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Whole-Life Embodied Carbon Reduction Strategies in UK Buildings: A Comprehensive Analysis

Maryam Keyhani[1] | Ali Bahadori-Jahromi[1] | Changfeng Fu[1] | Paulina Godfrey[2] | Hexin Zhang[3]

[1]Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London, UK | [2]Energy and Environment, Engineering Operations EMEA, Hilton, Maple Court, Reeds Crescent, Watford, UK | [3]School of Engineering and the Built Environment, Edinburgh Napier University, Edinburgh, Scotland, UK

Correspondence: Maryam Keyhani (Maryam.keyhani@uwl.ac.uk)

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ABSTRACT

This paper presents a detailed analysis of embodied carbon (EC) in various case studies using life cycle assessment (LCA) methodology. Through comprehensive assessments, including modules A, B and C, the study evaluates EC across different stages of building life cycles. This study also considers the EC savings achievable through current end-of-life strategies in the UK context. As Module A accounts for the highest EC in the case studies, the majority of reduction strategies should focus on this stage. The most impactful strategy for reducing EC emissions involves incorporating Ground Granulated Blast Furnace Slag (GGBS) as a replacement for cement. This approach has the potential to achieve a substantial reduction in the EC of concrete within the buildings under investigation, ranging from 60% to 70%. The study reveals that specification strategy can lead to significant Whole Life Embodied Carbon (WLEC) reductions, with the residential building achieving a 30.59% reduction, the college building a 46.86% reduction, and the hotel building a reduction of 23.69%. Effective mitigation strategies, such as utilizing recycled and reclaimed materials, demonstrate promising results, showcasing significant reduction in WLEC emissions in the buildings.

1 | Introduction

In recent years, there has been a considerable rise in worldwide awareness of global warming and climate change resulting from greenhouse gas (GHG) emissions [1]. GHG emissions in the United Kingdom must decrease by approximately 68% by 2030 and reach net zero by 2050 [2]. Figure 1 illustrates the GHG emissions in the United Kingdom spanning the years 1990 to 2021. As carbon emissions (CO_2) account for the majority of GHG emissions (80% on average over the years 2017 to 2021), changes in CO_2 tend to be reflected in changes in GHG emissions overall [3].

The Global Buildings Climate Tracker (GBCT) tracks decarbonization progress in the buildings sector from 2015 (Figure 2). The target value in the year 2050 is set at 100 to reflect the maximum decarbonization needed in the sector [4].

In 2020, the GBCT index improved due to the COVID-19 slowdown, but this is seen as an outlier. Despite a 68% improvement from 2019 to 2021, the gap between the target and reality grew from 6.6 to 9.0, moving further from zero-carbon buildings [4]. The UK's Sixth Carbon Budget necessitates a 78% reduction in carbon emissions by 2035, compared to 1990 levels [5], to reach net zero emissions by 2050. At COP26, the UK Government pledged to reduce carbon emissions by 68% by 2030, compared to 1990 levels (United Nations, 2022). Carbon emissions are incurred in all stages of a building's life cycle and are generally categorized into operational carbon (OC) and

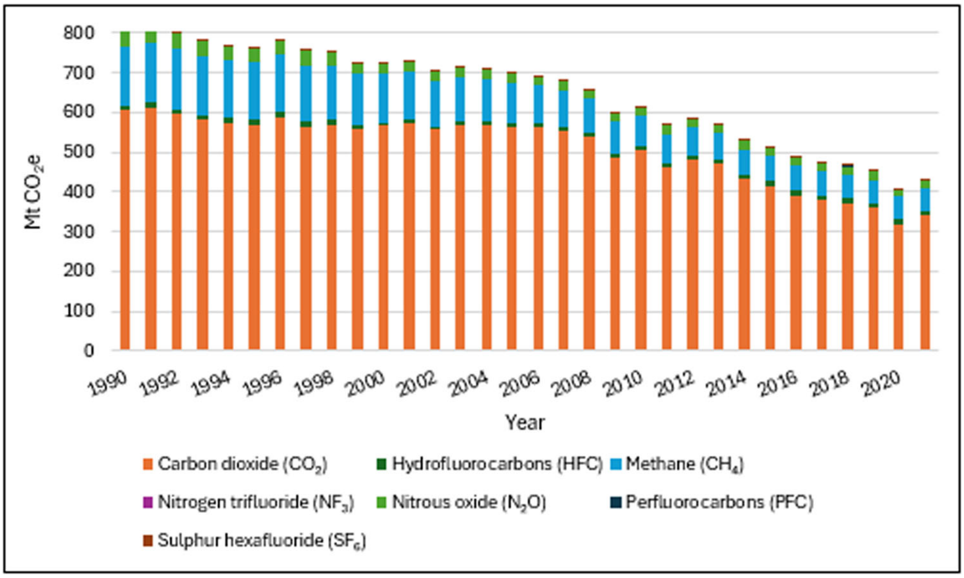

FIGURE 1 | GHG emissions in the United Kingdom spanning the years 1990 to 2021 reproduced from 'Emissions' [3].

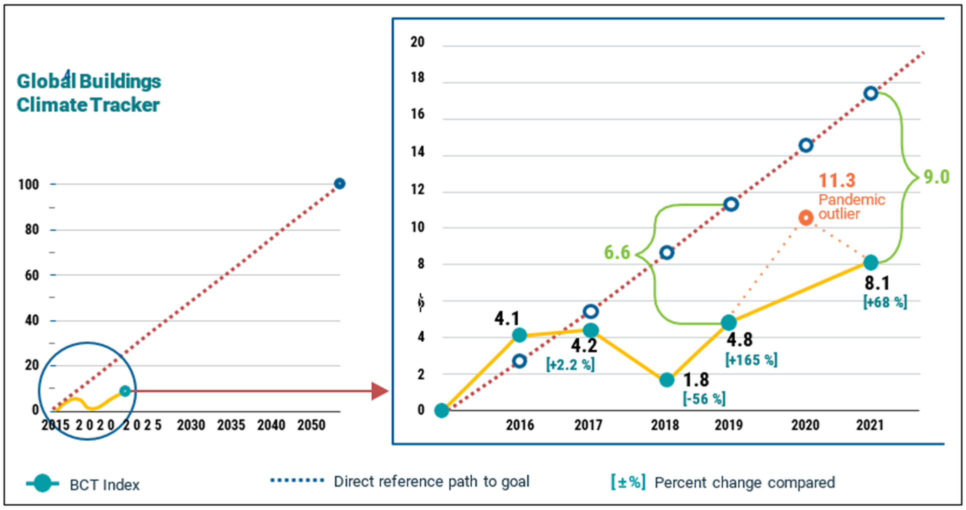

FIGURE 2 | Decarbonization progress in the buildings sector reproduced from 'Global status report for buildings and construction' [4].

embodied carbon (EC) [6]. Pomponi, D'Amico [7] emphasizes that designs often reduce operational carbon but overlook EC from materials and construction. Addressing both emissions is crucial for reducing a building's full lifecycle emissions. A recent study on high-rise office buildings further emphasizes the need for enhanced carbon reduction strategies. This research, which compares the local GreenRE certification with the international LEED standard, found that GreenRE focuses more on EC reduction, offering up to 28.7% reduction, while LEED emphasizes OC, achieving up to 61.1% reduction [8].

EC is significant and can represent 40-70% of whole-life carbon (WLC) in a new building [9]. Therefore, the challenge for the profession is to expand excellent practice to all future work, as highlighted by WorldGBC's report on net zero EC [10].

Assessing EC in buildings is crucial but challenging due to limited data and lengthy evaluations. Traditional methods, based on general parameters, often lack accuracy. A recent study introduced an LCA-MLR framework to improve carbon emission predictions for green office buildings, identifying cement and steel as the main contributors, responsible for nearly two-thirds of emissions [11].

LCA is a systematic method for evaluating the EC of a product throughout its entire life cycle, from raw material extraction to disposal [12]. Dunant et al. [13] stress that early design decisions significantly reduce buildings' EC. Optimizing material efficiency can lower structural frame costs by 10%–20% and carbon intensity by 40%–60%, underscoring the need to integrate carbon reduction strategies early for maximum sustainability. Once a building is completed, there are limited opportunities to reduce embodied carbon, which is why early decision-making is critical [14].

One of the challenges in EC assessment is calculating carbon emissions during the use stage, which involves repair, replacement, refurbishment, and maintenance. Due to the complexity and variability of building components' lifespans, such as roofing and windows, predictions in this stage are difficult and often subjective [15]. Consequently, there is limited research on this aspect. Hart et al. [16] analysed EC in multistorey buildings, excluding the use stage. EC values for timber, concrete, and steel frames were 119, 185, and 228 $kgCO_2e/m^2$, respectively. Module D has also received limited attention in research. It focuses on the potential benefits of reusing, recycling, or recovering energy from materials at the end of their life cycle. To be effective, Module D must be consistent with the end-of-life pathways outlined in Module C [17].

There are currently three primary strategies of low-embodied-carbon solutions for buildings: whole-building design, one-for-one material substitution, and specification [18].

Whole-building design involves adaptive reuse, reducing project size, using efficient structural systems and prefabricated components, and minimizing waste [18]. Jayasinghe et al. [19] found that optimizing concrete slab design and alternative floor systems can reduce embodied carbon by 12%–36%, with innovative systems like thin-shell structures achieving up to 65% savings.

One-for-one material substitution involves replacing a material with a lower GWP alternative while maintaining functionality. For instance, prefabrication reduces embodied carbon by optimizing material use and processes [20, 21]. In the Robati et al. [22] study, the largest EC reduction was achieved by replacing a concrete structure with mass timber, concluding that a full timber structure (ST.5S) and high-performance facade (ST.6c) could lower lifecycle carbon emissions by 446 $kgCO_2e/m^2$.

This research focuses on examining the influence of specification on the WLEC of the case studies. Specification means establishing a value or limit for a material characteristic that will dramatically reduce EC content [18].

In the UK construction industry, concrete makes up over 80% of material mass and contributes around two-thirds of embodied carbon, compared to steel at 22% and clay products at 7% [23]. Chen et al. [20] show that using supplementary cementitious materials (SCMs), like GGBS or Fly Ash, is the most common and cost-effective way to reduce the environmental impact of concrete, promoting sustainable construction. GGBS can replace up to 75% of cement with minimal impact on compressive strength [24, 25]. Studies show that using GGBS in concrete can reduce embodied carbon by 10% to 30% without significantly affecting structural performance [26, 27].

By incorporating Fly Ash, research indicates that the physical and structural performance of concrete is minimally impacted even when replacing 30% to 40% of ordinary cement [20].

For energy-intensive materials like steel, improving recycling and using low-carbon energy in manufacturing are key strategies. This research critically examines WLEC emissions in domestic and nondomestic buildings, focusing on detached homes, hotels, and college buildings due to their high EC and available data. Residential buildings in the United Kingdom account for 75% of total floor space, with detached homes being major contributors (BPIE, 2010 [23];). Hotels, covering 8% of nonresidential space, contribute 21% of hospitality sector emissions [28], while the sector overall accounts for 15% of global emissions [29]. Educational buildings, representing 12% of nonresidential space, emitted over 18 million tonnes of CO_2e in 2020/21, contributing 2.3% to the UK's carbon footprint [30]. These findings underscore the need to reduce building emissions, advancing efforts to lower the construction industry's environmental impact.

2 | Research Methods and Materials

2.1 | Introduction to Case Studies

This paper collects data from three typical UK buildings: a two-story detached residential building (145.86 m^2), a three-level detached college building (2500 m^2), and the Hilton Watford, a four-level hotel built in the 1970s (11,800 m^2). Figure 3 presents the Revit 3D models of these case studies.

2.2 | Calculation Model

2.2.1 | Life Cycle Assessment (LCA) Methodology

LCA is a method for evaluating the environmental impact of products and procedures throughout their entire life cycle. It seeks to identify environmental impacts at all stages of a product's life cycle and generates data representing the environmental burden of the product [31]. BS EN 15978 divides the life cycle of a building into the following modules: product (A1–A3), construction (A4–A5), use (B), end-of-life (C) (Figure 4), and re-use/recovery potential (D), with the latter accounting for advantages outside the system boundary. As more of these steps are considered, a more complete picture of the environmental effect emerges [33].

2.2.2 | Embodied Carbon Definition

Cradle-to-Cradle carbon refers to the carbon emitted during material extraction, processing, manufacturing, demolition, transport, waste processing, disposal, and impacts outside the life cycle scope. EC calculations multiply the material quantity by a carbon factor for relevant life cycle stages (Equation 1) [32]. Carbon factors come from trusted sources like the ICE database, IStructE guidelines, Environmental Product Declarations (EPD), One Click LCA, and other validated resources.

$$EC_i = \sum i(Q_{mat,i} \times ECF_i). \qquad (1)$$

EC assessment during module A and C is comprehensively explained in my previous research [34]. A default road transport distance of 50 km on average laden was assumed in this research [35].

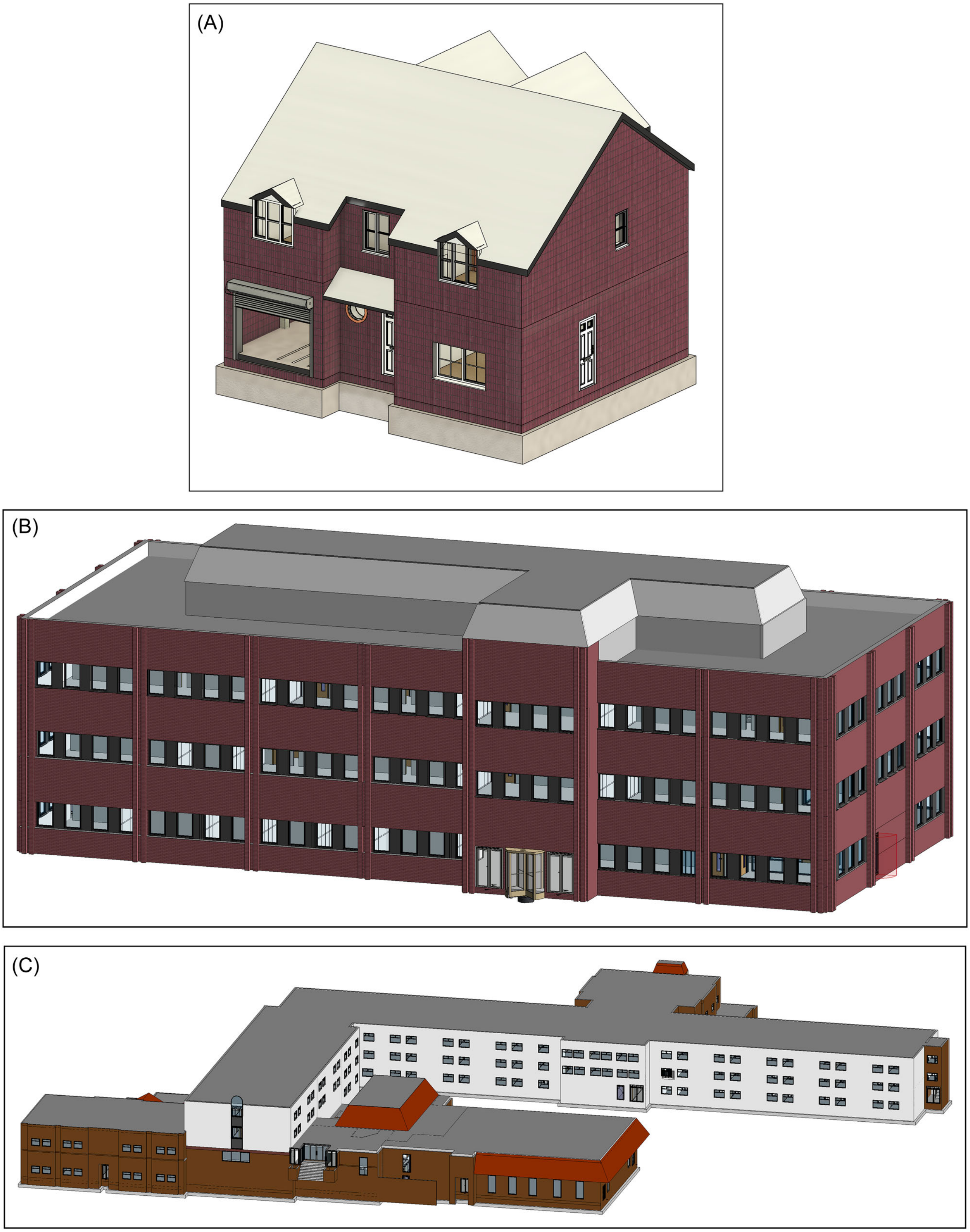

FIGURE 3 | Revit 3D model of the case studies. (A) Residential building, (B) the London college building, and (C) Watford Hilton hotel building.

- **Maintenance impacts (B2)**

Module B2 must account for carbon impacts from maintenance activities, including cleaning, products used, and waste produced over the reference study period (RSP) [17]. According to EN 15978 and EN 17472, the RSP for both domestic and nondomestic buildings is 60 years. Due to limited data on maintenance carbon factors (B2) [32], the London Plan

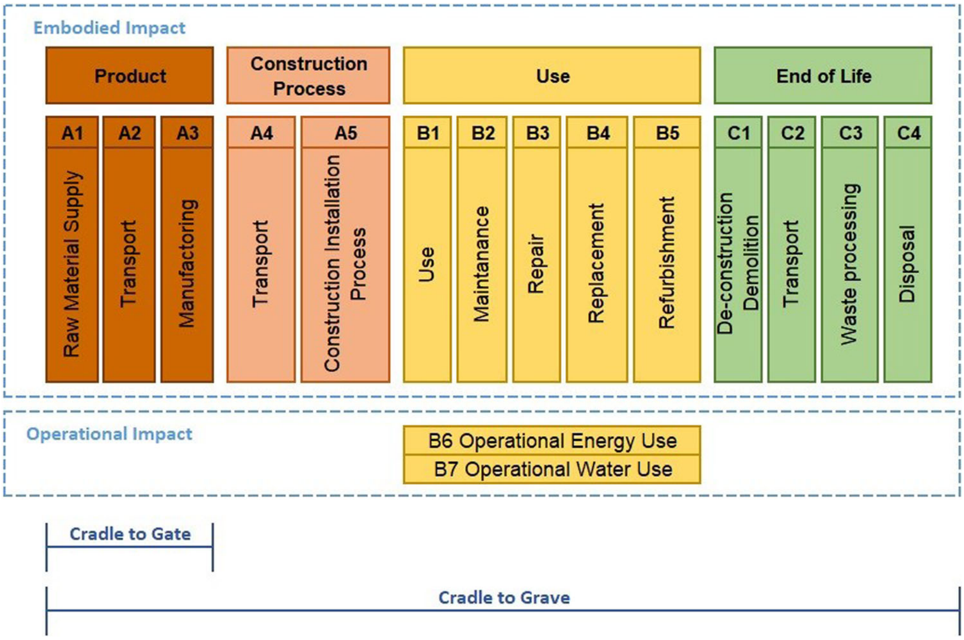

FIGURE 4 | WLC emissions of a building reproduced from IStructE 'How to Calculate Embodied Carbon' [32].

Guidance [36] recommends a standard figure of 10 $kgCO_2e/m^2$ GIA for module B2 impacts in the United Kingdom, covering all building element categories.

- **Repair impacts (B3)**

Module B3 is intended to provide a reasonable allowance for repairing unpredictable damage over and above the maintenance regime, where repairing a product or system involves returning it to an acceptable condition through the renewal, replacement or mending of individual worn, damaged or degraded parts. Due to the scarcity of data informing carbon factors for repair (B3), in the UK context, it is advisable to consider repair impacts as approximately 25% of B2 maintenance impacts, as suggested by Sturgis et al. [17].

- **Replacement impacts (B4)**

Module B4 relates to the EC associated with replacing building elements during the RSP, for example, replacement of the facade during RSP [32]. In the United Kingdom, the lifespans provided in Table 1 should be used for building components.

The carbon factor for Module B4 is the number of times a component is replaced in the built asset's RSP multiplied by the sum of the carbon factors for life cycle modules A1–4, A5w and C2–C4 (Equation 2).

$$\mathrm{ECF}_{\mathrm{B4,i}} = \left[\frac{\mathrm{RSP}}{\mathrm{CL_i}} - 1\right] \times (\mathrm{ECF}_{\mathrm{A13,i}} + \mathrm{ECF}_{\mathrm{A4,i}} + \mathrm{ECF}_{\mathrm{A5w,i}} + \mathrm{ECF}_{\mathrm{C2,i}} + \mathrm{ECF}_{\mathrm{C34,i}}), \tag{2}$$

$\mathrm{ECF}_{\mathrm{B4,i}}$ is the replacement emissions for ith material, RSP the asset reference study period. The suggested default RSP is 60 years for buildings [17], and $\mathrm{CL_i}$ the estimated component lifespan for ith material.

- **Module D carbon factor**

Module D estimates the benefits and burdens of materials and components beyond the building's end-of-life date. According to [17], to calculate Module D emissions, compare the difference between carbon emissions of recovered materials (reuse, recycling, or incineration) and carbon emissions of the primary material (Equation 3).

$$\text{Module D} = \left(M_{\text{MR out}} - M_{\text{MR in}}\right) \times \left([E_{\text{MR after EoW out}}] - \left([E_{\text{VMSub out}}] \times \left[\frac{Q_{\text{R out}}}{Q_{\text{R in}}}\right]\right)\right), \tag{3}$$

$M_{\text{MR out}}$ is the amount of material that will be recovered (recycled and reused) in a subsequent system, $M_{\text{MR in}}$ the amount of material that has been recovered (recycled or reused) from a previous system, $E_{\text{MR after EoW out}}$ Specific emissions and resources consumed, per unit of analysis, arising from the material recovery (recycling and reusing) processes of a subsequent system after the end-of-waste state; $E_{\text{VMSub out}}$ the specific emissions and resources consumed, per unit of analysis, arising from acquisition and pre-processing of the primary material; $\frac{Q_{\text{R out}}}{Q_{\text{R in}}} = \frac{Q_{\text{R out}}}{Q_{\text{R in}}}$ the quality ratio between outgoing recovered material (recycled and reused) and the substituted material.

Module D is relevant to any end-of-life output from the asset during transportation and construction (module A4–A5); maintenance, repair, replacement and refurbishment (modules B2–B5); and from waste treatment and disposal

TABLE 1 | Indicative component lifespans [17].

Building part	Building elements/components	Expected life span
Substructure	Foundation	60 years
Superstructure frame, upper floor and roof structure	Structural elements, e.g., columns, walls, beams, upper floor and roof structure	60 years
Facade	Brick, stone, block and precast concrete panels	60 years
	Hardwood/steel/aluminium windows	30 years
	Doors	20 years
Roof	Roof covering:	
	Standing seam metal	30 years
	Tiles, clay and concrete	60 years
Superstructure	Internal partitioning:	
	Studwork	30 years
	Blockwork	60 years
Ceiling	Suspended grid (ceiling system)	25 years

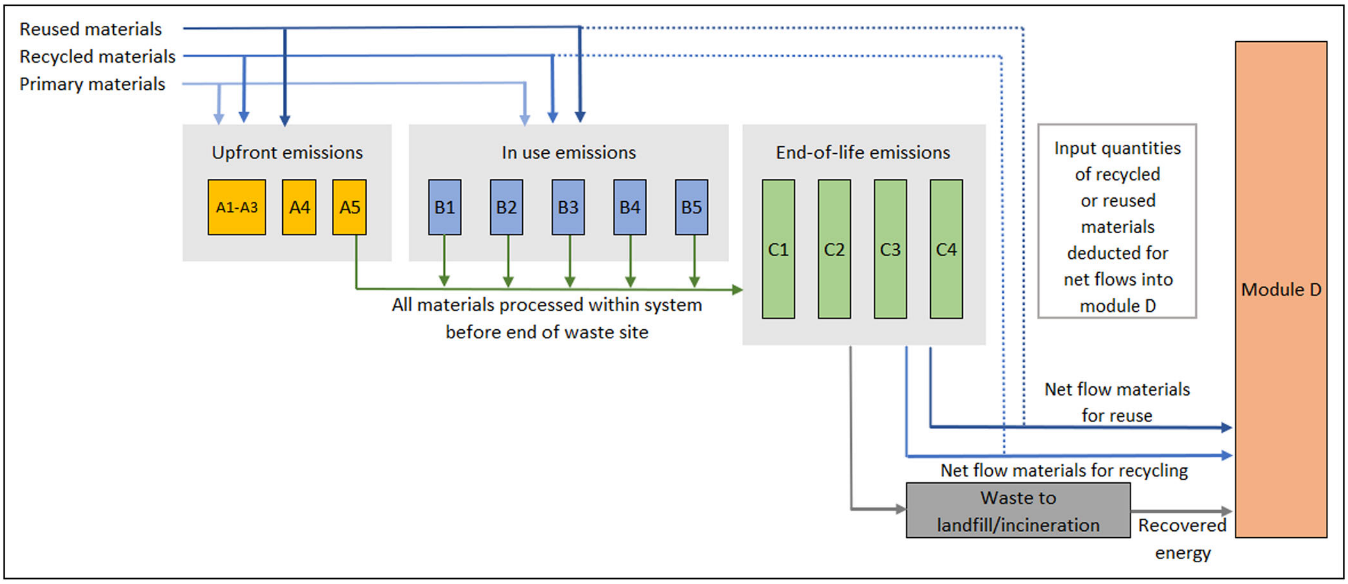

FIGURE 5 | Flow of materials and emissions between modules reproduced from RICS guideline 'Whole life carbon assessment for the built environment' [17].

(modules C3 and C4) [17] (Figure 5). The waste management practices for end-of-life materials in the United Kingdom is outlined in Table 2.

Table 2 highlights that, at present in the United Kingdom, re-using materials is not a widespread practice. The predominant approaches involve either recycling the materials or directing them to landfills.

- **Biogenic Carbon**

Biogenic carbon is the carbon absorbed and stored in trees during growth through photosynthesis. Trees capture CO_2 from the atmosphere, storing it in their wood. While storing biogenic carbon in timber structures offers climatic benefits, it doesn't offset the immediate effects of fossil carbon emissions. Table 3 shows the ECF of biogenic carbon in timber materials across three buildings, sourced from the ICE database. Timber materials are assumed to originate from a sustainably managed forest with FSC certification.

3 | Analysis and Discussion

As mentioned in the preceding sections, evaluating EC is imperative in addressing the challenges of climate change. In this sense, this section conducts a thorough evaluation of the EC associated with all the modelled and studied case studies.

TABLE 2 | The waste management practices for end-of-life materials in the United Kingdom.

Material	Reuse	Recycle	Incineration	Landfill	Source
Plasterboard	0	4%	0	96%	[37]
Steel	0	85%	0	15%	[32]
Aluminium	0	95%	0	5%	[32]
Glass	0	50%	0	50%	[38]
Timber	0	55%	44%	1%	[32]
Concrete	0	90%	0	10%	[32]
Rebar	0	92%	0	8%	[32]
Sand/Cement Screed	0	80%	0	20%	[39]
Plastic	0	33%	38%	29%	[40]
Brick	0	90%	0	10%	[32]
Rock Wool	0	0%	0	100%	[41]
Polyethylene (membranes, pipes)	0	5%	85%	10%	[42]
Burnable insulation (e.g., EPS, PUR)	0	95%	0	5%	[42]

TABLE 3 | The biogenic carbon for timber materials.

Material	ECF(Biogenic Carbon) ($kgCO_2e/kg$)
Timber, MDF	−1.5
Timber, Softwood	−1.55
Timber, Hardwood	−1.59
Timber, I Joist Beam	−1.53
Timber, Glulam	−1.41
Timber, Chipboard	−1.52

TABLE 4 | EC during module (A1–A5) and (C1–C4) for the case studies.

Building	A1–A5 ($kgCO_2e/m^2$)	C1–C4 ($kgCO_2e/m^2$)
Residential	521.78	31.32
College	511.51	19.42
Hotel	708.57	18.39

3.1 | Embodied Carbon Assessment of the Case Studies

3.1.1 | Module A and C

Table 4 displays the EC values for the three case studies across modules (A1–A5) and (C1–C4). Notably, the hotel building exhibits the highest EC emissions, while the residential building demonstrates the lowest.

Figures 6 and 7 show hot zones in terms of EC. In other words, they will determine which materials and stages have the highest EC and have the potential to mitigate the total EC. Figure 6 highlights the crucial importance of reducing EC during the A1–A3 stage, as it consistently presents the highest carbon impact across all case studies. The A1–A3 stage accounts for over 80% of the EC emissions in the majority of materials. Plasterboard and brick have higher A5w values compared to other materials, primarily due to a relatively greater on-site wastage. Timber materials exhibit higher C3-C4 emissions compared to other materials, due to the energy consumed during the incineration and recycling processes. While most materials only consider recycling in their emissions assessments, timber materials encompass both incineration and recycling factors.

According to Figure 7, concrete accounts for 27% of the environmental impact in residential buildings, while metal makes up 61% in college buildings, and insulation leads with 34% in hotels. Since concrete dominates building composition, reducing its EC is crucial to lowering overall EC. Metal also contributes significantly, 25% in residential, 61% in college, and 28% in hotel buildings, making the use of recycled materials essential for reducing emissions. Insulation is another key factor, accounting for 16% in residential and 34% in hotel buildings, where choosing lower-carbon options can further decrease EC.

3.1.2 | Module B

According to [17], the RSP of the buildings are assumed to be 60 years. During this period, building components require maintenance, repair, and replacement, thus requiring the calculation and consideration of the EC associated with these stages of the buildings' life. During the replacement of materials, it is essential to treat these materials with the same level of consideration as primary materials at the end of their lifecycle.

Module B1 and B5 are excluded from this research for the following reasons:

Module B1 is generally insignificant for structural materials [32] and is not considered in this study. Additionally, refurbishment motivations vary for each building and cannot be generalized, so the specific impacts of refurbishment changes (B5) are

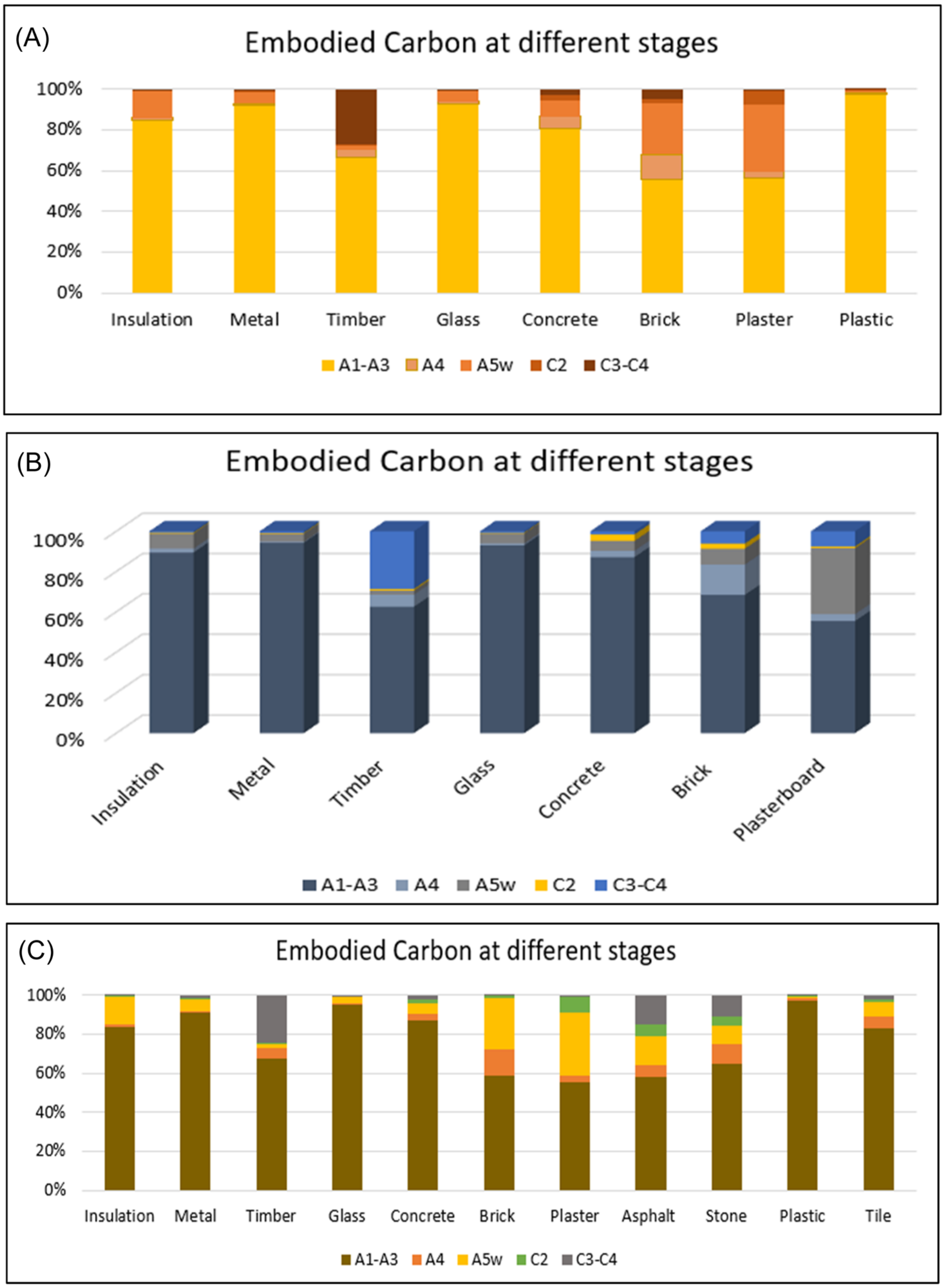

FIGURE 6 | Embodied carbon emissions at different stages of the residential, college, and hotel building's life. (A) Residential building, (B) college building, and (C) hotel building.

excluded. Tables 5 and 6 show the EC during module B, from building completion to the end of the reference study period (RSP). Table 5 highlights material replacements for facades, roofs, and finishes based on their lifespan. EC emissions in modules B2–B4 are significantly higher for the hotel due to the replacement of galvanized steel suspended ceilings every 25 years, which has high EC emissions.

3.1.3 | Module D Outside the LCA

Table 7 illustrates that timber materials offer significant advantages beyond the life cycle scope, particularly in terms of EC savings through incineration and recycling. Table 7 illustrates the benefits or burdens in Module D. EC in Module D turns negative when the environmental benefits of material recovery (e.g., recycling or reuse) outweigh the impact of producing and processing the original material. A negative value represents a net benefit, while a positive value indicates a net burden.

Among the case studies, timber materials demonstrate the most significant savings in EC, ranging from 16.18% to 50.42% across all instances.

For Aluminium made of 31% recycled material, which is recycled at a rate of 95% at end-of-life, Module D reports the

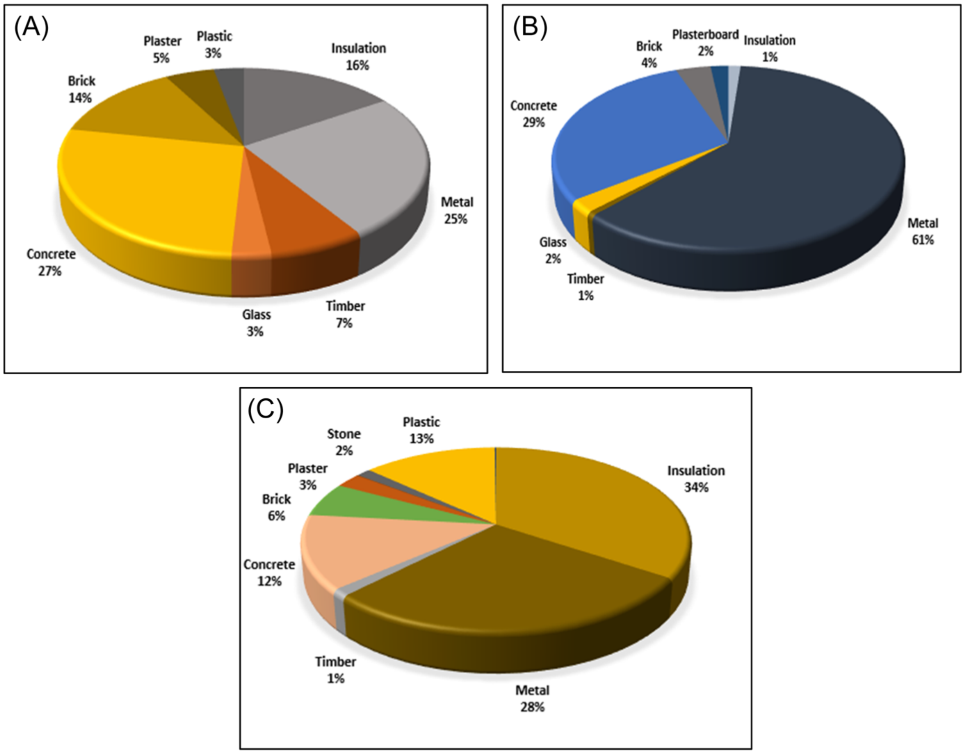

FIGURE 7 | Embodied carbon share of materials in the residential, college, and hotel building. (A) Residential building, (B) college building, and (C) hotel building.

TABLE 5 | Embodied carbon during module B4.

Building	Building part	Material	Expected lifespan (year)	Embodied carbon (B4) $kgCO_2e$
Residential	Façade	Window	30	3640.92
		Door	20	5072.66
	Roof	Roof covering	30	2498.91
College	Façade	Window	30	76,562.34
		Door	20	54,381.53
	Finishes	Ceiling finishes	25	69,284.48
Hotel	Façade	Window	30	96,303.84
		Door	20	143,512.80
	Finishes	Ceiling	25	3,498,664.67
		Roof	10	49,628.59

TABLE 6 | Embodied carbon during B2-B4.

Building	Area (m^2)	ECF (B2) ($kgCO_2e/m^2$)	EC (B2) ($kgCO_2e$)	EC (B3) ($kgCO_2e$)	EC (B4) ($kgCO_2e$)	EC (B2-B4) ($kgCO_2e/m^2$)
Residential	145.861	10	1,458.61	364.65	11,211.99	89.37
College	2500	10	25,000	6,250	199,488.18	92.30
Hotel	11843.29	10	118,432.9	29,608.22	3,788,109.91	332.35

additional benefits resulting from the 64% recycled Aluminium, which is not addressed by the recycled content approach. The environmental advantage of recycling aluminium is between 9.89% and 38.48%.

According to [43], the constructional steelwork used in the United Kingdom contains an average of 60% recycled content. Therefore, we assumed that the Galvanized sheet in this study incorporate a 60% recycled content. Considering the end-of-life

TABLE 7 | Relative importance of Module D in building variants compared to their total life cycle.

Material	Share of benefit/burden %
Timber	−38.48%, −50.42%[a]
Metal	−8.26%, −15.79%
Brick	−5.54%, −5.88%
Concrete	−0.40%, −2.87%
Rebar	1.15%, 1.20%

Note: Darker shades of green indicate the highest EC savings through material recovery, while lighter shades represent lower EC savings.
[a]Negative sign shows the EC savings achieved through recycling or reusing.

strategy aiming for an 85% recycling rate, the additional 25% recycled materials lead to significant reductions in environmental impact. This results in notable EC reductions from 8.26% to 11.40% among all case studies.

In addition, 90% recycling brick resulted in the 5.54% to 5.88% EC reduction. For concrete materials, the environmental benefit is very low. In the recycling process, concrete is commonly transformed into aggregate for utilization in new projects, with the associated EC typically ranging from 0.4% to 2.87%, showcasing minimal environmental impact.

While the mentioned materials enhance environmental advantages, it's crucial to note that rebar carries an environmental burden. It comprises 97.9% recycled content during production and exhibits 92% recyclability at the end of its life cycle. Therefore, the discrepancy between the recycled content during manufacturing and the recycling capability at the end-of-life raises an important consideration. Therefore, the higher recycled content during the product stage implies a greater demand for recycling rebar to produce an equivalent quantity of material.

3.1.4 | WLEC of the Case Studies

Figure 8 shows the WLEC of the three case studies. This includes emissions from upfront production to end-of-life stages, categorized into modules A1–A5 (Upfront), B1–B5 (In Use), and C1–C4 (End of Life). Additionally, WLEC asset performance involves separately reporting potential benefits from future energy recovery, reuse, and recycling (Module D). Figure 8 illustrates the potential for minimizing upfront carbon emissions. However, we must proceed cautiously to ensure that reducing EC during stages A1-A5 does not disproportionately impact stage B. It is imperative to avoid utilizing materials of inferior quality and shorter lifespans in an attempt to lower upfront carbon emissions, as this may inadvertently increase the burden during stage B. Figure 8 shows a significant storage of biogenic carbon in timber materials during the upfront carbon for the residential buildings. However, this storage is less pronounced for the college and hotel buildings, as their timber components represent only 0.47% and 1.25%, respectively, of the total building quantity. In addition, when timber materials are replaced at the building's ages of 20 and 40 years, additional biogenic carbon is generated. This carbon storage is reduced during end-of-life stages, as 44% of timber materials are incinerated, releasing their stored biogenic carbon.

Figure 8 also illustrates that the amount of EC generated varies throughout the lifespan of the building, largely depending on the longevity of the building materials used. Module A has the largest share of EC, significantly surpassing the other two modules. Following Module A, Module B ranks as the second highest, while Module C exhibits the lowest proportion of EC. The share of module B for the hotel building is more significant than the two other case studies. This is primarily due to the assumption that its suspended ceiling, containing a substantial amount of EC, will need replacement every 25 years.

Regarding EC savings for the college building, it stands at 28.4 $kgCO_2e/m^2$, surpassing both the residential and hotel buildings, which are at 20.83 and 19.75 $kgCO_2e/m^2$, respectively. Nevertheless, there is potential for further EC savings across all three buildings during module D through improved end-of-life scenarios.

Table 8 highlights the variation in WLEC emissions across the studied buildings. It reveals that the residential building has the lowest WLEC emissions, measuring 642.47 $kgCO_2e/m^2$, while the hotel building records the highest WLEC emissions, reaching 1059.31 $kgCO_2e/m^2$.

3.2 | Embodied Carbon Reduction Strategies

The construction industry plays a significant role in contributing to EC emissions, underscoring the need for swift and effective measures to reduce its environmental impact. As mentioned before, various strategies exist for mitigating EC emissions within the construction industry, including whole building reduction, one-for-one material substitution, and specification.

This research investigates a specification approach designed to minimize carbon emissions, with the goal of evaluating its potential impact on achieving EC savings in building construction.

3.2.1 | Utilizing Materials With Lower Carbon Intensity

In previous section, it was demonstrated that concrete possesses high EC among the materials used in the case studies. The residential building was constructed using RC20/25 strength grade concrete, while the college and hotel buildings were built using RC32/40 strength grade concrete. Within the materials utilized in concrete production, cement significantly contributes to 7% of global GHG emissions. This figure is expected to increase alongside ongoing development. It is the most commonly used material in construction globally and represents the highest EC material in concrete [44].

Fly Ash and GGBS are selected as partial cement replacements to determine their impact on EC reduction. There are various

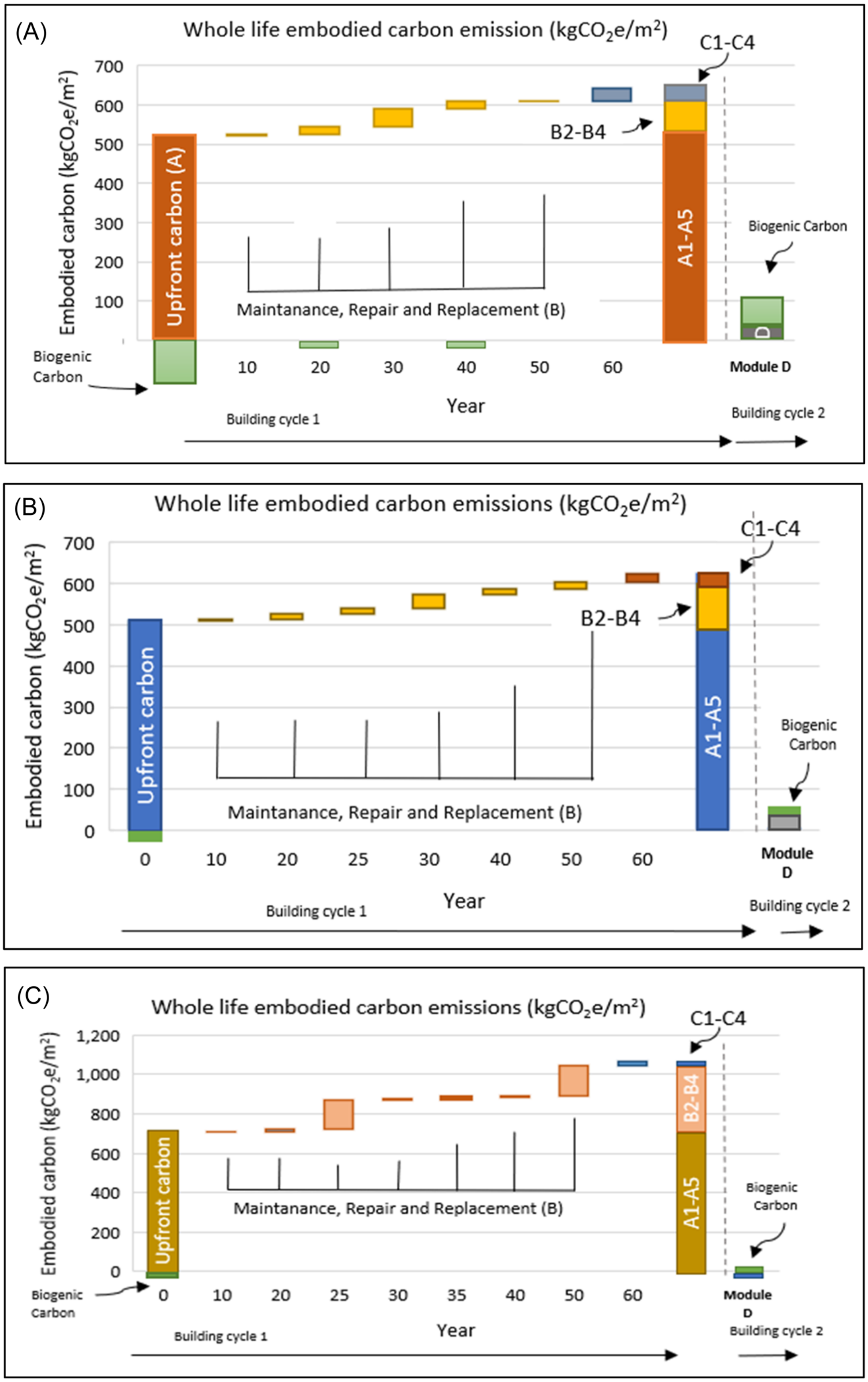

FIGURE 8 | WLEC of the case studies during (A1–A5), (B2–B4), (C1–C4), and module D. (A) Residential building, (B) college building, and (C) hotel building.

advantages to using Fly Ash as a partial replacement for cement in concrete. Because of its environmental benefits and cost-effectiveness, Fly Ash, a by-product of coal-fired power plants, is considered a sustainable alternative to cement. Additionally, GGBS can be used as a partial cement substitute. According to [45], partial substitution of GGBS for cement enhances the workability of the mixture. Various scenarios for EC reduction in concrete materials of the case studies are analysed using Fly Ash and GGBS as cement replacements. In more detail, 15%, 30%, and 40% Fly Ash replacement, as well as 25% and 50% GGBS replacement, were examined. As shown in Figure 9, using a blend of 50% cement and 50% GGBS leads to a notable

TABLE 8 | WLEC of the case studies during all stages of the building's life.

Building	A1–A5 ($kgCO_2e/m^2$)	B2–B4 ($kgCO_2e/m^2$)	C1–C4 ($kgCO_2e/m^2$)	Total WLEC ($kgCO_2e/m^2$)
Residential	521.78	89.37	31.32	642.47
College	511.51	92.30	19.42	623.23
Hotel	708.57	332.35	18.39	1,059.31

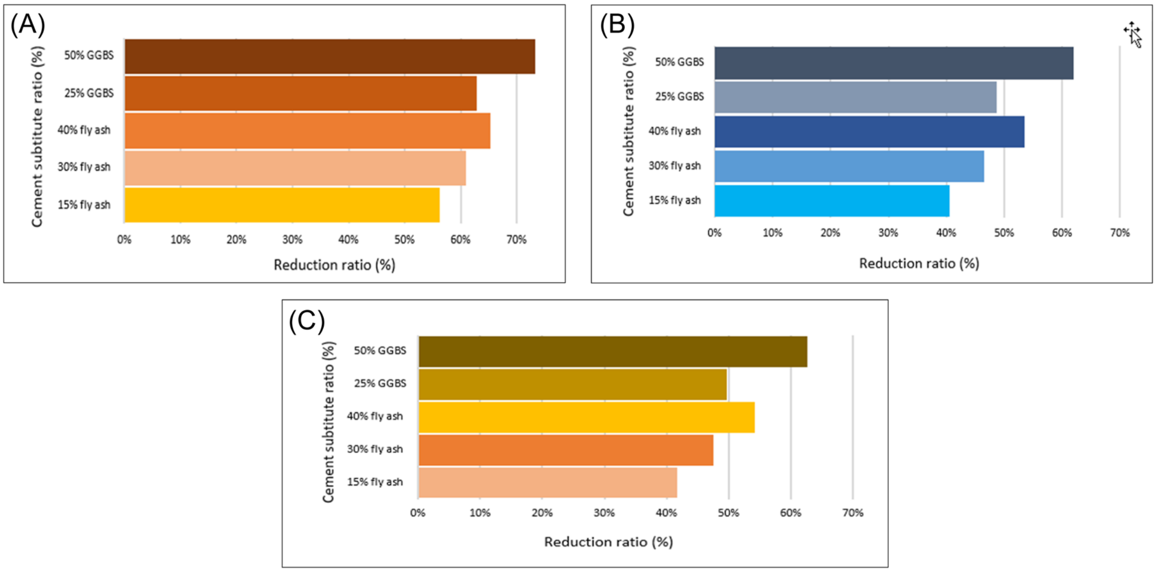

FIGURE 9 | Minimizing EC emissions with GGBS and Fly Ash as Cement Substitution. (A) Residential building, (B) college building, and (C) hotel building.

decrease in EC by 73%, 61.97%, and 62.64% in residential, college, and hotel buildings, respectively, compared to other mixtures. This blend emerges as the most efficient option based on our analysis. Following that, utilizing 40% Fly Ash results in the most significant reduction in EC, with reductions of 65.38%, 53.43%, and 54.24% observed in residential, college, and hotel buildings, respectively.

Figure 10 illustrates the potential emissions reduction of WLEC in the case studies using various strategies aimed at reducing EC. Metal materials, especially rebar is among the primary contributors to EC. In the United Kingdom, reinforcement can be manufactured using 98% recycled scrap metal [46]. In the case studies, we assumed a recycled content of 97.9% for rebar, indicating that this material is already at its lowest carbon footprint. Therefore, they cannot be less carbon-intensive than they currently are. However, utilizing galvanized steel with 90% recycled content can reduce total EC emissions by 1.64% and 8.26% in the residential and hotel buildings.

Producing high-quality aluminium extrusions with substantial recycled content has been proven feasible. According to Hydro, the recycled content of aluminium can be more than 75%. Therefore, aluminium with 80% recycled content is regarded for assessing its potential reduction in EC. The result in showed 1.28%, 6.58%, and 0.19% reduction in total EC of the residential, college and hotel buildings.

Moreover, Bricks have high EC emissions. One effective method to mitigate EC in brick is by incorporating reclaimed brick. Reclaimed brick is considered a sustainable building material since it reduces the demand for new brick production and minimizes waste by repurposing materials that would otherwise be discarded. Utilizing reclaimed brick materials in this project significantly reduces the WLEC by 7.37%, 2.78%, and 3.41% in the residential, college and hotel buildings.

According to [47], Expanded Polystyrene (EPS) can be made from 100% recycled materials. Therefore, by using EPS made from 100% recycled materials offers another approach to reduce the building's environmental impact, although not significantly. It could result in WLEC reductions of 0.85%, 0.42%, and 0.01% in the buildings mentioned.

Exploring various strategies to reduce EC, significant reductions of 30.59%, 46.86%, and 23.69% are achievable in residential, college, and hotel buildings, respectively.

4 | Conclusion

In conclusion, this paper has thoroughly examined the EC profiles of various case studies, providing valuable insights into the environmental impacts of activities during modules A, B, C and D. Through a detailed assessments of EC associated with the studied buildings; several significant findings have emerged.

It was found that the most effective strategy for mitigating EC emissions entails the integration of GGBS as a substitute for cement. This approach holds significant promise, offering a

FIGURE 10 | Total EC reduction through different EC reduction strategies in three case studies. (A) Residential building, (B) college building, and (C) hotel building.

remarkable reduction in the EC associated with concrete within the buildings under study, with potential decreases ranging from 60% to 70%.

Furthermore, our investigation into specification strategies has demonstrated significant reductions in WLEC, with the residential, college, and hotel buildings achieving reductions of 30.59%, 46.86%, and 23.69%, respectively. Effective mitigation measures, such as the use of recycled and reclaimed materials, have shown promising results in reducing WLEC emissions. Nonetheless, the lack of comprehensive and standardized data for certain materials, particularly those with high recycled content, remains a critical challenge. To fully leverage the potential of these strategies, it is imperative that future research focuses on enhancing the consistency and availability of such databases, which is essential for advancing sustainable building practices.

Additionally, this study has considered the EC savings achievable through current end-of-life strategies in the United

Kingdom. By integrating these strategies into the analysis, a more comprehensive understanding of the potential avenues for reducing EC throughout the building life cycle is provided.

Overall, the insights gained from this study underscore the importance of strategic interventions at various stages of building's life to mitigate EC emissions. Moving forward, implementing these findings can contribute significantly to achieving sustainability goals within the construction industry.

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