Life cycle carbon assessment of a contemporary house in the UK built to zero carbon.

Venkatesh Kalidoss[1] and Haniyeh Mohammadpourkarbasi[2]

[1] School of Architecture, University of Liverpool, Liverpool L69 7ZN, UK or email venkateshkalidoss@gmail.com
[2] School of Architecture, University of Liverpool, Liverpool L69 7ZN, UK or email Haniyeh.MPK@liverpool.ac.uk

Abstract: This research presents for the first time the Life cycle assessment (LCA) of a contemporary zero energy terraced house built using MMC in the UK and compares the results with a traditional terraced house. The UK has set a net-zero target and the pace of achieving the target depends on how the contemporary houses are built. The current regulations by the government focus only on reducing the operational carbon of houses rather than looking from a life cycle perspective. This leads to an increase in embodied carbon emissions in newly built houses. There are 244000 houses built every year approximately in the UK and many are overlooked as zero-carbon houses which are only zero operational energy use, and the embodied emissions are unknown. Therefore, a real-life contemporary (zero energy) terraced house built using MMC in Liverpool, UK is chosen as a case study and LCA was conducted using one-click LCA software to calculate the lifetime carbon emission. Though operational carbon has achieved net zero by MMC, it is identified from this research that the embodied carbon of contemporary houses (62tCO2e) has increased by 2.3times the traditional house (26tCO2e). Further, Strategies and methods to reduce embodied carbon were discussed.

Further, the top five carbon contributing building elements of the case study were identified and different scenarios were proposed to understand the potential impact of choosing low carbon products and organic materials as alternatives.

Keywords: Net-zero target, low carbon, new house, Life cycle assessment (LCA), embodied carbon.

1. Introduction

The emission of carbon dioxide and other greenhouse gases emission is the leading cause of global warming. The construction and operation of buildings contribute to carbon emissions, increasing over the years. According to the Intergovernmental Panel on climate change (IPCC), the global temperature has already risen by 1°C from the preindustrial level roughly due to human activities, and it is expected to increase further by 1.5°C by 2040 if the current warming rate continues (IPCC, 2021, Rabani et al., 2021). Therefore, Countries such as Uruguay, Finland, Austria, and Iceland have set an earlier target by 2035 and 2040. Yet, the earliest target enforced in law is Sweden's 2045 target (Climate action, 2021).

The building sector's carbon emission is more adverse than the world average in the UK. 45% of the total UK carbon emission is from the built environment, with 27% from domestic buildings and 18% from non-domestic buildings (IGPP, 2021, U. K. Construction Online, 2018). The Climate Change Act in the UK was amended in 2019 and passed laws to achieve a net-zero target by 2050 (change and the environment, 2021, Gov.Uk, 2019). This means that the UK will have to bring all greenhouse gas emissions to net zero by 2050; incorporating carbon offset activities such as planting trees and using new technologies to capture and store any emissions (Gov.Uk, 2019).

Though several sources indicate the UK has reduced 38% carbon emission from 1990 levels, it is predominantly from the energy supply sector by generating more renewable energy (Broad et al., 2020). From the latest report by the Department of Business Energy and Industrial Strategy (BEIS), it is found that the carbon emissions in the residential sector have reduced only to 69.1 $MtCO_2e$ from 80.1 $MtCO_2e$ in the past 20 years, as shown in Figure 1 (BEIS, 2021a). This is equivalent to less than a 15% reduction in the past two decades from 1990 levels. Many analysts have suggested that given the difficulty of saving carbon in other sectors we are likely to need to come close to complete decarbonisation of our building stock by 2050 (Energy Saving, 2017).

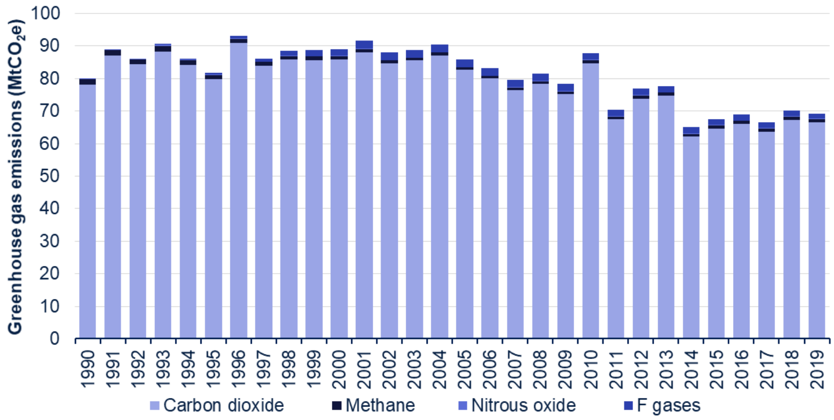

Figure 1. Residential carbon emissions from 1990-2019 (BEIS, 2021a).

The residential sector can be classified into existing and new buildings built each year. The Ministry of Housing, Communities and Local government (HCLG) indicates that 244,000 new homes were built in 2019, and 24.4 million homes will exist by 2050 (HCLG, 2022, Statista, 2022). In addition, the contemporary (new) houses built every year are designed to high-performance standards with renewables and promoted in the construction market as net-zero buildings, which are only net-zero operational, and the true lifetime carbon emission is unknown. Sturgis (2019) indicated the same in his book that the current use of the term 'zero carbon' refers to zero operational carbon emissions only, which is incorrect and misleading as they still have a carbon impact on the environment due to embodied emissions. Therefore, this research intends to determine the life cycle carbon emissions of contemporary (new) houses.

1.1. Life cycle carbon emission of buildings

Life cycle carbon emissions in the buildings can be classified as operational and embodied carbon (Sturgis, 2019). The whole life cycle carbon emission of buildings is the sum of embodied and operational carbon emitted over a building lifecycle (Sturgis, 2019).

1.2. Challenge – UK Current regulations and importance of the life cycle carbon assessment

In response to the increase in greenhouse gas (GHG) emissions, the UK government has implemented many regulations on operational carbon emissions and there are no regulations on embodied carbon emissions (Almeida et al., 2016, Sahagun and Moncaster, 2012). It is found that 84% of newly built properties have achieved low operational carbon emission with an EPC rating of A or B (Epc for, 2018). However, embodied carbon emission is completely neglected by regulations (Sanchez, 2021). The carbon trajectory by the London Energy Transformation Initiative (LETI) guidelines indicates that the embodied emissions would hold a significant share of carbon emissions from 2030 (LETI, 2021). Architecture 2030 iterates that the embodied carbon possesses more than 50% risk in the future (Building, 2018).

As there are no regulations to control embodied carbon emissions, organisations such as UK Green Building Council (UKGBC), and LETI are alerting and insisting on incorporating embodied carbon as part of regulations. The UK Green building council has released the first "whole life carbon net-zero road map" (UKGBC, 2021b). Climate emergency design guidelines by LETI has set a limiting factor of 500 kg CO_2e/m^2 (embodied carbon) and $35kWh/m^2/yr$ (operational energy use) for small and medium scale houses (LETI, 2021).

Sturgis (2019) indicated in his book that considering operational or embodied emissions in insolation can lead to poor decision making with unintended consequences. From the author's point of view, the potential method identified to calculate the true carbon emissions of houses is by life cycle assessment (LCA) method as it calculates operational and embodied carbon emissions collectively over a building lifetime (from construction till the demolition of the building). Yang et al. (2021) iterated the same that LCA is an effective method to analyse the lifetime carbon emissions of buildings.

1.3. Reasons for this research and contribution

This research contributes to a growing knowledge of the environmental impact of new residential construction in the UK by conducting LCA on a real-life contemporary net-zero energy house. The research would elaborate and present the carbon associated with all the building elements or materials used in the case study. It would aid developers, architects, and builders in understanding the carbon emissions of conventional building materials used in practice.

1.4. Research Aims, Objectives, methodology

The research aims to identify the life cycle carbon emissions of contemporary houses in the UK, which are overlooked as zero-energy houses and proposes possible measures to reduce embodied carbon emissions by:

- Identifying the share of embodied and operational carbon emission in life cycle carbon emission of a contemporary house in the UK.

- Comparing the contemporary house (21st century) LCA results with the traditional house (20th century) in the UK to identify the trend of carbon emission in the UK houses.

The life cycle carbon emissions of the house are calculated through a standardised methodology, LCA, using One-Click LCA software.

2. Literature review

2.1. History of LCA

The concept of life cycle analysis was developed over the years, especially in the 1970s and has been used in the building sector since 1990 (Passer et al., 2012, Cabeza et al., 2014). Life cycle analysis focuses on quantifying the materials, energy used and waste released back to the environment over its lifecycle (Cabeza et al., 2014, Sharma et al., 2011). Over the years, Life cycle analysis has been called life cycle assessment (GRDC, 2021). Life cycle assessment is a multi-step procedure for calculating the environmental impact of a product or service over its lifetime. It is often considered a "cradle to grave" approach to the calculation of environmental impact (Cabeza et al., 2014, Ciambrone, 2019, Joshi, 1999).

2.2. Standards and components of LCA study and Evolution of EPD

Standardisation is required to implement the sustainability concept into the construction industry (Passer et al., 2012). The International standardization organization (ISO) prepared the first standard for the construction sector. These standards are found in the LCA methodology in ISO 14040 (Passer et al., 2012). Based on ISO, the European Committee for standardization developed the framework "Sustainability of construction works – Assessment of Buildings" (EN15643, EN15804 and EN1597)(Passer et al., 2012, Passer et al., 2016).

Buildings are complex with several materials, and the appropriate LCI or LCIA data of materials is required to conduct a life cycle assessment (Takano et al., 2014). Building LCA is more sensitive to background data selection and it is a data-intensive method (Takano et al., 2014). There are several databases available for LCA such as Gabi, Ecoinvent, IBO, CFP and Synergia.

Takano et al. (2014) compared five different databases for the same design, and the results revealed that the LCA results are different according to the different databases. However, all five cases demonstrated that carbon emission of the concrete building is higher than timber building. This shows that the databases are broadly reliable for life cycle assessment (LCA) but not precise due to significant variation in data between databases. EPD's were introduced to overcome this variation in LCA results due to different databases (Bragança et al., 2007, Buyle et al., 2013).

Environment product declarations (EPD) are the third-party verified and standardized descriptions of the environmental impact of products during their lifetime. EPDs are developed based on life cycle assessment calculations according to the ISO 14040, ISO14044 and EN15804 standards in European countries (One click LCA, 2021).

2.3. Operational carbon VS Embodied carbon in LCA

The share of operational carbon (OC) and embodied carbon (EC) in buildings has been long debated in several articles. Ramesh et al. (2010) found in their study that embodied carbon (EC) contributes to only 10% while operational carbon (OC) accounts for 80-90% of life cycle carbon emissions in conventional residential buildings. Chastas et al. (2016) demonstrated EC emissions as 6-20%, while Kovacic et al. (2018) mentioned as 10-20% and Sartori and Hestnes (2007) identified as 2%-38% in their respective studies for conventional buildings. It should be noted that the low contribution of EC mentioned above in all the studies is for conventional buildings. It is contrary to low energy or zero energy buildings, as EC holds a significant share due to low OC emissions (Sanchez, 2021).

Increase in EC with the decrease in OC:

Hurst and O'Donovan (2019) developed a graph by analysing several case studies (see figure 2). Figure 2 represents the reduction in life cycle carbon with a reduction in OC until a saturation point of passive houses. Further reduction of operational energy to zero by self-sufficient buildings increases the embodied carbon significantly (due to high consumption of insulation and building services) and thus increases the life cycle carbon emissions ultimately (see figure 2). Further, the study mentioned that the EC emission accounts for 26-57% for a low energy building but could increase up to 74-100% for a self-sufficient building as in figure 2 (Hurst and O'Donovan, 2019).

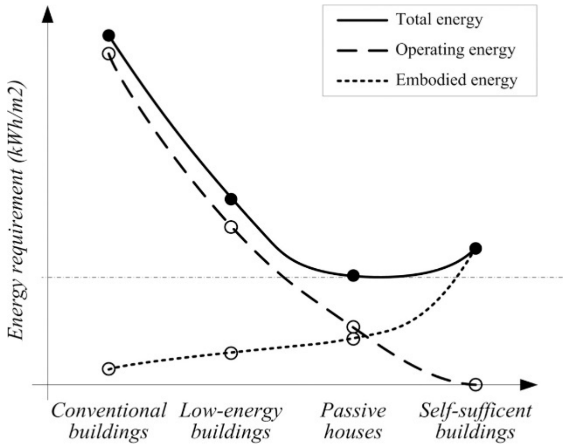

Figure 2. Relationship between embodied and operational energy (Hurst and O'Donovan, 2019)

Concluding, though there is variation among different studies, it is seen that EC increases with low or zero energy buildings contributing to more than 50% or near 100% when the building achieves net-zero operational carbon emission. Hence it is essential to investigate embodied carbon emissions through life cycle assessment (LCA) incorporating all stages of carbon emissions. Sahagun and Moncaster (2012) indicated in his studies that one should avoid shifting carbon emissions from one part (operational carbon) of the lifecycle to another (embodied carbon). Therefore, life cycle carbon emission is calculated using Life cycle Assessment (LCA) investigating operational and embodied carbon emissions collectively.

Several LCA studies have been conducted to calculate the environmental impact of the buildings. There are LCA studies of houses (Cuéllar-Franca et al., 2012, Monahan and Powell, 2011, Asif et al., 2007, Bribian et al., 2009), apartments (Blengini, 2009), universities (Lukman et al., 2009) and office buildings (Junnila and Horvath, 2003) in Europe.

In the UK housing sector, only five LCA case studies have been identified by the author. Monahan and Powell (Monahan and Powell, 2011) compared the embodied carbon of a contemporary timber frame construction in the UK with two traditional houses. However, this study only considered construction stage emissions and all LCA stages (cradle to grave) were not included in the study. Hammond and Jones (2008) conducted an LCA study on several houses in the UK but also considered only the construction stage emissions. Asif et al. (2007) calculated the embodied energy for a three-bedroom house in Scotland while Hacker et al. (2008) considered only the construction and use stage emissions.

As far as the author is aware, Cuéllar-Franca and Azapagic (2012) is the only study in the UK that conducted a whole life LCA on houses that includes modules from A1-C4 (cradle to grave). However, this LCA study was on three traditional dwellings, and there is no whole life LCA study found on contemporary houses in the UK. Indeed, no study in the UK also compares the lifetime carbon emissions of the contemporary house (new) with the traditional house (old). Therefore, the study's goal is to identify the whole life cycle carbon emissions (cradle to grave) of a contemporary house using LCA and compare the results with the traditional house (Cuéllar-Franca and Azapagic, 2012) to identify the trend of carbon emission in the UK houses.

3. Methodology

There are different types of contemporary houses concerning various construction techniques practised, and their carbon emissions vary drastically. Therefore, a quantitative analysis might result in an imprecise result. To calculate the house's carbon emissions through LCA, it is fundamental to identify the quantity of materials used in the building. Therefore, the methodology section of the research presents the material quantity calculation, followed by the parameters and boundaries of the LCA study.

3.1. Approach for data collection and case study selection

Offsite manufacture and modern method of construction (MMC) are energy-efficient construction techniques with low material wastage and a quicker time frame when compared with conventional in-situ construction. The UKGBC roadmap proposes increasing MMC investment (UKGBC, 2021a). Farmer (2016) recommends in his report that the UK government should promote the use of pre-manufactured solutions and incorporate them into policies.

In 2017, The UK government announced a £44bn in funding for five years to boost housing delivery and prioritise offsite construction (GCR, 2017). It is seen that MMC is growing rapidly, and many houses are expected to build using MMC in the coming years. Therefore, selecting a house built using offsite construction would be more optimal for this research to conduct LCA. The research case study, New Ferry House by Starship Group developers, incorporated complete offsite construction with all building elements made offsite except the foundation. In addition, the New Ferry house type (terraced) and it’s gross internal area are identical to the traditional house’s LCA study conducted by Cuéllar-Franca and Azapagic (2012). Therefore, to facilitate a better comparison between contemporary (this research) and traditional (Cuéllar-Franca and Azapagic, 2012), the New Ferry project by Starship Group developers is selected as the case study for this research.

3.2. Description of case study and parameters

The selected case study is located in a temperate climate zone in Wirral, near Liverpool, UK. It was designed by Shack Architecture and built by Starship Modular developers in 2021. The house elements were premade using panelised construction technique (offsite construction) in the Dee Side factory located 40 km away from the site (see figure 3). Further, the building elements were assembled on-site (see figure 4). The project comprises three zero energy terraced houses (see figures 5 and 6), with only one house considered for this research.

Figure 3. Offsite manufacture at Deeside factory (Starship Group, 2021)

Figure 4. MMC - assembly of building elements at site (Starship Group, 2021)

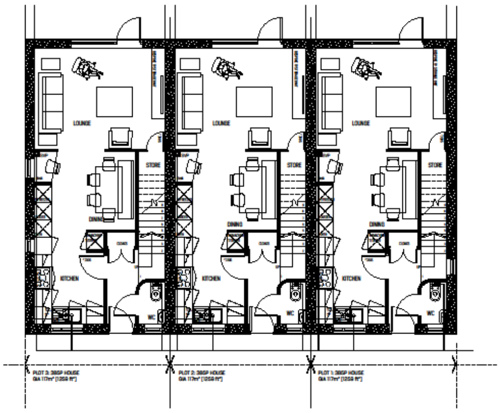

Figure 5. Ground floor plan (Starship group, 2021)

Figure 6. Completed zero energy house (Starship group, 2021)

A two-storied terraced house with a kitchen, dining and living rooms on the ground floor extending to a small backyard (see figure 5). The first floor comprises two bedrooms with a toilet and the second floor incorporates a master bedroom with an attached bathroom. Foundation is made of ready-mix concrete. The main structure is light gauge steel, which is the frame for attaching the building envelope (roof, floors, and exterior walls). The external walls comprise rock wool insulation, PIR insulation, timber studs, brick cladding and light gauge steel frame. The internal walls are made of timber stud framework, insulation in between and plasterboards on both sides. The roof is made primarily of the Light gauge steel frame, rock wool insulation, composite panel, and roof tiles. Floors comprise mainly PIR insulation, chipboard and carpets. Windows are low emissive, argon filled, triple glazed with UPVC frames. Doors are made of UPVC. The key parameters of the zero-energy terraced house are indicated in Table 1 below.

Table 1. Case study parameters:

Parameters	**Case study description**
Location/Climate	The United Kingdom/Temperate Climate
Building/Usage type	Residential, new built
Construction type	Offsite construction
Gross Floor Area	$138m^2$
Internal Floor Area	$114m^2$
Heating and Cooling system	8kW Air source heat pump
PV system	4.62kWp Monocrystalline photovoltaic system
MVHR	91% efficiency
Number of floors	3

The thermal standards of the building were identified from the SAP report collected from the builder and indicated in Table 2 below

Table 2. Thermal standards of the building

External Wall	0.13 W/m^2k	**Air permeability**	3.1m^3/m^2h @50Pa
Floor	0.13 W/m^2k	**Air change rate**	2.5ach
Roof	0.11 W/m^2k	**DER**	-0.8kg CO_2e/m^2
Openings	1.44 W/m^2k	**DFEE**	39 $KWh/m^2/yr$
Window	1.01 W/m^2k	**Door**	1.0 W/m^2k

3.3. Modelling and quantity calculation

From the architecture and detailed drawings provided by Starship Group developers, the house was modelled in Revit to get the quantities of all materials used in the construction of house. Every building element, such as foundation, external walls, party walls, internal walls, floor, roof, internal and external doors, windows were modelled (see figure 7). Refer to Table 3 for the building elements and components included in this research and their quantities. Components such as furniture, plumbing fixtures, electrical fixtures, kitchen interiors, sanitary fixtures, toilet tiles, lighting fixtures, switchboards, staircase, screws, bolts, and energy systems, were not modelled and not considered in the scope of LCA for this research. Outdoor elements such as parking and fence were not considered in this study due to limited timeframe.

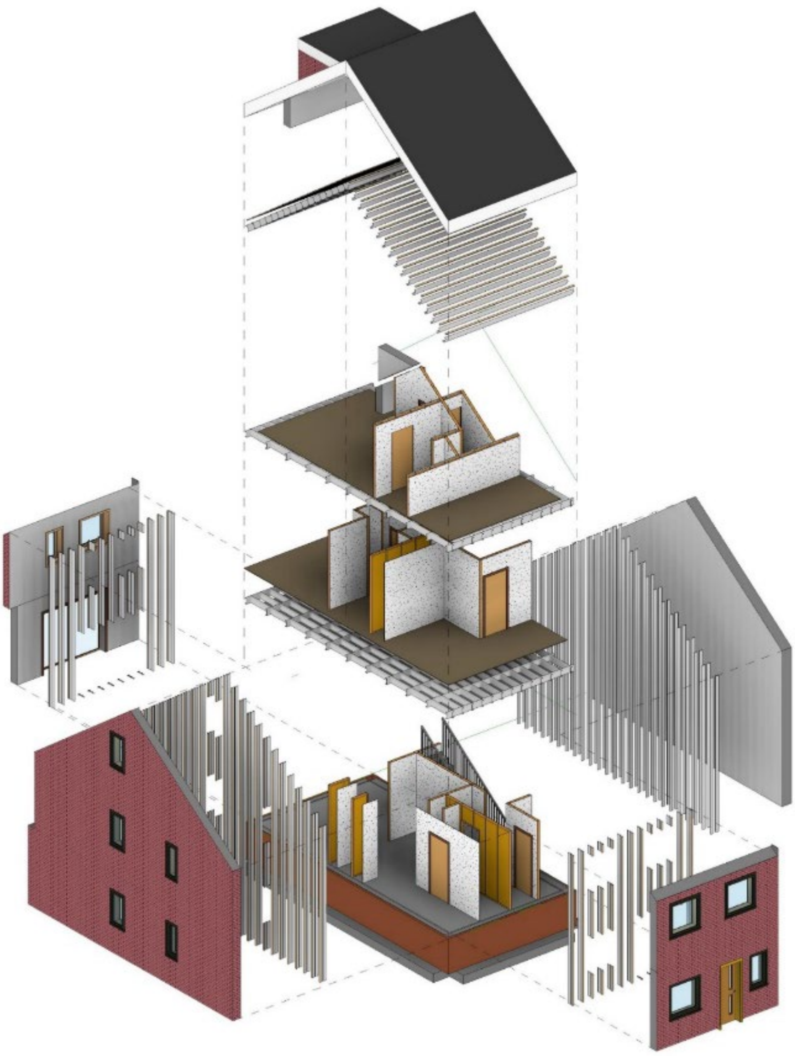

Figure 7. Exploded view of the building elements modelled in Revit

Table 3. Materials used for the construction of the case study

Element	Thickness (mm)	Components/materials	Surface (m^2)	Volume (m^3)
1. Foundation and substructure		Foundation and grade beam	-	16.65
		Concrete blocks	-	6.45
		Concrete T beam	-	4.30
		Hollow bricks	-	3.64
2.VERTICAL STRUCTURE				
2.1 External walls	15	Brick Slip and mortar cladding	113	1.70
	12.5	Cement Particle board	114	1.42
	120	PIR insulation	115	13.71
	12.5	Glassroc X sheathing board	115	1.44
	100	Rockwool Insulation	249	26.83
	15	Gyprock board (British gypsum)	498	7.46
	12.5	Cedral Cladding	36	0.22
	-	Self-adhesive breather membrane (Wraptite)	116	-
	0.15	Vapour Control layer	249	-
		Treated timber batten (50mmx25mm)		0.54
	50	Mineral wool insulation	5	4.99
	11	Orient Strand board	1.4	1.46
2.2 Load bearing structure	100x1.5	Light gauge steel frame (Column, beam, Slab)		0.6
2.3 Internal Walls	50	Isover Insulation	78	3.9
	12.5	Gyproc plaster board	206	2.58
	38	Timber studs (38mmx75mm)	27.6	1.07
3. HORIZONTAL STRUCTURE				
3.1 Floor and Ceiling	75	Floor Screed	43	3.23
	150	PUR insulation	43	6.46
	19	Chipboard Flooring	86	1.90
	9	Carpet	129	1.16
	0.15	Vapour Control Layer	43	-
	-	Damp-proof membrane	52	-
	12.5	Gypsum board (ceiling)	120	1.5
3.2 Roof	0.05	Metal Slate roof tile	73	
	120	Sandwich/composite Panel	73	8.71
	100	Rockwool Insulation	73	7.26
	12.5	Gyprock board	145	2.18
	-	Self-adhesive breather membrane (Wraptite)	145	-
4. OTHER				
4.1 Windows and Door	-	UPVC doors	23.09	-
	-	UPVC Triple glazed windows	10.12	-
			Total	131.3

3.4. Life cycle assessment (LCA) methodology and input parameters

Following the quantity calculation of building materials, the carbon emissions of those materials are calculated through life cycle assessment (LCA) using One-Click LCA software. It is a web-based software designed explicitly for LCA of construction products and incorporates

EPDs, completed together with upstream data from the established LCA database (Rabani et al., 2021). The One-Click LCA software is compliant with EN 15978 standards (Petrovic et al., 2019). In One-Click LCA, EPD is the primary source of information; LCI and LCIA data required for life cycle assessment (LCA) are included within the EPD (Shaun, 2021).

There are four different types of data available in OneClick LCA for the users: generic, manufacture, private, and plant data. Manufacture data includes EPDs provided by the manufacturer for the specific product, and it is used when the exact manufacturer and model of the product are known. Generic data EPD is the average emission of a product, which is country specific. It could be used when the exact manufacturer is unknown (OneClickLCA, 2018). Plant data presents the EPD of products based on specific factories where it is manufactured, and this option is used when products are directly sourced from nearby plants (Steven, 2021).

As this research's case study is already built and the builder provided information (manufacturer name and model) of most material used, the order of preference with data type choices while selecting the EPDs in OneClick LCA is as follows:

1. When the exact manufacturer and model of the building material are known, manufacturer data was chosen to get the precise results.
2. Though the manufacturer and model name are known, some manufacturers' EPDs were unavailable in the OneClick LCA database. In this scenario, materials' density and thermal conductivity were identified, and similar EPDs from other manufacturers were chosen.
3. Some building materials by the builder were purchased from dealers, and neither the model number nor the density of materials was known. In this scenario, generic EPDs representing UK average emissions were chosen.
4. When the UK generic EPD is unavailable, generic EPD from the closest European countries such as the Netherlands, Belgium, and France was selected.

3.5. LCA Boundaries

Table 4 represents the life cycle modules considered in the lifecycle assessment for the New Ferry case study. The following sections present the source of data for each stage of analysis.
Table 4. LCA boundaries of the case study

Product stage			Construction stage		Use stage							End of life stage				Beyond system boundary		
Raw material supply	Transport	Manufacturing	Transport to site	Construction and Installation	Use	Maintenance	Repair	Refurbishment	Replacement	Operational energy	Operational water	Deconstruction & Demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	D	D
✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
*✓ - modules included in LCA for this case study																		

Product stage (A1-A3):

The product stage covers cradle to gate process emission for building elements (components/materials) used for building construction. 26 different building materials were identified in this case study, excluding doors and windows. The product stage emissions of all these materials are calculated in the software. Table 5 represents the 26 different material and their respective EPDs chosen in OneClick LCA.

Construction stage (A4, A5):

A4: The software automatically includes transport distance and mode based on the parameters chosen in the software. The parameter determined is "UK-RICS". This incorporates transport distance (UK average) and transportation mode according to RICS guidelines. Refer to table 5 for transport distance considered for all 26 materials.

A5: As it is an offsite manufacturer incorporating MMC, only the energy consumption for excavation is included in A5 stage emissions. From the foundation drawings provided, it was found that a total of 44.2m^3 of land was excavated for this case study. "UK generic data for excavation work" representing 1.3kgCO_2e/m^2 removed is chosen in the software. This LCA study did not include energy consumed by small machinery such as impact wrench tools for bolting.

Use stage (B1-B7):

B1-B5: The B4 and B5 stage emissions are dependent on the service life of the materials used in the building (OneclickLca, 2021). 'Technical service life' was determined as it is the recommended option by the software when the service life of all materials is unknown. See Table 5.

B6: As the case study house was recently built in 2021 and unoccupied yet, neither the energy bills nor the post-occupancy evaluation (POE) is available to calculate the operational energy use. Therefore, the SAP report provided by the developer was used. The Dwelling fabric energy efficiency (DFEE) is 39 kWh/m^2/yr. This is equivalent to 4436kWh heating demand annually, summing to 221,800kWh operational energy use for 50 years. Please note that this calculation has ignored future warmer climates and possible heating demand reduction in the houses. The operational energy use is converted to operational carbon emissions using the UK electricity conversion factor of 0.233kgCO_2/kWh (BEIS, 2021b). From the calculation, it was found that the operational carbon emission of this case study is 51,710 kgCO_2e.

B7: As the house is unoccupied, assumptions of annual water usage have to be made from other literature studies. Cuéllar-Franca and Azapagic (2012) assumed occupancy of 2.3 people for an average UK household size with daily water consumption of 150L per person in their traditional house LCA study. This is equivalent to 6280m^3 of water usage over a 50year period. The same amount of water usage has been considered in this study. In the software, "UK generic tap water, clean" emissions representing 0.3kgCO_2e/m^3 of water consumed are chosen to calculate the operational carbon emissions of water usage.

Demolition stage (C1-C4):

In the software, the "Material locked (recommended)" option was chosen for the End-of-life calculation method. In this option, the C1-C4 end of life emissions are grouped, and the emissions are calculated automatically by the software (Shaun, 2022). Deconstruction/demolition emissions from RICS guidelines representing 3.4kg CO_2e/m^2 of GIA demolished are considered by default in the software for UK projects.

Building service life:

RICS recommends a service life of 60years for LCA study (RICS, 2017). However, many authors have considered 50 years as the service life for research purpose (Cuéllar-Franca and Azapagic, 2012, Bribian et al., 2009, Ortiz et al., 2009). To facilitate the comparison of results with other papers, 50 years is considered as the service life for this research.

Table 5. One-click LCA EPD, service life and transport distance of building materials

Components/Materials	Trans port (km)	Service life (years)	One-click LCA EPD chosen	Technical specification (Density, thermal resistance)
1. FOUNDATION AND SUBSTRUCTURE				
Foundation and grade beam	50	50	Ready-mix concrete	C32/40 – 10% recycled
Concrete blocks	300	50	Precast concrete block	1425.0 kg/m^3
Concrete T beam	300	50	Precast T beam	33.4 kg/m
Hollow bricks	300	50	Hollow bricks	127.0 kg/m^2
2.1 EXTERNAL WALLS				
Brick Slip and mortar cladding	300	50	Red brick average	1485kg/m^3
Cement Particle board				
PIR insulation	300	50	Fibre cement board	1300kg/m^3
Glassroc X sheathing board	300	50	PIR rigid insulation	33.08 kg/m^3,R=5.45m^{2}k/W
Rockwool Insulation	300	40	Gypsum sheathing	758kg/m^3
Gyprock board (British	300	50	Rockwool Insulation	50kg/m^3, R=2.89m^{2}k/W,
gypsum)	300	50	British Gypsum board	668kg/m^3
Cedral Cladding	300	50	Fibre cement slates	1950kg/m^3
Self-adhesive breather membrane (Wraptite)	1500	30	4layer vapour permeable underlay	0.173 kg/m^2
Vapour Control layer	1500	30	Plastic vapour control	933kg/m^3, (0.15mm thick)
Treated timber batten (50mmx25mm)	1500	50	Treated GLT	450kg/m^3
Mineral wool insulation	300	50	Glass wool	75kg/m^3, R=3.03m^{2}k/W
Orient Strand board	300	50	Orient strand board	610kg/m^3
2.2 LOAD BEARING STRUCTURE				
Light gauge steel frame (Column, beam, Slab)	10000	50	Structural hollow steel, Cold rolled	7850kg/m^3, 20% recycled content
2.3 INTERNAL WALLS				
Isover Insulation	300	50	Glass/mineral wool(iso	24kg/m^3, l=0.039w/mK
Gyproc plaster board	300	50	British Gypsum plaster	668kg/m^3
Timber studs (38mmx75mm)	1500	50	Planed timber, conifer	420kg/m^3
3.1 FLOOR, CEILING				
Floor Screed	50	50	Floor screed mortar	1500kg/m^3
PUR insulation	300	50	PIR insulation board	32kg/m^3, R=3.33m^{2}k/W
Chipboard Flooring	300	50	Chipboard, untreated	633kg/m^3
Carpet	1500	15	Carpet tiles	4.462kg/m^2
Vapor Control Layer	1500	30	Plastic vapor control	933kg/m^3, 0.15mm thk
Damp proof membrane	1500	30	Damp insulation	0.08kg/m^2
Gypsum board (ceiling)	300	50	Gypsum plasterboard	668kg/m^3 kg CO_2e
3.2 ROOF				
Metal Slate roof tile	10000	50	LW steel roofing tile	8.6kg/m^2, 0.6mm thk
Sandwich/composite Panel	1500	50	Sandwich panel	104.2kg/m^3, R=7.14m^{2}K/W
Rockwool Insulation	300	50	Rockwool insulation	50kg/m^3, R=2.89m^{2}k/W
Gyprock board	300	50	Gypsum plasterboard	668kg/m^3
Self-adhesive breather membrane (Wraptite)	1500	30	4layer vapor permeable underlay	0.173kg/m^2
4.1 WINDOWS AND DOOR				
UPVC doors	1500	40	PVC frame doors	79.5kg/m^2, R=1.6m^{2}k/W
UPVC Triple glazed windows	1500	40	Triple glazed PVC frame window	27.4kg/m^2

4. Results

The results section will discuss the whole life cycle carbon emissions of the New Ferry case study (contemporary house), and its operational and embodied carbon contribution.

4.1. Life cycle carbon: Classification by modules (stages)

For the New Ferry case study, it was found that the operational carbon contributes to 51t CO_2e (45%) in the B6 module, whereas the embodied carbon contributes to 62tCO_2e (55%) in A1-A3, B1-B5 and C1-C4 modules. figure 8 represents the operational, embodied carbon contribution of the New Ferry case study and its respective life cycle module.

The contemporary house's total life cycle carbon emission is 113tCO_2e over 50 years. Considering future decarbonization of grid energy, it is possible that operational carbon can become zero, and embodied carbon could contribute to 100% emissions.

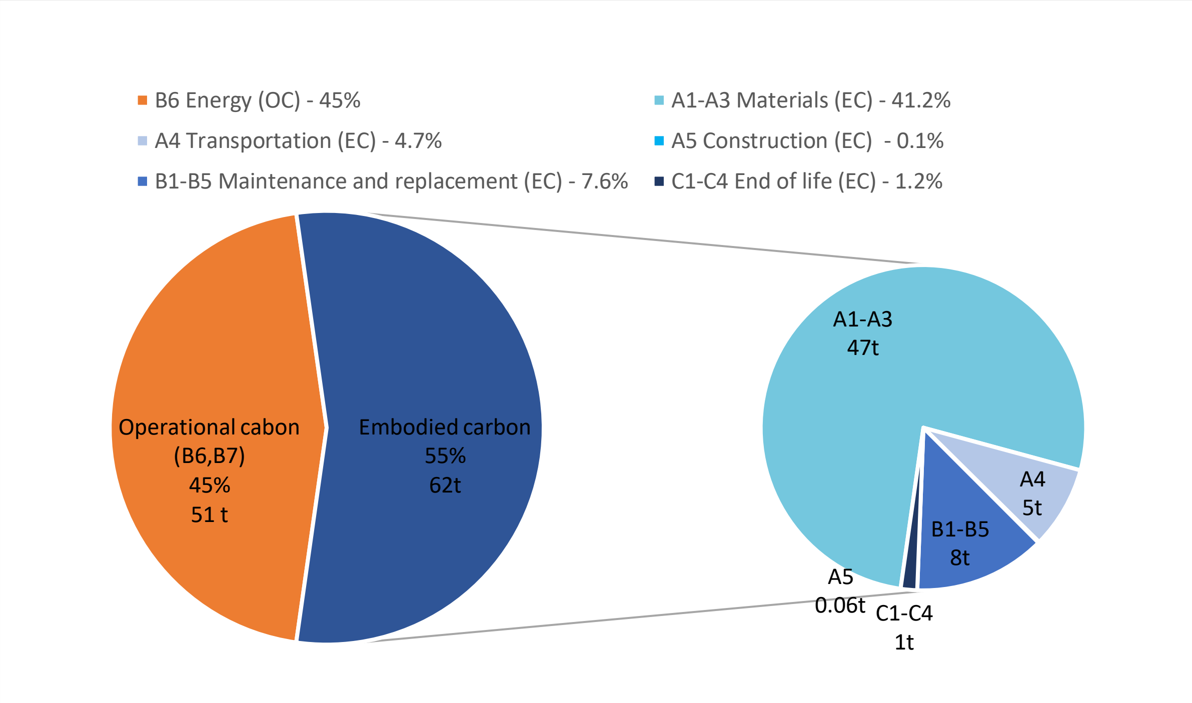

Figure 8. Carbon emissions of the case study (contemporary) over its lifetime; the share of embodied and operational carbon in different LCA modules [tonnesCO_2e]

4.2. Comparison with a traditional terraced house – embodied carbon doubled

The LCA results of the contemporary house in this study are compared with another traditional house LCA results to identify the drift in carbon emissions in the UK houses. The LCA study conducted by Cuéllar-Franca and Azapagic (2012) on traditional terraced house revealed that the operational and embodied carbon emissions are 282tCO_2e and 26tCO_2e, summing up to a total of 309tCO_2e during its lifetime. The operational carbon emissions of the contemporary house (this research) are 51tCO_2e, whereas the embodied emissions are 62tCO_2e, summing to a total of 113tCO_2e (see figure 9).

From the comparison, it is evident that the improved fabric of the contemporary houses built these days have aided in reducing total life cycle carbon emissions of houses by reducing the operational carbon significantly from 282tCO_2e to 51tCO_2e. However, the embodied carbon has increased by 2.3 times of the traditional house, from 26tCO_2e to 62tCO_2e. This is due to the high amount of steel frame, insulation, UPVC doors, and triple glazing in contemporary houses.

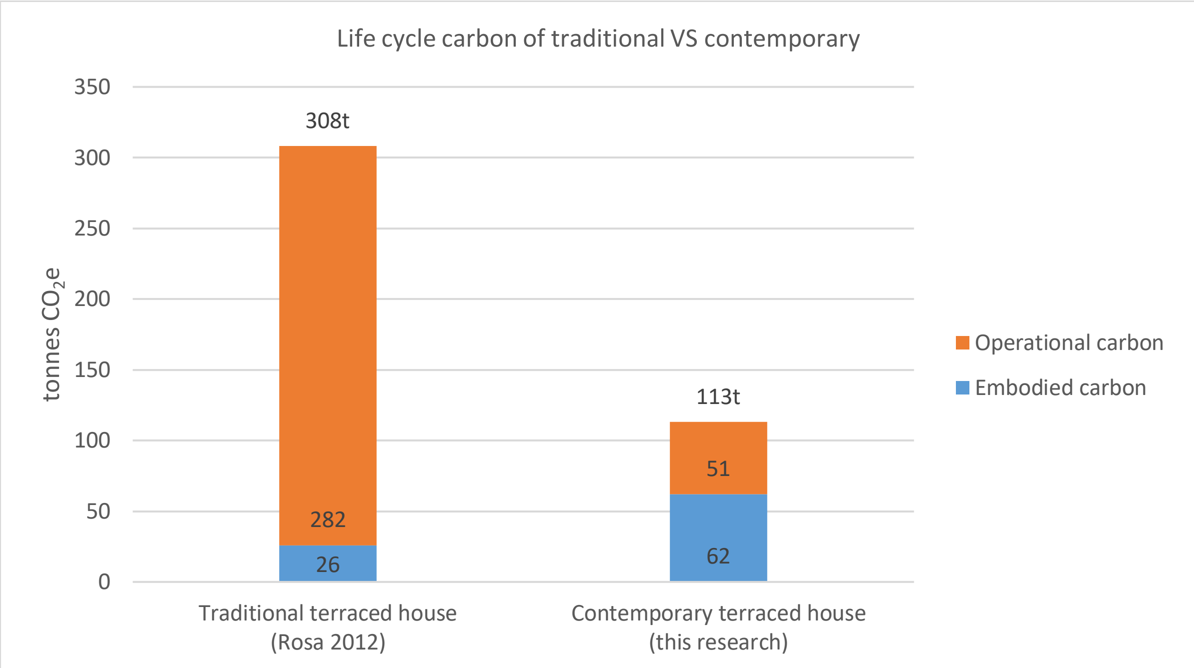

Figure 9. Lifetime carbon emission comparison of traditional house with contemporary house (this research); the share of embodied and operational carbon

4.3. Embodied carbon

The building accounts for 62tCO_2e over a period of 50 years. This is equivalent to 543kgCO_2e/m^2 of gross internal floor area (GIA). As seen in figure 10, the majority of embodied emissions are from the product stage (A1-A3) itself, accounting for 412kgCO_2e/m^2 (75%); followed by the B1-B5 use stage with 75kgCO_2e/m^2 of (14%); A4 transport stage with 47kgCO_2e/m^2 (9%); C1-C4 End of life stage with 11kgCO_2e/m^2 (2%) respectively.

The embodied carbon contribution of different building elements in tonnes and their percentage contribution is as follows:

- Horizontal structure (floor slabs, ceiling, roof) - 15.3tCO_2e (25%)
- External walls and façade – 15tCO_2e (24%)
- Load bearing structure (column, beam) – 13tCO_2e (22%)
- Foundation and substructure – 10tCO_2e (16%)
- Windows and doors – 7.3tCO_2e (12%)
- Internal walls – 0.9tCO_2e (1.5%)

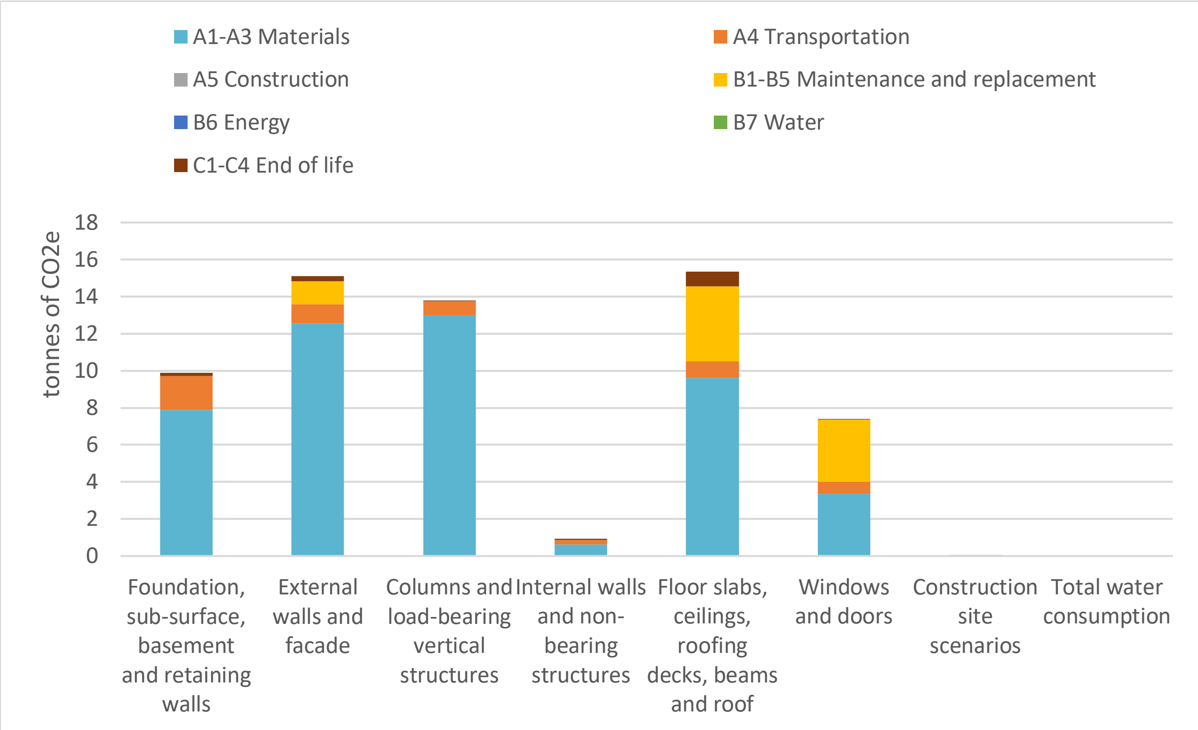

Figure 10. Embodied carbon emissions with respect to building elements in different life cycle stages

A1-A3:

The product stage emissions are highest in load-bearing structures (column, beam), followed by external walls (see figure 10). This is due to the use of light gauge steel for framing, which accounts for 14tCO_2e (22%) of total life cycle carbon emissions.

B1-B5:

Horizontal structure and openings alone account for more than 80% of maintenance replacement emissions (B1-B5) (see figure 10). This is due to the shorter service life of carpets (15years), and doors and windows (40 years). Thus, it is seen that building elements with shorter service life increases the embodied carbon emissions.

5. Discussion

Life cycle carbon emissions of a contemporary house in the UK have been assessed through LCA. The research now focuses on the main strategies and material alternatives to reduce embodied carbon emissions in buildings.

5.1. Major carbon contributors from this case study

The Embodied carbon emissions of building elements in this case study is 62 tonnes CO2e. Detailed analysis of materials resources used in the buildings revealed that steel frames, insulation, and openings themselves account for more than 60% of total embodied carbon emissions (see figure 11). Therefore, further research was conducted to find the alternatives for these materials with various scenarios. Emissions from these three resources and the individual building element are presented in figure 11.

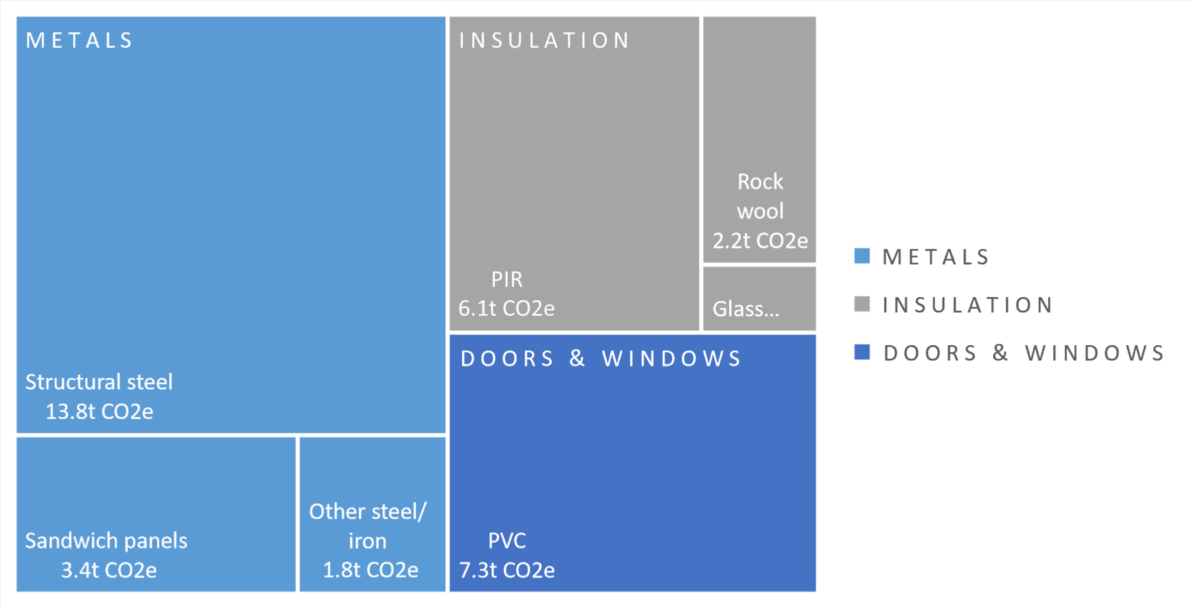

Figure 11. Major embodied carbon contributors (metals, insulation, openings) of the case study; building materials and respective carbon emissions [expressed in tonnes kgco2e]

5.2. Scenario 1 – Low carbon manufacturers or products alternative

The first scenario looks at alternative sourcing of the same materials from other low carbon manufacturers. This scenario is to insist on the benefits of sourcing the same materials from low carbon-emitting manufacturers or products as alternatives without any changes to the thickness or size of the existing materials. While selecting the alternatives, the same density and thermal resistivity were considered for steel, insulation. Refer to Table 7 for existing materials and the respective alternatives chosen in different scenarios.

The results show that the embodied carbon emissions can be reduced by 15tCO_2e from 62tCO_2e to 47tCO_2e when sourced from manufacturers and selecting products which has low embodied carbon (see figure 13).

5.3. Scenario 2 – Organic material alternative

The second scenario considers organic elements as an alternative that serves the same purpose. This scenario does affect the design of the existing house as the size and thickness of the building elements have to be altered to achieve the same strength or thermal standards. For example, cellulose insulation proposed in this scenario needs double the thickness of existing PIR insulation to achieve the same thermal resistivity. This scenario incorporates a timber structure replacing steel structure as shown in figure 12.

The results show that the embodied carbon emissions can be reduced by 24tCO_2e from 62tCO_2e to 38tCO_2e when organic materials are selected as alternatives (see figure 13).

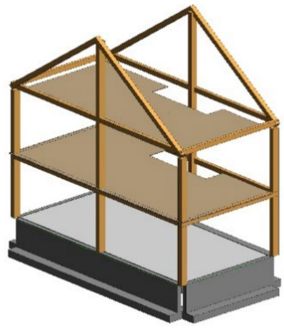

Figure 12. Proposed timber frame structure

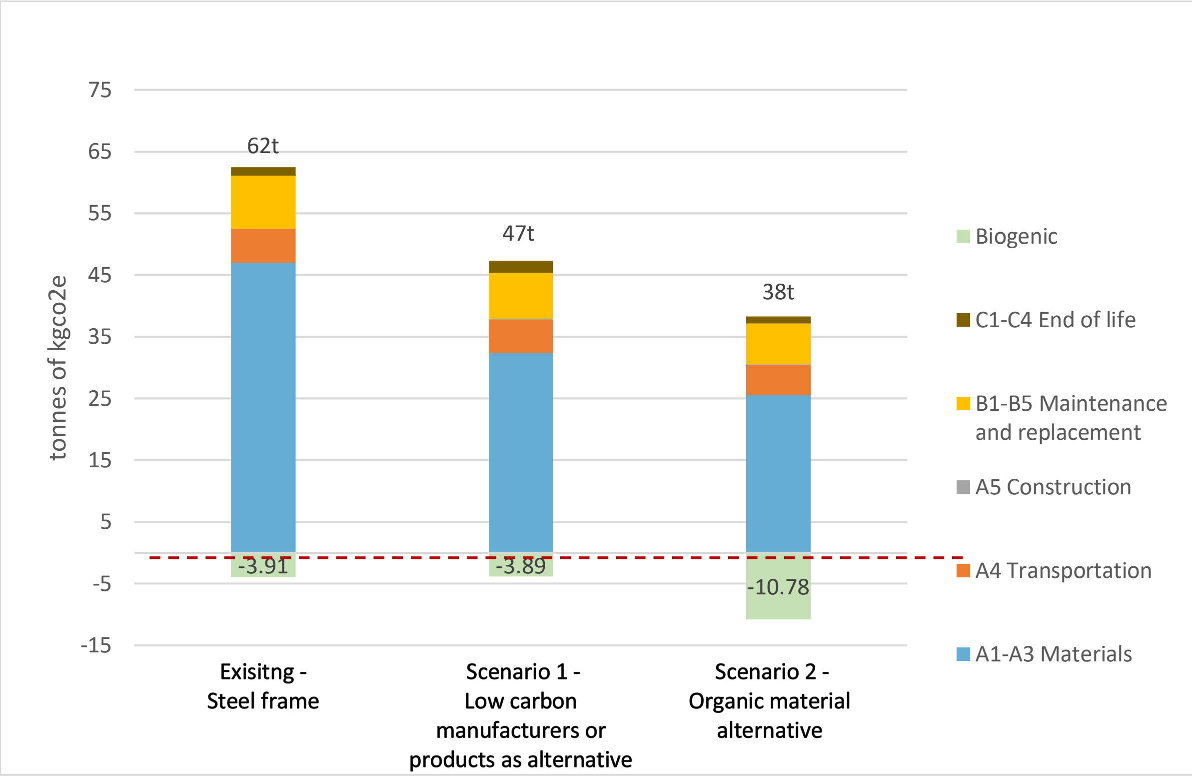

Figure 13. Existing case study embodied carbon and proposed scenarios embodied carbon emission

From the above scenarios, it is seen that the embodied carbon of contemporary houses can be reduced from 62tCO_2e to 47tCO_2e with a material selected from low carbon manufacturers or products (scenario 1) (see figure 13). In comparison, a more significant reduction in embodied carbon emission to 38tCO_2e is possible with organic materials (scenario 2) such as timber frames, cellulose insulation and wooden frames for openings. Therefore, for the practitioners (Architects, developers and builders), low carbon or organic products are crucial to reduce embodied carbon in their practice.

5.4. Biogenic carbon:

Biogenic carbon is the carbon stored in biologic materials such as plants or soil. The biogenic carbon in the existing building and scenario 1 are approximately 3.9tCO_2e, whereas the biogenic carbon in scenario 2 increased drastically to 10.7tCO_2e (see figure 13). This is due to the use of organic building elements which has high biogenic as indicated in table 7.

In scenario 2, when the biogenic carbon storage (10.7tCO_2e) is subtracted from the life cycle emissions, the house's carbon emissions reduce from 38tCO_2e to 28tCO_2e over its lifetime. Therefore, in addition to a selection of low carbon materials, it is essential that indicating building elements with high biogenic content would also aid in reducing lifetime carbon emissions significantly.

Table 7. Existing case study materials and proposed alternatives

Existing	Scenario 1 – Low carbon manufacturer or product alternative	Scenario 2 – Organic material alternative
Load bearing structure Cold rolled steel, generic, 20 % recycled content GWP: 21628.12 kg CO_2e / m^3	Structural steel profiles, generic, 90% recycled content GWP: 5808.05 kg CO_2e / m^3	Glued laminated timber (GLT) Duobalken® und Triobalken® GWP: 291.4 kg CO_2e / m^3 Biogenic: 932.0 kg CO_2e / m^3
Wall insulation PIR rigid insulation boards (KNAUF) GWP: 153.33 kg CO_2e / m^3 ***Floor insulation*** Floor: PIR insulation board (Quinn) GWP: 174.55 kg CO_2e / m^3	PIR insulation board (Xtratherm Limited) GWP: 137.42 kg CO_2e / m^3 PIR rigid insulation boards (KNAUF) GWP: 134.62 kg CO_2e / m^3	Blown loose-fill cellulose insulation R=7 m^2K/W (ECIA) GWP: 7.4 kg CO_2e / m^3 Biogenic: 17.5 kg CO_2e / m^2 Blown loose-fill cellulose insulation R=7 m^2K/W (ECIA) GWP: 7.4 kg CO_2e / m^3 Biogenic: 17.5 kg CO_2e / m^2
Doors Dark coloured PVC frame doors and windows, R = 1.6 m^2K/W (GIMM Menuiseries) GWP: 73.6kg CO_2e/m^2 ***Window*** Triple-glazed PVC frame window (Munster Joinery) GWP: 139kg CO_2e/m^2	White coloured, PVC frame doors and windows, R = 1.6 m^2K/W (GIMM Menuiseries) GWP: 54.0 kg CO_2e / m^2 Triple-glazed PVC frame window (Munster Joinery) GWP: 76.4 kg CO_2e / m^2	Wooden frame Doors GWP: 12.74 kg CO_2e / m^2 Biogenic: 23.83 kg CO_2e / m^2 Triple glazed Wooden frame windows GWP: 80.4 kg CO_2e / m^2 Biogenic: 28.7 kg CO_2e / m^2

6. Conclusion

Many practising firms and the UK government are promoting to delivery of 'zero operational energy house' to reduce carbon emissions from buildings. Therefore, this research conducted LCA on a real-life contemporary terraced house built using MMC and found that the 'zero operational energy house' emits 78tCO_2e of embodied carbon over its lifetime.

It was found that the contemporary house (New Ferry case study) contributes to 62tCO_2e (55%) embodied carbon and 51tCO_2e (45%) operational carbon summing up to a total of 113 tonnes of carbon emission over a lifetime of 50 years. Compared with a traditional house, the results revealed that the contemporary houses have significantly reduced operational carbon emissions from 390tCO_2e to 51tCO_2e . However, the UK's embodied carbon of contemporary (new built) houses has increased by 2.3 times the of traditional houses. And when the building services that aid in achieving net-zero operational carbon are included in LCA, the embodied carbon further increases, accounting for 100% life cycle emissions.

With the shift in increasing embodied carbon emissions of houses in the UK, the research investigated strategies and alternatives to reduce embodied carbon emissions. Further, this research looked at different scenarios for top five carbon contributing materials and revealed that embodied carbon emissions could be reduced by 20% with a selection from low carbon manufacturers/products and by 40% with organic materials.

Material recycling and future work:

Building material recycling is crucial in reducing end-of-life emissions. Many materials in this case study could be recycled with the recent innovations in recycling. Further studies could be carried out on material recycling of net zero operational houses to identify the percentage of possible recycling.

In this case study, the steel containing the highest embodied carbon is highly recyclable. However, the energy consumed to recycle steel is significantly higher compared to other building materials recycling processes. Therefore, it is an important factor to examine the recycling process in addition to the use of recycled materials in buildings.

Limitations of this study:

There are 26 different materials involved in this New Ferry case study. Due to the limited timeframe, the alternative scenarios proposed (section 5.3) considered low carbon alternatives only for the top five carbon contributing building elements. With the optimal low carbon material alternatives chosen for all the 26 materials of the building, it is clearly ambitious to achieve the life cycle zero energy house standards (LCZEB) or even a lifetime carbon-negative house.

7. Acknowledgement

Special thanks to Ms Yashika Narula for helping me with the data collection and supporting me throughout the research.

I would like to thank Mr Karl Ventre from Starship group developers for showing interest and providing information about the zero-energy house in Liverpool.

8. References

ALMEIDA, M. G. D., MATEUS, R., FERREIRA, M. A. P. S. & RODRIGUES, A. 2016. Relevance of embodied energy on building retrofit assessment. Universidade Federal do Espírito Santo (UFES).

ASIF, M., MUNEER, T. & KELLEY, R. 2007. Life cycle assessment: A case study of a dwelling home in Scotland. *Building and Environment,* 42**,** 1391-1394.

BEIS 2021a. 2019 UK Greenhouse Gas Emissions.

BEIS. 2021b. *Greenhouse gas reporting: conversion factors 2020* [Online]. Available: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020 [Accessed 23/12/2021].

BLENGINI, G. A. 2009. Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Building and Environment,* 44**,** 319-330.

BRAGANÇA, L., MATEUS, R. & KOUKKARI, H. 2007. Assessment of building sustainability.

BRIBIAN, I. Z., USON, A. A. & SCARPELLINI, S. 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment,* 44**,** 2510-2520.

BROAD, O., HAWKER, G. & DODDS, P. E. 2020. Decarbonising the UK residential sector: The dependence of national abatement on flexible and local views of the future. *Energy Policy,* 140**,** 111321.

BUILDING, G. 2018. The Urgency of Embodied Carbon and What You Can Do about It.

BUYLE, M., BRAET, J. & AUDENAERT, A. 2013. Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews,* 26**,** 379-388.

CABEZA, L. F., RINCÓN, L., VILARIÑO, V., PÉREZ, G. & CASTELL, A. 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews,* 29**,** 394-416.

CHANGE, G. R. I. O. C. & THE ENVIRONMENT. 2021. *What is the 2008 Climate Change Act?* [Online]. Available: https://www.lse.ac.uk/granthaminstitute/explainers/what-is-the-2008-climate-change-act/ [Accessed 23/12/2021].

CHASTAS, P., THEODOSIOU, T. & BIKAS, D. 2016. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment,* 105**,** 267-282.

CIAMBRONE, D. F. 2019. *Environmental Life Cycle Analysis*, CRC Press.

CLIMATE ACTION. 2021. *Sweden's goal to be carbon neutral by 2045 written into law* [Online]. @Climate_Action_. Available: https://www.climateaction.org/news/swedens-goal-to-be-carbon-neutral-by-2045-written-into-law [Accessed 23/12/2021].

CUÉLLAR-FRANCA, R. M. & AZAPAGIC, A. 2012. Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Building and Environment,* 54**,** 86-99.

CUÉLLAR-FRANCA, R. M., AZAPAGIC, A. J. B. & ENVIRONMENT 2012. Environmental impacts of the UK residential sector: Life cycle assessment of houses. 54**,** 86-99.

ENERGY SAVING, T. 2017. *The Clean Growth Plan: A "2050-ready" new-build homes policy*, Energy saving trust.

EPC FOR, Y. 2018. *Energy performance: why new builds are superior | EPC For You* [Online]. @epcforyou. Available: https://www.epcforyou.co.uk/2018/03/09/energy-performance-new-builds-superior/ [Accessed 23/12/2021].

FARMER, M. 2016. The farmer review of the UK construction labour model. *Construction Leadership Council*.

GCR. 2017. *UK government to promote offsite manufacture for construction - Global Construction Review* [Online]. Available: https://www.globalconstructionreview.com/uk-government-promote-offsite-manufacture-construc/ [Accessed 23/12/2021].

GOV.UK. 2019. *UK becomes first major economy to pass net zero emissions law* [Online]. Available: https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law [Accessed 23/12/2021].

GRDC. 2021. *Life cycle analysis and assessment* [Online]. Available: https://www.gdrc.org/uem/lca/life-cycle.html [Accessed 23/12/2021].

HACKER, J. N., DE SAULLES, T. P., MINSON, A. J. & HOLMES, M. J. 2008. Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. *Energy and Buildings,* 40**,** 375-384.

HAMMOND, G. P. & JONES, C. I. 2008. Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers-Energy,* 161**,** 87-98.

HCLG. 2022. *Live tables on dwelling stock (including vacants)* [Online]. Available: https://www.gov.uk/government/statistical-data-sets/live-tables-on-dwelling-stock-including-vacants [Accessed 04/01/2022].

HURST, L. J. & O'DONOVAN, T. S. 2019. A review of the limitations of life cycle energy analysis for the design of fabric first low-energy domestic retrofits. *Energy and Buildings,* 203**,** 109447.

IGPP. 2021. Sustainability - The greatest challenge of the construction industry | IGPP. Available from: https://igpp.org.uk/blog/article/sustainability-greatest-challenge-of-construction-industry.

IPCC. 2021. *FAQ Chapter 1* [Online]. Available: https://www.ipcc.ch/sr15/faq/faq-chapter-1/ [Accessed].

JOSHI, S. 1999. Product environmental life-cycle assessment using input-output techniques. *Journal of Industrial Ecology,* 3**,** 95-120.

JUNNILA, S. & HORVATH, A. 2003. Life-cycle environmental effects of an office building. *Journal of Infrastructure systems,* 9**,** 157-166.

KOVACIC, I., REISINGER, J. & HONIC, M. 2018. Life Cycle Assessment of embodied and operational energy for a passive housing block in Austria. *Renewable and Sustainable Energy Reviews,* 82**,** 1774-1786.

LETI. 2021. *Climate Emergency Design Guide | LETI* [Online]. Available: https://www.leti.london/cedg [Accessed 23/12/2021].

LUKMAN, R., TIWARY, A. & AZAPAGIC, A. 2009. Towards greening a university campus: The case of the University of Maribor, Slovenia. *Resources, Conservation and Recycling,* 53**,** 639-644.

MONAHAN, J. & POWELL, J. C. 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings,* 43**,** 179-188.

ONE CLICK LCA. 2021. *Environmental Product Declarations (EPDs)* [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/360015034920-Environmental-Product-Declarations-EPDs- [Accessed 23/12/2021].

ONECLICKLCA. 2018. *Using EPDs for Building LCA: a guide to Environmental Product Declarations in LCA* [Online]. @OneClickLCA. Available: https://www.oneclicklca.com/epds-for-building-lca/ [Accessed 23/12/2021].

ONECLICKLCA. 2021. *General Infrastructure LCA Guidance* [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/360014993380-General-Infrastructure-LCA-Guidance [Accessed 23/12/2021].

ORTIZ, O., BONNET, C., BRUNO, J. C. & CASTELLS, F. 2009. Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain. *Building and Environment,* 44**,** 584-594.

PASSER, A., KREINER, H. & MAYDL, P. 2012. Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings. *The International Journal of Life Cycle Assessment,* 17**,** 1116-1130.

PASSER, A., OUELLET-PLAMONDON, C., KENNEALLY, P., JOHN, V. & HABERT, G. 2016. The impact of future scenarios on building refurbishment strategies towards plus energy buildings. *Energy and Buildings,* 124**,** 153-163.

PETROVIC, B., MYHREN, J. A., ZHANG, X., WALLHAGEN, M. & ERIKSSON, O. 2019. Life cycle assessment of a wooden single-family house in Sweden. *Applied Energy,* 251**,** 113253.

RABANI, M., MADESSA, H. B., LJUNGSTRÖM, M., AAMODT, L., LØVVOLD, S. & NORD, N. 2021. Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian office building. *Building and Environment,* 204**,** 108159.

RAMESH, T., PRAKASH, R. & SHUKLA, K. K. 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings,* 42**,** 1592-1600.

RICS. 2017. *Whole Life Carbon Assessment for the Built Environment, 1st edition* [Online]. @RICSnews. Available: https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/ [Accessed 23/12/2021].

SAHAGUN, D. & MONCASTER, A. 2012. How much do we spend to save? Calculating the embodied carbon costs of retrofit.

SANCHEZ, M. 2021. *We can't ignore embodied carbon in buildings any longer, here's why... — PDP London* [Online]. Available: https://pdplondon.com/think-blog/embodied-carbon [Accessed 23/12/2021].

SARTORI, I. & HESTNES, A. G. 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings,* 39**,** 249-257.

SHARMA, A., SAXENA, A., SETHI, M., SHREE, V. & VARUN 2011. Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews,* 15**,** 871-875.

SHAUN. 2021. *The difference between LCA, LCI, LCIA and EPD data* [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/360015064259-The-difference-between-LCA-LCI-LCIA-and-EPD-data [Accessed 23/12/2021].

SHAUN. 2022. *Selecting Project Parameters* [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/360014827480-Selecting-Project-Parameters [Accessed 23/12/2021].

STATISTA. 2022. *Number of dwellings in England 2001-2020 | Statista* [Online]. Available: https://www.statista.com/statistics/232302/number-of-dwellings-in-england/ [Accessed 23/12/2021].

STEVEN. 2021. *How to use the building material filters* [Online]. Available: https://oneclicklca.zendesk.com/hc/en-us/articles/4408781692050-How-to-use-the-building-material-filters [Accessed 23/12/2021].

STURGIS, S. 2019. *Targeting zero. embodied and whole life carbon explained*, RIBA Publishing.

TAKANO, A., WINTER, S., HUGHES, M. & LINKOSALMI, L. 2014. Comparison of life cycle assessment databases: A case study on building assessment. *Building and Environment,* 79**,** 20-30.

U. K. CONSTRUCTION ONLINE. 2018-06-22 2018. How sustainable construction is key to government's Clean Growth Strategy. Available from: https://www.ukconstructionmedia.co.uk/features/sustainable-construction-key-governments-clean-growth-strategy/.

UKGBC. 2021a. *Net Zero Whole Life Carbon Roadmap Stakeholder Action Plans* [Online]. [Accessed 23/12/2021].

UKGBC. 2021b. *UKGBC Consults on Net Zero Whole Life Carbon Roadmap - UKGBC - UK Green Building Council* [Online]. @UKGBC. Available: https://www.ukgbc.org/news/ukgbc-consults-on-net-zero-whole-life-carbon-roadmap/ [Accessed 23/07/2021].

YANG, A. X., ZHANG, S. & WANG, K. 2021. Quantitative study of life cycle carbon emissions from 7 timber buildings in China. *The International Journal of Life Cycle Assessment,* 26.