A critical evaluation of the sustainability of building codes and policy when embodied carbon is considered for the construction of three-bedroom houses in the United Kingdom

Abstract

UK house building focuses on operational emissions from newly built houses, this paper aims to evaluate how policy can be changed to help reduce Scope 3 emissions within the house building sector. Greenhouse Gas (GHG) emissions result in global warming and are caused by three different Scopes (1, 2, and 3) across an organisation’s products, services, and activities. Scope 1 relates to direct GHG emissions from a business such as fuel used for transportation, release of refrigerants from Heating, Ventilation and Air Conditioning units and fuels used for heating. Scope 2 relates to indirect energy use such as electricity generated from power generation or steam generated offsite such as from a District Heating Network. Scope 3 are regarded as all indirect emissions from the organisations supply and value chain. Newly constructed houses release GHG emissions for Scopes 1, 2 and 3. In the UK, the Government is introducing standards to reduce operational emissions in the form of building codes and policy documents such as The Future Homes Standard. However, considerable emissions are generated from Scope 3, the cradle-to-gate Life Cycle Assessment phase. This research therefore investigates the significance of embodied carbon within structural frames of new houses and its policy implications. The structural frame of a three-bedroom house was used to calculate the embodied carbon of building materials. Results from One Click LCA, an automated lifecycle tool that can be used to calculate the Life Cycle Assessment GHG emissions, were compared to manually calculated values. The annual average number of new houses was calculated providing total embodied carbon for each material. Results demonstrate that houses generate significant Scope 3 emissions because of the significant amount of materials that are used to build the houses. Since these emissions relate to the materials of house, they are therefore related to Scope 3 as they are supply chain GHG emissions. Wooden frames had the lowest embodied carbon when compared to houses made with steel frames and bricks and mortar. Policies should address embodied carbon to reduce emissions from new build houses. Full Life Cycle Assessment analysis within building standards, replacing bricks and mortar with wooden or steel frames, and GHG intensity scoring are recommended. This would impact society by reducing the significant amount of embodied carbon emissions from the materials of newly built houses and be a significant contribution to staying within 1.5°C and preventing extreme climatic conditions.

**Keywords:** Embodied carbon; new build houses; three-bedroom homes; Scope 3 emissions; Cradle-to-Gate; Life Cycle Analysis; carbon emissions; sustainability; building codes; construction.

**1 Introduction**

The Intergovernmental Panel on Climate Change (IPCC) (2023) has confirmed that in the next 20 years, human activities that release carbon dioxide (CO2) will result in an increase in global temperatures, a change that will alter weather patterns, disrupt seasons, and affect both planetary boundaries and ecosystems (Zeng et. al, 2023). By 2050 greenhouse gas (GHG) emissions need to be reduced by 84%, with a 99% reduction of CO2 emissions based on 2019 (IPCC, 2023). This has precipitated worldwide action to reduce carbon emissions through policies such as the United Nations (UN) Paris Agreement.

In 2023 210,320 houses were built in the United Kingdom (UK) and between 2011-2017 there was an increase of 51.6% in new planning permits, demonstrating the increasing quantity of new homes constructed (Office for National Statistics, 2023; NHBC Foundation, 2018). The average number of bedrooms in a newly built house in the UK has consistently been three, and the average size of a three-bedroom house is 90.41 square metres (O’Neil, 2022; Statista Research Department, 2015). The UK is, however, currently facing a housing crisis because of policy and legislative processes for building new houses (Armstrong, 2016). Statistics estimate that 340,000 newly built houses are required each year of which 145,000 must be affordable (Wilson and Barton, 2023; Bramley, 2019). This creates issues for the sustainability of houses, as developers focus on the cost of materials and thereby their profits over their impacts on the environment. Figure 1 indicates that there is a decline in newly constructed houses with an average deficit of housing of 200,589 houses per year when compared to demand. This means that the UK needs to speed up the completion of houses to meet the demand, increasing the actual completions by 1.4 times (Wilson and Barton, 2023; Bramley, 2019; The Ministry of Housing, Communities and Local Governments, 2021).

Embodied carbon, as considered within the context of this study, is the atmospheric release of carbon caused by the production of construction materials. Its boundaries include manufacturing, transportation, construction and maintenance, and demolition (Amirtharaj and Mariappan, 2023). The Life Cycle Assessment is a carbon and environmental tool that helps to evaluate the environmental and carbon impacts of a product or service-led product from extraction of raw ingredients and materials, to transporting ingredients and materials to a factor for their manufacturing, to the use of the product which includes the energy consumption, and the end of life of the product when it becomes post-consumer waste. The A1-A3 phases of Life Cycle Assessment relate to the extraction, transportation, and manufacturing of the ingredients and materials. In this study only the A1-A3 carbon emissions are being considered. In the UK alone, buildings contribute 25% of the total yearly carbon emissions; embodied carbon accounts for an average of 50% (UK Parliament, 2022; Lützkendorf and Baloukts, 2022). However, as buildings become more energy efficient and grids decarbonise because of increasing renewables, embodied carbon will play a larger part in the UK’s carbon budget (LETI, 2020; Gov.uk, 2021a; IEA, 2022; Office of Energy Efficiency & Renewable Energy, 2022).

The Low Energy Transformation Initiative (LETI, 2020) found that even with energy-efficient buildings and buildings built to current building standards, the material emissions of the embodied carbon remain the same and so remain high. Buildings require bricks, mortar, cement, wood, steel, paint, and a variety of other materials (Figueiredo et. al, 2021). These can be considered as the most used materials for the construction of a new building in the UK (Heeren and Hellweg, 2019). However, the materials that require resource extraction from the ground contribute to significant carbon emissions due to the diesel used by mining machinery. Furthermore, limestone is a key ingredient of concrete, and it was found that to make crushed limestone ready for concrete mixing it generated 3.13 kg CO2 eq. per ton crushed rock product (Sizirici et. al, 2021). This suggests that alternative low embodied carbon building materials will not be extracted from the ground as limestone is also a lower carbon alternative to concrete therefore, since the emission for its use is high, other forms of natural materials will need to be considered. Whilst steel production starts with the mining of the raw materials, 70 to 80% of its carbon footprint is linked to the smelting process which converts iron ore to steel (Sizirici et. al, 2021). Therefore, mineral extraction and energy intensive processes are factors to be considered when attempting to reduce embodied carbon within construction materials. This will feed into global commitments to lower carbon emissions.

The UK has a Net Zero target of 2050 (HM Government, 2021). The UK has also signed commitments such as the Kyoto Protocol and Paris Agreement, which has led to nationally determined contributions. These do not cover Scope 3 emissions including embodied carbon and the UK’s strategy focuses on energy and transport emissions (UN, 2024; UNFCCC, 2024; Crown Copyright, 2022). However, this could be a result of the IPCC (2022) forecasts for emission abatement relying on reducing Scope 1 and 2 emissions by investments in renewable energy technologies because of reduced market price. That said, currently, despite such global commitments carbon emissions are projected to increase by 14% by 2030 (UN, 2024). Globally, embodied carbon accounts for 11% of energy related emissions which is currently not considered within the sustainability of building codes in the UK (HM Government, 2023).

For the UK, this exemplifies that policy and legislation promise to be the important drivers for changing the types of materials used in the construction of new houses. Furthermore, Malmqvist et al. (2018) found that with increasing energy efficiency, decarbonising electrical and energy grids, and onsite generation will mean that operational energy consumption is an ever-decreasing proportion of the entire Life Cycle Assessment. Consequently, the embodied carbon of the construction materials is becoming an increasing proportion of a new home’s carbon footprint. For example, Marinova et. al (2020) found that in a case study of a UK school, 30% of the embodied energy was due to fittings, fixtures, and furniture.

The Future Homes Standard is a building standard due to be published later in 2024 and comes into effect in 2025 which advocates for them to be operationally zero carbon once the grid has decarbonised (Future Homes Hub, 2022b). This is likely to mean that the houses that follow this standard burn no fuel for heating purposes, are well insulated to retain the heat, and instead will heat the house if needed through electric heating. Currently, the Standard does not consider embodied carbon. Reducing embodied carbon emissions can save energy which is vital to reduce global carbon emissions and support global commitments. Röck et. al (2020) found that 20-25% of life cycle emissions from houses were related to embodied carbon. Li and Densley Tingley (2021) have found that the UK focuses on operational energy efficiency and carbon emissions through their policies and legislation which is a significant problem where policy should be a driver of reducing carbon emissions. Furthermore, this problem will only get worse as the housing crisis magnifies it (Future Homes Hub, 2022a; UN, 2020).

Considering the growing demand for newly constructed houses in the UK, it is worrying that the embodied carbon will make up an ever-increasing percentage of carbon emissions, inherently increasing the risk of globally inhabitable temperatures rising (IPCC, 2023). This paper therefore uses scientific methodologies to evaluate the significance of the embodied carbon emissions of newly constructed houses, as well as what new policy measures would help to reduce the carbon emissions for the house building sector. It is considered that the embodied carbon emissions of construction materials for the structural elements of houses are considerable and that efforts to reduce this must come from policy advice. Policies should address embodied carbon to reduce emissions. The aim of this study is to consider whether UK building codes and standards should consider embodied carbon, and if so, what recommendations could be suggested at the policy level to drive down global emissions.

**2 Methodology**

*2.1 Research method*

Quantitative data was collected from secondary sources such as both industrial and peer reviewed sources that related to the sizes of the different types of houses. Since a desk top study was undertaken to evaluate the sizes of the housing structure this can be regarded as descriptive. Since GHG emissions are an already quantified unit of environmental impact on the environment, no further statistical tests were undertaken to compare the results.

*2.2 Calculation to create a model for a standard three-bedroom house in the UK*

Secondary data was used to inform the methodology and complete the calculations to derive the inputs needed for the Life Cycle Assessment methodology. Figure 2 demonstrates the processes that were undertaken to derive the A1-A3 embodied carbon emissions in tonnes of Carbon Dioxide Equivalents (kg CO2e).

Desk-based collection of UK national statistics was used to review the most commonly built house in the UK, which demonstrated that three-bedroom houses were most common. This study is based on a three-bedroom house where the quantities have been modelled using the floor plan of a large UK property developer. The length of the perimeter formed by the external walls was calculated (Barratt Homes, 2024). The heights of the walls were taken from commercial sources (Design for me, 2023; PBC today, 2017), and the volume of bricks and mortar per house was calculated; this is outlined in Table 1. This exercise was repeated a further two times and then averaged to create a value for a standard house for example houses A, B and C. The external walls were quantified in Table 2. The model excluded non-structural walls, roof, fitting, and fixtures, as these differ in materials and floor layouts are inconsistent; therefore, not easily standardised for the purposes of calculating embodied carbon emissions within the A1-A3 Life Cycle Assessment phases (Figueiredo et. al, 2021).

*2.3 A study of a three-bedroom house, case studies*

In this paper both a UK case study and a case study from New Zealand were used, both of which focused on the structural requirements of three-bedroom houses. The UK case study was supplemented with information from the New Zealand case study to evaluate carbon emissions for structural walls and frames, specifically the data on wooden and steel structural frames as these are not commonly used for residential houses in the UK (Dani et. al, 2022). The measurements therefore facilitated a comparison of different structural materials, outside of the common practice of bricks and mortar in the UK and are demonstrated in Table 3. The results were generalised where the wooden built houses from New Zealand were compared to brick houses in the UK.

The A1-A3 constants that were used as part of the independent calculations were taken from Greece as UK-specific data was not available. These constants came from peer-reviewed sources by Shi et. al, (2022) and Manjunath et. al., (2023). A1-A3 constants were kept the same, across calculations and therefore factorised to deliver accurate results. However, in addition to the independent calculations, an Automated Life Cycle Assessment Software was used as a comparison to the independent embodied carbon calculations. The cost was not considered because the aim of this study focuses on embodied carbon emissions.

*2.4 Wood and Steel Framed Houses*

It was found that whilst the volume of bricks can be calculated based on the floor area of the house; for the structural materials of steel and wood, due to factors such as tensile strength and standards, these materials are not proportional to the floor area previously calculated (Department for Communities and Local Government, 2013). Dani et. al, (2022) produced transcribed Table 4.

The closest matching material density was allocated to the description of the material for example for ‘Timber softwood, dressed kiln-dried’ the density of wood was used, which was an average of the two provided. Since the material ‘cold-rolled profile metal sheet’ was non-descriptive in terms of the relative specific density, an average was taken of aluminium and copper sheet metal as it is similar.

The percentage makeup of ingredients for mortar was calculated by Małgorzata et. al (2020) using ‘P3’ mortar which was a typical mortar without any plasticiser in it, and their masses were converted into percentages displayed in Table 5.

For each of the house’s A, B, and C the ‘total perimeter’ of the house was calculated by adding together the ‘total’ for the lengths and widths, the working is in Table 2. Design for me (2023) and PBC today, (2017) were used in the calculation as constants that related to the ceiling height and floor void.

The ‘total surface area of external brickwork’ was calculated by multiplying the ‘total perimeter’ by two lots of the ‘ceiling height of a room’ and ‘the floor void’ as three-bedroom houses have two floors in the UK. Weinerbergner (2021) displayed the length, width, and height of bricks with mortar surface and without a mortar surface.

The 'total volume of external brickwork’ was multiplied by the width of a brick without mortar to convert to its volume which is the ‘total volume of external brickwork’. This was then converted from mm3 to m3 using a conversion factor (1\*10-9).

The volume of a single brick with and without mortar was calculated. This was then used to create a percentage of mortar, and the percentage of brick for a mortared brick. These percentages were used as percentage factors to convert the solid brick and mortar wall into masses of each material by multiplying the 'total volume of external brickwork’ in m3 by its material percentage and material density.

*2.5 Conversion of material carbon*

Research from Shi et. al, (2022) and Manjunath et. al., (2023) informed the embodied carbon emissions per kg of construction materials in Table 6. An average was taken for the 'total surface area of external brickwork’ in mm2 and masses of houses A, B, and C, creating the ‘House Average’. The wooden and steel framed house, and houses A, B, C, and average total material volumes were converted to mass in kilograms which was needed as the A1-A3 conversion factors are in kg of material per kg CO2e. kg CO2e is a carbon factor measurement which is a standardised unit of carbon emissions that is often used to compare different greenhouse gases meaning all greenhouse gases can be accounted for, within reason (Figueiredo, Pierott, Hammad, and Haddad, 2021). The masses of each material were converted into A1-A3 emissions using the conversion factors from Table 6. Since mortar is a mixed material, the total mass of mortar was multiplied by the A1-A3 emission factors in the correct percentages. This series of calculations derived the ‘independent calculations’ methodology for this paper.

*2.6 Automated Life Cycle Assessment Software Calculations*

‘One Click LCA’ was also used to convert the materials into embodied carbon emissions. The calculated masses that were calculated from the dimensions of the houses were used within ‘One Click LCA’ to calculate the A1-A3 emissions. This was done by each of the housing frameworks closest matching materials from the drop-down selection was considered. The A1-A3 embodied carbon calculated from Tables 3 and 4 for each material were used to calculate the A1-A3 emissions using this Automated Life Cycle Assessment Software, of ‘One Click LCA’ (One Click LCA, 2023).

Both the independent calculations and the value from the Automated Life Cycle Assessment Software were averaged to create the most accurate A1-A3 emissions for materials, however, as discussed in the introduction embodied carbon values can vary significantly. The calculation of the two carbon emissions calculations was undertaken to attempt to resolve this inaccuracy. However, the range was deemed too significant with the result that the average was not useful and so the independent A1-A3 emission factors were used as they are peer reviewed.

The average number of completed houses was then multiplied by the independent A1-A3 embodied carbon emissions for each of the structural houses demonstrated in Table 7.

*2.7 Assumptions*

This study used embodied One Click LCA (2022b) and One Click LCA (2023) carbon coefficients from global databases. It is assumed that these coefficients would be similar for procurement of resources due to global supply chains. The study focuses on the structural walls of newly built houses in New Zealand and the UK. It is assumed that these countries will have similarly designed walls for bricks and mortar, wooden framed, and steel framed houses for the most frequently built houses. It also assumes that the materials used are going to be of similar character to those used before, created by similar processes to produce them. This study also assumes that the UK will continue to construct and complete houses at a similar rate as has been observed between the time horizons. The time horizon for this study is July 2022 to July 2023.

**3 Results**

Table 8 demonstrates the results of independent calculations. Table 9 demonstrates the results from the Automated Life Cycle Assessment Software. Tables 8 and 9 demonstrate that bricks and mortar structural walls have the highest amount of A1-A3 embodied carbon when compared to the steel and wooden framed equivalents. Specifically of the brick-framed houses, House A had the highest emissions. This was due to it enclosing a larger area. Wooden framed houses had the lowest A1-A3 carbon emissions. Tables 8 and 9 demonstrate steel framed houses have two and half times the A1-A3 carbon emissions than wooden framed houses even though they require less material input, because of the greater structural strength of steel.

Table 9, the Automated Life Cycle Assessment Softwareresults followed the same results as the A1-A3 independent calculations above, however, the total A1-A3 carbon emissions appear to be lower. Since the same masses of materials were used, the variations were created by the fact that the specific materials chosen between the independent calculations and Automated Life Cycle Assessment Softwarecould be dissimilar due to the nature of material choices within the software (One Click LCA, 2022c, Shi et. al, 2022, and Manjunath et. al. 2023). Additional variables will be the A1-A3 embodied carbon factors that were chosen for the independent calculations and those used in the Automated Life Cycle Assessment Software, as part of the database it uses.

Table 9 shows that brick and mortar houses typically had the highest overall ‘A1-A3 carbon emissions/Gross Floor Area (kg CO2e per m2)’ and ‘A1-A3 carbon emissions/mass (kg CO2e per kg)’ Life Cycle Assessment is impacted by the input of materials for the calculations. Table 9 shows the A1-A3 carbon emissions per floor area and per volume of mass utilised were therefore considered to give a representative consideration of the volume of CO2e emitted. Table 9 also shows that wooden and steel framed houses of the New Zealand model had a relatively low ‘A1-A3 Emissions/Gross Floor Area (kg CO2e per m2)’ and ‘A1-A3 Emissions/mass (kg CO2e per kg)’

**4 Discussion**

The relatively high overall ‘A1-A3 carbon emissions/Gross Floor Area (kg CO2e per m2)’ and ‘A1-A3 carbon emissions/mass (kg CO2e per kg)’ Life Cycle Assessment for bricks and mortar is likely to be a result of their relatively high material consumption for creating structural walls out of bricks and mortar when compared to wooden or steel frames. These results prove that for UK housebuilders these carbon emissions from the materials they choose will end up being a significant proportion of their Scope 3 emissions and carbon footprint, especially as Malmqvist et al., (2018) demonstrated the decarbonisation of operational energy for houses. Although Figueiredo et. al, (2021) highlighted that houses are made of significantly more materials than considered within this study, the A1-A3 carbon emissions are likely to be significantly lower than the true amount for all materials within a newly constructed house. The results are also indicative of Sizirici et. al, (2021), and Heeren and Hellweg (2019) who found that material emissions are significant and relate to the complexity of the manufacturing process or ore extraction which is observed by the results above. These considerations are not applicable to wood as it is a natural biogenic material and requires less processing.

Although the results of Tables 8 and 9 vary slightly, they are in the same order of magnitude so can be used to draw reasonable conclusions about the magnitude of A1-A3 embodied carbon emissions created by the building industry and so are useful in deciding whether this source of carbon emissions should be considered within building codes and policy (Li and Densley Tingley, 2021). This also identifies that bricks and mortar consume more resources which impacts the sustainability of resource management globally when considering mass and volume. Furthermore, it is likely to impact transport and distribution-related carbon emissions (Gibbons and Orr, 2020). Consequently, since Life Cycle Assessment does not consider resource depletion these ratios demonstrate that not only do wooden and steel frames have fewer A1-A3 carbon emissions, but they also require fewer resources. This is interesting as Dani et. al (2022) has demonstrated that a typical New Zealand house is significantly larger in floor area when compared to a typical house in the UK. Leading to thoughts towards not only lower carbon buildings but higher standards of living too.

Table 9’s results clearly indicate that wood has the lowest A1-A3 embodied carbon emissions and with an ever-growing demand for UK houses, UK house builders will have to consider choosing wooden frames and fillings to fulfil a transition to climate objectives such as net zero and carbon budgets (Heffernan, 2015; Gov.uk, 2022). For countries such as the UK where grids are decarbonising, this will enable significantly reduced operational carbon emissions for houses in the UK. This is the reason why the embodied carbon emissions are a core focus for decarbonising the lifecycle impacts for new build houses globally, as there is a global trend of countries decarbonising their grids by increasing the renewable electricity generation (LETI, 2020; Gov.uk, 2021b; IEA, 2022; Office of Energy Efficiency & Renewable Energy, 2022). Whilst this will focus on Scope 3 carbon emissions for house building, it will also help reduce emissions with respect to IPCC requirements and Science Based Target Initiatives (SBTi’s) for the corporate housebuilders (IPCC, 2021; Giesekam et al. 2021). This identifies the importance of carbon accounting and Life Cycle Assessment methodology as it depicts the sheer number of variables which impact the choices being made for the materials being considered (Robati, Daly and Kokogiannakis, 2019). Therefore, the best practice would be to consider the carbon baseline for all materials within each house. However, as these structures are complex, a valid model to consider the baseline was developed. Consequently, the decision was made to simplify the calculations by simplifying the structures in common between the three types of houses as explained in the methodology.

Since so much of the carbon emissions are related to the embodied carbon phases, a full Life Cycle Assessment would grant the housing industry the ability to weigh up the material impacts more effectively. However, this study has its weaknesses, where key structures such as roofs are not considered. Thereby a full Life Cycle Assessment of a house would enable further policy adjustments in the future, and it would be able to consider the embodied carbon beyond structural walls of a house.

In summary, bricks and mortar houses have the highest carbon emissions followed by steel frames. This is because the extraction processes used to make the bricks consume a lot of energy together with their manufacture. Whilst steel has a relatively high energy consumption within its manufacturing process, less is used within the construction industry for the frames of houses as it has a high tensile strength. This is important as it helps to reduce resource consumption as less steel is used by mass for housing frames when compared to other materials (Sizirici et. al, 2021). Wooden framed houses would help to reduce sector emissions beyond emissions associated with the operational energy phase.

*4.1 Further areas of study*

This study shows that there are significant CO2 emissions from the construction of structural walls for houses in the UK. However, Gibbons and Orr (2020) demonstrated that it is not the complete picture of the carbon emissions as a full Life Cycle Assessment would need to be undertaken to consider life cycle phases such as B1-B5 (‘operational’), and C1-C4 (‘end of life’). Further information could be obtained from the evaluation of energy consumption on construction sites, which would give an understanding of the B1-B5 emissions. In addition, a material balance could be considered for the procurement of the materials considered in this study and the related waste generated from the construction sector, this would evaluate C1-C4 carbon emissions (Gibbons and Orr, 2020).

Li and Densley Tingley (2021) found that policy focused on operational energy efficiency, concluding that the phases such as the A1-A3 within the Life Cycle Assessment will have a larger impact on the lowered carbon footprint because of these changes. However, since only operational energy efficiency has been considered within this study, it can be understood that it will also reduce the carbon emissions associated with the lifecycle phases such as the A4-A5 as both these phases can use electricity as an energy source for transportation and the electrical power for the services within the construction installation process. Since the grid is decarbonising within the UK these phases will also be decarbonised. Since Dascalaki, et. al, (2021) found that material manufacturing is significant, the same considerations within this study could be considered with the B2 - B5 (‘refurbishment’) phases, specifically the materials used within these phases (Gibbons and Orr, 2020).

*4.2 Recommendations*

The recommendations below are based on the outcome of this research which has been designed to improve the ability of building codes and policies to reduce the embodied carbon emissions for newly constructed houses in the UK.

Building standards need to consider the full life cycle of carbon emissions, rather than focusing on operational energy efficiencies. Building standards need to consider replacing traditionally constructed houses of bricks and mortar with wooden and steel-framed houses, infilled with wooden or natural walls. A mandatory Life Cycle Assessment should be produced for all new buildings with emphasis placed on reducing the carbon emissions across the building's lifecycle. This should include a carbon balance approach, which considers the A1-A3 emissions versus the carbon payback, if possible, from materials. A carbon budget per unit volume of a new build house focusing on embodied carbon-related emissions should be compiled, as lower carbon results of Life Cycle Assessment could be made from operational energy efficiencies, low carbon technologies such as heat pumps, and grid decarbonisation for new build housing. This study considered so-called steel framed houses but excluded the floors as the models only considered the external structural walls. Since the floors may create high embodied carbon emissions further studies are needed to quantify this. This can be replicated for studies relating to embodied carbon of newly built houses’ roofs.

**5 Conclusion**

Production of core building materials releases a substantial volume of CO2 and other GHG into the atmosphere. The release is linked to the UK’s growing demand for newly constructed houses so will only increase. Current policies do not support the reduction of carbon emissions other than those related to energy. This needs to change, as embodied carbon emissions will release a higher percentage of a house’s life cycle carbon emissions as grids decarbonise, and heating is electrified.

This study can be used to steer policy and building code-related considerations for UK housing developers to help them reduce their material carbon emissions. Results demonstrate relationships between materials’ weight, volume, and embodied carbon emissions within the production phases. The limitations of this study were that it only considers the structural walls of newly built houses, the full results for all fabrics, fixtures, and fittings used in a newly built house is likely to be significantly higher (Marinova et. al, 2020). However, these calculations would prove to be complex and likely to be inaccurate, due to the variety of materials. The structural walls of steel framed houses did not contain steel itself because the steel was used to support floors and ceilings, therefore was ignored in this study. This meant that the embodied carbon comes from other materials used in the construction of the steel-framed house.

However, this study has identified some possible significant changes that will need to be made within current UK housing practices to enable housing developers to reduce their A1-A3 carbon emissions. This is critical to the global climate change goals, as Scope 3 carbon emissions enable best practices of collaboration and innovations to help achieve lower carbon emissions globally.

This study aimed to understand what additions to building codes and policy could be used to reduce the UK’s house-building industries' global carbon footprint through reduced embodied carbon houses. Key recommendations have been outlined which will help to reduce embodied carbon through material selection, and more detailed analysis through more stringent Life Cycle Assessment led regulations as part of the house design process. Material selections such as wooden frames will help drive down global carbon emissions in the short term, whilst longer-term use of Life Cycle Assessment will help reduce global carbon emissions through enhanced ‘Measurement and Verification’. However, further policy-related considerations beyond these areas will require an additional study that conducts A1-A3 embodied carbon calculations with more of a focus on materials within other structures of a house.

Looking at the future, the latest IPCC report in 2023 requires more efforts globally to be made to achieve Net Zero carbon emissions as global carbon budgets are likely to be exhausted before the next report which is due around 2030. This study suggests that Scope 3 emissions are well placed to achieve the latest IPCC targets due to their breadth of carbon emissions coverage. Moreover, considering material use and consumption will help to reduce carbon emissions further as populations grow, and cities urbanise. Influencing the supply and value chain-related carbon emissions will also help major carbon-emitting countries to reduce their carbon emissions.

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Figure 1. Number of completed houses between 2008 – 2021 (The Ministry of Housing, Communities and Local Governments, 2021, pp. 6)

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Figure 2. Process of understanding A1-A3 embodied carbon emissions

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Table 1. Calculations, units, formulas, and descriptions

|  |  |  |  |
| --- | --- | --- | --- |
| **Calculation** | **Units** | **Formula/Description** | **Sources** |
| Total Perimeter of the ground floor (mm) | mm | Total of external walls | Barratt Homes, 2024 |
| Total Perimeter of the ground floor (m) | m | Total Perimeter of the ground floor (m) / 1000 | Barratt Homes, 2024 |
| Total surface area of external brickwork | mm2 | Total Perimeter of the ground floor \* (ceiling height \*2) + (floor void \*2) | Design for me, 2023; PBC today, 2017 |
| Total volume of external brickwork | mm3 | Total surface area of external brickwork \* width of the brick \* 2    Total surface area of external brickwork \* 102.5 \* 2 | Design for me, 2023 |
| Total volume of external brickwork | m3 | Total volume of external brickwork \* 1\*10-9 | Design for me, 2023 |
| Volume of Brick + Mortar | mm3 | Width of the brick plus mortar \* Length of the brick plus mortar \* Breadth of the brick plus mortar    112.5\*225\*75 | Weinerbergner, 2021 |
| Volume of brick | mm3 | Width of the brick \* Length of the brick \* Breadth of the brick    102.5\*215\*65 | Weinerbergner, 2021 |
| Percentage of bricks within bricks and mortar | % | (Volume of bricks/volume of bricks + mortar) \*100    =75% | Weinerbergner, 2021 |
| Percentage of mortar within bricks and mortar | % | (Volume of mortar/volume of bricks + mortar) \*100    =25% | Weinerbergner, 2021 |
| Volume of mortar per brick | mm3 | (Length of mortar brick \* width of mortar brick \* (height of mortar brick – height of brick)) + ((height of brick \* width of mortar brick \* (length of mortar brick – length of brick)    (225\*102.5\*10) + (75\*102.5\*10) | Weinerbergner, 2021 |
| Total amount of mortar | mm3 | Total number of bricks required \* Volume of motor per brick (mm3) | Weinerbergner, 2021 |
| Total amount of mortar | m3 | Total amount of mortar / 1000 | Weinerbergner, 2021 |

Table 2. Length, and width for brick houses A, B, and C

|  |  |  |
| --- | --- | --- |
| *House A* | | |
| **Room** | **Length (mm)** | **Width (mm)** |
| Lounge end wall and front exterior | 5,540 | 3,322 |
| Lounge rear exterior wall | 0 | 3,322 |
| Kitchen/Breakfast Room end wall and front exterior | 3,212 | 2,375 |
| Dining Room end wall and front exterior | 3,364 | 2,400 |
| WC end wall and rear exterior wall | 1,692 | 1,692 |
| **Total (mm)** | 13,808 | 13,111 |

|  |  |  |
| --- | --- | --- |
| *House B* | | |
| **Room** | **Length (mm)** | **Width (mm)** |
| Kitchen and utility end wall and front exterior | 5,317 | 2,528 |
| Garage and Lounge exterior wall | 4,913 | 3,189 |
| Kitchen exterior wall | 0 | 2,528 |
| Garage exterior wall | 5,095 | 2,663 |
| **Total (mm)** | 15,325 | 10,908 |

|  |  |  |
| --- | --- | --- |
| *House C* | | |
| **Room** | **Length (mm)** | **Width (mm)** |
| Rear exterior wall | 8,503 | 0 |
| Right hand end exterior wall | 4,863 | 0 |
| Left hand end exterior wall | 4,863 | 0 |
| Front exterior wall | 8,503 | 0 |
| Right hand WC wall | 0 | 929 |
| Left hand WC Wall | 0 | 929 |
| **Total (mm)** | 18,229 | 1,858 |

Table 3. Volume and masses for wooden and steel framed houses (Dani et. al, 2022)

|  |  |  |
| --- | --- | --- |
| *Wooden house* | | |
| **Material description** | **Volume (m3)** | **Mass (kg)** |
| Engineered wood, glued laminated timber (glulam) | 0.298 | 178.80 |
| Timber Softwood dressed kiln-dried | 6.645 | 3987.00 |
| 200 \* 75 parallel flange channels (PFC), steel primary | 0.028 | 220.08 |
| 200U-46.2, steel (primary) | 0.056 | 440.16 |
| Fiber Cement Sheet | 2.122 | 4488.03 |
| **Total** | 8.851 | 9135.27 |

|  |  |  |
| --- | --- | --- |
| *Steel Framed House* | | |
| **Material description** | **Volume (m3)** | **Mass (kg)** |
| Timber softwood, dressed kiln-dried | 0.0410 | 24.6 |
| Timber Softwood dressed kiln-dried | 0.2610 | 156.6 |
| cold-rolled profile metal sheet | 0.2350 | 0.87 |
| Fiber Cement Sheet | 2.4630 | 5209.25 |
| **Total** | 2.9590 | 5366.71 |

Table 4. The material description and volume for wooden and steel framed houses (Dani et. al, 2022, Chudley, Greeno and Kovac (2020) pp. 132 - 133, Amin et. al, 2022, pp. 9 and Almeraya-Calderon and Kolisnychenko, 2021, pp.4)

|  |  |
| --- | --- |
| *Wooden Framed House* | |
| **Material description** | **Volume (m3)** |
| Engineered wood, glued laminated timber (glulam) | 0.298 |
| Timber Softwood dressed kiln-dried | 6.645 |
| 200 \* 75 parrallel flange channels (PFC), steel primary | 0.028 |
| 200U-46.2, steel (primary) | 0.056 |
| Fibre Cement Sheet | 2.122 |
| **Total** | 8.851 |
| Ratio wooden frame: A1-A3 emissions | 2.541798505 |

|  |  |
| --- | --- |
| *Steel Framed House* | |
| **Material description** | **Volume (m3)** |
| Timber softwood, dressed kiln-dried | 0.0410 |
| Timber Softwood dressed kiln-dried | 0.2610 |
| cold-rolled profile metal sheet | 0.2350 |
| Fibre Cement Sheet | 2.4630 |
| **Total** | 2.9590 |

Table 5. Percentage make up of mortar (Małgorzata et. al, 2020)

|  |  |
| --- | --- |
| **Ingredients of Mortar** | **Percentage composition of mortar (%)** |
| CEM 42.5 R-C1 | 8.52% |
| Lime T | 4.12% |
| Sand | 74.10% |
| Water | 13.16% |

Table 6. Mortars’ ingredients and other building materials carbon factors (Małgorzata et. al, 2020; Shi et. al, 2022; and Manjunath et. al., 2023)

|  |  |
| --- | --- |
| **Material** | **Material (kg) per kg CO2 equivalents** |
| Cement | 0.82 |
| Wood | 2.910 |
| Bricks | 3.57 |
| Steel | 6.960 |
| Mortar | 0.1463 |

Table 7. Reflection based on number of houses embodied carbon emissions

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | **A1-A3 Emissions (tonnes CO2e)** | | |
| **Year ending** | **Completions** | **Average House** | **Wooden Frame** | **Steel Frame** |
| 2008 | 170,610 | 145,896,871.94 | 1,136,135.64 | 2,648,336.38 |
| 2009 | 140,990 | 120,567,375.74 | 938,888.48 | 2,188,552.52 |
| 2010 | 119,910 | 102,540,847.04 | 798,511.37 | 1,861,332.95 |
| 2011 | 107,870 | 92,244,860.07 | 718,333.93 | 1,674,439.04 |
| 2012 | 118,580 | 101,403,499.64 | 789,654.56 | 1,840,687.70 |
| 2013 | 107,980 | 92,338,926.39 | 719,066.44 | 1,676,146.55 |
| 2014 | 112,330 | 96,058,822.02 | 748,034.21 | 1,743,670.51 |
| 2015 | 124,640 | 106,585,699.07 | 830,009.65 | 1,934,755.56 |
| 2016 | 139,710 | 119,472,785.76 | 930,364.63 | 2,168,683.40 |
| 2017 | 147,520 | 126,151,494.92 | 982,373.42 | 2,289,916.08 |
| 2018 | 160,900 | 137,593,380.78 | 1,071,474.26 | 2,497,610.48 |
| 2019 | 169,500 | 144,947,657.19 | 1,128,743.86 | 2,631,106.13 |
| 2020 | 175,250 | 149,864,760.61 | 1,167,034.58 | 2,720,361.94 |
| 2021 | 155,960 | 133,368,947.58 | 1,038,577.54 | 2,420,928.09 |
| **Average** | **139,411** | **119,216,852** | **928,371.61** | **2,164,038** |

Table 8. Results of A1-A3 embodied carbon independent calculations

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Gross floor area (m2)** | **Mass (kg)** | **A1 - A3 Emissions (tonnes CO2e)** |
| **House A** | 0.06 | 4,889,234.84 | 942.93 |
| **House B** | 0.061 | 4,764,638.27 | 918.90 |
| **House C** | 0.048 | 3,648,354.70 | 703.62 |
| **House Average** | 21.52 | 4,434,075.93 | 855.15 |
| **Wooden Frame** | 8.85 | 9,135.27 | 6.66 |
| **Steel Frame** | 2.96 | 5,366.71 | 15.52 |

Table 9. Results of A1-A3 embodied carbon calculations using ALCAS

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Gross floor area (m2)** | **Mass (kg)** | **A1-A3 carbon emissions (tonnes CO2e)** |
| **House A** | 23.73 | 4889235 | 765 |
| **House B** | 23.12 | 4764638 | 745 |
| **House C** | 17.71 | 3648355 | 594 |
| **House Average** | 21.52 | 4434076 | 693 |
| **Wooden Frame** | 8.85 | 9135.27 | 29 |
| **Steel Frame** | 2.96 | 5366.71 | 4 |