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Article

Whole Life Carbon Assessment of a Typical UK Residential Building Using Different Embodied Carbon Data Sources

Maryam Keyhani [1,*], Atefeh Abbaspour [1], Ali Bahadori-Jahromi [1], Anastasia Mylona [2], Alan Janbey [3], Paulina Godfrey [4] and Hexin Zhang [5]

[1] Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK
[2] Research Department, the Chartered Institution of Building Services Engineers [CIBSE], London SW12 9BS, UK
[3] Research Department, London College, London TW5 9QX, UK
[4] Hilton, Maple Court, Reeds Crescent, Watford, Hertfordshire WD24 4QQ, UK
[5] School of Computing Engineering and the Built Environment, Edinburg Napier University, Edinburgh EH11 4BN, UK
* Correspondence: maryam.keyhani@uwl.ac.uk

Abstract: The climate crisis in many sectors is driving rapid and substantial changes. Considering the fact that the building sector accounts for 39% of energy related carbon emissions, it is important to take swift actions to reduce these emissions. This study will identify the accuracy and availability of the embodied carbon databases. In this regard, the effect of using different embodied carbon databases on the total emissions during product and end-of-life stages will be compared. The results showed that using the UK Department for Business, Energy, and Industrial Strategy database (BEIS) overestimates the embodied carbon emissions. Additionally, using the Environmental product declarations database (EPDs), compared to the Inventory of Carbon and Energy database (ICE), can reduce embodied carbon for some materials up to 100%. The end-of-life calculation showed a huge difference between the two databases. In addition, Whole Life Carbon Assessment (WLC) has been carried out. The findings revealed that 67% of emissions come from operational carbon and embodied carbon is responsible for 33% of emissions. Using LED lights and installing PV panels can reduce the total CO_2 emissions by 24.82 tonCO_2. In addition, using recycled metal, less carbon intensive concrete, and recyclable aluminium can reduce the total CO_2 emissions by 18.57, 2.07, and 2.3 tonCO_2e, respectively.

Keywords: climate change; whole life carbon; embodied carbon; operational carbon; reduction strategy; data accuracy

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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], and building sector energy consumption accounts for one-third of total energy consumption and GHG emissions [2]. United Nations Environment Program (UNEP), International Energy Agency (IEA), and Global Alliance for Buildings and Construction (GABC) reports indicate that building construction and operations account for 36% of global final energy use and 39% of energy related GHG emissions [3].

According to UNEP, the building industry should cut energy use and GHG emissions in both developing and developed nations [2]. Given the potential negative effects of energy use and climate change [4], the building sector should provide environmentally friendly structures to reduce GHG emissions and energy consumption [5].

The Paris Agreement (COP21), established in December 2015, intends to limit the effects of global warming by reducing carbon emissions [6]. Therefore, lowering carbon emissions as one of the essential parts of GHG from buildings is a crucial goal of government climate policy [7]. The Intergovernmental Panel on Climate Change (IPCC) has determined that to limit global warming to 1.5 °C by 2030, CO_2 emissions should be reduced by around 45%, and to net zero by 2050 [8]. CO_2 emissions are incurred in all stages of a building's life cycle and are generally categorized into operational carbon and embodied carbon [9]. In the building sector, operational carbon accounts for 28% of carbon emissions, whereas embodied carbon accounts for 11%, according to a report by The World Green Building Council (WorldGBC) [10]. The 2019 Green Construction Board Buildings Mission 2030 report shows that net zero operational carbon is already possible [11–13]. The challenge for the profession is to expand excellent practice to all future work, as highlighted by the WorldGBC's report on net zero embodied carbon [10]. In addition, according to current building regulations, for a typical residential building, operational carbon contributes as much as 67% of emissions and 33% of emissions come from embodied carbon, but in Ultra low-energy buildings, operational carbon can be as low as 23%, and 77% of emissions come from embodied carbon [14].

To have a better understanding of CO_2 emissions during a building's lifetime, it is necessary to consider both operational results from energy consumption in the day-to-day running of a property as well as embodied carbon arising from procuring and installing the materials and components and lifetime emissions from maintenance, repair, replacement, and ultimately demolition and disposal. Most of the structural embodied carbon is in the construction phase, which is before the building is occupied. As it will be released before 2050 (the deadline to get to net zero), it is necessary for it to be reduced as soon as possible. The Royal Institute of British Architects (RIBA) joined the global 'declare' movement in June 2019 and has set RIBA Chartered Practices to achieve embodied carbon reduction of <750 $kgCO_2e/m^2$ for non-domestic office buildings and <625 $kgCO_2e/m^2$ for domestic buildings by 2030 (minimum 40% reduction in embodied carbon compared to the current business as usual benchmarks) by using low carbon materials that are ethically sourced [15].

Ref. [16] analysed Whole-life embodied carbon (WLEC) in multistory buildings including steel, reinforced concrete, and engineered timber frames. In this research, carbon coefficients embodied during product, construction process and end of life stages are derived from Ecoinvent 3.5 database, UK Government emission factors and literature benchmarks. The results for WLEC showed that embodied carbon values for the timber frame, concrete frame, and steel frame are 119, 185, and 228 $kgCO_2e/m^2$, respectively.

Ref. [17] estimated the annual embodied carbon dioxide from the China's building sector using a process-based approach and a disaggregated input-output model. This study only took steel, timber, cement, brick, glass, and aluminum into consideration in the estimation of the embodied carbon from transportation stage. The results of embodied carbon dioxide emissions were 1421.70 Mt and 1599.62 Mt in the building sector in 2015, respectively. In terms of building types, the embodied carbon dioxide in the residential building sector is about 1.5–2.2 times that of the non-residential building sector.

A product stage embodied carbon assessment of a UK educational building, initially undertaken using single data points for each material, gave an embodied carbon prediction of 525 $kgCO_2e/m^2$ GIFA [18]. In this research, Scenario one (considering the full building scope) resulted in an average embodied carbon value (mean $\pm$ CoV) of 526 $kgCO_2e/m^2$ GIFA $\pm$ 10.0% with the embodied carbon range from 50 to 140% of the original result. The second scenario (sub- and super-structure only) resulted in an average embodied carbon value of 312 $kgCO_2e/m^2$ GIFA $\pm$ 11.9% with a full range of 45–155% of the original result. The ICE database used in this study only provides embodied carbon coefficient for the product stage [18].

Ref. [19] proposes quick prediction calculation models of embodied carbon emissions (ECE) based on carbon emissions of main building materials during scheme design phase by conducting case studies on 129 residential buildings (RBs) of different structures in Jiangsu, China. Embodied carbon factors come from other literatures. It is proved that the proposed models simplify ECEs calculation, guide low-carbon building design, and facilitate policy making in the sustainable development of buildings and cities.

Considering the importance of embodied carbon in the building sector, it is necessary to make sure that we are using a validated database. Since there is not much research on comparison between different databases, this research will compare different common databases common in the UK and their effects on total embodied carbon emissions, cradle-to-grave.

Commonly, the embodied carbon of buildings is quantified using an adapted version of Life Cycle Assessment (LCA), a method for analysing the environmental impacts of a product throughout its entire life [20]. The Life Cycle Assessment methodology, which was widely standardized in the 1990s, strives to measure the environmental impacts of products and processes over their whole life cycle, i.e., "from cradle to grave" [21]. This method provides a solid methodological base for calculating CO_2 emissions and other environmental indicators over the full life cycle of buildings [22–24], and it is becoming more widely accepted in the context of national and international environmental standards.

2. Research Methods

2.1. Case Introduction

This paper collected data from a typical residential building in the UK. It is a double Storey detached structure with a timber truss roof, concrete block walls, air-filled double-glazed windows, and an area of 145.86 m^2. Table 1 shows Building Elements and Structural Components of the residential building. The building has been surveyed and standard design model was simulated using Building Information Modelling (BIM) software, Autodesk® Revit®, version 2023 which provided an accurate quantity of materials within the project.

Table 1. Building Elements and Structural Components.

Building Element	Structural Element and Component
Substructure	Strip Foundation
Superstructure	Structural framing: T-Beam Concrete, Universal Beam, I joist Floor: Floor block, Concrete Screed, Rock Wool, Polyurethane, Chipboard, Plasterboard, Timber stairs Roof: Metal Roof Panel, Softwood, Polyurethane
External Envelope	External Walls: Brick, Rock Wool, Aerated Concrete Block, Plasterboard
Interiors	Internal Walls: Aerated Concrete Block, Plasterboard, Koolthermal Kingspan

2.2. System Boundary

In order to meet the required result for an Environmental Impact Assessment in a short time and considering the high amount of calculation required, it was necessary to define a boundary for the project, which in this case was carbon emissions from cradle to grave. It involved embodied carbon emitted from cradle to practical completion (A1–A5), end of life to grave (C1–C4) and operational carbon (B6–B7). Finally, the Whole Life Carbon Assessment (WLC) of the building was assessed.

2.3. Calculation Model

2.3.1. Life Cycle Assessment Methodology

Life Cycle Assessment 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 [25]. 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), and re-use/recovery potential (D), with the latter accounting for advantages outside the system boundary. As more of these steps were considered, a more complete picture of the environmental effect emerged [6]. Figure 1 shows the life cycle stages of an asset [26]. According to the International Organization for Standardization (ISO), the LCA procedure consists of the following steps: 1. Goal and Scope: determines which processes of the unit's life cycle will be included in the assessment [27]. In this phase, the boundary, functional unit, assumptions, and purpose are mentioned [28]. 2. Life cycle inventory (LCI): collection of input data needed for assessment. 3. Life cycle impact assessment (LCIA): evaluation of the size and significance of the environmental impacts of a product throughout its life cycle. 4. Life cycle Interpretation: analysis of the results of the LCI and LCIA within the goal and scope [27]. Figure 2 shows the description of LCA methodology in the ISO standards [29].

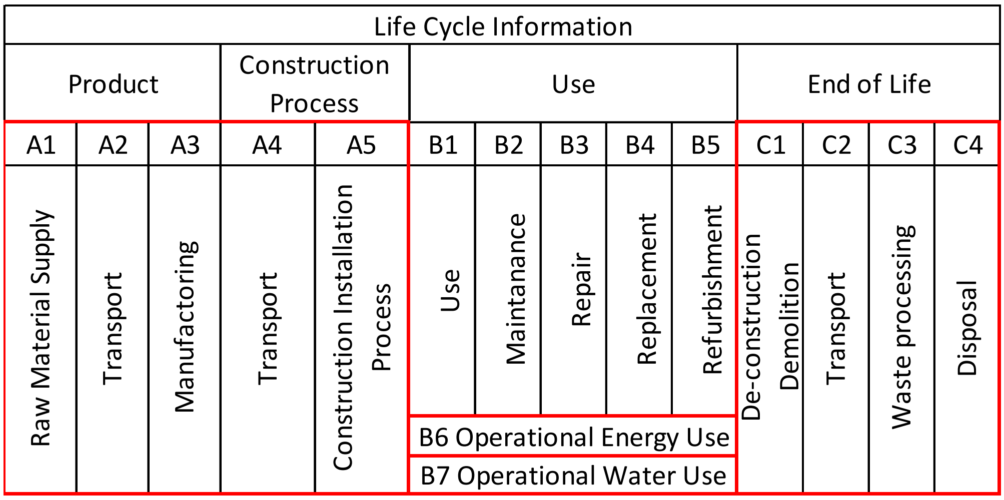


Figure 1. Life cycle stages reproduced from IStructE 'How to Calculate Embodied Carbon' [26].

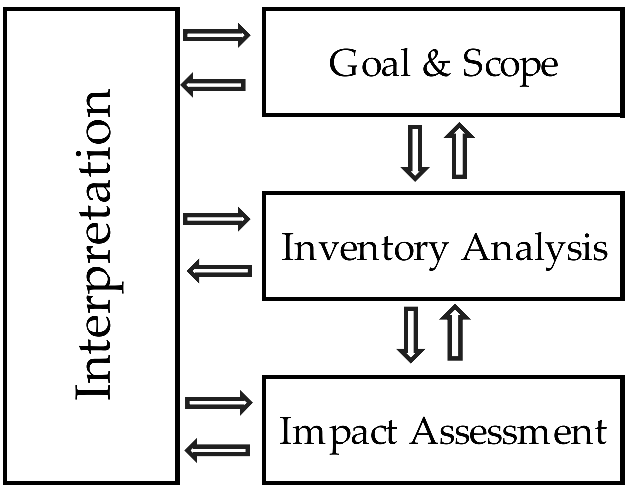


Figure 2. LCA stages reproduced from ISO 14,044 [29].

2.3.2. Embodied Carbon Definition

Cradle-to-grave carbon is the carbon released during material extraction, processing, manufacturing, demolition, transportation, waste processing, and final disposal. The fundamental principle of an embodied carbon calculation is to multiply the quantity of each material by a carbon factor for the life cycle modules being considered (Equation (1)).

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

Material quantities can be calculated in a number of different ways, depending on the stage of design and the tools available, including:

- Manual calculations;
- BIM models;
- Structural analysis models;
- Scheming manuals (e.g., Structural Engineer's Pocket Book: Eurocodes18);
- Preliminary calculations on representative/repeated structural elements;
- Previous project experience;
- A quantity surveyor's cost plan [26].

Product Stage Embodied Carbon (A1–A3)

This stage involved the processing of raw materials and the manufacturing of building materials. The emissions are primarily caused by chemical reactions and energy consumption (e.g., diesel, gasoline, and electricity) during the manufacturing of a product from raw materials. The total amount of carbon emissions associated with the product stage (A1–A3) was calculated by Equation (2).

$$EC_{A13} = \sum_{i=1}^{n} [Q_i(ECF_{A13,i})] \quad (2)$$

where Q_i is the weight of ith material, $ECF_{A13,i}$ is the embodied carbon factor (ECF) associated with ith material.

Demolition Stage Embodied Carbon (C1)

The demolition of the building structure was carried out using excavators. Excavators must deal with the interior and the building structure at the same time. Mixed waste was mainly obtained at the end of demolition, as sorting is less precise.

$$EC_{C1} = \sum_j \left(Q_{mac,j} \times ECF_{mac,j}\right) + \left(Q_{energy,e} \times ECF_{energy,e}\right) \quad (3)$$

EC_{C1} represents the carbon emissions concern with on-site machinery operation and energy consumption for demolition where $Q_{mac,j}$ Refers to time of type j machinery operation and $Q_{energy,e}$ is the quantity of type 'e' energy.

Waste Transport Stage Embodied Carbon (C2)

Any carbon emissions related to the transportation of deconstruction and demolition waste to the proper disposal site, including landfills, reuse, and recycle plants, had to be captured in module C2.

$$EC_{C2} = \sum_k (Q_{tran,k} \times ECF_{C2,k}) \quad (4)$$

$$ECF_{C2,k} = \sum_k (TD_{mode} \times TEF_{mode}) \quad (5)$$

where $Q_{tran,k}$ is the quantity of type 'k' transport material from site, TD_{mode} is the transport distance for each transport mode considered and also TEF_{mode} is the transport emission factor for each transport mode considered.

Waste Processing Stage Embodied Carbon (C3)

When materials and/or parts were to be recovered, reused, or recycled at the end of a built asset's life, all carbon emissions related to their treatment and processing before reaching the end-of-waste state had to be included in module C3.

$$EC_{C3} = \sum_l \left(Q_{wap,l} \times ECF_{C3,l}\right) \quad (6)$$

where $Q_{wap,l}$ is the quantity of type 'l' material for waste processing.

Waste Disposal Stage Embodied Carbon (C4)

For elements not expected to be recovered and recycled but intended for final disposal in a landfill or incineration, C4 had to account for the emissions resulting from their disposal. Table 2 represents site waste disposal scenarios. It depicts three different scenarios for the embodied carbon produced from the product stage to the end of life.

$$EC_{C4} = \sum_{m} (Q_{dis,m} \times ECF_{C4,m}) \quad (7)$$

where $Q_{dis,m}$ is the quantity of type 'm' material for disposal.

Table 2. Site waste disposal scenarios reproduced from RICS 'Whole life carbon assessment for the built environment' [6].

Site Waste Disposal Scenarios		
Disposal to landfill/incineration	Reuse or recycling on-site	Reuse or recycling off-site
(A1–A3) +(A4) + (C2) + (C4)	(A1–A3) +(A4) + (C3)	(A1–A3) +(A4) + (C2) + (C3)

2.3.3. Operational Carbon Definition

Operational carbon is generated due to Heating, Ventilating, Air Conditioning (HVAC), cooling, lighting, equipment, and Domestic Hot Water (DHW). It plays a key role in total carbon emissions. According to current building regulations, for a typical residential building, operational carbon contributes as much as 67% of emissions and 23% of emissions come from embodied carbon [14]. Therefore, analysing the operational phase of the building is an essential part of investigating a building's carbon emission during its life cycle.

Various software could be used for building energy performance simulation in order to calculate the operational carbon emission and energy consumption such as EDSL TAS, Energy Plus, and so forth. In this study, EDSL TAS has been used as the most appropriate tool for research purposes and applying part L UK building regulation on the final results.

2.3.4. Assumptions

The following assumptions have been considered in this study.

- In the UK, industry standards state that recycled steel and concrete should be used in the construction phase. In this research, however, it was assumed that all parts are made from virgin materials, so different methods could be well compared.
- It was assumed the entire building would be demolished at the end of its useful life, and a recycling method for all demolished materials was also considered.
- All the factors in the Inventory of Carbon and Energy database (ICE) account for cradle-to-grave emissions [26].
- In embodied carbon calculations, transport distances should be estimated based on project-specific scenarios. A default road transport distance of 50 km on average laden was assumed in this research [6].
- According to the Royal Institution of Chartered Surveyors (RICS) guideline, carbon factors for waste processing for reuse, recovery, or recycling (C3) and disposal (C4) are often grouped together in embodied carbon assessments as the two scenarios are mutually exclusive. As materials and/or components are intended to be recycled after the end of the life of the built asset, in the line with RICS guidance, C3 and C4 together was assumed 0.013 $kgCO_2e/kg$ for all materials [26].
- Due to the lack of information from the contractor, the following could be assumed about the average rate:

$$EC_{C1} = 3.4\ kgCO_2e/m^2\ GIA \tag{8}$$

where EC_{C1} is embodied carbon due to demolition and deconstruction, GIA is gross internal area (i.e., the area of a building measured to the internal face of the perimeter walls at each floor level) [26].

- A natural gas-fired boiler was defined as delivering the demanded heat to the zones using hot water radiators. Therefore, natural gas and grid-supplied electricity CO_2 factors were assumed 0.21 kg/kWh and 0.1388 kg/kWh, respectively, from EDSL TAS default assumptions [30].
- No cooling was defined considering the typical weather of the building's location.
- Lighting was provided using halogen lights.
- A 200 L hot water tank was defined by the author in DHW circuit having a 90 percent distribution efficiency.

2.4. Modelling and Simulation

2.4.1. Embodied Carbon Simulation

This study used two software to calculate the WLC Assessment, namely Revit and TAS.

The selected case study building was modelled by BIM software Autodesk® Revit®, version 2023 (Figure 3) and based on design plan data provided by the constructor to identify the quantity of materials applied in this building. The quantity of materials was calculated by Equation (9) and represented in Table 3.

$$Quantity\ (kg) = Volume\left(m^3\right) \times Density\left(\frac{Kg}{m^3}\right) \tag{9}$$

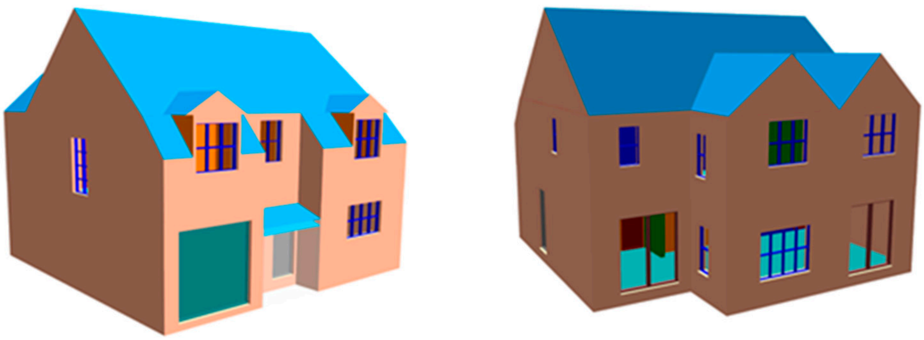
Table 3. Material quantity in the residential building.

Building Element	Structural Element	Component	Volume (m^3)	Weight (kg)
Substructure	Strip Foundation	Concrete	28.28	70,417
Superstructure	Structural Framing	T-Beam Concrete	1.91	5075
		Universal Beam	0.05	393
		I joist	0.61	367
	Floor	Floor block	10.73	24,677
		Concrete Screed	4.9	11,704
		Rock Wool	14.34	645
		Polyurethane	7.81	250
		Chipboard	4.35	3482
		Plasterboard	4.116	1525
		Timber Stairs	0.12	70
	Roof	Metal Roof Panel	5.4	14,588
		Softwood	8.71	5097
		Polyurethane	18.96	607
	Window	Glass	0.31	769
		PVC	0.54	810
External Envelope	External Walls	Brick	15.43	30,094
		Rock Wool	15.11	680
		Aerated concrete	17.49	10,491
		Plasterboard	2.161	2423
Interiors	Internal Walls	Aerated concrete	12.19	7312
		Plasterboard	2.853	3190
		Koolthermal Kingspan	0.43	15

Figure 3. 3D model of Residential Building.

2.4.2. Operational Carbon Simulation

In order to analyse the operational carbon emission of the case study, another simulation was conducted using Thermal Analysis Software (TAS), version 2022 by EDSL (Environmental Design Solutions Limited, Milton Keynes, UK) (Figure 4) to calculate the average energy consumption and operational carbon emitted from the building during its 50 years life span. In this model, the building's materials and construction were considered the same as the Revit model.



(a) **(b)**

Figure 4. Schematic of the modelled building in TAS (**a**) Front elevation (**b**) Rear elevation.

All the parts of the building, such as bedrooms, dining/living room, staircase, kitchen and so forth, were defined as separate zones with relevant internal conditions assigned to them using National Calculation Methodology (NCM) standard database. Moreover, NCM standard calendar was selected in the model to define the workdays, weekends, and holidays throughout a year which have a direct impact on occupants' presence in the home and therefore the level of energy consumption and carbon emissions.

One of the most important actions in operational carbon stage is assigning the most suitable weather data based on the purpose of the modelling and the case study's location. In this regard, CIBSE has provided two types of weather files for various locations: Test Reference Year (TRY) and Design Summer Year (DSY) which are appropriate for energy performance assessment and overheating analysis [31], respectively. As per this study's objective and considering that the modelling is following part L of the UK building regulations, the TRY file (2020) for London was selected in the modelling.

2.5. Data Collection

2.5.1. Embodied Carbon Database for Product Stage

The carbon factors for product stage of this study were derived from three primary datasets. Environmental product declarations (EPDs) were the inaugural database. They are regarded as the most reliable source of information about a product's environmental impact. However, manufacturers in the United Kingdom only produce a limited number of EPDs, so it was not possible to get EPDs for all the project's materials. The EPDs used in this study were sourced from UK manufacturers to ensure that the geographical and regional conditions of production, procedures, construction practices, energy consumption, and building design characteristics were met. In this study, EPDs for Rock Wool, Plasterboard, Metal Roof panels, Precast concrete, T-Beam concrete, I-joist, Softwood, Brick, aerated concrete block and Koolthermal Kingspan were accessible. These materials accounted for 78 percent of the total weight.

The ICE database was the second database explored. The ICE databases, created by Hammond and Jones in 2008, are the second-most current and commonly used databases in the UK. This database contains the carbon factors from A1 to A3 for over 500 of the most prevalent construction materials. However, it does not consider the operational phase or end-of-life.

The third database was derived from the UK Department for Business, Energy, and Industrial Strategy (BEIS). In this database, the ECFs are divided into forty categories, while construction materials are split into twelve categories. Aggregates, Asbestos, Asphalt, Bricks, Concrete, Insulation, Metals, Soils, Mineral oil, Plasterboard, Tires, and Wood are the materials used in building. Table 4 shows the assigned ICE and BEIS embodied carbon databases and their sources.

Table 4. Assigned embodied carbon factor for each residential building material.

Material	**ECF ICE Database ($kgCO_2e/kg$)**	**Source**	**ECF BEIS Database ($kgCO_2e/kg$)**	**Source**
Chipboard	0.4	ICE-Timber, Chipboard	0.312	Wood
Concrete Block	0.0931	ICE-concrete block	0.131	Concrete
Concrete Screed	0.163	ICE-Mortar 1:4	0.131	Concrete
Rock Wool	1.12	ICE-Rockwool	1.861	Insulation
Plasterboard	0.39	ICE-Plasterboard	0.120	Plasterboard
Polyurethane	4.26	ICE-Polyurethane	1.861	Insulation
Metal Roof Panel	3.06	ICE-Steel, organic coated sheet	4.018	Metals
Precast Concrete	0.1591	ICE-concreteRC40/50	0.131	Concrete
T-Beam Concrete	0.1939	ICE-Precast concrete beam and column	0.131	Concrete
Universal Beam	1.55	ICE-steel, section	4.018	Metals
I Joist	0.4833	ICE-timber, wood I-Beam	0.312	Wood
Softwood	0.26	ICE-timber, softwood	0.312	Wood
Brick	0.21	ICE-General common brick	0.241	Brick
Aerated concrete block	1.59	ICE-AAC concrete block	0.131	Concrete
Koolthermal Kingspan	1.86	ICE-General Insulation	1.861	Insulation
Glass	1.6256	ICE-Double glazed unit	1.402	Glass
PVC	3.1	ICE-General PVC	3.413	Plastics:PVC

In order to see the databases' differences, two approaches were taken in the assignment of appropriate ECFs. The first approach was to contrast the differences between the ICE and Enhanced databases. Enhanced database is the combination of EPDs, and the ICE database and the ICE database is used whenever EPDs are not available. The second approach was to compare the BEIS database with the Enhanced database, to see how reliable the BEIS database can be.

2.5.2. Embodied Carbon Database for End-of-Life Stage

Module C had to account for all emissions resulting from disassembly, deconstruction, and demolition, as well as the transport, processing, and disposal of materials at the end of the project's life. There are not many databases available to calculate embodied carbon at the end of life, and the BEIS was not applicable as this database only covers emissions from the collection of materials and delivery to the point of treatment or disposal. They do not cover the environmental impact of different waste management options [32]. The RICS professional statement, "whole life carbon assessment for the built environment", aims to provide guidance on the interpretation and practical implementation of the EN 15978 methodology [6]. It provides a guideline to calculate embodied carbon for the whole life cycle of emissions, including the end of life. This research calculated the embodied carbon of the case study using RICS guidance. In addition, the London Energy Transformation Initiative (LETI) represents, according to current building regulations, an approximate distribution of A1–A3 and C1–C4 for a residential building is 21% and 1% of the whole emissions from A1–C4 [14]. In this research, the results from the end-of-life scenarios of the LETI and the RICS guidelines were compared.

3. Results and Discussion

The results presented in Table 5 shows the significant effect that the choice of an A1–A3 ECF database can have on an LCA. EPDs are the most reliable database to calculate embodied carbon emissions. However, there were a limited number of EPDs available as it is not mandatory for manufacturers to produce them. In this research, the EPDs related to a few materials, including Rock Wool, Plasterboard, Metal Roof panels, Precast concrete, T-Beam concrete, I-joist, Softwood, Brick, aerated concrete block, and Koolthermal Kingspan, which were applied (Figure 5). The Enhanced database, which is a combination of the ICE database and EPDs, is the most reliable database in this research. The comparison of the Enhanced database to the ICE database revealed that using the ICE database overestimates the calculated embodied carbon for all the materials. The biggest significant difference was shown in Softwood, where the ICE database overestimated embodied carbon by 100%. For Plasterboard, Rock Wool and Brick, the ICE database overestimates the embodied carbon calculated by 62%, 50% and 45%, respectively. In addition, Precast Concrete, T-Beam Concrete, I joist, and Metal Roof panels showed differences between 10% and 25%. The difference between two databases for Koolthermal Kingspan and Aerated Concrete was negligible and less than 1% (Table 5).

Table 5. The calculated embodied carbon using ICE and Enhanced value databases for material.

Material	Weight (kg)	ICE Database ($kgCO_2e$)	Enhanced Value ($kgCO_2e$)
Chipboard	3481.60	1392.639	1392.639
Concrete Block	24,676.84	2297.413	2297.413
Concrete Screed	11,704.12	2713.478	2713.478
Rock Wool	1325.34	1484.381	990
Plasterboard	7137.54	2783.639	1722.8
Polyurethane	856.67	3649.407	3649.407
Metal Roof Panel	14,588.18	44,639.826	39,645.16
Precast Concrete	70,417.20	15,863.383	12,641.16
T-Beam Concrete	5074.50	1160.72	1014.96
Universal Beam	392.64	608.594	608.594
I Joist	366.80	177.275	146.72
Softwood	5167.31	1343.499	671.31
Brick	30,093.78	6319.694	4346.176
Aerated concrete block	17,803.2	4987.83	4984.9
Koolthermal Kingspan	14.95	27.798	27.72
Glass	768.80	1249.761	1249.761
PVC	810.00	2511	2511

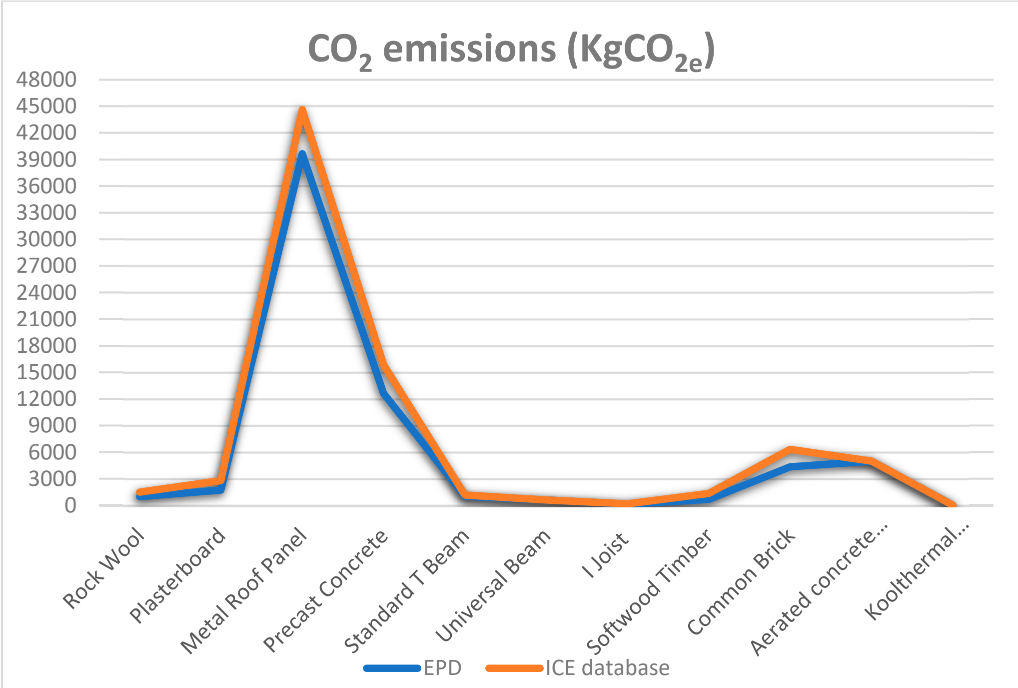


Figure 5. Comparison of EPDs and ICE sources Embodied Carbon of Building Materials.

According to Table 6, for Plasterboard, Polyurethane, and Aerated concrete block, BEIS database accounted for almost half the amount of embodied carbon compared to the Enhanced database. In addition, the BEIS database underestimated the embodied carbon by 22% for both Chipboard and I joist. However, in total, the BEIS database recorded a higher proportion of embodied carbon compared to the Enhanced database by 31%. As can be seen in Table 6, the most surprising aspect of the data is that for Universal Beams, the BEIS database overestimated the embodied carbon by 159% compared to Enhanced database, representing a difference of 970 $kgCO_2e$ between these two databases.

Table 6. The calculated embodied carbon using ICE and BEIS databases for each material.

Material	CO_2 Emissions Enhanced Database ($kgCO_2e$)	CO_2 Emissions BEIS Database ($kgCO_2e$)
Chipboard	1392.639	1088.382
Concrete Block	2297.413	3251.173
Concrete Screed	2713.478	3255.85
Rock Wool	990	2467.452
Plasterboard	1723	856.861
Polyurethane	3649.407	1594.902
Metal Roof Panel	39,645.16	58,615.3
Precast Concrete	12,641.16	19,168.75
T-Beam Concrete	1012.961	1154.73
Universal Beam	608.594	1577.634
I Joist	146.72	114.666
Softwood	671.31	1615.351
Brick	4346.175	7275.172
Aerated concrete block	4984.9	2345.571
Koolthermal Kingspan-Insulation	27.72	27.824
Glass	1249.761	1078.45
PVC	2511	2764.595

In addition, there are significant differences between these two databases for Rock Wool and Softwood. According to the BEIS database, Rock Wool and Softwood were overestimated by 150%, and 141%, respectively, compared to the Enhanced database.

In addition, it is apparent that there were differences between the two datasets for concrete. For most concrete materials, the BEIS database overestimated the calculated embodied carbon by 15–50% compared to the Enhanced database. Since concrete materials account for almost 66% of the total quantity of the building, this difference is immense. Table 6 shows that this caused an 8190 $kgCO_2e$ difference between the two databases. Furthermore, the BEIS database overstated the embodied carbon by 47 and 67 percent for Metal Roof Panels and Brick, respectively.

For the rest of the materials, there was not a big difference between the two databases, with T-Beam Concrete, Screed, and PVC in the BEIS database overestimating the embodied carbon by 10–20% and Glass underestimating the embodied carbon by 14%. For materials such as Koolthermal Kingspan, the difference between using different databases was not as significant as the choice within one database, with both emitting around 28 $kgCO_2e$.

Table 7 shows an overview of the calculated end-of-life embodied carbon for the different materials in the residential building using LETI and RICS guidelines. According to current building regulations for a typical residential building, only 1% of WLC belongs to End-of-Life carbon [14].

Table 7. The calculated embodied carbon using RICS and LETI guidelines for each material.

Material	RICS (C1–C4) ($kgCO_2e$)	LETI ($kgCO_2e$)
Chipboard	72.797	66.316
Concrete Block	515.972	109.401
Concrete Screed	235.502	129.213
Rock Wool	27.712	47.143
Plasterboard	149.240	82.048
Polyurethane	17.912	173.781
Metal Roof Panel	305.027	1887.865
Precast Concrete	1419.147	601.960
T-Beam Concrete	95.701	48.236
Universal Beam	8.210	22.381
I Joist	7.670	6.987
Softwood	108.044	31.967
Brick	629.236	206.961
Aerated concrete block	372.250	237.376
Koolthermal Kingspan	1.422	1.320
Glass	16.075	59.512
PVC	16.936	119.571

Comparing these two databases revealed that there are significant differences between them for individual materials. In more detail, for polyurethane PUR, the LETI guideline showed that it was overestimated by 870% compared to the RICS default value. Additionally, the embodied carbon for standard PVC and metal roof panels was overestimated by 606% and 519%, respectively, in the LETI guidance compared to the RICS default value.

For Universal Beam, and glass, the two databases showed a significant difference, with LETI being 253% and 270% more than the RICS. Given the differences in results between the two databases, which may be attributable to the limited availability of carbon factors for end-of-life analysis, neither database appeared to produce an acceptable result. As the choice of data source for carbon variables can significantly impact the results' reliability, LCA evaluators should proceed with caution.

Table 8 shows the total embodied carbon of the building from (A1–A5) to (C1–C4). Total embodied carbon emissions using Enhanced database and RICS guideline was 95.9 $tonCO_2e$. Figure 6 shows hot zones in terms of embodied carbon. In other words, it will determine which materials have the highest embodied carbon and have the potential to mitigate the total embodied carbon. The highest contributor to the embodied carbon was Metal materials with 40.56 tonCO_2e. Since 42% of all emissions come from virgin metal materials, using recycled metals reduce embodied carbon by 18.57-tonCO_2e. In addition, since Concrete materials with 31.03 tCO_2e are the second highest contributor and have almost 66% of the total quantity of the building, using less carbon-intensive materials can cut the total embodied carbon. For instance, replacing an Autoclaved aerated concrete block (AAC) containing 61% aggregate, 14% cement, 8% quicklime, and 3% water with another concrete block containing 84.7% aggregate, 8% cement, 5% PFA, and 2.3% water can cut embodied carbon by 2.07-tonCO_2e. Moreover, given that the Polyvinyl chloride (PVC) used in window frames is not recyclable, the use of recyclable aluminium in window frames can reduce total embodied carbon by 2.3-tonCO_2e.

Table 8. The total embodied carbon of the residential building.

Material	A1–A5 (kgCO_2e)	C1–C4 (kgCO_2e)	Total (kgCO_2e)
Timber	2607.85	188.51	2796.36
Concrete	28,767.09	2266.32	31,033.41
Insulation	5213.66	47.04	5260.70
Plasterboard	2863.38	149.24	3012.62
Metal	40,253.36	313.233	40,566.59
Brick	8191	1001.49	9192.49
Glass	1320.59	16.07	1336.66
PVC	2648.48	16.94	2665.42

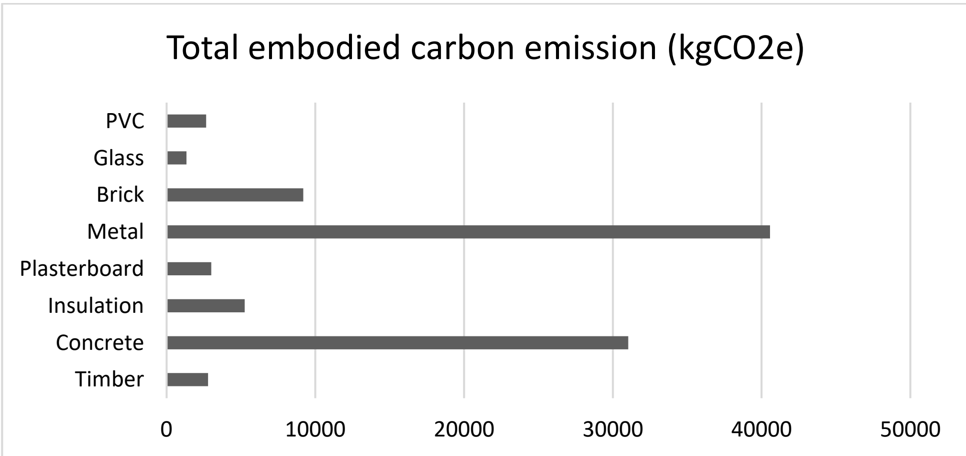


Figure 6. Total embodied carbon of the building.

Table 9 and Figure 7 presents the final results related to the operational carbon stage. As aforementioned, the building's floor area is 145.86 m^2. Therefore, total operational carbon emissions in a 50-year life span would be 169.345 tonCO_2, which accounts for nearly 67 percent of the total carbon footprint of the building. The average operational carbon emission of residential buildings in the UK is 26 kgCO_2/m^2/year [33] which is in line with the result of this simulation. The reason for acceptable performance of this building in comparison to the average value would be using various insulations in the building's fabric and implementing double-glazed windows. As per Figure 7, DHW, heating, and lighting are responsible for most of the operational carbon emissions and energy consumption of the building during its lifetime. This result serves as a useful guide when looking for building components with the greatest potential for retrofitting and lowering emissions. In this regard, LED lights are replaced with halogens in the first step of refurbishment, resulting in a 9.4-ton reduction in CO_2 emissions. At the next step, two different sets of photovoltaic (PV) panels with the total power of 2.3 kW (group A) and 3.3 kW (group B) are modelled to be installed on the south facing side of the roof. The first group contains 7 panels of

325 W with the surface area of 1.68 m^2 each, and the latter group consists of 13 panels of 1 m^2 with 250 W capacity. Incorporating the PV panels in the model introduces the "displaced electricity" factor to the results, which demonstrates the panels' impact on the reduction of both energy consumption and CO_2 emissions. As a result of the refurbishment, by installing PV panels and changing the lights, the total CO_2 emissions would be reduced to 145.2 tonCO_2 with group A panels and 140.1 tonCO_2 with group B panels. As per current study's objectives, implementing group B panels combined with LED lightings are selected as the final retrofitting strategies to reduce the operational CO_2 emissions by 29.2 tonCO_2.

Table 9. Comparison of the baseline and retrofitted model's results in TAS in terms of energy consumption and CO_2 emission.

		Heating	**Auxiliary**	**Lighting**	**DHW**	**Equipment**	**Displaced Electricity**		**Total**	
Baseline	Energy consumption (kWh/m^2)	32.66	1.23	44.18	37.8	16.1	0		131.88	
model	CO_2 emission ($kgCO_2/m^2$)	6.86	0.17	6.09	7.93	2.17	0		23.22	
							Group A	Group B	Group A	Group B
Retrofitted model	Energy consumption (kWh/m^2)	48.63	1.23	6.63	37.8	16.1	−14.8	−17.69	95.48	92.61
with LED lights and PV panels	CO_2 emission ($kgCO_2/m^2$)	10.21	0.17	0.91	7.93	2.17	−1.88	−2.29	19.51	19.22

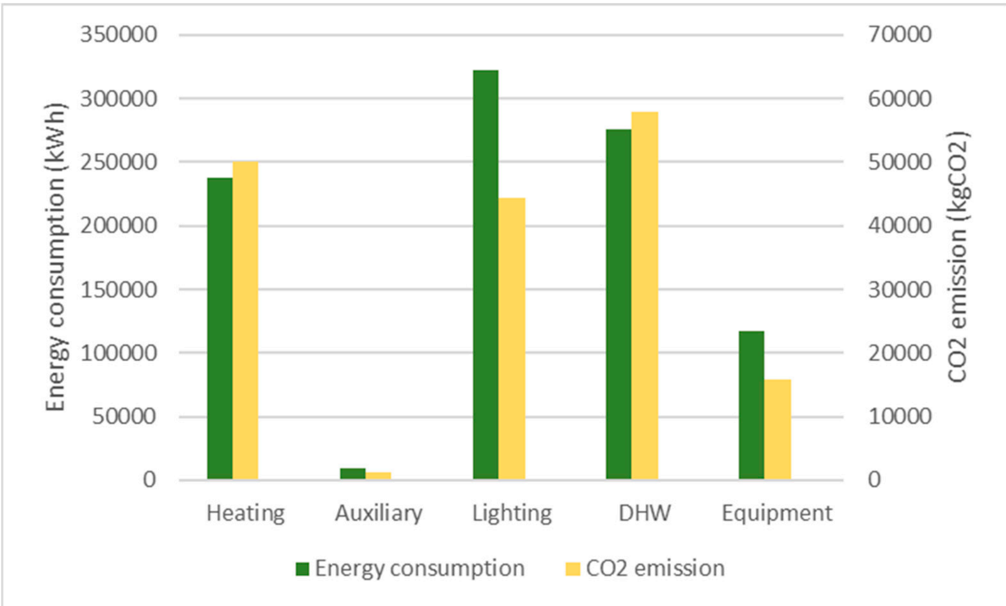


Figure 7. Comparison of the total energy consumption and operational carbon of the model.

By applying PV panels and LED lightings we should also consider their embodied carbon burden during manufacturing and End of life to see how much they effect embodied carbon (Table 10). Embodied carbon of LED lighting is calculated using EPD which is the most reliable database in the UK. Since EPD for PV panels is not available, this research used One Click LCA software to calculate the embodied carbon of PV panels. One Click LCA is a software tool for life cycle assessments of buildings.

Table 10. Embodied Carbon of LED Lighting and PV Panels.

Material	A1–A5 ($kgCO_2e$)	C1–C4 ($kgCO_2e$)	Total ($kgCO_2e$)	Source of Data
LED Lighting	972.18	45.06	1017.24	EPD
photovoltaic (PV) panels	3355.7	7.9	3363.6	One Click LCA

The results show that the embodied carbon produced during (A1–A5) and (C1–C4) for LED lighting and PV panels were 1017.24 and 3363.6 $kgCO_2e$, respectively. Comparing these figures with the amount of operational carbon reduction shows that, despite their embodied carbon burden, Whole Life Carbon will reduce significantly.

Taking all this into account, the WLC assessment (Figure 8) shows that 67% of total CO_2 emissions come from operational carbon, 31% from embodied carbon (A1–A5), and end of life is responsible for only 2% of emissions.

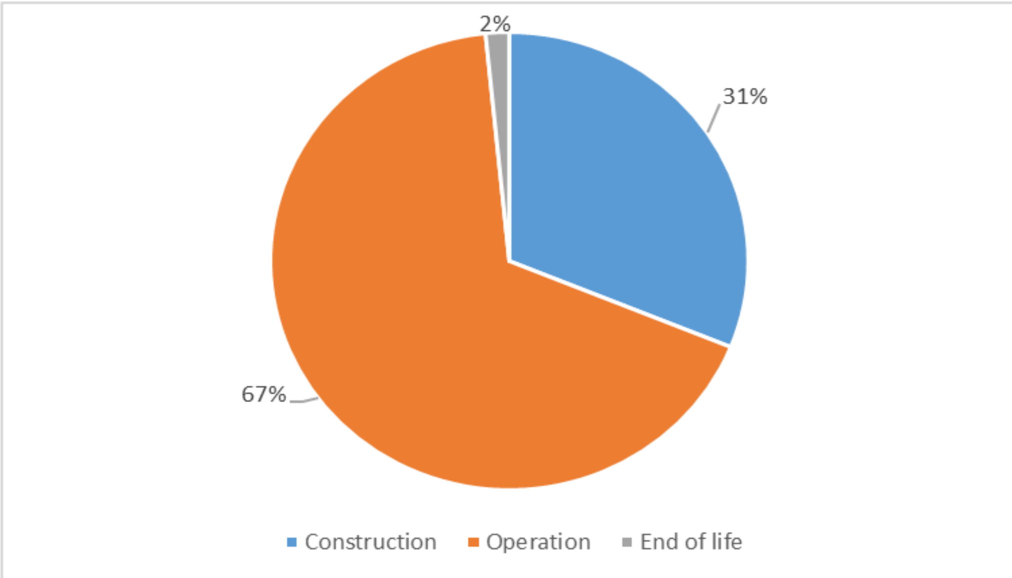


Figure 8. Whole Life Carbon (WLC) of the building.

4. Conclusions

Two principal objectives were investigated in the present project: 1—comparing various ECF data sources to evaluate the reliability of embodied carbon calculations, and 2—analysing the WLC emission (A1–A5, B6–B7, and C1–C4) of a typical UK residential building. Even though this study was conducted for UK residential buildings, the suggested methodology is applicable for analysing the environmental impact of other types of buildings around the globe.

In order to achieve the aims of this research, the case study was simulated in Revit and EDSL TAS to calculate the embodied and operational carbon emissions and conduct further comparisons.

This study showed that using the BEIS database overestimated embodied carbon calculations during A1–A3 stage, especially for materials such as steel, which can result in an overestimate of up to 159% compared to using the Enhanced database. If an LCA is performed to reduce the embodied carbon of a design, the overestimation that can arise from a database can result in a misinterpretation of the real situation. Thus, it is important to have the most reliable baseline for embodied carbon calculation. Moreover, using the Enhanced database is a favourable approach as it can make noticeable changes up to 100% embodied carbon reduction for individual materials compared to using ICE database and make it necessary for manufacturers to produce more EPDs. In addition, the end-of-life results showed that there is a significant difference between the embodied carbon calculated by RICS and LETI guidelines for each material which is due to the lack of a reliable database for ECFs for buildings' end-of-life phase. Therefore, it is beneficial to have a common UK methodology for the end-of-life of construction materials.

The Whole Life Carbon Assessment, using Revit and TAS tools for the model, found that operational carbon accounts for 67% of emissions, while embodied carbon accounts for 33% of emissions. The overall CO_2 emissions of this building have the potential to be reduced by 47.76 tonCO_2e when all stages are considered. Using recycled metals reduces embodied carbon by 18.57 tonnes of CO_2e; using concrete with a lower carbon intensity reduces embodied carbon by 2.07 tonnes of CO_2e; using recyclable aluminium instead of non-recyclable PVC saves 2.3 tonnes of CO_2e; and installing 3.3 kW PV panels, and using LED lights instead of the current lighting reduces CO_2 emissions by 24.82 tonCO_2.

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References

1. Pachauri, R.K.; Meyer, L. *Climate Change 2014*; The Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2015.
2. Asensio, O.I.; Delmas, M.A. The effectiveness of US energy efficiency building labels. *Nat. Energy* **2017**, *2*, 17033. [CrossRef]
3. Brian, D.; John, D.; Ksenia, P.; Peter, G. *Global Status Report 2016: Towards Zero-Emission Efficient and Resilient Buildings*; Global Alliance for Buildings and Construction: Paris, France, 2017.
4. Li, H.X.; Zhang, L.; Mah, D.; Yu, H. An integrated simulation and optimization approach for reducing CO_2 emissions from on-site construction process in cold regions. *Energy Build.* **2017**, *138*, 666–675. [CrossRef]
5. Zhang, L.; Li, R. Impacts of green certification programs on energy consumption and GHG emissions in buildings: A spatial regression approach. *Energy Build.* **2022**, *256*, 111677. [CrossRef]
6. Papakosta, A.; Sturgis, S. Whole life carbon assessment for the built environment. In *RICS Professional Standards and Guidance*; Royal Institution of Chartered Surveyors: London, UK, 2017.
7. Nadoushani, Z.S.M.; Akbarnezhad, A. Effects of structural system on the life cycle carbon footprint of buildings. *Energy Build.* **2015**, *102*, 337–346. [CrossRef]
8. Webster, M.; Arehart, J.; Ruthwik, C.; Aloisio, J.; Karineh, G.; Gryniuk, M.; Hogroian, J.; Jezeritz, C.; Johnson, L.; Kestner, D.; et al. *Achieving Net Zero Embodied Carbon in Structural Materials by 2050*; American Society of Civil Engineers: Reston, VA, USA, 2020.
9. Akbarnezhad, A.; Xiao, J. Estimation and Minimization of Embodied Carbon of Buildings: A Review. *Buildings* **2017**, *7*, 5. [CrossRef]
10. Adams, M.; Burrows, V.; Richardson, S. *Bringing Embodied Carbon Upfront*; World Green Building Council: London, UK, 2019.
11. Godefroy, J. *Buildings Mission 2030*; Construction Leadership Council: London, UK, 2019.
12. Salem, R.; Bahadori-Jahromi, A.; Mylona, A.; Godfrey, P.; Cook, D. Energy performance and cost analysis for the nZEB retrofit of a typical UK hotel. *J. Build. Eng.* **2020**, *31*, 101403. [CrossRef]
13. Salem, R.; Bahadori-Jahromi, A.; Mylona, A.; Godfrey, P.; Cook, D. Nearly-zero energy buildings: Retrofitting to meet the standard. *Constr. Eng.* **2020**. [CrossRef]
14. LETI Embodied Carbon Primer. *London Energy Transformation Initiative*; LETI: London, UK, 2020.
15. RIBA. *RIBA 2030 Climate Challenge*; Royal Institute of British Architects: London, UK, 2021.
16. Hart, J.; Amico, B.; Pomponi, F. Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *J. Ind. Ecol.* **2021**, *25*, 403–418. [CrossRef]
17. Zhu, W.; Feng, W.; Li, X.; Zhang, Z. Analysis of the embodied carbon dioxide in the building sector: A case of China. *J. Clean. Prod.* **2020**, *269*, 122438. [CrossRef]
18. Marsh, E.; Orr, J.; Ibell, T. Quantification of uncertainty in product stage embodied carbon calculations for buildings. *Energy Build.* **2021**, *251*, 111340. [CrossRef]
19. Cang, Y.; Luo, Z.; Yang, L.; Han, B. A new method for calculating the embodied carbon emissions from buildings in schematic design: Taking "building element" as basic unit. *Build. Environ.* **2020**, *185*, 107306. [CrossRef]

20. Moncaster, A.M.; Symons, K.E. A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy Build.* **2013**, *66*, 514. [CrossRef]
21. Hellweg, S.; Milà i Canals, L. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* **2014**, *344*, 1109–1113. [CrossRef] [PubMed]
22. Basbagill, J.; Flager, F.; Lepech, M.; Fischer, M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Build. Environ.* **2013**, *60*, 81–92. [CrossRef]
23. Lasvaux, S.; Achim, F.; Garat, P.; Peuportier, B.; Chevalier, J.; Habert, G. Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: What matters? *Ecol. Indic.* **2016**, *67*, 174. [CrossRef]
24. Buyle, M.; Braet, J.; Audenaert, A. Life cycle assessment in the construction sector: A review. *Renew. Sustain. Energy Rev.* **2013**, *26*, 379–388. [CrossRef]
25. Kumanayake, R.; Luo, H.; Paulusz, N. Assessment of material related embodied carbon of an office building in Sri Lanka. *Energy Build.* **2018**, *166*, 250–257. [CrossRef]
26. Gibbons, O.P.; Orr, J.J.; Archer-Jones, C.; Arnold, W.; Green, D. *How to Calculate Embodied Carbon*, 2nd ed.; The Institution of Structural Engineers: London, UK, 2022.
27. Mohebbi, G.; Bahadori-Jahromi, A.; Ferri, M.; Mylona, A. The Role of Embodied Carbon Databases in the Accuracy of Life Cycle Assessment (LCA) Calculations for the Embodied Carbon of Buildings. *Sustainability* **2021**, *13*, 7988. [CrossRef]
28. Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on LCA. *Constr. Build. Mater.* **2009**, *23*, 28–39. [CrossRef]
29. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
30. EDSL TAS. 2023. Available online: http://www.edsl.net/ (accessed on 19 January 2023).
31. CIBSE. CIBSE Weather Data Sets. Available online: http://www.cibse.org/knowledge/cibse-weather-data-sets (accessed on 19 January 2023).
32. Thistlethwaite, G.; Karagianni, E.; Collins, A.; MacCarthy, J.; Thomas, H.; Mullen, P.; Kelsall, A.; Bramwell, R.; Wong, J.; Quinn, P.; et al. *2022 Government Greenhouse Gas Conversion Factors for Company Reporting. Department for Business*; Enenrgy & Industrial Strategy: London, UK, 2022.
33. Committee on Climate Change (CCC, 2016). The Fifth Carbon Budget. Available online: https://www.theccc.org.uk/wpcontent/uploads/2016/07/5CB-Infographic-FINAL-.pdf (accessed on 19 January 2023).