Sweden have around 24% of such homes [7]. In the UK, 80% of the current stock will still exist by 2050. The annual average rate of decarbonisation in the UK building sector was only 0.8% per person during the period 2011–2016, which is similar to the global average of less than 1%, but significantly lower than the EU decarbonisation rate of 1.6% [8,9]. As a result, the UK's building stock is among the most inefficient in Europe [7,9]. A survey of 80,000 dwellings in eleven European nations found

Abbreviations: AECB, Association for environment conscious building; BBA, British board of agreement; BRE, Building research establishment; CO_2e, CO_2-equivalent emissions; cop, coefficient of performance; COP, Conference of the parties; BEIS, Department for business, energy and industrial strategy; EC, embodied carbon emissions; EPC, energy performance certificate; EPDs, environmental product declarations; EPS, expanded polystyrene; XPS, extruded polystyrene; GW, glass wool; GHG, greenhouse gas; HTT, hard-to-treat homes; HVAC, heating, ventilation, and air conditioning; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle carbon assessment; LETI, Low energy transformation initiative; OC, Operational carbon emissions; PHI, Passivhaus Institute; PHPP, Passivhaus planning package; PU, polyurethane; RIBA, Royal Institute of British Architects; SAP, standard assessment procedure; SDGs, Sustainable development goals; BSI, The British standards institution; TFA, Total floor area; UKGBC, UK green building council; UNFCCC, United Nations framework convention on climate change; VOC, volatile organic compound

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that UK dwellings lose heat three times faster than other European dwellings [10]. The increase in home-working has also led to a 7% increase in emissions from residential buildings in 2020 and a 4% decrease in non-residential buildings. All of these figures highlight the importance of upgrading the approximately 28 million existing homes in the UK to make significant progress towards achieving net zero [11].

Furthermore, research has indicated that embodied carbon - that is, the carbon related to the materials used during the construction of a building - will become a bigger proportion of a building's total carbon emissions as operational carbon demand decreases. Embodied carbon may constitute up to half of the total carbon footprint of new constructions worldwide by 2050 [12]. Therefore, in line with the UK Green Building Council (UKGBC) Net Zero Framework, the Royal Institute of British Architects (RIBA) states that whole-life carbon emission reduction (operational and embodied carbon) must be considered in order to meet the UK's zero carbon target and not just the benefits of reducing operational carbon over the life of the building [13]. This is especially true for the deep retrofitting of existing buildings that reduce CO_2-equivalent emissions (CO_2e) during operation but produce additional emissions from manufacturing, maintaining, and disposing of the materials used in the retrofitting process as non-operation CO_2 emissions or embodied carbon. Currently, there is a lack of research on the non-operational carbon emissions of retrofit and reducing the life cycle carbon of retrofit [14].

1.1. Retrofit and life cycle carbon assessment (LCA)

According to the Royal Institution of Chartered Surveyors (RICS), whole life thinking is an approach that considers all stages of a project's life cycle, from the extraction of raw materials, product manufacturing, transportation, and on-site installation, to the operation, maintenance, and eventual disposal of materials [15]. The concept of whole life thinking is outlined in BS EN 15978 [15,16], which also presents a modular approach to the life cycle of a built asset. BS EN 15978 divides life cycle assessment (LCA) into different stages, including the product stage (A1-A3), the construction process stage (A4-A5), use stage (B1-B7), and the end-of-life stage (C1-C4).

In a comprehensive review of thirteen LCA studies, Vilches et al. [17] revealed that significant variations in methodologies made comparing the results from different studies challenging. Their study found that Modules A1-3 (product stage) and B6 (energy use stage) were consistently considered in the retrofit LCA studies but that major differences were found regarding the end-of-life stage. Based on the analysis of the studies, it is evident that energy retrofit is environmentally beneficial when the building's lifespan is extended beyond the payback period. Many other inherited challenges in LCA include a lack of robust databases, sufficient information, and case studies to compare and validate the results. The review recommended that the key methodological choices need to be defined in further research to make quantitative comparisons possible between LCAs of different building refurbishment choices.

1.2. Retrofit standards and guides

Building regulations in many country have been regularly amended in recent years depending on each country's vision, potential, and capability to implement such changes so as to significantly impact how buildings are built and used [6]. Building regulations in the UK, specifically Part L, which were last updated in 2021, have addressed limiting the U-values for new fabric elements in existing dwellings. However, it is felt that the performance requirements in Part L are inadequate and unlikely to meet the ambitious goal of net zero carbon emissions [18, 19]. In addition, the UK's current policies aim to decrease a building's operational carbon footprint and promote renewable energy utilisation. This involves reducing CO_2 emissions during building use, such as carbon emissions from operational energy consumption for heating, rather than the building's whole life cycle.

In 2020 the Living Housing Association established a new target for energy efficiency as a part of the Clean Growth Strategy, which aimed to bring the whole residential building stock to an Energy Performance Certificate (EPC) rating of C or higher by 2030 [6,19]. Since 1993, the Standard Assessment Procedure (SAP) has been a widely used as an independent methodology for evaluating and certifying the energy performance of dwellings through Energy Performance Certificates (EPCs) to pass building regulations. EPCs form the basis of the UK Government's policy for identifying the energy upgrading needs of existing dwellings (Part L1B) and ensuring the energy requirements of new construction (Part L1A) as per [20]. While Part L will continue to influence how UK buildings thermally perform in the future, there is limited information on the LCA of retrofitting to Part L standard and a lack of understanding of the co-benefits associated with deep retrofits (e.g. cost-effectiveness and ventilation for air quality).

1.3. Deep retrofit

The British Standards Institution (BSI) publishes the PAS 2035/2030:2019 + A1:2022 specification and guidance for energy retrofits in UK domestic projects every two years [21], which is sponsored by the UK government's Department for Business, Energy and Industrial Strategy (BEIS). A collaboration of organizations such as the Association for Environment Conscious Building (AECB), the British Board of Agreement (BBA): Construction Product Certification and the Building Research Establishment (BRE), developed the document to support the EU and UK's goals of nearly zero energy buildings and reducing carbon emissions through whole building retrofit work. However, it is more of a guidance than a tool or standard.

According to the AECB, in order to meet the UK government's carbon reduction target by 2050, approximately 28 million homes will require deep retrofitting. Shallow retrofits have often been shown to be counter-productive [22]. Many researchers concur that deep retrofitting is a cost-effective and practical approach to achieving net-zero targets [23].

A few energy standards currently exist that exceed building regulations and serve as optional guidance in the UK. These include Passivhaus EnerPHit and AECB Retrofit. The AECB has its own retrofit standard, but it utilises the Passivhaus Planning Package (PHPP) developed by the Passivhaus Institute (PHI) as a verification tool. The Low Energy Transformation Initiative (LETI) has also provided a guide to support a high level of retrofit, but it recommends following recognised retrofit standards and quality assurance processes [11].

The EnerPHit standard is a Passivhaus retrofit specification that utilises the same criteria as the classic new-build Passivhaus standard but with some relaxation for certain requirements. This relaxation recognises the difficulties of upgrading existing buildings, such as achieving airtightness and implementing passive strategies [24]. The PHPP is used as both a design tool and to evaluate the performance of the retrofit before construction. The criteria for achieving the conventional EnerPHit standard varies depending on the climate zone, including cold, cool, and warm temperatures. Some of these criteria are compared in Table 1 [11].

Research suggests that increasing energy benchmarks for deep retrofits is necessary in order to achieve net zero emissions by 2050. The effectiveness of measures such as EnerPHit in lowering operational carbon usage raises questions about their impact on other phases of a building's life cycle, where there is a gap in the research. Therefore, evaluating a scheme's embodied carbon impact and overall life-cycle carbon impact is important. This evaluation can also provide a basis for assessing the total carbon expenditure and costs over time and, eventually, provide data and tools to encourage the wider adoption of deep retrofit.

Table 1
Comparison of the different criteria between Passivhaus and EnerPHit standards.

Criteria		Passivhaus Standard	EnerPHit standard
Space Heating	Heating demand	< 15 kWh/(m^2.yr)	≤ 20* / ≤ 25** / ≤ 30*** kWh/(m^2.yr)
	Heating load	< 10 W/m^2	n/a
Space cooling	Cooling demand	< 15 kWh/(m^2.yr)	< 25 kWh/(m^2.yr)
	Cooling load	< 10 W/m^2	n/a
Airtightness		< 0.6 n50 1/h	< 1.0 n50 1/h
Renewable Primary Energy (PER)		Classic ≤ 60 kWh/(m^2.yr) Plus ≤ 45 kWh/(m^2.yr) Premium ≤ 30 kWh/(m^2.yr)	
Renewable energy generation		Plus ≤ 60 kWh/(m^2.yr) Premium ≤ 120 kWh/(m^2.yr)	

* Warm Temperate Climate Zone.
** Cool Temperate Climate Zone.
*** Cold Climate Zone.
**** Classic, Plus, or Premium Options.

1.4. Natural vs petrochemical insulation materials and biogenic carbon storage

Arora and Guermanova [25] conducted a comprehensive analysis of the carbon emissions throughout the life cycle of a building retrofit for three scenarios: an unrefurbished terrace, a Part L compliant retrofit, and a deep retrofit to the EnerPHit standard. The findings strongly supported the argument that over a 60-year life cycle assessment, total carbon emissions are significantly lower for the EnerPHit standard, particularly when incorporating on-site renewable energy sources such as photovoltaics. While the embodied energy increased noticeably for the EnerPHit scenarios, the corresponding reduction in operational carbon was more substantial, making the adoption of these high benchmarks more environmentally beneficial. However, one limitation of the study was that the materials used in the analysis were chosen based on more conventional insulation materials with higher embodied carbon content, such as polyisocyanurate (PIR), aerogel, and mineral wool.

Regardless of the type of retrofit, the fabric-first approach, which includes increasing wall and roof insulation and window replacement, is the most common approach [26,27] and has proven to be an efficient way of reducing carbon emissions [28,29]. Currently, in European buildings, the non-renewable or volatile organic compound (VOC) petrochemical insulation materials, such as expanded polystyrene (EPS), glass wool (GW), extruded polystyrene (XPS) and polyurethane (PU), are the most widely used [30,31] However, several natural and renewable forms of insulation are now available, including hemp cotton, wood wool, recycled newspaper, sheep wool and fibre board. These could be used instead of non-renewable products, but their life cycle environmental impact is so far relatively unexplored [32,33].

As strategies for meeting zero-carbon targets should include substituting non-renewable materials, it is important to assess the environmental impact of these natural materials throughout their life cycle. A related discussion involves biogenic carbon storage. Biogenic carbon refers to carbon stored in biomaterials, such as plants, and absorbed from the atmosphere during plant growth. Currently, there is no consensus on allocating biogenic carbon throughout different stages of a life cycle [34]. Bio-based materials, such as wood, hemp, and straw, contain about 50% carbon by dry mass, which favours storing carbon in buildings made from these materials. To avoid providing incorrect information, it is important to conduct transparent and comparable assessments of carbon content and related global warming score calculations for these natural materials [35–37].

1.5. Aims of study

Despite the apparent benefits of retrofitting of the existing housing stock in the UK, questions over the embodied carbon (EC) emissions of retrofit projects, specifically deep retrofit, arise when the EC of a retrofit is compared to shallow retrofit and/or demolishing ‘hard to treat (HTT)’ houses and building new, near-zero carbon homes. Therefore, this paper aimed to investigate the carbon footprint of different types of retrofits, explicitly comparing the impact of deep retrofit versus low-level or shallow retrofit. This study also evaluated the whole-life carbon impact of using natural (low embodied carbon) insulation materials compared to ‘standard’ petrochemical-derived insulation, taking into account biogenic storage. The study includes an analysis of carbon emissions associated with thermal insulation, building façades, windows, and building services, and considers the CO_2e emissions produced during the retrofitting process and the carbon reduction of energy savings resulting from the retrofit. The authors also present the carbon avoidance achieved through retrofitting against the carbon emissions from demolition.

2. Methodology

2.1. The baseline case study

The UK has an estimated 10 million ‘hard to treat’ and ‘hard to decarbonise’ homes built before 1930 [38]. A HTT home is one where the energy efficiency cannot be improved with lower-cost measures – such as cavity wall insulation – due to the property's age or the nature of its construction [39]. These homes mainly have solid walls. The total number of solid wall properties in December 2019 was around 8.5 million. As of December 2021, it is estimated that there were still around 7.7 million uninsulated solid wall properties [40].

If the UK government is to meet its 2050 net-zero emissions target, then the poor energy performance of HTT homes must be greatly improved through retrofit. It is a topic of rising importance when considering the new UK Building Regulations and the recently announced RIBA embodied carbon targets. Tackling HTT homes is an exceptionally technical and architectural retrofit challenge, as many of these homes are made of traditional materials, such as stone or handmade bricks, and have great heritage value. Therefore, analysing an HTT precedent case study can test different approaches and provide a robust methodology for answering this challenge. To examine the carbon footprint of the retrofit of hard-to-treat homes, this research employed a case study approach based on pre-1919 Victorian houses.

The Zetland Road Passivhaus project in Manchester, UK, involved a pair of semi-detached houses, built in c. 1894, in an area with a strong Victorian vernacular style of great historical value. Fig. 1 shows the houses before refurbishment. These houses were selected for four principal reasons: (i) In England, 17% of all residential buildings were constructed prior to the year 1900 and are mainly Victorian terrace houses [41] (ii) they represent an important part of the UK's housing resource and architectural heritage, (iii) since virtually all these Victorian houses have single-skin, un-insulated solid walls, they are difficult and expensive to retrofit, and (iv) few have been subjected to major refurbishment [42]. Hence, often there is a significant challenge in renovating them to a low carbon level whilst maintaining their aesthetic character.

Ecospheric Ltd is a UK sustainable property developer and green building consultancy that tackled this renovation challenge, believing that the “ordinariness” of the Victorian houses, which required a complete refurbishment, was their most significant asset, and refurbished this pair of hard-to-treat (HTT) four-storey Victorian townhouses to meet the EnerPHit Plus standard (see Table 1). The homes, retrofitted by Ecospheric Ltd, were the first dwellings in Europe to receive the stringent EnerPHit Plus certification and achieved a 95% reduction in space-heating demand [43]. Furthermore, Ecospheric Ltd used ecologi-

Fig. 1. The Zetland Road Victorian townhouses pre-retrofit [43].

cal and renewable, non-petrochemical, and natural materials and products in the retrofit to deliver both healthy and energy-efficient living spaces. Fig. 2 shows the post-retrofit houses, and Fig. 3 presents the floor plans of the two houses, with a Total Floor Area (TFA) of 374.3 m^2. As with most Victorian houses, the energy performance of the Zetland Road houses was compromised by (i) a poor loft structure, (ii) an unsound floor, (iii) no roof insulation, (iv) single-glazed windows, and (v) poor airtightness. Table 2 details the building's structural elements and areas, and Table 3 summarises the key features of the dwellings prior to renovation and the target values for different retrofit scenarios.

The houses' pre-retrofit EPCs were unavailable. However, similar semi-detached houses on Zetland Road have EPC ratings of D and E. The EPC documents estimated heat consumption of 15,790 and 3,034 kWh/yr for space heating and water heating, respectively. These heating figures are close to the upper quartile of gas consumption for band D as per UK government statistics (15,600 kWh/yr) [44].

The mean consumption for band D semi-detached properties is 12,500 kWh/yr. The mean and upper quartile electricity consumptions are 3,800 and 4,600 kWh/yr, respectively. The band E-rating properties had an estimated space heating consumption of 33,251 kWh/year and water heating of 2,340 kWh/year, which is significantly higher than the government statistic of 14,800 kWh/yr.

Fig. 2. Zetland Road Victorian townhouses after refurbishment [43]- colour should be used in print.

Based on this information for the pre-retrofitted properties regulated energy consumption, the sum of 15,790 and 3,034 kWh/yr for space heating and water heating, and 3,800 kWh/yr for electricity consumption per house was used to estimate the emission reductions from different scenarios. It is important to note that this figure is an average for all homes in the UK. However, it would likely be much higher for a Victorian house built around 1894. As a result, it can be assumed that the comparisons of carbon reductions presented in this scenario are on the lower end of possible values.

2.2. Standards/scenarios used for assessment

Six types of retrofit scenarios were considered in this study, and they are presented in Table 4. Scenario S1 is a deep retrofit involving a Passivhaus Plus retrofit (EnerPHit Plus) with natural (low embodied carbon) insulation materials. EnerPHit Plus has renewable energy requirements, such as PV solar panels, in addition to the building fabric requirements of the standard EnerPHit criteria given in Table 1. The deep retrofit Scenario S2 also adopted EnerPHit Plus but with 'standard' petrochemical-derived insulation materials. The deep retrofit Scenario S3 applied just the standard EnerPHit criteria to the houses without incorporating renewable energy generation. Scenario S4 is a shallow retrofit to Part L using 'standard' petrochemical-derived insulation materials and heat pumps. In heating-dominated climates such as the UK, air-to-water heat pumps are considered a crucial aspect of climate action. They are widely regarded as a key technology for decarbonising the built environment [46,47]. Scenario S5 is a shallow retrofit to Part L using natural (low embodied carbon) insulation materials. Scenario S6 is a shallow retrofit to Part L using 'standard' petrochemical-derived insulation materials but with no heat pumps. There is still much uncertainty surrounding the embodied carbon of renewable technologies, and so investigating S3 and S6 gives a useful comparison of retrofits that do not use renewable technologies.

Fig. 3. Zetland Road Victorian townhouses floorplans [43].

Table 2
The Zetland Road townhouses' structural features.

Building elements	Area
Total building floor areas under refurbishment	374.3 m^2
Internal component, cellar stairwell landing floor	0.9 m^2
Ground floor	130.4 m^2
First floor	128.5 m^2
Second floor	114.6 m^2
Volume (Vn50)	1066.5 m^3
Total building exterior area (façade and walls)	492.1 m^2
Front elevation main wall and bay fronts	115.5 m^2
Side returns (both sides)	20.3 m^2
Main rear elevation	101.1 m^2
Side elevation	121.2 m^2
Side elevation main wall	134.0 m^2
Total roof area	205.5 m^2
Bay roofs	5.7 m^2
Main front roof (front-facing)	49.5 m^2
Main rear roof (rear facing)	53.9 m^2
Side elevation dormer roof	48.1 m^2
Side elevation dormer cheek (2 cheeks)	48.1 m^2
Internal component, cellar stairwell existing brick wall	25.1 m^2
Windows and frames	81.4 m^2

2.3. Modelling and inventory of materials

A summary of the main steps and processes used for the life cycle assessment (LCA) is presented in Fig. 4, and a detailed explanation follows in the subsequent sections. The methodology includes utilising PHPP to ensure the fulfilment of EnerPHit certification criteria and evaluating the thermal properties of the retrofitted houses. For the shallow retrofit scenarios, the UK's Standard Assessment Procedure software (SAP10.0) [48] was employed to calculate and ensure compliance with thermal building regulations. The life cycle carbon assessment adheres to the guidelines provided by RICS and BS EN 15978, EN 15804 [16] principles and considers various stages of the building's life cycle (Fig. 5). Operational carbon emissions were calculated using PHPP, while One-Click LCA software was utilised to calculate embodied carbon emissions. Both the “0/0{\Prime} and ”-1/+1{\Prime} approaches to biogenic carbon are examined in the assessment process ().

2.3.1. Thermal simulation modelling

The two houses were retrofitted to the EnerPHit Plus standard based on the Passivhaus construction standard of nearly zero operational energy using natural or renewable materials. Ecospheric Ltd used PHPP to calculate and meet EnerPHit certification criteria. The component criteria of the standard are compared with the as-built (S1) components' thermal properties in Table 3. PHPP was also used to model the theoretical EnerPHit scenario with petrochemical materials, Scenarios 2 and 3 (Table 4).

For the shallow retrofit, Scenarios 3 to 6, the calculations were first run according to the SAP10.0 [48] to ensure the suggested retrofit options met the UK's thermal building regulations (Part L1A) [18]. The scenario with petrochemical-derived insulation materials, Scenario 4, was configured in SAP10.0 using Manchester weather data to comply with Part L. This scenario could meet the Part L Target Fabric Energy Efficiency (TFEE) rate but did not meet the Target Carbon Emission Rate (TER). As a result, notional building specifications were applied for most of the building's fabric and air tightness (see Table 3). To ensure consistency in the calculation of operational energy, all shallow retrofit scenarios, Scenarios 4 to 6, were modelled in the PHPP software using appropriate U-values.

2.3.2. Life cycle carbon assessment

Environmental impact assessments were conducted in accordance with the guidelines for whole-life carbon assessment outlined in the RICS guidance. These guidelines apply BS EN 15978 and EN 15804 [16, 16]principles and related professional guidance from RIBA [15].

This study focused on comparing the carbon emissions of the product stage, cradle to gate [A1-3] when using natural or petrochemical materials for refurbishment and the carbon emissions from the operational energy use stage [B6] of the deep and shallow retrofit options. The carbon emissions of other stages, such as the construction process [A4-5] and maintenance and replacement [B1-5], are reported in this paper. Research has shown that after the operational stage [B6], the

Table 3
Standards criteria and retrofit scenarios.

Thermal element	pre-retrofit Typical existing construction of Victorian houses [45]	Standard's Criteria			Retrofit Scenarios	
		Part L1B(a) [18]	Notional Building [18]	EnerPHit criteria [43,24]	As-built retrofit of Zetland road	Part L1B scenarios
Airtightness	14.5 $m^3/(h{\cdot}m^2)$@50 Pa	8.0 $m^3/(h{\cdot}m^2)$ @ 50 Pa	5.0 $m^3/(h{\cdot}m^2)$@50 Pa	1.0 ach@50 Pa	0.9 ach@50 Pa	4.4 ach@50 Pa
Ventilation requirement	Natural ventilation	Natural ventilation with intermittent extract fans	Natural ventilation with intermittent extract fans	Whole house MVHR-Ventilation rate of 30 m^3/h per person and minimum efficiency of 75%	Whole house MVHR-Ventilation rate of 30 m^3/h per person and efficiency of 91%	Natural Ventilation
Heat requirement	15,790 and 3034 kWh/yr for space heating and water heating for one household on EPC D [40]	–	–	25 kWh/m^2a and 10 W/m^2 heating load	12 kWh/m^2a and 11 W/m^2 heating load	52 kWh/m^2a and 27 W/m^2 heating load
Energy demand	3800 kWh/yr electricity consumption average for one household [40]	–	–	–	Energy Demand: 43 kWh/m^2a	Energy Demand: 102 kWh/m^2a
PER	–	–	–	EnerPHit Classic: 60 kWh/m^2a EnerPHit Plus: 45 kWh/m^2a EnerPHit Premium: 30 kWh/m^2a	Renewable Energy Generation: 55 kWh/m^2a	–
Roof (W/m^2K)	2.30	0.16	0.11	≤0.15	0.13	0.14
Wall (W/m^2K)	2.10	0.26	0.18	≤0.15	0.16	0.19
Floor (W/m^2K)	2.30	0.18	0.13	≤0.15	0.15	0.18
Windows/ g-value (W/m^2K)	PVC frame 1980′s double glazing ~ U-value: 3.0 W/m^2 K	1.6	1.40	≤0.85–1.10	0.77	1.7
Doors (W/m^2K)	3.00	1.6	1.00	≤0.85–1.10	1.00	1.00

Table 4
The retrofit scenarios.

Deep retrofit scenarios	Scenario 1 (S1)	As-built: EnerPHit Plus with natural insulation materials and PV panels
	Scenario 2 (S2)	EnerPHit Plus with 'standard' petrochemical-derived insulation materials and PV panels
	Scenario 3 (S3)	EnerPHit with 'standard' petrochemical-derived insulation materials
Shallow retrofit scenarios	Scenario 4 (S4)	Part L with 'standard' petrochemical-derived insulation materials and heat pumps
	Scenario 5 (S5)	Part L with natural insulation materials
	Scenario 6 (S6)	Conventional retrofit: Part L with 'standard' petrochemical-derived insulation materials

manufacturing stage [A1-3] is the second most significant source of carbon emissions throughout the entire life cycle of a building, and the contribution of other stages to the carbon footprint is less than 10% of the whole life cycle of a building [49]. The outcome of this research also confirmed this; therefore, only the mentioned stages are reported. Kellenberger and Althaus [50] suggested that less than 10% of inputs should not significantly impact analysis results.

The maintenance and replacement stage, B1-5, are also discussed in relation to the materials and building systems. The life expectancy of the building technology was taken from manufacturers' data, and it was assumed that other retrofit components' life expectancy would be the same as the building's and that they would not need replacement. The payback time analysis includes all component replacement carbon costs.

Following the quantity calculations of building materials provided by the designer, the carbon emissions of different scenarios were calculated throughout the building life span using One-Click LCA software (https://www.oneclicklca.com/). This web-based software is designed explicitly for the LCA of construction products and incorporates Environmental Product Declarations (EPDs) and upstream data from the established LCA database. The One-Click LCA software complies with EN 15978 standards [51], with EPDs as the primary source of information. The authors used localised data points in their life cycle analysis—mainly European EPDs.

The results for scenarios involving natural materials are presented with and without accounting for biogenic carbon storage. In building life cycle carbon assessments, there are two main approaches for assessing biogenic carbon uptake and release. The first approach, known as the "0/0{\Prime} approach, ignores biogenic carbon altogether and assumes that the release of CO_2 from bio-based products at the end of their life is balanced by an equivalent uptake of CO_2 during biomass growth. This approach does not consider biogenic CO_2 uptake or release. However, when retrofitting a building, especially one with heritage value, the building is expected to have a longer lifespan than the retrofit components. Therefore, the second approach, known as the "-1/+1{\Prime} approach, was also considered. The "-1/+1{\Prime} approach tracks all biogenic carbon flows during the building's life cycle, including the uptake (-1) and release (+1) of biogenic CO_2, as well as transfers of biogenic carbon between different systems [35]. However, using the −1/+1 approach and considering only certain stages of the life cycle can result in a net negative impact, which can potentially mislead decision-makers [36,37]. Therefore, this research presents and compares results for both the 0/0 and −1/+1 approaches.

2.3.3. Inventory data

The first step in the LCA involved gathering data on the quantities of materials. The as-built retrofit material inventory and other scenarios' inventories are presented in Appendix 1, and Table 2 shows the structural features of the selected case studies. In both deep and shallow retrofit scenarios, existing materials were preserved as much as possible to retain heritage value and limit the embodied carbon. Accordingly, roof timber, floor joists, floorboards, staircase, and over 183 tonnes of brick were saved.

In addition, the same amount of damp-proof membrane and fire insulation was considered for all scenarios. The demolitions and environmental impact of decommissioning were not considered in the calculations as these were the same for all the retrofit proposals. The main difference between Part L and EnerPHit Plus is the heating, ventilation, and air conditioning (HVAC) system. When modelling the HVAC, there were significant differences between the embodied carbon of the various options depending on the selected manufacturers. To avoid a biased comparison, when the actual manufacturers' data was unavailable in

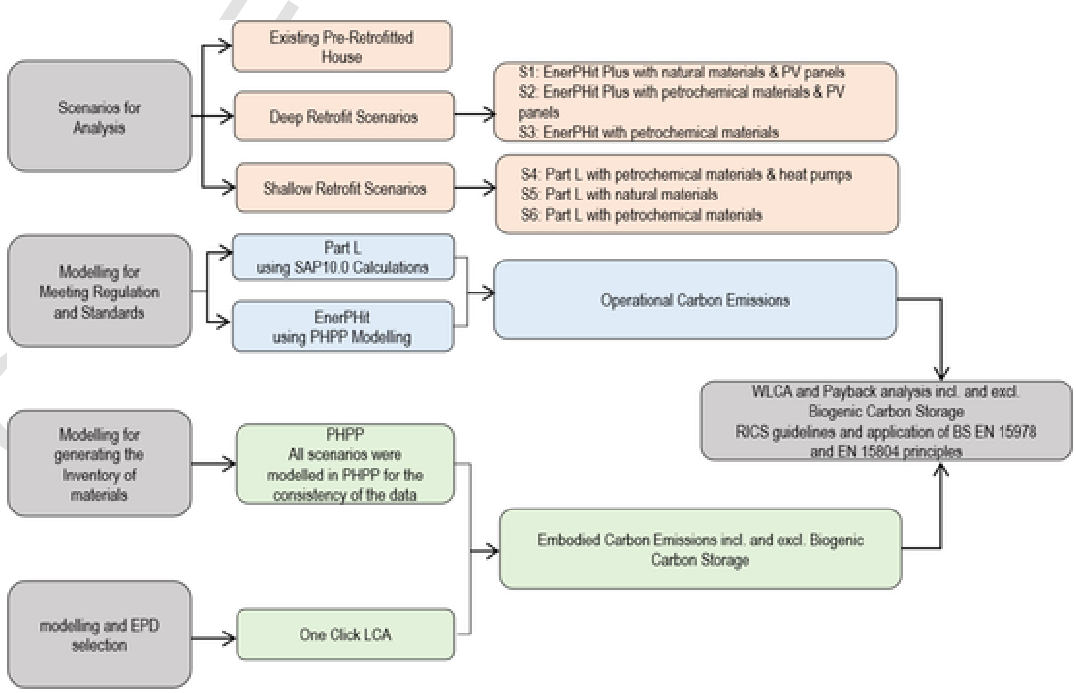

Fig. 4. Summary of the main steps and processes of analysis.

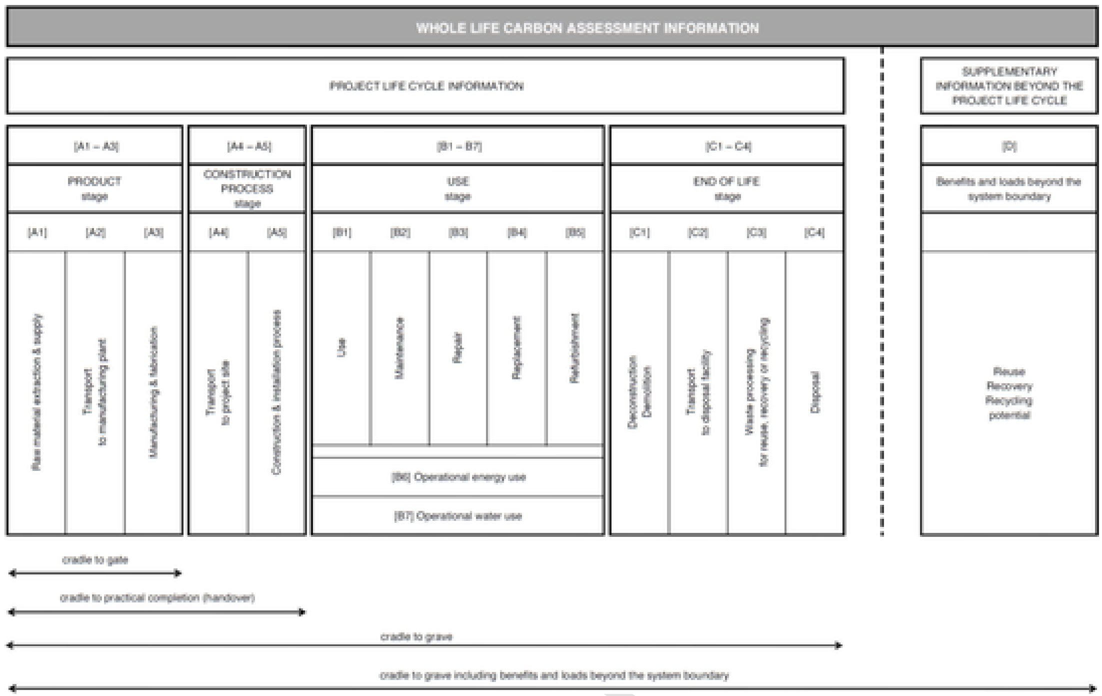

Fig. 5. Modular information for the assessment as per EN 15978 including typical system boundaries [15,16].

the modelling software, the HVACs for different scenarios were selected from the same manufacturers.

Generally, finding the materials for the scenarios with natural materials in the software was challenging, and the authors had to obtain the materials' EPDs from the manufacturers and upload them into the modelling software. A significant difference was noted in the EPDs of different window manufacturers, and the embodied carbon of these windows, especially regarding PVC and aluminium frame windows [52, 53]. However, the difference between the embodied carbon of double and triple-glazed windows was insignificant when selecting them from similar manufacturers.

3. Results and discussion

3.1. Environmental assessment of the embodied carbon stages of the various retrofit scenarios

Fig. 6 compares the breakdown of the total embodied carbon contributions of the alternative retrofit scenarios over 60 years and for different embodied carbon stages (A1-3, A4, and B1-5), including and excluding biogenic carbon storage. All scenarios were also compared with the conventional retrofit (S6). Scenario S4, which incorporated heat pumps, had the highest total embodied carbon emissions. Conversely, Scenario S5, which involved a shallow retrofit using natural materials, had the lowest embodied carbon emissions. The inclusion of heat pumps in a conventional retrofit (S6) resulted in a 117% increase

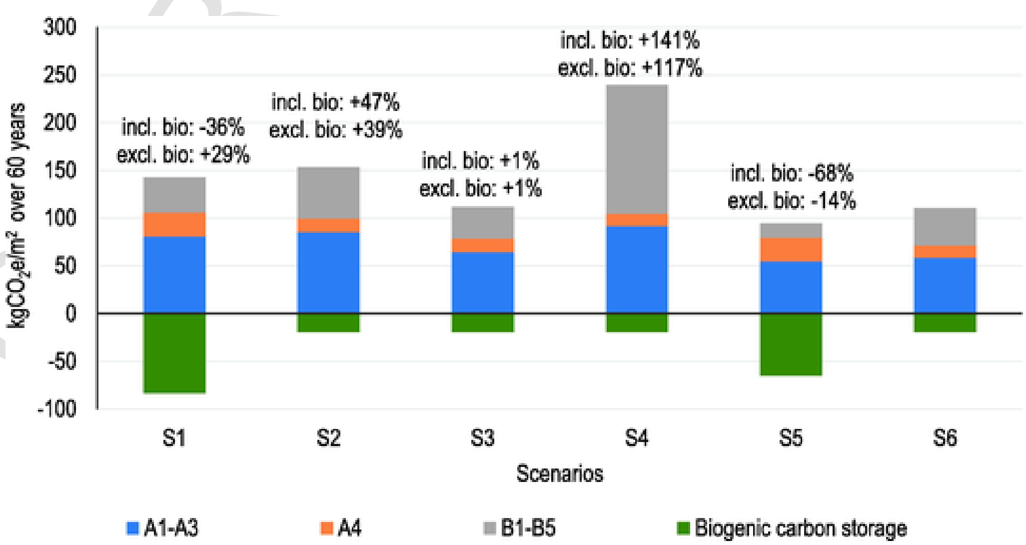

Fig. 6. Contribution of different embodied carbon of product stage (A1-A3), transport to the construction site (A4) and the use stage (B1-B5) to global warming for the six retrofit scenarios presented in Table 4 over 60 years. Labels are comparing alternative retrofit scenarios' additional (+) or less (-) EC to the conventional retrofit (S6), including and excluding biogenic carbon storage- colour should be used in print.

in embodied carbon emissions, whereas the use of natural materials (S5) led to a 14% reduction in embodied carbon emissions.

Deep retrofit to the EnerPHit Plus standard using natural or petrochemical materials, Scenarios S1 and S2, increased the total embodied carbon by 29% to 39%, or 32.1 to 43.1 kgCO_2e/m², over 60 years, compared to the conventional retrofit (S6), when biogenic carbon storage was not considered. However, when the biogenic carbon storage of insulation materials was considered, the embodied carbon of the EnerPHit Plus retrofit scenario with natural materials and PV panels (S1) was lower than a conventional retrofit (S6) by as much as 36% or 32.5 kgCO_2e/m². This suggests that the materials used in the retrofit process are more critical in reducing embodied carbon than the retrofit standard itself.

Building services and renewable technologies in S1, S2, and S4 contributed 30%, 28%, and 50% of the total embodied carbon, respectively. In every case, around 50–67% of the total emissions of these technologies came from maintenance and replacement (stages B1-5) over 60 years. Accordingly, a significant proportion of the additional embodied carbon for the EnerPHit Plus scenarios (S1 and S2) compared to the conventional retrofit (S6) can be attributed to the use of PV panels.

It is possible to meet the basic Passivhaus retrofit standard, EnerPHit, without renewable generation (see Scenario 3 in Table 4). Comparing the EnerPHit standard (rather than the EnerPHit plus) with the conventional retrofit (S6) shows a negligible additional impact of 1% over 60 years. Comparing the same retrofit standards with natural and petrochemical materials (S1 vs S2 and S5 vs S6) for this case study showed that selecting low-environmental impact insulation materials could reduce a retrofit's embodied carbon by 56 to 68% when biogenic carbon storage is included and 7% to 14% when biogenic carbon storage is excluded.

Fig. 7 presents the contribution of different retrofit measures over various embodied carbon stages to global warming for the retrofit scenarios over 60 years. As shown in Fig. 7, the total embodied carbon impact of the materials used in retrofitting the roof, floors, and ceiling was greater for all of the retrofit proposals than the total embodied carbon used for the windows or walls. However, when considering the surface areas of the different structures, as presented in Table 5, the impact per m² of surface area was highest for the windows. The surface areas of the retrofit measures are presented in Table 2.

According to Fig. 7b, the transport stage (A4) in scenarios utilising natural materials (S1 and S5) has 43 to 45% higher emissions compared to scenarios using petrochemical materials (S2 and S6). However, the global warming impact of stages B1-B5 in natural materials scenarios were 43 and 55% lower than those using petrochemical materials.

Of all the life cycle EC stages, the product stage, A1-A3, had the most significant global warming impact. This stage accounts for 55–58% of the total embodied carbon impact in retrofit proposals. As a result, the following section will focus on evaluating the embodied carbon of the breakdown of insulation fabric measures used during the production stages.

3.2. Environmental impact of building fabric measures

As indicated before, the fabric-first approach is the most common and recommended passive solution for reducing energy consumption and CO_2 emissions [14,29]. Accordingly, the influence of building fabric (insulation and windows) on the A1-3 environmental performance of deep and shallow retrofit proposals was observed and is presented in

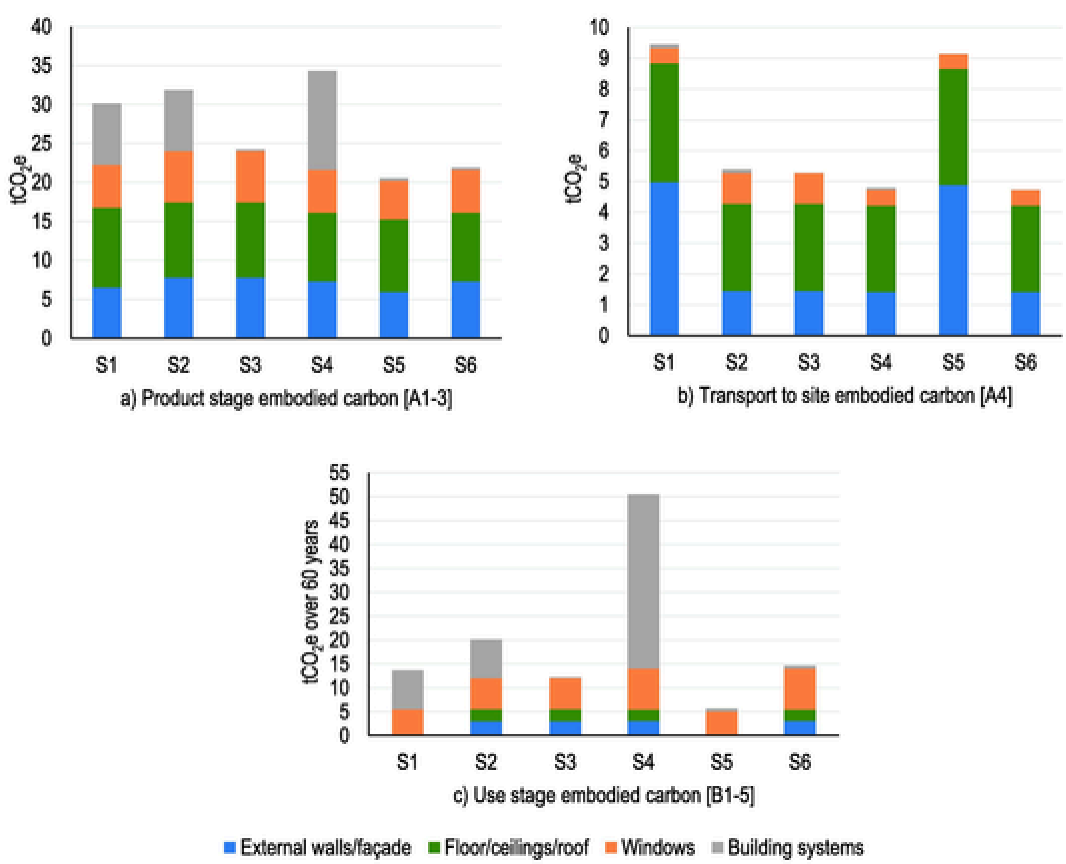

Fig. 7. Comparison of the contribution of different retrofit measures over various embodied carbon stages to global warming for the six retrofit scenarios over 60 years- colour should be used in print.

Table 5
Embodied carbon impact (A1-3) of the building fabric retrofit measure per m² of surface area, excluding biogenic carbon storage.

Retrofit Scenarios and structures	S1	S2 & S3	S4 &S6	S5
External walls/façade ($kgCO_2e/m^2$)	22.4	23.8	22.9	21.2
Floor/ceilings/roof ($kgCO_2e/m^2$)	24.3	25.8	24.2	22.2
Windows ($kgCO_2e/m^2$)	140.7	172.7	144.4	130.7

Fig. 8. In addition, considering the significant impact of the A1-3 stages compared to the other EC stages, the comparison was based on the emissions of the A1-A3 stages.

It is evident from Table 6 that natural materials were needed in greater quantity, as measured by weight, for both deep and shallow retrofit scenarios to meet the same thermal performance (i.e. U-values) as petrochemical materials. However, as can be seen from Fig. 8, their embodied carbon was lower. Interestingly, even excluding biogenic carbon storage, the embodied carbon of building fabric for deep retrofit (S1) was lower than that of a shallow retrofit (S6), even though the weight of thermal insulation and gypsum materials is about twice as high in S1 (see Appendix 1 and Table 6).

Comparing shallow retrofit scenarios (S5 and S6), the insulation weight used in the natural materials scenario (S5) is 1.8 times more than that of petrochemical materials (S6). Conventional petrochemical products generally have lower thermal conductivity, meaning they deliver more insulation for a given thickness than the equivalent green insulation products [29]. However, a study by Piccardo et al. (2020) found that using natural materials can reduce both embodied carbon and waste emissions, regardless of the electricity production method used for material production. On the other hand, when adding insulation on the inside or outside of solid walls, space usually is at a premium, and higher weight in the scenarios with natural materials would make them less attractive.

Most studies that compare natural and petrochemical materials have focussed on cork as a natural material, with their results concluding that using natural materials does not necessarily imply a reduction of environmental impacts [29,54]. Ecospheric Ltd has used cellulose insulation, consisting of recycled newspaper, and this study concludes that using natural materials would reduce the A1-3 and B1-5 environmental impacts and help mitigate climate change, although natural materials create higher carbon emissions at the A4 stage. Ecospheric Ltd also used Graphenstone's organic, lime-based, breathable paint, which resulted in reducing the A1-3 embodied carbon of the paint by 98% or 3.4 tonnes of CO_2e in S1 and S5.

The labels in Fig. 8 show the overall A1-A3 environmental impact of the retrofitting building fabric measures, including biogenic carbon storage. Utilising natural materials, which are often overlooked in discussions about achieving zero carbon, plays a significant role in decreasing carbon emissions over the entire life of the building, particularly when choosing deep retrofit options.

The carbon footprint of different retrofit options can only be calculated by evaluating the energy savings they produce. Consequently, this information is presented in the following sections. Additionally, the effectiveness of both deep and shallow retrofits is assessed by considering the respective carbon avoidance to that of demolition.

3.3. *Environmental impacts of the operational phase*

3.3.1. *Embodied carbon vs operational carbon*

This section compares the results of the B6 stage with the EC stages for various retrofit proposals. The B6 figures are from the PHPP models and show the carbon emissions from predicted operational electricity consumption (Table 7). The conversion factor of 0.14 $kgCO_2e/kWh$, as recommended in SAP 10.2, is selected in One Click LCA for assessments.

The emissions from regulated energy consumption are considerably reduced compared to the pre-retrofit state of the building in all the retrofit scenarios. The carbon reduction benefits of refurbishing Victorian houses built before the implementation of building regulations are clear from Table 7.

The operating regulated energy for the two pre-retrofitted houses is assumed to be 45,248 kWh/year (see Section 2.1 and Table 3), 25,600 kWh/year for the shallow retrofit scenarios (S5 and S6) and 12,100 kWh/year EnerPHit scenarios (S1, S2, and S3). The conversion factor of 0.14 $kgCO_2e/kWh$ and 0.2 $kgCO_2e/kWh$, as recommended in SAP 10.1 and 10.2 for electricity and gas respectively and applied in One Click LCA, has been used for calculations, respectively. These are LCA profiles matching the UK government's Standard Assessment Procedure for Energy Rating of Dwellings Version 10.0 [48]. All the consumption figures include savings from the low carbon technologies.

The O'Hegarty et al. [47] study of 378 heat pumps with a mean coefficient of performance (cop) of 4.12 concluded that the average seasonal cop was 2.6, or 40% lower than the figure predicted by the manufacturers. Accordingly, in this research, a cop of 3 was assumed for the heat pump in S4 [55] and the energy consumption of S4 with a heat pump was predicted to be 8,533 kWh/year.

These calculations suppose 59% reductions for shallow retrofit scenarios (S5 and S6) and 84% carbon emissions reductions for the S4 retrofit proposals. The generation from PV panels for the EnerPHit Plus scenarios is 8,600 kWh/year, and the figures for the deep retrofit scenarios represent savings in regulated energy and CO_2e of 81% without PV (S3) and 94% with PV (S1 and S2) respectively.

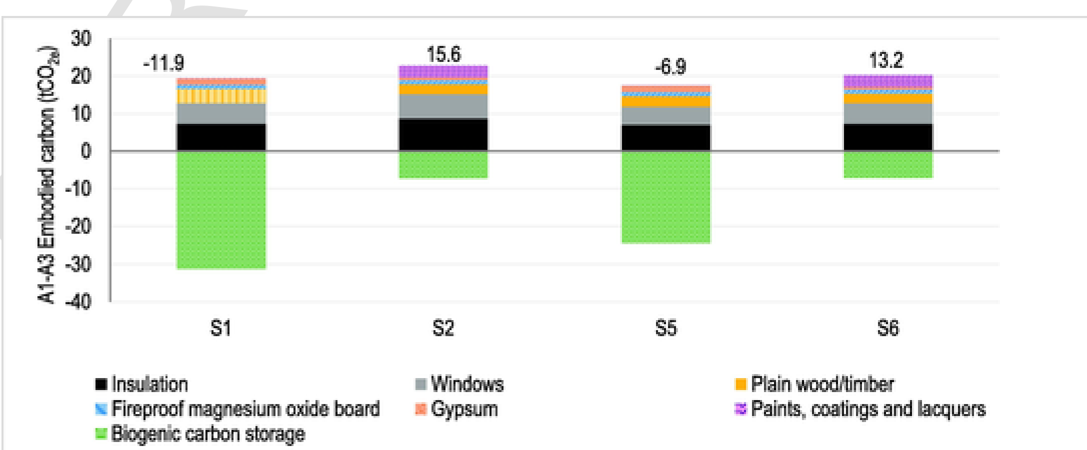

Fig. 8. Global warming impact of the A1-3 stage of building fabric measures for the different retrofit scenarios. Labels show the total EC of A1-3, including biogenic carbon storage-- colour should be used in print.

Table 6
Building fabric measures weight (kg) for the different retrofit scenarios.

Materials	S1	S2 & S3	S5	S4 & S6
Thermal insulation (kg)	6278.3	4006.1	5997.3	3401.3
Windows, incl. frames (kg)	3072.6	3125.0	2437.8	2657.0
Plain wood/timber (kg)	5692.9	7587.5	5355.6	7393.3
Fireproof magnesium oxide board (kg)	2444.4	2444.4	2444.4	2444.4
Gypsum (kg)	10506.1	5898.3	10506.1	5684.1
Paints, coatings and lacquers (kg)	57.3	3417.3	57.3	3417.3
Total weight (kg)	28051.7	26478.8	26798.5	24997.4

Table 7
Total operational energy and operational carbon emissions (B6) for different retrofit scenarios compared with the existing pre-retrofitted house.

Scenarios and items	S1 & S2	S3	S4	S5 & S6	Existing house-no retrofit
Total operational energy ($kWh/m^2.yr$)	9.4	32.3	22.8	68.4	120.9
B6 ($kgCO_{2e}$ / $m^2.yr$)	1.3	4.4	3.6	9.3	22.9
% Reduction in B6 compared to the existing house	94%	81%	84%	59%	–
B6 over 60 years (tCO_{2e})	28.6	98.7	81.6	208.9	515.6

Comparing the B6 carbon emission reductions generated by the heat pump and the PV panels shows that the heat pump would create a reduction of approximately 2.1 tCO_2e/year, compared to S6, while the total installed PV, covering most of the roof area, would reduce emissions by half of that, or 1.2 tCO_2e/yr, compared to S3. However, the PV panels do not need to reduce the operational carbon by as much as the heat pump as the PV is in a EnerPHit situation where the energy demand is already significantly reduced.

In addition, a heat pump's life cycle carbon emissions are three times higher than those of PV panels. It should be noted that retrofitting a heat pump is more challenging and costly than installing one in a new build. The carbon reduction from the heat pump in the B6 stage relates to the environmental impacts of the grid, including energy generation and heat production. Piccardo et al. [14] suggest that savings from deep retrofits are higher than from clean electricity production from the grid. Fig. 9 compares the embodied carbon of each scenario with its operational carbon from the regulated energy consumption.

The as-built retrofit scenario (S1), with EnerPHit Plus and using natural materials, has the lowest environmental impact over 60 years. This scenario had an overall emission of 81.8 tCO_2e, exclusive of biogenic carbon storage, and 50.6 tCO_2e, when including biogenic carbon storage. Although the embodied environmental impact of the EnerPHit scenarios (S1, S2, and S3) were higher than that of the Part L scenarios (S5 and S6), their operational and total environmental impacts were significantly lower, generating higher energy savings over the building's life cycle.

The environmental impact of S4 with the heat pump was twice that of the EnerPHit Plus scenarios (S1 and S2), and the total carbon emissions of shallow retrofit proposals (S5 and S6) are three times that of the deep retrofit scenarios (S1 and S2). For all the scenarios without heat pumps or PV panels (S3, S5, S6), the percentage of operational carbon was significantly higher than the embodied carbon emissions. In all cases, dividing the embodied impact into 60 years, the lifespan suggested by RICS [15], the operational carbon reduction at the B6 stage per year will be much more significant, between 2.5 and 6.4 times higher, than the embodied energy each year.

Fig. 9 shows that a higher level of insulation and natural materials (e.g. S1) were more effective in reducing whole-life carbon emissions reduction and meeting zero carbon targets than applying shallow retrofit with renewable or cleaner technologies. However, given the potential for overheating, preparing for future cooling and ventilation requirements is essential. Therefore, retrofit scenarios incorporating PV panels (S1 and S2), generating green energy, are better suited for the future climate.

3.3.2. *Carbon payback time of the different scenarios*

Fig. 10 presents the carbon payback time of each scenario. Among the retrofit proposals, all the deep retrofit scenarios (S1, S2 and S3) have the lowest carbon payback time (four to five years) when biogenic carbon storage is excluded from the calculation.

The carbon payback time of shallow retrofit scenarios (S4, S5 and S6) is between five to six years; after the fourth year, the total carbon emissions of all the shallow retrofit scenarios will be more than all of the deep retrofit scenarios. This shows that the type of retrofit must be decided on with the LCA in mind - in this case, 60 years - rather than taking only embodied carbon or operational impact into account.

Generally, the results show that the carbon payback time of retrofit for all scenarios is considerably lower than the lifespan of the retrofit measures. Incorporating the biogenic carbon storage into the calculations significantly reduces the payback time for scenarios with natural materials, S1 and S5, to just one year.

3.4. *Knocking-down and new-build compared to the retrofit scenarios*

Given that millions of uninsulated solid wall homes in the UK need refurbishment [56], it is crucial to consider the carbon savings achieved through retrofitting and preserving existing materials and housing stock in the UK net-zero roadmap plans.

Hence, in this section, the (i) embodied carbon emissions of retrofit, (ii) carbon avoidance of demolition from retained materials, and (iii) operational carbon reduction of different retrofit scenarios have been

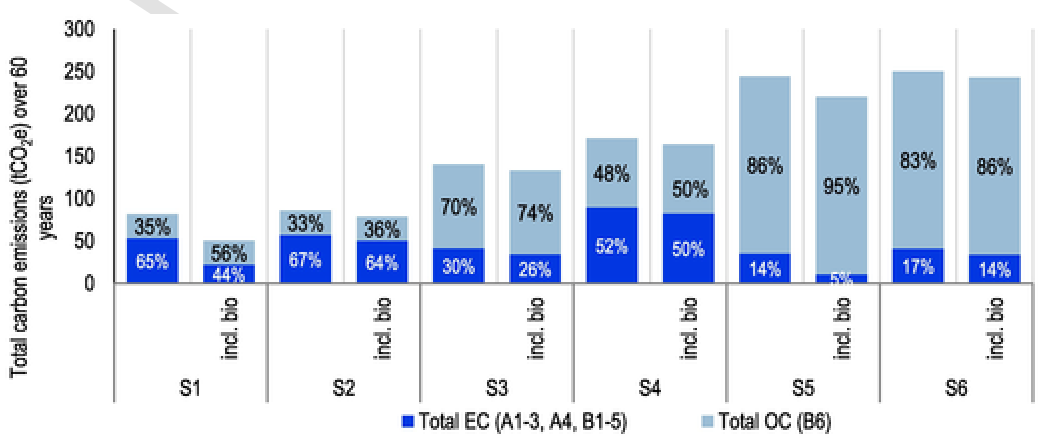

Fig. 9. Comparison of total operational CO_2e and embodied CO_2e (including and excluding biogenic carbon storage).

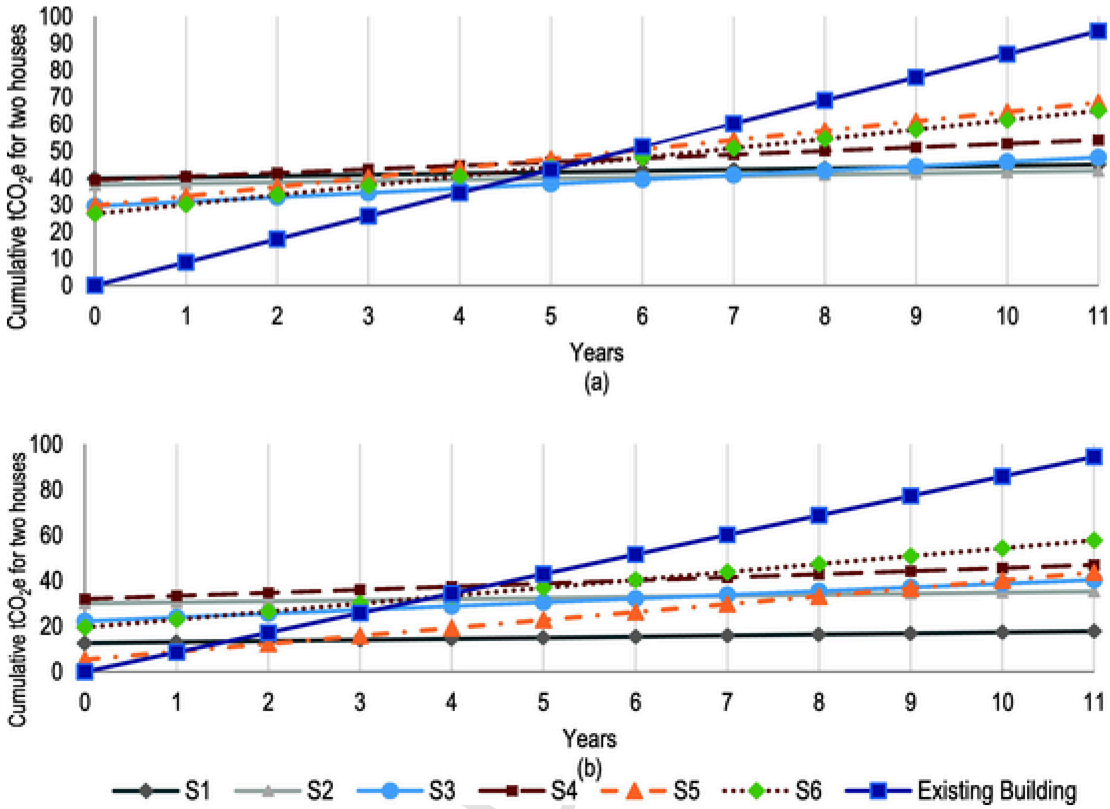

Fig. 10. Payback times of the various retrofit scenarios: (a) excluding biogenic carbon storage), (b) including biogenic carbon storage.

assessed and are presented in Table 8. In addition, to determine the benefits of retrofit compared to knocking down the existing dwellings and building again, two new build Passivhaus dwellings with renewable energy generation are selected for comparison. These are:

- Larch Corner Passivhaus, a 162 m² detached single-storey three-bed timber-frame house in Warwickshire, UK, with embodied carbon of 473.2 $kgCO_2e/m^2$ and an estimated biogenic carbon storage of 300.0 $kgCO_2e/m^2$ [57]
- Carrstone Passivhaus, a 230 m² detached two-storey timber frame house in Bedfordshire, UK, with embodied carbon of 490.0 $kgCO_2e/m^2$ and an estimated biogenic carbon storage of 160.0 $kgCO_2e/m^2$ [58]

Table 8
Carbon emission, carbon reduction and carbon avoidance of different retrofit scenarios.

Scenarios	S1	S2	S3	S4	S5	S6
EC (A1-3, A4, B1-5) over 60 years ($kgCO_2e/m^2$)	142.4	153.5	111.5	239.3	94.5	110.3
Biogenic carbon storage ($kgCO_2e/m^2$)	−72.1	19.2	−19.2	−19.0	−65.0	−19.0
Carbon avoidance of demolition and disposal-C1-4 EC stage ($kgCO_2e/m^2$)	−25.1	−25.1	−25.1	−25.1	−25.1	−25.1
EC avoidance from saving timber and brick ($kgCO_2e/m^2$)	−201.3	−201.3	−201.3	−201.3	−201.3	−201.3
Predicted OC (B6) reduction over 60 years ($kgCO_2e/m^2$)	−1301.2	−1301.2	−1113.8	−1159.5	−819.4	−819.4
Whole life net, excluding biogenic carbon storage ($kgCO_2e/m^2$)	−1385.2	−1374.1	−1228.7	−1146.6	−951.3	−935.5
Whole life net, including biogenic carbon storage ($kgCO_2e/m^2$)	−1457.3	−1354.9	−1247.9	−1165.6	−1016.3	−954.5

Considering the UK and EU's zero carbon policies, selected new build houses are relevant as they are constructed to meet zero operational carbon standards.

As demonstrated in Table 8, the embodied carbon of retrofit scenarios is significantly lower than that of new builds. In addition, all retrofit scenarios align with the UK zero carbon strategy, considering the RIBA 2030 climate challenge of 625 $kgCO_2e/m^2$ for the new build embodied carbon emissions [59].

The carbon cost of demolition is relatively low, with 9.4 tCO_2e for the two houses. However, in this case, retaining 3.5 tonnes of timber structure and over 183.3 tonnes of brick equals around 75.3 tCO_2e or 0.2 tCO_2e per m² of TFA.

Overall, the embodied carbon of retained materials is 41%, 31% and 81% higher than those used for deep retrofit scenarios to EnerPHit standard, S1, S2 and S3, respectively, when excluding the biogenic carbon storage. The net total carbon emissions of retrofit were negative in all scenarios, with savings in operational carbon much more significant for the deep retrofit scenarios than the shallow retrofit scenarios.

The estimated payback time and energy savings for retrofitting homes depend on the energy consumption of the existing house. The authors used average data from EPC documents and government statistics for all homes in the UK, which may underestimate the actual energy consumption of a hard-to-treat Victorian house. Therefore, the carbon reductions presented in the study may be lower than the actual values. This highlights the importance of understanding the current energy performance of the housing stock before making decisions about retrofit interventions on a larger scale.

4. Discussion

The UK has set ambitious CO_2 emissions reduction targets, and energy-efficient retrofit of the existing housing stock is crucial in achieving these targets. However, such retrofit schemes present significant environmental and economic challenges. To address these challenges, important questions regarding suitable retrofit types, construction techniques, the effectiveness of the applied measures, indoor air quality and comfort levels, monetary and carbon cost paybacks, and the potential risk of summer overheating must be considered.

This research does not provide answers to all these critical questions when selecting retrofit scenarios. However, through a life cycle carbon assessment of various retrofit scenarios, the study aimed to identify the most efficient and effective retrofit methods to meet carbon reduction targets. The study investigated the life cycle carbon of retrofitting a common but challenging dwelling type, Victorian terrace houses built in 1894, as the measures applied to these houses can be applied to millions of similar hard-to-treat and hard-to-decarbonise homes nationwide. The property was located in Manchester, which has a climate that can be considered more representative of much of England than London, which is frequently chosen for thermal studies.

This study evaluated the impact of deep retrofit following the Passivhaus retrofit standard (EnerPHit and EnerPHit Plus) to shallow or conventional retrofit following UK building regulation requirements. It also assessed the whole-life carbon impact of using natural insulation materials versus standard petrochemical-derived insulation. Overall, the paper concludes that retrofitting can achieve significant operational carbon reduction and carbon avoidance compared to demolition and building new, and that using natural materials can further reduce embodied carbon.

4.1. Deep vs shallow retrofit

Comparing the LCA of deep and shallow retrofit standards using petrochemical materials over 60 years indicated that both approaches led to significant energy savings, reducing operational carbon emissions by 59–94%, compared to the existing Victorian house built around 1894.

The carbon emissions reduction from energy saving was much more significant for deep retrofit (S1), at 94% or 21.7 $kgCO_2e/m^2$, compared to shallow retrofit (S6) at 59% or 13.7 $kgCO_2e/m^2$ per year.

The payback time for both retrofit scenarios was less than five years. However, after the fourth year, the total carbon emissions of all the shallow retrofit scenarios (S5 and S6) will be more than all the deep retrofit scenarios.

Over a 60-year lifespan of the building, the deep retrofit without low carbon technologies (S3) had a total environmental impact of 375.3 $kgCO_2e/m^2$, with the embodied carbon (EC) contributing 30% and the operational carbon (OC) contributing 70% to the life cycle assessment (LCA). The shallow retrofit (S6) had an overall environmental impact of 668.4 $kgCO_2e/m^2$, with the EC contributing 17% and the OC contributing 83% to the LCA. Therefore, when considering insulation and building fabric, the operational carbon stage contributes significantly more than the embodied carbon stage.

The conventional retrofit proposal (S6) following UK Part L building regulations had a slightly lower EC (A1-3, A4, B1-5) of 1% but resulted in much lower operational energy savings and carbon emissions than deep retrofit (S3).

The 45% reduction in operational carbon (B6) for conventional retrofit (S6) was mainly due to increased energy efficiency requirements and the limiting U-values for fabric elements in existing dwellings required by the recently updated UK building regulation (Part L) [60]. However, the result shows that current regulation performance requirements are inadequate and unlikely to meet the ambitious goal of reducing emissions by 78% from 1990 levels by 2035 and net zero by 2050 for dwellings. It should be noted that EnerPHit as-built performance is shown to be consistent with the modelled performance as opposed to the Part L building regulations. Therefore, the savings for the Part L models might be different from the predicted values in the model.

The only scenarios meeting the 2050 target are the deep retrofit scenarios with PV panels, S1 and S2, that generate 94% carbon emissions reduction, with S1 reducing EC as well by using natural insulation materials.

The study discovered that implementing S4, a shallow retrofit scenario that utilises heat pumps, can effectively reduce operational carbon emissions by 84%. However, it also revealed an additional embodied carbon of 117%. This finding holds great importance as the UK government aims to increase the number of heat pump installations to around 600,000 per year by 2028 as a way of decarbonising heat in homes [61].

4.2. Deep retrofit vs shallow retrofit with heat pump

The UK's policies aim to decrease buildings' carbon footprint by promoting renewable energy sources and efficient building services utilisation. The most effective solution is to shift towards energy sources that are low or zero carbon, such as renewably sourced electricity combined with heat pumps. Deep retrofitting is not mandatory for achieving net zero, and shallow retrofit and heat pumps have been encouraged for hard-to-treat homes. However, the plan ignores the financial and carbon cost of these technologies. As a result, this study evaluated deep retrofit scenarios following the EnerPHit standard, incorporating renewable technology (S1 and S2) and shallow retrofit with heat pumps (S4).

The LCA total carbon emissions of S4 with the heat pump were twice that of the deep retrofit scenarios (S1 and S2), and the total carbon emissions of shallow retrofit proposals (S5 and S6) were three times that of the deep retrofit scenarios over 60 years. The inclusion of heat pumps in a conventional retrofit (S6) results in a 117% increase in embodied carbon emissions, with around 67% of the total emissions coming from maintenance and replacement (stages B1-5) over 60 years.

Comparing the reductions in operational carbon emissions generated by heat pumps and PV panels revealed that the former would result in a reduction of about 2.1 tCO_2e/year, compared to S6, whereas the latter, installed over most of the roof area, would cut emissions by half that amount, or 1.2 tCO_2e/year when added to S3. However, the life cycle carbon emissions of heat pumps are three times higher than those of PV panels.

Additionally, the carbon reduction resulting from the heat pump in the B6 stage is related to the environmental impact of the grid, including energy generation and heat production. Nevertheless, Piccardo et al. [14] suggest that deep retrofits result in more significant savings than low carbon electricity production from the grid. Moreover, retrofitting a heat pump is more challenging and more costly than installing one in a new build. Palmer and Lewis [11] emphasise the limitations of meeting peak heating load and estimate that the current capacity of the electric grid is significantly lower than the current demand and will still be even by 2050.

For all the scenarios without heat pumps or PV panels (S3, S5, S6), the percentage of operational carbon is significantly higher than embodied carbon emissions. In all cases, dividing the embodied impact into 60 years of buildings' lifespan, as RICS [15] suggested, the operational carbon reduction at the B6 stage per year will be much more significant, 2.5 to 6.4 times, than the embodied energy each year.

With concerns about overheating, planning for future cooling and ventilation needs is essential as the UK's National Grid has estimated that the demand for air conditioners in the domestic sector will be 18 times more than current figures [62]. Therefore, deep retrofit scenarios with PV panels (S1 and S2) that provide green energy are more suitable for the future climate.

4.3. Natural and petrochemical insulation materials

It is clear from the results of this study that using natural materials, which are often overlooked in discussions about achieving zero carbon, plays a significant role in decreasing embodied carbon emissions over the entire life of the building, particularly when choosing deep retrofit options. According to the results, the materials used in the retrofit process have a more significant impact on reducing embodied carbon than the retrofit standard itself.

Retrofitting the Zetland Road houses to the EnerPHit Plus standard using natural materials (S1), including PV panels, resulted in an embodied carbon of 58.8 $kgCO_2e/m^2$. In contrast, the conventional retrofit (S6) had an estimated EC of 36% higher at 91.3 $kgCO_2e/m^2$. It should be noted that PV panels accounted for 24.6% or 19.8 $kgCO_2e/m^2$ of S1′s embodied carbon. All figures include biogenic carbon storage. When biogenic storage is discounted, the embodied carbon associated with retrofit measures of the thermal building fabric, at 51.9 $kgCO_2e/m^2$, was 4% lower for deep retrofit with natural materials (S1) than shallow retrofit with petrochemical materials (S6) at 54.1 $kgCO_2e/m^2$.

Comparing the same retrofit standards with natural and petrochemical materials (S1 vs S2 and S5 vs S6) for this case study showed that selecting low- environmental impact construction materials can reduce 56–68% of retrofit's embodied carbon when biogenic carbon storage is included and 7–14% excluding biogenic carbon storage. However, in the biogenic storage calculations, the timing of carbon emissions and the rotation periods associated with biomass growth are not considered, which can be problematic when assessing the impact of bio-based products. A study by Pittau et al. [36] found that not all bio-based products are carbon–neutral. For example, timber products have a more extended rotation period due to slow forest growth periods and cannot be considered carbon–neutral in the short term. On the other hand, fast-growing bio-based materials, such as straw and hemp, have a short rotation period and can effectively mitigate GHG emissions by quickly removing carbon from the atmosphere [35,36].

Evaluating different EC stages for natural and petrochemical materials, this study concludes that using natural materials would reduce the A1-3 and B1-5 environmental impacts and help mitigate climate change, although they create higher carbon emissions at the A4 stage.

5. Conclusion

The UK has established ambitious CO_2 emissions reduction targets, and energy-efficient retrofitting of existing housing is vital for achieving these goals. The primary objective of this study was to examine prevailing assumptions about the embodied carbon of deep retrofit and its implications for deep retrofit policies. The study evaluated building regulations and potential strategies for the existing housing stock, specifically comparing the "heat pump first" and "fabric first" approaches, as well as the choice between retrofitting and demolishing. Six retrofit scenarios were considered, including deep retrofit, shallow retrofit, shallow retrofit with a heat pump, and the use of natural and petrochemical materials. Whole-life carbon emissions were calculated, taking into account a building life extension of 60 years. Key findings include:

1. **Retrofit vs demolition**: The embodied carbon of the brick and timber saved due to the refurbishment was much greater than the product stage embodied carbon (A1-3) of deep retrofit. This finding demonstrates that when it comes to reducing CO_2 emissions from buildings, the discussion should not be about whether to refurbish but rather the most effective way to do so.
2. **Deep vs shallow retrofit:** Contrary to current assumptions that deep retrofit of existing buildings always produces additional non-operational CO_2e or embodied carbon, the study found that the materials used in the retrofit process have a more significant impact on reducing embodied carbon than the retrofit standard itself.
3. **Insulation materials:** Natural materials, which are often overlooked in discussions about achieving zero carbon, play a substantial role in decreasing carbon emissions over the entire life of the building, particularly when choosing deep retrofit options. The embodied carbon of building fabric retrofit measures for deep retrofit, following EnerPHit Plus with natural materials, was lower than that of a shallow retrofit with petrochemical materials. This shows the importance of applying LCA in the decision-making of wide-retrofit schemes and the necessity of a regulatory framework in assessing biogenic carbon storage and supporting the manufacturing of natural materials.
4. **Deep retrofit vs shallow retrofit with heat pump:** The results of this study showed that deep retrofit with a higher level of insulation using natural materials was more effective in reducing whole-life carbon emissions and meeting zero carbon targets than shallow retrofit or shallow retrofit with a heat pump. This finding is significant, as the UK government aims to support the growth of the heat pump market to around 600,000 installations per year by 2028 to decarbonise heat from homes. While heat pumps increase the embodied carbon of shallow retrofit significantly, their operational stage carbon reduction is lower than deep retrofit and incorporating PV panels. It should also be noted that retrofitting a heat pump is more challenging and more costly than installing one in a new build when compared with PV panels.

The EnerPHit standard and deep retrofit are relatively uncommon practices, and existing economic analyses indicate that the associated payback periods are not necessarily economically viable. Nevertheless, given the imperative to achieve zero carbon targets, a comprehensive evaluation incorporating factors like health impacts, climate change damage, and energy supply security could make aspects of the deep retrofit approach more financially attractive. By adopting this broader perspective, the economic feasibility of deep retrofitting could be meaningfully reconsidered, potentially rendering it a more viable approach to meeting zero targets.

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.

Data availability

We will decide to share or not to share the data when receive a request

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Appendix 1.

Material type	Resource	GWP (A1-A3) $kgCO_{2e}/kg$	Variation (±%)	Biogenic carbon storage $kgCO_{2e}$ bio	Deep Retrofit (EnerPHit) Scenarios		Shallow Retrofit (Part L) Scenarios		Existing Structure	Service life (years)
					Natural material	Petrochemical material	Natural material	Petrochemical material		
					Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)	
Brick	Clay bricks, masonry	0.24	20.2	–	–	–	–	–	183333.3	60
Insulation	Wood fibre insulation board, from dry process	1.11	3.5	236.4 $kgCO_{2e}/m^3$	5585.6	–	5405.4	–	–	60
	Cellulose insulation, blown (loose)	1.19	28.4	12.0 $kgCO_{2e}/m^2$	436.9	–	336.1	–	–	60
	Phenolic insulation, Kingspan K118	2.48	20.2	–	–	1129.0	–	685.5	–	60
	Phenolic insulation, Kingspan K108	2.03	20.2	–	–	1083.7	–	1133.0	–	60
	Phenolic insulation, Kingspan K105	1.9	20.2	–	–	842.1	–	631.6	–	60
	Thermoset foam insulation	2.2	20.2	–	–	681.8	–	681.8	–	60
	PIR insulation boards	4.61	20.2	–	–	23.9	–	23.9	–	60
	Extruded polystyrene (XPS)	2.77	34.6	–	9.4	9.4	9.4	9.4	–	60
Membranes	Damp proof insulation	8.84	34.6	–	46.4	36.2	46.38	36.20	–	60
	Polypropylene roofing membrane	0.75	34.6	–	200.0	200.0	200.00	200.00	–	60
Fibre cement products	Fireproof magnesium oxide board	0.45	28.3	–	2444.4	2444.4	2444.4	2444.4	–	30
Gypsum	Gypsum plasterboard, standard	0.15	28.4	0.56 $kgCO_{2e}/m^2$	6666.7	3266.7	6666.7	3266.7	–	60
	Gypsum plasterboard, tapered or square edges	0.22	20.2	–	2636.4	–	2636.4	–	–	60
	Gypsum plasterboard, with cellulose fibre	0.08	28.3	–	1203.1	1203.1	1203.1	1203.1	–	60
	Gypsum plaster	0.14	34.6	–		1428.6		1214.3	–	60
Stone	Natural stone roofing slate	0.08	20.2	–	27131.8	27131.8	27131.8	27131.8	–	60
Tiles	Ceramic tiles, glazed, for floor application	0.53	34.6	–	830.2	830.2	830.2	830.2	–	60
Tile adhesive	Adhesives, for tiles	2.29	34.6	–	148.5	148.5	148.5	148.5	–	60
Paints and coatings	Interior wall paint	1.72	34.6	–	–	639.5		639.5	–	10
	Organic paint for interior application	0.67	28.4	–	44.8	–	44.8	–	–	10
	Exterior paint, silicone based	1.12	20.2	–	12.5	–	12.5	–	–	60
Cement	Thin-coat renders based on organic binders, silicone based	0.72	28.3	–	–	2777.8		2777.8	–	60
Plain wood/ timber	Structural sawn timber, kiln dried, planed or machined	0.22	20.2	819.0 $kgCO_{2e}/m^3$	863.6	727.3	863.6	727.3	3409.1	60
	Wooden stud framing system	5.7	34.6	19.1 $kgCO_{2e}/m^2$	7.7	9.1	7.7	9.1	–	60
	Wooden I-beams with fibreboard	1.65	3.5	10.1 $kgCO_{2e}/m$	1575.7	–	1090.9	–	–	60
	Wooden cladding and decking, pine or spruce	0.16	20.2	728.0 $kgCO_{2e}/m^3$	1875.0	1875.0	1875.0	1875.0	–	60
	Solid wood flooring, GLT	0.46	34.6	1.84 $kgCO_{2e}/kg$	–	3478.3		3478.3	–	60
	Wood flooring, conifer	0.13	34.6	660.0 $kgCO_{2e}/m^3$	Reclaimed pine	923.1	923.1	923.1	–	60
	Planed and strength-graded timber, pine or spruce	0.063	28.4	727.0 $kgCO_{2e}/m^3$	23.8	–	23.8	–	–	60
CLT	Glued laminated timber (Glulam)	0.79	34.6	1049.0 $kgCO_{2e}/m^3$	–	291.1	–	278.5	–	60
OSB	Wooden/OSB I-Joists	0.49	20.2	6.1 $kgCO_{2e}/m$	1346.9	283.7	571.4	102.4	–	30
Windows	Window, triple glazed, PVC-U frame	2.08	34.6	–	–	3125.0	–	–	–	30
	Fixed window, triple glazed, with wooden frame	1.79	28.3	12.4 $kgCO_{2e}/m^2$	3072.6	–	–	–	–	30
	Window, double glazed H, wood-aluminum frame, hinged	2.01	28.3	10.9 $kgCO_{2e}/m^2$	–	–	2437.8	–	–	30

Material type	Resource	GWP (A1-A3) $kgCO_{2e}/kg$	Variation (±%)	Biogenic carbon storage $kgCO_{2e}$ bio	Deep Retrofit (EnerPHit) Scenarios		Shallow Retrofit (Part L) Scenarios		Existing Structure	Service life (years)
					Natural material	Petrochemical material	Natural material	Petrochemical material		
					Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)	
	PVC frame window, double glazed	2.07	34.6	–	–	–		2601.5	–	30
HVAC	Synchronous inverters, for motor control, French average	131.0 $kgCO_{2e}$/unit	34.6	–	2 units	2 units	–	–	–	30
	Monocrystalline PV module, per m2	123.46 $kgCO_{2e}/m^2$	28.4	–	60.3 m^2	60.3 m^2	–	–	–	30
	Mechanical ventilation system, with air purifier filter	98.4 $kgCO_{2e}$/ unit	28.4		2 Units	2 Units	–	–	–	20
	Gas condensing boiler	153.89 $kgCO_{2e}$/unit	28.3	–	–	–	2 Units	2 Units	–	20
	Air/water heat pump	6363.0 $kgCO_2e$/unit	34.6					2 Units (only for the heat pump Scenario)		20

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