The practical, technical and economic impacts of measuring and reducing embodied carbon in new buildings

Prepared by AECOM for The Ministry of Housing, Communities and Local Government (MHCLG)

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Executive summary

The construction and use of buildings creates both embodied and operational carbon emissions. Historically, Government policies and voluntary efforts from the industry have primarily focused on the reduction of operational carbon emissions of buildings. However, for the UK to reach its 2050 net zero target [1], focusing efforts on reducing the embodied carbon of buildings is also critical.

AECOM has been commissioned by The Ministry of Housing, Communities and Local Government (MHCLG) to review and present recommendations for the sector-wide technical, practical, and economic impacts of measuring and reducing embodied carbon. This has resulted in a holistic understanding of the impacts of the widespread adoption of carbon assessments and the current challenges and opportunities facing the industry.

Across the built environment industry, there are large opportunities to track and reduce carbon impacts across new buildings through developing industry skillsets and through consistent methodologies, data, and tools.

Government and corporate commitments to net zero emissions are expected to lower costs and increase the availability of sustainable materials. However, substantial investment is needed in key areas such as training for sustainable design, standardisation of modelling approaches, and consistent carbon assessments using an array of modelling tools, both simple and advanced.

Additionally, AECOM recommends that the Government considers how insurance frameworks, innovative materials, and fire regulations contribute to progressing carbon-efficient buildings.

Improving data quality for building materials is vital, and adopting a tiered data tracking approach for carbon assessment datasets will support the UK's decarbonisation goals. Extensive data collection and analysis of functional units' impact on carbon assessment results will enable robust benchmarks and targets that mitigate gamification and facilitate informed decision-making across the industry.

1 The 'net zero target' refers to a government commitment to ensure that the UK reduces its greenhouse gas emissions by 100% from 1990 levels by 2050 (38).

Enabling and supporting consistency within carbon assessments is therefore key to supporting new buildings to decarbonise and achieve a sustainable future.

A summary of the key findings and recommendations associated with the technical, practical, and economic considerations for measuring and reducing embodied carbon in new buildings is displayed within the following sections.

Technical considerations for measuring and reducing embodied carbon in new buildings - Summary of key findings and AECOM recommendations from the technical research

1. **There is a lack of consistency in reported carbon assessment outputs:** The variation between the outputs of carbon assessments limits the ability to compare results across different developments. This is a challenge for developing consistent datasets of carbon assessments. In turn, this impacts the development of consistent benchmarks and targets.

   AECOM recommendations:
   - Develop consistent reporting mechanisms that enable streamlined carbon assessment data tracking.
   - In reporting, three scope elements of carbon assessments must be clearly defined: the building type, the building element category scope and the BS EN 15978 and BS EN 17472 life-cycle modules covered by the benchmarks and targets.

2. **There is a need to improve the quality of carbon assessments undertaken:** Mitigate misreporting of carbon impacts.

   AECOM recommendations:
   - Upskill and train carbon modellers to ensure proficiency in carbon assessment methodologies.
   - Create a clear definition of a competent carbon assessor, including developing and specifying training and/or experience requirements.

3. **There are large gaps in the availability of both product specific EPDs and generic data:** Across a variety of carbon tools, there are gaps in the availability of generic data among common building elements and materials. An assessment of data availability was conducted for a sample of common building materials to identify gaps in EPD data availability. The results of the sampled exercise showed that External Works, Services and Furniture, Fittings, and Equipment (FF&E) building elements exhibited the poorest EPD data availability, possibly due to product complexity and a fluctuating supply chain for building services elements. One third of materials and products sampled lacked UK based EPDs.

   AECOM recommendations:
   - A UK-based carbon dataset should be created using the carbon data that is currently accessible.

- Coordinate the generation of product and manufacturer specific carbon data across current and planned policies to enable further generation of consistent carbon data. This could include developing systems to support manufacturers in developing carbon data and collating this data centrally to inform generic UK-based carbon databases.
- In the short term, create interim methodologies, such as how CIBSE TM65 is working for building services products, to reduce the gaps in data availability.
- Development of low-cost LCA tools should be explored for use by SMEs to ensure that cost is less of a barrier to generating carbon data.

4. **There is a large variation in product carbon results for similar building products:** The large variation found in both the generic and product specific EPDs creates a lack of consistency across carbon datasets. No clear correlation was found between data quality and magnitude of carbon impact.

   AECOM recommendations:
   - Consistent guidance should be created about how carbon tools should generate carbon factors.

5. **There is a lack of consistency across carbon tools:** The variation between carbon tools and their outputs limits the ability for carbon assessment results to be compared. This in turn, restricts the development of consistent datasets, impacting the development of clear, consistent benchmarks and targets. Furthermore, this may encourage gamification and hinder competition within the carbon tool market, as industry will likely wish to utilise the tool that produces the lowest carbon assessment results.

   AECOM recommendations:
   - Create a consistent methodology for both public and private carbon tools to follow. As a minimum, the following elements should be included in the methodology:
     - Whole life carbon (WLC) module scope.
     - Building element categories scope.
     - Modelling assumptions within carbon assessments.
   - Create a third-party verification process of the tools to ensure that they are robust. The verification should, at a minimum, confirm:
     - The data sources.
     - That the calculations are complete in line with the chosen methodology.
     - Confirm the scope of the module and building element category.
     - Confirm the assumptions used.
     - Verify the output format.
   - Create consistent guidance about how carbon tools should generate generic carbon factors.

Practical considerations for measuring and reducing embodied carbon in new buildings - Summary of key findings and AECOM recommendations from the practical research

1. **Limitations on the uptake of innovative and emerging products that have lower embodied carbon:** New materials and products do not benefit from economies of scale in the same way as existing well-established products. This causes new products to be typically more expensive than existing materials / products. New and emerging products can have variations in cost due to warranties, associated with contractor risks and insurance. In addition, the cost of producing Environmental Product Declarations (EPDs), hinders the ability of smaller manufacturers to prove their products as lower carbon.

   AECOM recommendations:
   - Government subsidies and support of both low carbon materials and UK based manufacturing. Support could also be provided for manufacturers in producing carbon data (such as EPDs) for new low carbon products.
   - Creation of an insurance playbook, similar to existing methods such as the mass timber insurance playbook, should be created to support new and innovative materials to address insurance concerns. This would enable further adoption of new and innovative materials.

2. **Fire risk as a barrier to the use of innovative and emerging products:** Blanket decisions are being made that are associated with perceived fire risk, limiting the development of new forms and construction methods.

   AECOM recommendations:
   - Greater awareness of the fire regulations and how to ensure fire safety must be incorporated into every project with the support of a fire engineer/specialist.
   - Clear provision of fire ratings of all products. For smaller manufacturers, governmental support could help to ensure this is undertaken quickly and consistently.

3. **Upskilling of the industry is required to enable the adoption of alternative methods of design and construction such as timber structure:** The current timber structural design code (Eurocode 5) does not cover mass timber structures, such as Cross Laminated Timber (CLT). The lack of official guidance has led to this becoming a specialist service, with few engineers and contractors holding the necessary knowledge. Existing initiatives, such as the Mass Timber Insurance Playbook have proven to successfully address the insurance market concerns of timber (1).

   AECOM recommendations:
   - Rescope professional competence to include fire protection systems and their limitations.

- A new version of Eurocode 5 is expected to be released soon, which is expected to detail design guidance of mass timber elements such as CLT. Once the new version is released, it will be necessary to fast-track the knowledge-building phase, which can be achieved through up-skilling programmes supported by both government and professional institutions.
- Continued investment, particularly in training, is required to reduce the skills gap across the board. This includes upskilling the entire value chain, including developers, designers, manufacturers, and contractors.
- Similar to existing methods such as the mass timber insurance playbook (1), a similar insurance playbook should be created to support new and innovative materials enabling further adoption of these across new construction, whilst acknowledging and addressing insurance constraints.

4. **Barriers to widespread access of carbon tools:** Cost and knowledge of carbon tools, including the knowledge required to use carbon tools accurately prevents the widespread uptake of carbon tools, particularly for Small and Medium-Sized Enterprises (SMEs).

   AECOM recommendations:
   - Work with the industry to increase access to carbon tools and increase knowledge and skill sets across the industry.
   - Offer various carbon tool solutions, including free options (similar to Future Homes Hub's carbon tool (FHH)), to ensure widespread access to carbon tools, particularly for SMEs.

Economic considerations for measuring and reducing embodied carbon in new buildings - Summary of key actions from the economic research

1. **Direct economic impacts of widespread carbon assessments:** New A range of demand scenarios were assessed to understand the potential national annual cost for carbon assessments. For the low demand scenario, the estimated mean national costs for carbon assessments were estimated to be:
   - Upfront carbon: £0.98 million.
   - Embodied carbon: £1.71 million.
   - Whole life carbon: £3.91 million.

   For the medium demand scenario, the estimated mean national costs were estimated to be:
   - Upfront carbon: £8.82 million.
   - Embodied carbon: £15.4 million.
   - Whole life carbon: £35.3 million.

   For the high demand scenario, the estimated mean national costs were estimated to be:
   - Upfront carbon: £29.0 million.
   - Embodied carbon: £48.0 million.
   - Whole life carbon: £105.9 million.

2. **Widespread carbon assessments can have a broader economic cost benefit:** Widespread carbon assessments can help to reduce embodied carbon nationally. The Green Book supplementary toolkit estimates the value of carbon as £269/tCO_2e [2] (2). This means that the cost benefit of reducing carbon may offset the cost of introducing carbon assessment requirements. However, further research is required to establish the cost benefit of reducing industry-wide embodied carbon across new-buildings through a range of carbon reduction scenarios that are deemed to be achievable.

3. **Carbon assessments can create 'Green Jobs' [3] within the 'Green Economy':** Carbon assessments can form part of the emerging 'Green Economy'. The outcome of this new economy can create positive job-creation effects, increasing employment and opportunities for people to up-skill into an emerging new niche occupation.

   Supporting the emergence of the green economy can also help to offset any negative effects from process innovations or the implementation of new and significantly improved production methods that could lead to technological unemployment because of increasing productivity.

4. **There are currently enough suitably qualified carbon assessors to meet some of the projected demand scenarios:** It is estimated that the minimum number of trained, competent, and active carbon assessors in the UK is circa. 80no., though this could range by up to circa. 330no. based on the sensitivity analysis undertaken.

   There is currently estimated to be a sufficient number of competent carbon assessors for the majority of the low and medium demand scenarios modelled, although it is cautioned that this result is based on limitations and uncertainty within the economic analysis. There are not enough carbon assessors to meet the high and very high demand scenarios. However, it is likely that where drivers for undertaking carbon assessments increases, the number of carbon assessors would also increase.

   It is recommended that a definition of competent or suitably qualified carbon assessors is created which includes recommended training material. The number of competent of suitably qualified carbon assessors should also be tracked.

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2 Based on the central scenario.

3 Green Jobs' are described as having two main components. First, they are decent, fair, and meaningful jobs, and second, they are jobs which reduce negative environmental impacts. Subsequently, green jobs are defined by the International Labour Organisation (ILO) as jobs that 'help reduce negative environmental impact ultimately leading to environmentally, economically, and socially sustainable enterprises and economies (17).

5. **The cost of a carbon assessment varies based on the carbon assessment scope and stage:** Based on the outcomes of an industry questionnaire, the mean costs associated with carbon assessments were:
   - Early design stage: £3,700 (158 respondents).
   - Design optioneering: £5,200 (157 respondents).
   - Upfront carbon: £7,500 (150 respondents).
   - Embodied carbon: £8,100 (151 respondents).
   - Whole life carbon: £9,600 (150 respondents).

6. **Cost effective decarbonisation solutions:** The most cost-effective embodied carbon optimisations were found to be:
   - Optimised column gird in lieu of standard column grid.
   - Pad foundations based on ground conditions in lieu of pile foundations.
   - Optimised rectangular mezzanine office layout in lieu of standard mezzanine office layout.
   - Exposed ceiling in lieu of suspended ceiling.
   - Hybrid Variable Refrigerant Flow (VRF) system in lieu of VRF with VRF serving Air Handling Unit (AHU) coils.
   - Electric arc furnace steel in lieu of blast furnace steel.
   - Reused steel in lieu of new steel.
   - Hybrid timber steel structure in lieu of steel structure.
   - Air Source Heat Pump (ASHP) with fan coil units and mixed mode operation in lieu of VRF with VRF serving AHU coils.

7. **There are a number of key challenges to the scalability of decarbonisation solutions which need to be addressed:** The key challenges to the scalability of decarbonisation solutions were identified as:
   - Sourcing constraints due to supply chain availability and supplier preference.
   - Warranties and insurance.
   - Skills shortage, particularly for timber construction.
   - Fire regulations.
   - Limited availability of both cost and carbon information.

1. Introduction

AECOM has been commissioned by The Ministry of Housing, Communities and Local Government (MHCLG) to understand the sector-wide technical, practical, and economic impacts of carbon assessments. This is with a view to developing a holistic understanding of how widespread carbon assessments can drive reductions in embodied carbon within new buildings. In addition, the research aims to understand the cost implications of building with reduced embodied carbon and the challenges and opportunities of implementing these across new buildings.

1.1 Project aim

The aim of this research into the sector-wide practical, technical, and economic impacts of measuring and reducing embodied carbon is to inform policy driven embodied carbon reductions and better understand the cost of building with reduced embodied carbon. This includes compiling a robust evidence base to identify a series of recommendations to address the challenges and maximise the opportunities of widespread carbon assessments.

Technical considerations for measuring and reducing embodied carbon in new buildings

The research project investigates in depth the technical considerations of adopting widespread carbon assessments and building with reduced embodied carbon. Within carbon assessments currently undertaken, there are a range of scoping mechanisms, assumptions, carbon tools, and carbon data sources. This currently leads to uncertainty within carbon assessment results and may provide challenges when looking to utilise current carbon assessment data to underpin future benchmarks and targets. The research therefore aims to develop a detailed understanding of the variations and uncertainty within current carbon assessment calculations, the effects this may have, and how to mitigate uncertainty. In addition, developing a holistic understanding of the underlying carbon data underpinning assessments and detailing the challenges and opportunities for implementing low carbon solutions within new buildings. This includes investigating how existing carbon assessment data can be best utilised to inform embodied carbon reductions across new buildings.

Practical considerations for measuring and reducing embodied carbon in new buildings

To facilitate the widespread implementation of carbon assessments, the practical implications must be understood to prevent them from impeding the adoption of carbon assessments and designing low embodied carbon buildings. The research into the practical considerations aims to identify potential barriers to the implementation of widespread carbon assessments and propose recommendations to support building with reduced embodied carbon.

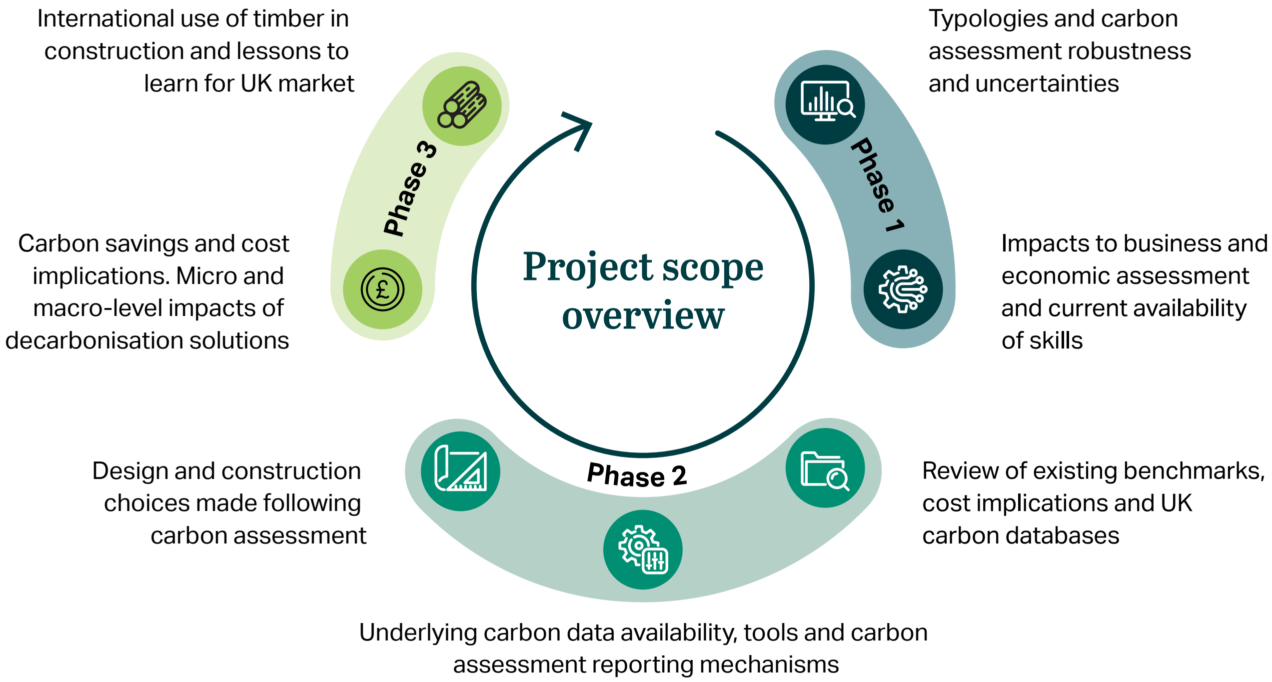
Economic considerations for measuring and reducing embodied carbon in new buildings

To understand the economic implications of widespread carbon assessments, the research project aims to investigate the current available information on the cost considerations of building with reduced embodied carbon. In addition, the cost impact of carbon reductions on common building typologies was quantified. This is to support the identification of easy wins, whilst determining the impact of key decarbonisation solutions at a national level. In addition, the research aims to identify the cost impacts to developers for conducting carbon assessments and understand their perceived drivers and barriers towards assessing and reducing embodied carbon across the built environment.

1.2 Phases of research project

The research project was split into three phases, as shown in Figure 1.1, with this report representing a summary of the research conducted across all phases of the project.

Figure 1.1. Summary of project scope and phasing



1.3 Structure of this report

The results of the extensive research undertaken for this project are summarised into three key sections:

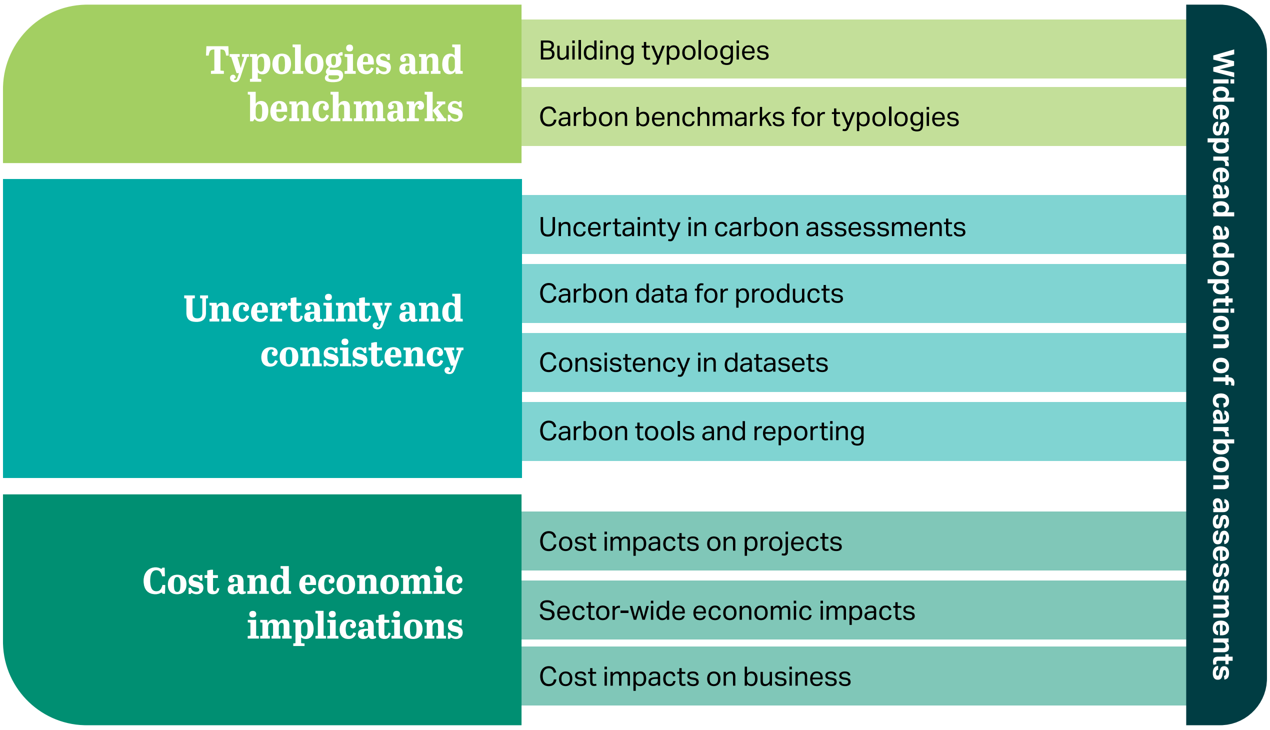
- **Typologies and benchmarks:** This section sets out the research undertaken to establish the current building types in the UK, how these are best categorised into specific types (or typologies), and the existing industry recognised carbon benchmarks and targets that can be applied to each of the categorised typologies. This includes detailing the different types of benchmarks available, their robustness, and how benchmarks and targets can drive embodied carbon reductions.

- **Uncertainty and consistency:** This section explores the causes of uncertainty within carbon assessments and then sets out how consistency can be improved for different levels of information, from product-level data to national carbon assessment datasets. The aim of this analysis is to derive recommendations for minimising uncertainty, thereby supporting robustness in assessments. Increasing robustness will help drive embodied carbon reductions across the built environment. Reducing uncertainty enables more reliable financial decision-making for funding projects and implementing embodied carbon reduction measures, not only for new buildings but also for infrastructure, which is intrinsically linked.

- **Cost and economic implications of measuring and reducing embodied carbon:** This section sets out the cost implications of the widespread use of carbon assessments on projects and businesses. This analysis also aims to establish the current availability of carbon assessors and whether this meets a range of demand scenarios for widespread assessments. In addition, this analysis includes detailing the cost impact of carbon reduction measures, enabling easy wins to be identified. Therefore, the research aims to estimate the potential economic impacts of carbon assessments on the built environment sector.

Figure 1.2 summarises the research topics covered by each section.

Figure 1.2. Structure of the technical sections of the report



Based on the research, recommendations and action plans have been developed, which are summarised in Section 6. During the research several areas were identified for further research; these are summarised in Section 7.

2. Background to carbon assessments

The construction and use of buildings create both embodied and operational carbon emissions. Carbon assessments can be undertaken to calculate and reduce these impacts, enabling a detailed calculation of the impact of buildings over their entire life span, from the extraction of raw materials to end-of-life disposal.

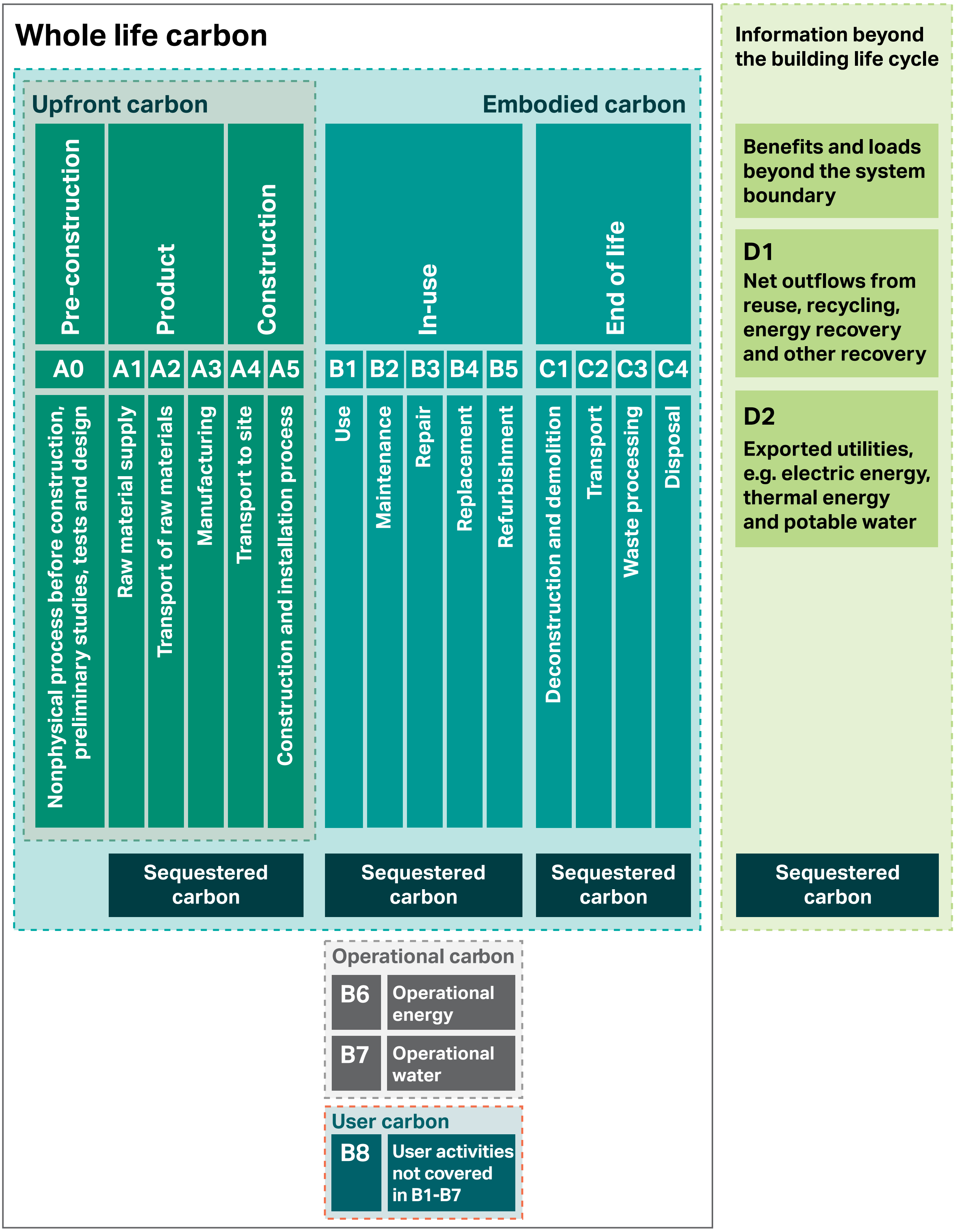
There are three types of carbon assessments for buildings, which are explored below and within Figure 2.1:

- **An upfront carbon assessment:** Upfront carbon (modules A1-A5, excl. carbon sequestration, as per Figure 2.1) assessments include the emissions associated with the materials and construction processes together with the product and construction stages. This may also be considered as the embodied carbon up to practical completion of a building.

- **An embodied carbon assessment:** Embodied carbon (modules A-C excl. B6-B8, incl. carbon sequestration, as per Figure 2.1) assessments include the emissions associated with the materials and construction processes throughout the whole life cycle of a building or infrastructure, from extraction of raw materials to demolition. Embodied carbon assessments notably exclude the carbon impacts of operational energy, operational water, and user carbon.

- **A whole life carbon assessment (WLCA):** A WLCA (modules A-C incl. B6-B8, incl. carbon sequestration, as per Figure 2.1) includes the emissions associated with both the embodied carbon and operational carbon emissions. A WLCA therefore provides the full scope of carbon emissions throughout a development's life cycle.

Figure 2.1. Life cycle modules as per RICS 2nd Edition based on BS EN 15978, BS EN 17472, and BS EN 15643 (3)



Historically, Government policies and voluntary efforts from the industry have primarily focused on the reduction of operational carbon emissions of buildings. However, for the UK to reach its 2050 net zero target [4], focusing efforts on reducing the embodied carbon of buildings is also critical. Within their latest whole life carbon roadmap, UK Green Building Council (UKGBC) currently estimate the embodied carbon from the construction and refurbishment of buildings to make up 20% of built environment emissions (4). The analysis by UKGBC estimates that this percentage will increase to over 50% by 2035 as operational emissions from buildings decrease, thereby highlighting the importance of reducing embodied carbon across the built environment.

Carbon emissions are typically quantified using Global Warming Potential (GWP), which is measured in kilograms of carbon dioxide equivalent ($kgCO_2e$). Carbon dioxide, by definition, has a GWP of 1 $kgCO_2e$, because it is the gas being used as the reference emission. Using $kgCO_2e$ allows a comparison of the global warming impacts of different gases, as CO_2e pertains to the equivalent carbon dioxide emissions of different substances. These gases are typically those reported as direct gases under the Kyoto Protocol (5). The larger the GWP, the more the gas warms the Earth's atmosphere compared to CO_2 over a 100-year period. It should be noted that under some scopes of carbon assessments, further impact categories aside from global warming potential are also assessed to ascertain their environmental impact (see Section 7.2).

At present, there are numerous industry efforts and local authorities looking to develop carbon assessment guidance aimed at driving carbon reductions across the built environment. This includes through the following mechanisms:

- **Local planning requirements** such as the Greater London Authority, or Bath and North-East Somerset, and others.

- **Sustainable assessment methodologies** such as Building Research Establishment Environmental Assessment Methodology (BREEAM), Home Quality Mark (HQM), Leadership in Energy and Environment Design(LEED), and others.

- **Cross-industry collaboration efforts** including but not limited to, Net Zero Carbon Building Standard (NZCBS), Low Energy Transformation Initiative (LETI), Built Environment Carbon Database (BECD).

- **Professional institutions** such as the Royal Institution of Chartered Surveyors (RICS) Whole Life Cycle Assessment (WLCA) guidance, Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum TM65, Royal Institute of British Architects (RIBA), etc.

4 The 'net zero target' refers to a government commitment to ensure that the UK reduces its greenhouse gas emissions by 100% from 1990 levels by 2050 (38)

These current guidance documents have greatly supported further carbon data availability for new buildings and awareness of the embodied carbon impact of new developments. This has enabled carbon assessments to become more developed and more commonly conducted across new buildings. However, there is still progress to be made to drive consistency within carbon assessments thereby increasing robustness and reducing uncertainty. Reducing uncertainty can support further reductions in embodied carbon across the sector through enabling robust financial decision-making for implementing and funding embodied carbon reduction measures.

In addition, a broader understanding is required of the sector-wide economic impacts of widespread carbon assessments in order to support informed decision-making. This includes understanding the cost effectiveness of different decarbonisation solutions to enable easy wins to be identified and implemented across the sector, whilst also understanding the macro-level challenges and opportunities with reducing embodied carbon.

The following sections of the document therefore detail comprehensive research into the technical and economic considerations for measuring and reducing embodied carbon in new buildings.

3. Typologies and benchmarks

This section sets out the research undertaken to establish the current building types in the UK, how these are best categorised into typologies, and the existing upfront and embodied carbon benchmarks and targets that can be applied to each of the categorised typologies. The aim of this is to understand the different types of current benchmarks and targets, their robustness, and how they can be utilised to drive embodied carbon reductions.

This initial research forms the basis for the cost analysis in Section 5.2, and the results inform the need for further research into the level of uncertainty and gaps in the data, which has been explored in detail in Section 4.

3.1 Literature review of carbon assessments to derive building typologies for further analysis

AECOM conducted a thorough literature review of current UK new-build building stock and the carbon assessment data available with the aim of establishing building typologies for further study and analysis.

To identify the building typologies which have the greatest potential embodied carbon impact at both an individual and national scale, the literature focused on the following aspects:

1. Anticipated embodied carbon impact nationally

The embodied carbon impact at a national scale is important to consider as this is anticipated to be a large contributor towards national carbon budgets. UKGBC estimate that the current embodied carbon from the construction and refurbishment of buildings to comprise 20% of built environment emissions, with this rising to over half of built environment emissions by 2035 (4). It also enables developments which may have a low embodied carbon impact per development but a large number of developments e.g., low rise residential to be considered.

2. Availability of carbon assessment data

It is important to have good data availability to be able to have sufficient data to inform robust benchmarks and targets.

3. Anticipated embodied carbon impact per building

There are developments which are very carbon intensive compared to the number of developments at a national scale for example data centres.

It was concluded that, although bespoke typologies can enable bespoke building types to be captured (e.g., funeral homes), the limited correlation with UK industry guidance documents could impact the development of robust benchmarks in the future. There is also the risk that defining bespoke benchmarks by building characteristics could reduce the ability of policy to drive embodied carbon efficiencies. For example, for a hypothetical 25-storey commercial office building with a 4-storey basement, a bespoke typology method could require the building to align with less stringent embodied carbon targets than a 10-storey commercial office with no basement.

Based on the literature review and technical steering group discussion, it was proposed that industry-standard typologies be used with definitions of building functions and key characteristics to clearly define the scope of the typologies [5]. A clearly defined scope will generate consistent datasets that could be used to develop benchmarks if desired. The proposed set of six building typologies is shown in Figure 3.1.

Figure 3.1. Six building typologies from the literature review undertaken

1	Low-rise residential	Buildings intended for private occupation, providing habitable spaces for occupants. Typically for single families. Includes buildings no greater than three storeys.
2	Mid or high-rise residential	Buildings providing a separate and self-contained premise constructed or adapted for use for multi-residential purposes and forming part of a building from some other part of which it is divided horizontally. This includes buildings greater than 3-storeys. Can be privately or publicly owned.
3	Commercial offices	A place of business where professional duties are undertaken, people do non-manual work, professional, commercial, or bureaucratic work. An office can include the following spaces: private offices; shared offices; open offices.
4	Industrial	A building enclosure and site within which goods are manufactured, assembled, stored, or shipped.
5	Education	Buildings which are used for the education of students from first year primary school to final year secondary school or sixth form college. This includes both state and private schools.
6	Other buildings	Buildings where the function is not covered in 1–5 above.

5 Please refer to Appendix A for a summary of the characteristics of the agreed building typologies.

To add context to these typologies, further research was conducted to establish the functional and form requirements based on industry standards and guidance. The six typologies defined in Figure 3.1 have been used to structure the further research in this report in relation to benchmarks and targets (see next section) and for the cost analysis presented in Section 5.2.

3.2 Literature review of existing benchmarks and targets for upfront and embodied carbon

Upfront and embodied carbon benchmarks provide metrics that can be used to assess buildings' performance. These benchmarks can serve as averages to inform targets, key performance indicators, maximum value and minimum values. However, within the analysis undertaken, the benchmarks typically refer to maximum embodied carbon limits. Targets on the other hand describe optimal levels to aim for in order to decarbonise buildings. Both benchmarks and targets are essential for supporting carbon reductions, as they help asset owners and developers understand project performance. Additionally, they enable developers to set ambitious goals that drive lower upfront and embodied carbon emissions across their projects and portfolio.

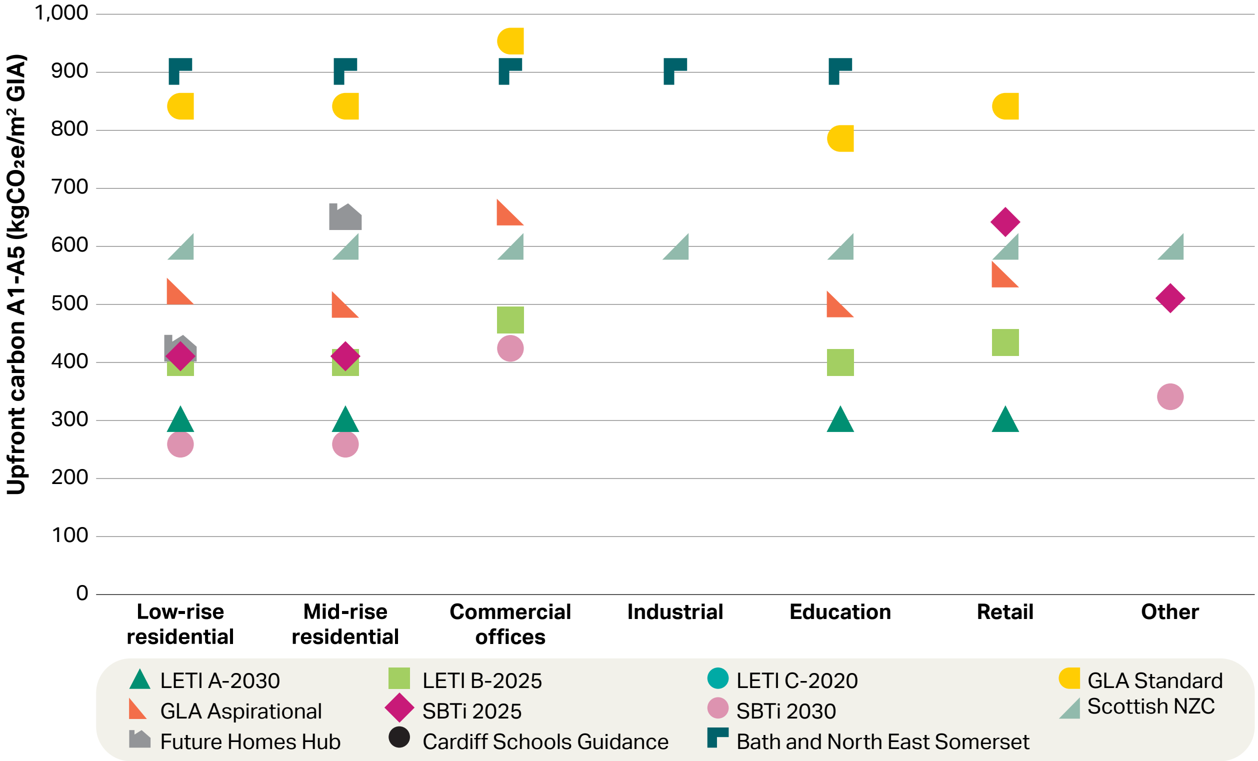
A significant challenge with existing benchmarks and targets is the variation between them, which stems from discrepancies in their base and scope. AECOM have conducted a comprehensive literature review of these benchmarks and targets to evaluate their value and applicability across the building typologies outlined in the previous section. This review compared their scope, the basis of the data underpinning them, and identified gaps in benchmarks for specific building types. The findings from this review provide a clearer understanding of how current benchmarks and targets can be improved and standardised to effectively guide the reduction of carbon emissions in the building sector.

3.2.1 Key findings

Based on the research undertaken, the following key findings were identified:

- **Significant variations in the availability of benchmarks and targets:** Different building typologies have large gaps in the number of available benchmarks and targets. This is due to a lack of both upfront and embodied carbon data available to inform the typology specific benchmarks and targets. Typology specific upfront carbon benchmarks and targets are only available for certain typologies, as most benchmarks and targets are for embodied carbon.

Figure 3.2. Comparison of upfront carbon benchmarks or targets



- **Variations in the carbon impact of benchmarks and targets:** Figure 3.2 demonstrates that the most significant variation in the benchmarks and targets is within the residential typology. This is underlined by the range of average data points (modules A1-A5 $kgCO_2e/m^2$) reported by the multiple sources of benchmarked data i.e., the mid or high-rise residential upfront carbon benchmarks and targets vary by 71%, and the low-rise residential embodied carbon benchmarks and targets vary by 73%. Embodied carbon has a more significant variation than the upfront carbon due to the inherent uncertainty within modules B and C, as the scenarios being modelled can occur several years in the future.

  The considerable variation across all the typologies highlights the challenge of setting upfront and embodied carbon benchmarks and targets, as the variation indicates the disparity in reported WLC emissions across the industry due to uncertainty in WLC assumptions and models (see Sections 5.1 and 5.2 for more information on uncertainty).

- **Variations in the scope of benchmarks and targets:** It is also clear that many benchmarks and targets do not specify the scope boundaries of their dataset. This leads to inherent challenges in comparability, which affects how beneficial they may be in driving carbon reductions. Furthermore, where benchmarks and targets do provide details on their scope, this is typically with varying levels of detail and clarity. This includes inconsistencies within the BS EN 15978 life cycle modules included, building elements included and the building element categorisations across the different sources.

The inconsistencies in the scope of benchmarks and targets prevent accurate comparison between building performance and the benchmark targets. This could be used to game WLCAs to enable the reported emissions to meet benchmarks and targets without implementing the corresponding design changes.

- **The basis and transparency of benchmarks and targets:** The basis of benchmarks and targets is not transparent across the sources assessed, which limits the ability to assess the robustness of the benchmarks and targets. There are also challenges in the validation of data that underpins benchmarks and targets, with this process also not being transparent. This hinders the ability of benchmarks and targets to provide a robust mechanism for enabling lower embodied carbon across developments.

  Furthermore, where there is transparency of the data underpinning benchmarks and targets, it is evident that these are typically underpinned by a small selection of developments, which may not be representative of the broader building stock. For example, the analysis found that the data underpinning benchmarks and targets is typically London-centric, which may limit their applicability to buildings outside of London due to differences in scale and proportions of buildings.

  In addition, the scope of the carbon data underpinning benchmarks and targets is commonly based on structural embodied carbon data only. It is unclear if and how this has been scaled to reflect the carbon impact of the whole building.

  Despite the challenges noted above, many of these benchmarks and targets were set when there was less embodied carbon data for buildings readily available. Therefore, as greater levels of embodied carbon data become available over time and the robustness of this increases due to an increasing industry skillset, the robustness of benchmarks and targets will improve.

- **Lack of consistency of normalisation units of benchmarks and targets:** Embodied carbon benchmarks and targets are generally reported as pro-rated figures, typically over GIA (kg CO_2e/m^2 GIA). However, around half of the benchmarks and targets analysed do not define the area type used to pro-rata the absolute carbon impact. This hinders comparability to benchmarks and targets and increases the risk of gamification. Some benchmarks and targets also use alternative functional units such as Net Internal Area (NIA), volume (m3) of internal area, or number of occupants. The use of alternative or multiple functional units has the potential to mitigate gamification, however this requires further research as detailed within Section 7.1.

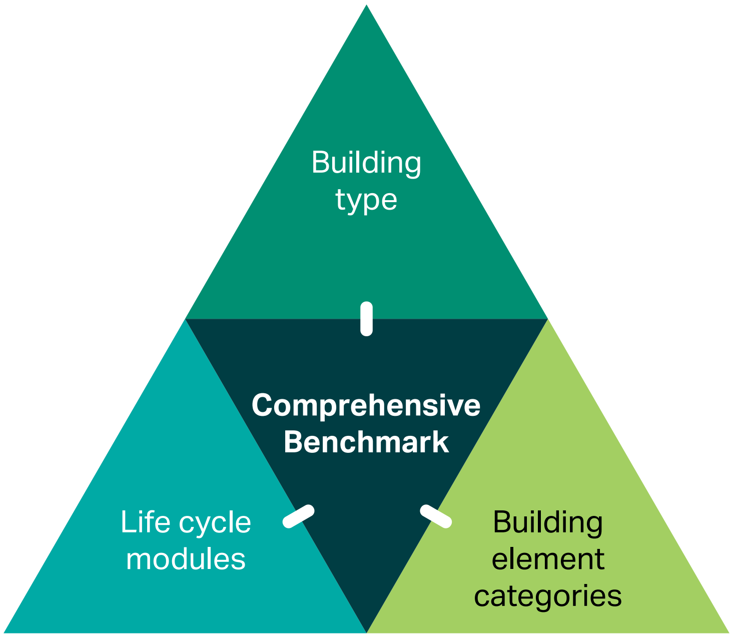
3.3 Typologies and benchmarks conclusion

Three scope elements need to be clearly defined to ensure consistency across the industry when understanding and reporting embodied carbon. They are; the building type, the building element category scope and the WLC life-cycle modules that are covered by the benchmarks and targets.

Figure 3.3 illustrates the scope elements required for comprehensive embodied carbon benchmarks. Accurate comparisons between benchmarks and targets and project data can be made by declaring these three elements.

As noted above, there is a considerable variation in benchmarks and targets for all the building typologies due to the lack of data and the uncertainty in the carbon assessment assumptions and models. The next section sets out the causes for uncertainty in the results and investigates how consistency can be improved.

Figure 3.3. Scope elements required for comprehensive embodied carbon benchmarking



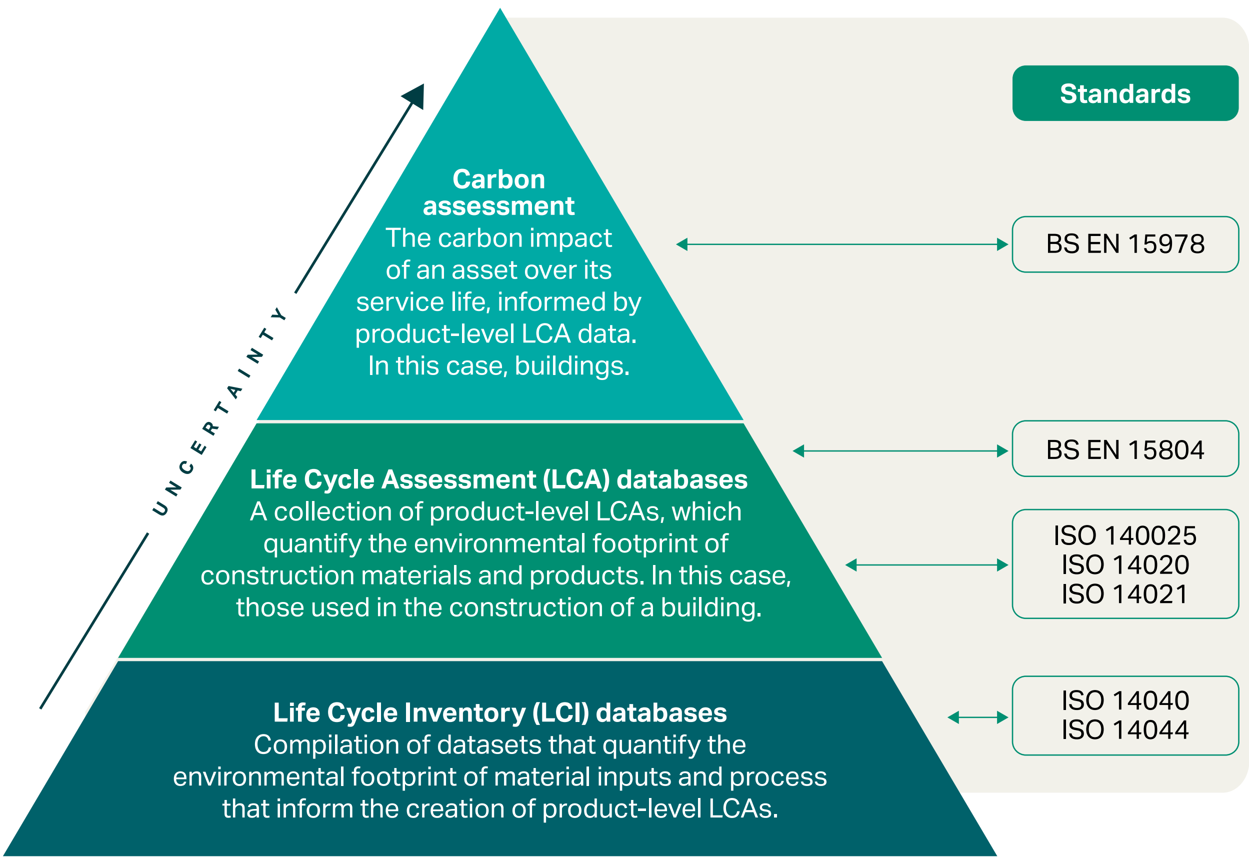
4. Uncertainty and consistency

Carbon assessments are reliant upon several layers of underlying data types to provide a complete figure for the upfront, embodied, and whole life carbon impact. However, each layer has a certain level of uncertainty, which is compounded as the assessment progresses.

This uncertainty remains regardless of whether the same guidelines are followed to develop carbon data. Figure 4.1 outlines the types of carbon data that feed into the production of product-level and building-level carbon assessments..

This section explores the causes of uncertainty at these different levels and then sets out how consistency can be improved.

Figure 4.1. How types of carbon data are used in carbon assessments



4.1 Qualitative assessment of the uncertainties in carbon assessment data and results

Firstly, a qualitative assessment of the uncertainties in the data and results of carbon assessments was undertaken. The research investigated critical areas of uncertainty across both building-level carbon assessment studies and the wider industry. This included examining how these uncertainties consequently impact building-level carbon assessments, as well as published industry benchmarks, targets, and datasets. Addressing uncertainty helps enable more reliable financial decision-making for funding projects and implementing embodied carbon reduction measures, not only for new buildings but also for infrastructure, which is intrinsically linked.

The research highlights trends in uncertainties within carbon assessments across the built environment. It included a literature review and discussions with the project's technical steering group to identify key uncertainties in carbon assessments.

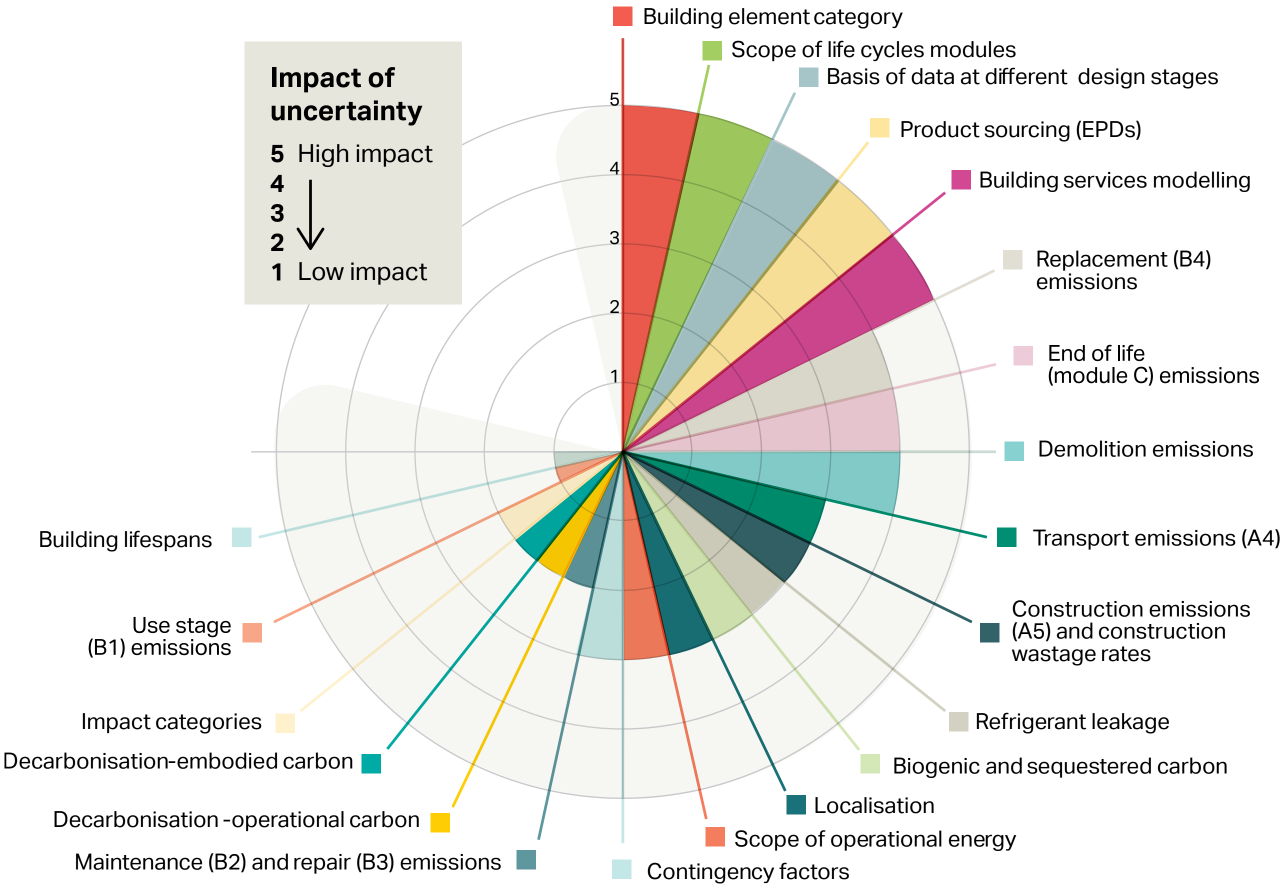
4.1.1 Key findings

Within carbon assessments, there are various sources of uncertainty, including the data inputs, the carbon assessors themselves, carbon tools and carbon assessment guidance. Figure 4.2 summarises the shortlist of uncertainties and uses a scoring system to rank the uncertainties [6] from the highest to the lowest impacts on both the carbon assessment datasets and on individual, building-level carbon assessments. The diagram shows that the most impactful uncertainties are the scope of building elements, product sourcing, Environmental Product Declarations (EPDs), and challenges with building services' WLC information. Further uncertainties which have been found as relatively impactful include demolition, as well as in-use replacement emissions. These topics are expected to have a more significant impact on WLCA datasets than at the building level as the assumed scenarios for these modules in a design stage WLCA could differ greatly from the as-built scenarios.

It has been estimated that inconsistent use stage repair and maintenance assumptions, building life spans, decarbonisation, impact categories reported, and the level of data available at different design stages are currently less impactful than other uncertainties analysed.

6 1: Anticipated low impact on both carbon assessment datasets and individual building-level carbon assessments; 2: Anticipated moderate impact on carbon assessment datasets and low impact on individual building-level carbon assessments. 3: Anticipated moderate impact on both carbon assessment datasets and individual building-level carbon assessments; 4: Anticipated high impact on carbon assessment datasets and moderate impact on individual building-level carbon assessments; 5: Anticipated high impact on both carbon assessment datasets and individual building-level carbon assessments.

Figure 4.2. Summary of the impact of shortlisted uncertainties



Each of the uncertainties displayed within Figure 4.2 has been further defined within Appendix D.

Following the qualitative analysis above, the following section details how key uncertainties were quantified to establish their likely impact.

4.2 Quantitative assessment of the uncertainties in carbon assessment data and results

Selected uncertainties from the qualitative assessment were quantified to establish the robustness of embodied carbon assessments and highlight uncertainties that may increase variations in embodied carbon assessment results. This helps to prioritise those that need addressing to reduce the levels of uncertainty in results.

4.2.1 Key findings

The uncertainties in embodied carbon data and modelling that have been quantified are set out in Table 4.1 along with the approach to quantification and a summary of the impact. Quantifying all the uncertainties identified in Section 4.1 was not possible due to a lack of data and/or resolution in the datasets or tools.

Table 4.1. Impact summary of uncertainties in the data and results of carbon assessments

Quantified uncertainties	Approach to quantification	Summary of impact
Basis of data at different design stages underpinning carbon assessments	Sampled approach of AECOM BREEAM Mat 01 carbon assessments across concept and technical design stages.	The results show that the percentage change between Stage 2 and Stage 4 may vary from around 4% to 29%, demonstrating the variation between WLCAs at different stages. Carbon assessment results typically reduced at Stage 4 when compared with Stage 2, which is likely due to level of detail available and lesser contingencies built into raw model inputs (i.e., the material quantities). This may affect how embodied carbon budgets are established at earlier project stages. However, it was not possible to draw an accurate conclusion due to the small size of dataset and data limitations. Further research is also required on how assessment results may vary at post-completion stage once sufficient carbon assessment data is available.
How product sourcing and transport assumptions affect A4 emissions	Theoretical analysis of the module A4 emissions for key construction materials (derived from a Material Flow Analysis (6)) across nine hypothetical building locations.	Scenario 1 assessed transport emissions between England-based manufacturing sites and hypothetical rural, suburban, and urban building site locations. Scenario 2 considered the transport emissions for materials typically imported to the UK from European and International manufacturing sites for the same site locations as Scenario 1. These were compared to RICS and Building Research Establishment (BRE) assumptions to be used for determining transport emissions. For Scenario 1, the RICS and BRE distances and associated emissions were higher than the average distances for the site locations assessed. As the production and site locations were all based in England, the transport modes used for this analysis, RICS and BRE were the same and therefore the emissions reported for each of the options followed the same relationship as the distance. For example, for Scenario 1, where the concrete was assumed to be delivered to a suburban site, the variation between our assessment and the RICS and BRE values was between 46% and 83%. For Scenario 2, on average, the RICS and BRE assumptions had a lower distance than in the cases assessed. Despite this, the emissions associated with each scenario were found to vary, with RICS assumptions tending to have the highest emissions impact. This is because the transport modes differ between our modelling and those assumed by RICS and BRE, and the carbon factor is different for each mode of transport. For example, for Scenario 2, where the steel was assumed to be sourced from Europe and delivered to a suburban site, the variation between our assessment and the RICS and BRE values was between 60% and 97%.

Quantified uncertainties	Approach to quantification	Summary of impact
Inconsistencies in how construction site emissions (A5) are accounted for in carbon assessments	The sampled approach of site emissions reported on AECOM projects for BREEAM under the Management 03 credit.	The results from actual construction projects indicate that the average site emissions per m^2 GIA are typically lower than the RICS 2nd Edition assumptions. Construction site emissions assessed demonstrate a large variance, with this ranging between 15% to 80% lower (exc. anomalies) than the RICS 2nd Edition assumptions. In contrast, actual construction project emissions were found to be higher than the One Click LCA generic assumptions. The uncertainty between actual construction site emissions and typical WLCA model assumptions may affect comparison to upfront carbon benchmarks, including construction site emissions (life cycle modules A5).
Effects of localisation	The sampled approach of AECOM projects with and without localisation using One Click LCA.	A particular problem is that carbon models allow turning localisation on or off at a building level and at time of analysis, not at a construction product level. Hence, with localisation on, if the carbon data is derived from a product produced in Germany, the same adjustment of carbon factors is applied whether the product installed in a building is actually sourced from the UK or Germany. Typically, construction products are sourced both from the UK and abroad, and localisation should only be applied to products that are sourced in the UK if no appropriate carbon data exists. This also affects average materials, which are typically global averages that are then localised to be appropriate for the region of the assessment. At a project level, the impact on total product stage emissions was relatively small, with up to a 2% difference between non-localised to localised results. The impact of localisation is more pronounced at a material level, with the product carbon impact differing by up to 33% (per kg of material). The materials most impacted by localisation were plastic, aluminium, steel, insulation, and glass. Given the prevalence of these materials in UK construction, further clarity is required over which products may typically be imported and, as such, localisation should not be applied to. Further guidance and training are required to ensure the industry understands the effect of localisation to improve carbon data quality at a material and asset level.

Quantified uncertainties	Approach to quantification	Summary of impact
Use of EPDs	Sampled approach of carbon factors for key construction materials based on Material Flow Analysis.	A significant variation in the generic carbon factors of the carbon tools was found. This is demonstrated by ready-mix concrete, one of the most common construction products, where the generic product stage impact varied by a maximum of 100% per tonne of material between the carbon tools assessed. This level of variation could have significant knock-on effects on the upfront and embodied results, and construction choices. The product-specific EPDs analysed had greater consistency in the product stage carbon impacts reported; however, it should be noted that the EPDs analysed were chosen as they represented the 'average' embodied carbon impact of each material analysed for comparison to generic factors. The inconsistency in reported carbon impact of similar products may lead to large variations in carbon assessment results by carbon tool, with further challenges arising due to EPDs that are used in models not necessarily being the product used in the built asset. This variance also enables gamification of carbon assessment results based on default tool assumptions and/or carbon datasets utilised.
Effect of decarbonisation on embodied carbon	Theoretical analysis of six decarbonisation scenarios based on the National Grid Future Energy Scenarios for 2023.	It is predicted that future carbon assessments will more commonly utilise RICS 2nd Edition guidance, which includes an embodied carbon decarbonisation scenario. The RICS decarbonisation scenario represents a much smaller benefit compared to the Future Energy Scenarios (FES). The results demonstrated that the impact of embodied carbon decarbonisation varies by building typology and is typically linked to replacement cycles of materials. Although including embodied carbon decarbonisation is not currently standard practice, this could be used to game results and demonstrate larger reductions, the scale of which depends on the methodology used. Consistency and transparency is required when applying decarbonisation across carbon assessments to ensure fair comparisons.
Effect of end-of-life scenarios on materials	Theoretical analysis of potential end-of-life scenarios for commonly used materials.	For each material there are several potential end-of-life scenarios, all of which creates a large amount of variation in the embodied carbon impact of each material emissions for all materials. Hence, across a building the impact on embodied carbon caused by the end-of-life scenarios is multiplied. This means it is possible to game embodied carbon assessment results due to a lack of consistency in the approach and reporting of end-of-life scenarios.

Quantified uncertainties	Approach to quantification	Summary of impact
Effect of replacement periods on embodied carbon emissions over 60 years	Theoretical analysis based on a range of service life scenarios.	The embodied carbon emissions of all materials analysed varied significantly due to large variations in the service lives. Without clearer guidance on typical replacement cycles for materials, module B4 replacement emissions may be calculated to be artificially lower or higher than actual emissions, leading to the potential gamification of carbon assessment results.
Inconsistencies in reporting of pre-construction demolition emissions	Theoretical analysis using an example pre-demolition audit.	Both the Greater London Authority (GLA) and RICS 2nd Edition pre-construction demolition assumptions have a higher impact per m² GIA when compared with the calculated values from the example pre-demolition audit. The potential variance between high reuse or recycled scenarios, as detailed in the pre-demolition audit, and default RICS end-of-life scenarios was approximately 10 $kgCO_2e/m^2$ GIA. This highlights the potential variance in pre-construction demolition emissions depending on the end-of-life scenarios implemented. For reference, 10 $kgCO_2e/m^2$ represents 1% of the modules A1-A5 GLA benchmark for offices and hence could be seen as a relatively small difference. The variation between current pre-demolition emissions assumptions (such as GLA and RICS) and calculated pre-demolition emissions from pre-demolition audits emphasises how the actual impact of asset demolition is still unknown. It is also expected that demolition emissions are significantly higher than what is currently reported due to limitations in the scope of pre-demolition audits. Hence, the uncertainty is predicted to be greater than what has been found by the analysis within this report. This relates to a wider national conversation on the importance of building retention and retrofitting of buildings where feasible.

The uncertainties analysed and the ability to artificially alter results create a high uncertainty level within carbon assessments at an asset and national carbon assessment dataset level. Further guidance is recommended to standardise modelling approaches and reporting of carbon assessments to reduce uncertainty and potential gamification.

The following section investigates the availability and consistency of data for construction products as this forms the foundations for the carbon assessment calculations and is the root cause of some uncertainty within carbon calculations.

4.3 Qualitative assessment of the carbon data availability of construction products

One of the primary challenges in conducting carbon assessments is obtaining and analysing variances in carbon data for construction materials. This lack of data and the variation between datasets produces inconsistent assessment results, reduces the value in comparing these results across the industry, and makes it challenging to monitor the built environment sector's progress towards net zero carbon. Therefore, the availability and accuracy of construction products' carbon data has been assessed, and an action plan has been proposed to address the data consistency issue.

To compare the results of embodied carbon assessments across the industry, AECOM sampled data from three commonly used databases: GaBi, EcoInvent, and ICE V3. These databases account for a large number of EPDs and were used to represent the availability of EPD data for construction products. Generic carbon data was also sampled from a wider number of sources, including these databases. AECOM selected construction products that represent a large portion of the embodied carbon typically seen across the building elements across all building typologies. 34 materials and products across 7 building elements (defined using RICS NRM1 categorisations) were assessed, and the results were analysed to determine the differences in carbon data quality between the databases.

The main focus points of the study were the comparison of variations in the life cycle modules presented, the material lifespans assumed, the biogenic carbon separation, and the reporting of other effect categories beyond global warming potential, like acidification and ozone depletion potential. These parameters were chosen in line with the primary reporting requirements set out under LCA standards, such as BS EN 15804:2012. The assessment reviewed various data sources concerning carbon emissions, particularly Life Cycle Inventory (LCI) data sources covering building elements throughout a building's life cycle, as defined by the BS EN 15804:2012 standard. However, inconsistencies were noted in coverage across different life cycle stages, highlighting industry challenges in determining what to include in building environmental impact calculations.

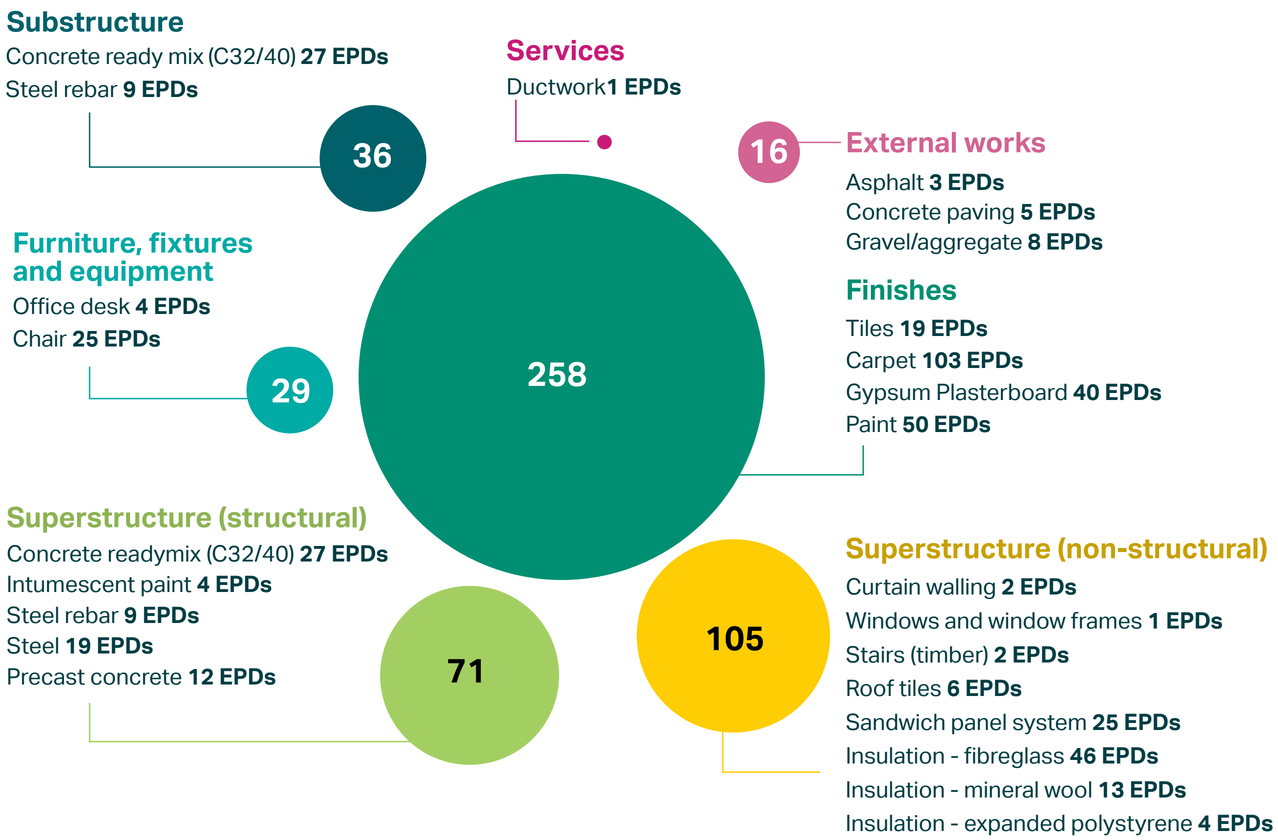
4.3.1 Key findings

The key findings from the study are set out below:

- **There are large gaps in the availability of EPD data for certain building elements:** An assessment of data availability was conducted for a sample of common building materials to identify gaps in EPD data availability.
  The results of the sampled exercise can be seen in Figure 4.3, which shows that External Works, Services and Furniture, Fittings, and Equipment (FF&E) building elements exhibited the poorest EPD data availability, possibly due to product complexity and a fluctuating supply chain for building services elements.

There is a misconception that FF&E products have minimal environmental impacts, often leading to their exclusion from carbon assessments, or these being calculated via a percentage addition that may not accurately represent their impact.

Figure 4.3. Environmental Product Declaration (EPD) availability in the UK



- **There is no clear correlation between data quality and magnitude of carbon impact:** The product stage emissions per tonne of material (kgCO_2e/tonne) were calculated for each EPD or alternative carbon data point (for example CIBSE TM65 data). This analysis showed that a high carbon result does not directly mean a poor-quality emissions factor has been selected.

- **There is a large variation in product carbon results for similar building products:** The variation was found to seemingly be unrelated to data quality. This may have the side-effect of carbon modellers using materials with lower carbon footprints within building-level carbon assessments, even if those materials are not used directly in the project. This method potentially gamifies the outcomes by inflating or deflating carbon emissions to achieve a particular conclusion, hence manipulating overall carbon assessment results.

- **One-third of materials and products sampled lacked UK-based EPDs:** The lack of information was primarily related to Mechanical Electrical and Public Health (MEP) products, highlighting the importance of UK-representative EPDs for accurate WLCA reporting.

- **Across a variety of carbon tools, there are gaps in the availability of generic data among common building elements and materials:** The analysis was conducted across commonly used tools and carbon datasets. The analysis found that some carbon datasets are more limited than others in providing generic data for construction products. These limitations may lead to inconsistent reporting within embodied carbon assessments, subsequently affecting uncertainty within carbon assessment datasets.

  Generic carbon data, unlike EPD data, is not specific to a manufacturer and usually represents an average percentile of available carbon data. However, this is commonly global data that is then localised to be more applicable to each region.

In addition to the uncertainty from the data that underpins the carbon assessment calculations, there are variations in the assumptions and approaches used in the various tools and reporting mechanisms. This has been explored in the next section.

4.4 Qualitative review of existing carbon tools and carbon assessment reporting mechanisms

Carbon assessment reporting mechanisms are consistent methods of reporting carbon assessment results, typically in spreadsheet format. An analysis of the variations between different carbon tools and reporting mechanisms across the industry has been undertaken to understand the barriers to the use of tools' and the challenges and opportunities of carbon assessment reporting mechanisms. The research is not intended to criticise or undermine the tools and reporting mechanisms discussed. Four industry carbon tools were analysed, and the tools were selected as they were the most frequently used tools from the industry questionnaire discussed in Section 5.3. In addition, nine carbon assessment reporting mechanisms were analysed. This included reporting mechanisms linked to local planning requirements, sustainable assessment methodologies and industry guidance.

4.4.1 Key findings

The analysis demonstrates that there are variations in both the method of inputting data and the results that each carbon tool analysed produced. The key variations included:

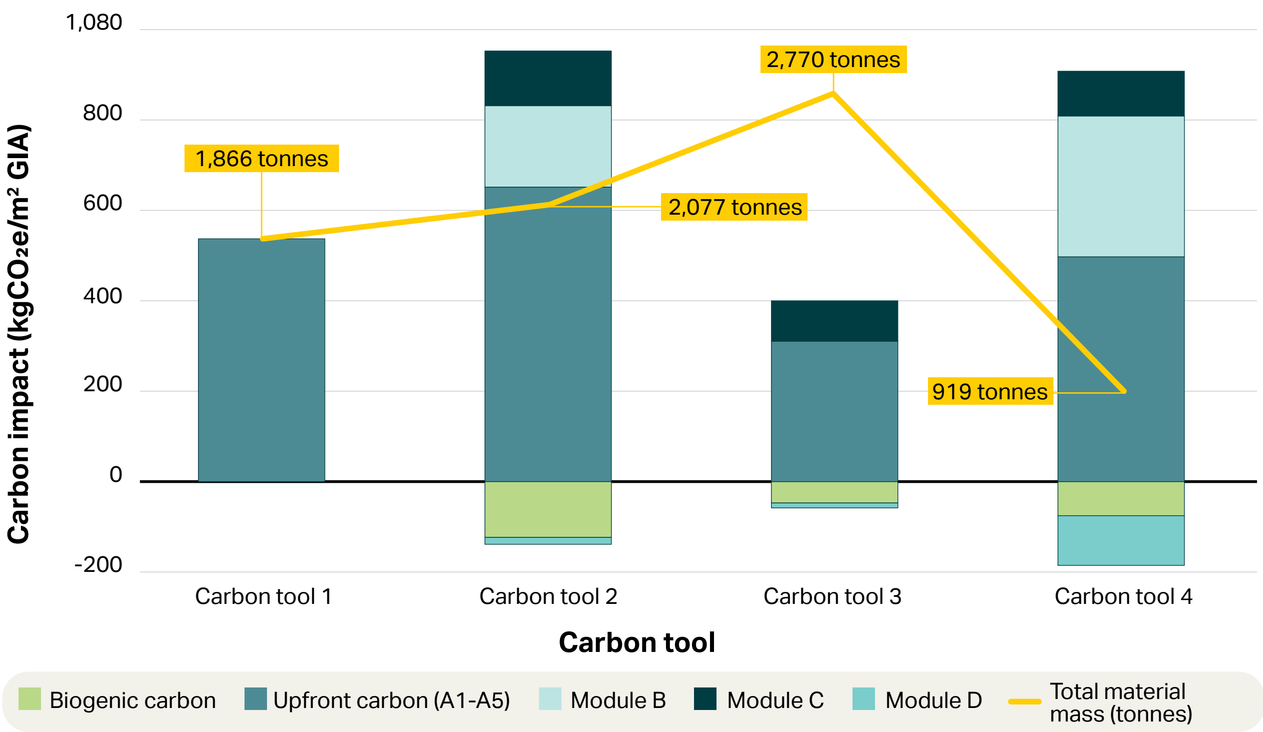
- **The scope of the tools:** Both in terms of BS EN 15978 life cycle modules included and building elements included within the tool's dataset.

- **The underlying datasets:** Different datasets are utilised across different industry tools, causing variations within results.

- **The modelling approaches and inputs:** Carbon models require material quantity data to be input in order to generate results. Depending on the carbon dataset used, this may be required to be converted to a single unit (i.e. mass) prior to inputting data, which causes uncertainty associated with this conversion.
- **The assumptions used:** Each tool has default assumptions to support the calculation of embodied carbon emissions. These differ between each tool, and can often be overwritten by carbon modellers themselves.

These differences led to variations in the total embodied carbon calculated and material mass results. A sample project was modelled using four different carbon tools to demonstrate this. Figure 4.4 demonstrates the variation in the total carbon tool results, with a maximum of 70% difference across upfront carbon.

Figure 4.4. Comparison of carbon tool results [7] [8]



The underlying datasets are a key source of variation in the tool outputs. Some carbon tools rely on generic data generated by the tool using bespoke methodologies, and others rely on product-specific EPDs. Designers should not view the lack of EPD (Environmental Product Declaration) data in tools as a barrier to influencing early-stage design. These tools are primarily used to optimise form and minimise material usage, playing a critical role in reducing the embodied carbon impact of buildings.

7 These results are based on one sample building which has been modelled in each carbon tool.
8 The scope of building elements included varies across each carbon tool based on the maximum level of detail possible to model.

To achieve more accurate carbon assessments, it is essential to have consistent data sources across carbon tools, which can theoretically lead to less variability in results. To improve the data that underpin these assessments, there must be an increase in both the availability and accessibility of product- and manufacturer-specific data. Enhancing the availability of this data for designers and within carbon tools will improve the accuracy of carbon assessments at later design stages. Additionally, it will better inform generic carbon data sources, which are crucial for ensuring consistency in reported results.

Overall, from AECOM's experience, whilst simplifying or automating processes (either by carbon tools or by guidance) can lower the expertise levels required to conduct a carbon assessment, it may increase the risk of carbon assessments being undertaken by people who do not have suitable expertise. This often results in incorrect WLCAs which can impact the development of accurate benchmarks and targets.

A balance should be sought between the ease of use of tools, their complexity and the degree of automation, all of which have the potential to influence the uptake of carbon assessment modelling and the applicability of any carbon results. In the near term, this will help train the industry to use carbon tools and increase broader awareness and understanding of how to reduce embodied carbon. A consistent definition of competency for carbon assessors is also required; this could include developing and specifying training and/or experience requirements with appropriate codes, similar to professional bodies and charterships. This would help to increase the robustness of assessments undertaken.

In addition, there are currently limited mechanisms for verifying carbon tools and their accuracy. This is likely to be one of the causes for variations between carbon tools, and demonstrates a key method for how to improve accuracy and consistency within them.

Similar to carbon tools, there is a large variation in carbon assessment reporting mechanisms from the scope of elements, functional units, and impact categories reported. Currently, only one of the nine reporting mechanisms analysed requests additional impact categories beyond carbon; this represents both a challenge and an opportunity for the industry to improve. Additional impact categories include, but are not limited to, acidification, ozone depletion potential and water use. It is recommended that further research is conducted into additional impact categories, refer to Section 7.2 for further information.

The use of consistent reporting mechanisms can also be utilised to drive better data quality and usability within carbon assessment datasets. This includes utilising carbon reporting mechanisms to track key metrics beyond carbon, such as the scope of assessment, building height, structural type, and further metrics explored within Section 4.5. This would enable carbon data to be further contextualised, helping to improve the usability of this to set informed benchmarks and targets, and drive further embodied carbon reductions across the industry.

Although there is uncertainty with building-level results, they have been turned into datasets that are used to inform benchmarks and targets. The current, publicly available databases have been explored in the next section.

4.5 Challenges and opportunities of carbon assessment datasets

Carbon assessment datasets comprise a collection of building-level upfront, embodied and/or WLCAs. These could be used as an evidence base to inform the development of any potential future benchmarks and targets. A data-driven approach to carbon reductions is key to supporting the UK's decarbonisation aspirations. Carbon datasets enable the tracking of building-level carbon assessments across a large range of projects, with the aim of using this data to inform decision making and further decarbonisation opportunities throughout the value chain. Carbon assessment datasets are also useful for developing future benchmarks, targets, or legislation.

A limited number of publicly available carbon assessment datasets exist across the built environment. Two primary publicly available datasets exist: the Built Environment Carbon Database (BECD), and Price & Myers' datasets. The Price & Myers' embodied carbon dataset is publicly available, but it comprises solely structural embodied carbon data and only embodied carbon results developed by Price & Myers, a structural engineering consultancy. The BECD dataset enables anyone to enter data and covers a full scope of building elements and life cycle modules, as per RICS WLCA guidance. However, this initiative was only launched in October 2023, so the current number of projects within the dataset is lower than the alternative carbon assessment datasets analysed in this work. The dataset also enables users to upload data privately, so this data is not all publicly available.

There are further carbon assessment datasets in the market which are not publicly accessible. This includes datasets from carbon tool providers and carbon assessment data from local authority planning regulations, such as the GLA. Furthermore, some private companies, including architecture firms, engineering consultancies, developers and contractors, have their own carbon assessment datasets to inform decarbonisation solutions on their projects.

4.5.1 Key findings

The literature review conducted for this study identified the following key challenges:

- **Transparency and accessibility of the datasets:** this is key to enabling data sharing across the value chain, supporting feedback loops to help all value chain members reduce carbon emissions. However, few of the datasets analysed are currently open source, with those being limited in terms of either scope (e.g., life cycle modules or building element categories reported) or the current number of projects within them.

- **Quality of data within the datasets:** ensuring that carbon assessment datasets can accurately reflect the building stock is important. This would help ensure accuracy and robustness within future benchmarks, targets, and potential legislation.

The review identified the following key opportunities:

- **Tracking of key metrics and carbon reduction design measures in addition to carbon:** by establishing key metrics (such as the Royal Institute of British Architects (RIBA) stage of study, building function, GIA, structure type, MEP system type etc.) and tracking carbon, carbon assessment datasets can be used by other members of the value chain, such as designers, manufacturers, and developers.

- **Linking carbon assessment datasets to carbon assessment drivers and methodologies:** such as those within planning requirements and sustainable assessment methodologies, would enable robust data to be provided consistently. Collating data via this method would also help to ease the burden of uploading data separately to carbon assessment datasets, which currently acts as a barrier to increasing the building-level data within these datasets.

- **Benefits from reducing uncertainty within carbon assessment results:** Robust carbon assessment datasets can help to minimise uncertainty within current benchmarks and targets. Addressing uncertainties is key for the industry, and decreasing uncertainty can also decrease financial risk for businesses and investors who make funding decisions based on the cost-effectiveness of carbon reductions (7).

Data tracking recommendations

Based on the research undertaken and the challenges and opportunities identified, three levels of data tracking were recommended by AECOM. These levels would help to establish consistency across carbon datasets which would reduce uncertainty and improve the impact that carbon datasets can have on the industry. The three data tracking levels recommended are: a minimum practice, standard practice, and a best practice approach. Moving from minimum to best practice would create a more valuable dataset however greater resources would be required to compile the data. Establishing a consistent scope aims to improve consistency across carbon assessment datasets while making it easier to interrogate the data within them.

The proposed carbon assessment scope that should be tracked within WLCA datasets is outlined in Table 4.2 and Table 4.3. Yellow blocks within the two tables below denote proposed optional scoping items, whereby datasets should enable these to be reported within them but not as mandatory minimum fields. Optional fields reduce the barrier for entry to the dataset and thus enables greater engagement with the dataset.

Table 4.2. Proposed life cycle modules scope

Life-cycle module scope	Biogenic carbon	A0	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6 Regulated	B6 Unregulated	B7	B8	C1	C2	C3	C4	D1	D2
Minimum	✓	⊖	✓	✓	✓	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖	⊖
Standard	✓	⊖	✓	✓	✓	✓	⊖	⊖	✓	⊖	⊖	⊖	⊖	⊖	✓	✓	✓	✓	⊖	⊖
Best practice	✓	⊖	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Key ✓ Mandatory requirement ⊖ Optional requirement* × Not required

*This is considered to be optional for the carbon assessment dataset to include this field, and also optional for the user to enter this data.

Table 4.3. Proposed global warming potential (GWP) and further impact categories scope, building element category scope, and NRM1 breakdown

	Global warming potential and further impact categories					Building element category scope								
Level of rating system	GWP total	GWP fossil	GWP biogenic	GWP LULUC	Further impact categories	0. Facilitating works	1.Substructure	2.Superstructure	3.Internal finishes	4.Fittings, furnishings, and equipment	5.Service	6.Prefabricated buildings and building units	7.Works to existing building	8.External works
Minimum	✓	×	×	×	×	⊖	✓	✓	⊖	⊖	⊖	⊖	⊖	⊖
Standard	✓	✓	✓	✓	×	✓	✓	✓	✓	⊖	⊖	⊖	⊖	⊖
Best practice	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Key ✓ Mandatory requirement ⊖ Optional requirement* × Not required

*This is considered to be optional for the carbon assessment dataset to include this field, and also optional for the user to enter this data.

Based on the analysis undertaken, key metrics in addition to carbon emissions have been proposed against the different levels of carbon assessment datasets established. These are shown in Table 4.4.

Table 4.4. Proposed key metrics in addition to carbon

Metric	Study period	Primary functional unit -m² GIA	RIBA stage of study	Building function	Structural frame type	New-build vs. refurbished GIA	Secondary functional unit	Area of demolition	Facade type and area	Roof type and area	Heating and cooling type	Material mass	Location and rurality	Foundation type	Building height and no. stories above ground	No. of storeys basement	Construction value	Carbon tool	Dataset used	Ground condition
Minimum	✓	✓	✓	✓	⊖	⊖	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Standard	✓	✓	✓	✓	✓	✓	⊖	⊖	✓	✓	✓	⊖	⊖	×	×	×	×	×	×	×
Best practice	✓	✓	✓	✓	✓	✓	⊖	✓	✓	✓	✓	⊖	✓	✓	✓	✓	✓	⊖	✓	⊖

Key ✓ Mandatory requirement ⊖ Optional requirement* × Not required

*This is considered to be optional for the carbon assessment dataset to include this field, and also optional for the user to enter this data.

4.6 Uncertainty and consistency conclusion

The research and analysis in this section show uncertainty at every level, from products to buildings and at the national carbon assessment dataset level. The results of this analysis can be used to understand the sources of uncertainty better. It is recommended that the results of this work are used to create guidance that standardises the approach to modelling and reporting of carbon assessments and that databases include the appropriate level of data tracking to ensure that they are of the most value.

The next section investigates the cost and economic implications of measuring and reducing embodied carbon for developments, businesses, and the construction sector.

5. Cost and economic impacts of measuring and reducing embodied carbon

This section sets out the cost implications of the widespread measuring and reducing embodied carbon impact on projects and on businesses. It then goes on to estimate the potential economic impacts of carbon assessments on the construction sector.

The cost implications explored include the direct impacts on projects from implementing carbon reduction measures. The research investigates the current available information on the cost implications of building with low embodied carbon as well as quantifying the cost impact of carbon reductions on common building typologies. Developing an understanding of the cost implications supports the identification of easy wins, whilst determining the impact of key decarbonisation solutions at a national level. In addition, this section details research into the impacts of undertaking carbon assessments on businesses in terms of additional fees for assessments and the programme implications. This is with an aim to understand these cost impacts, alongside the perceived drivers and barriers towards assessing and reducing embodied carbon within new buildings.

The sector-wide implications of widespread carbon assessments have been explored by looking at different scenarios, from low to very high demand [9]. In particular, this affects the number of competent assessors required and the associated training costs. This is to establish whether there is a critical mass of carbon assessors currently to support widespread carbon assessments, and the key challenges and opportunities with training new carbon assessors to meet the demand.

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9 Low Demand: All domestic developments ≥ 150no. dwellings and all non-domestic buildings ≥ 10,000 m² floor area require carbon assessments.
Medium Demand: All domestic developments ≥ 50no. dwellings and all non-domestic buildings ≥ 1,000 m² floor area require carbon assessments.
High Demand: All domestic developments ≥ 10no. dwellings and all non-domestic buildings ≥ 500 m² floor area require carbon assessments.
Very High Demand: All domestic developments and/or buildings and all non-domestic buildings require carbon assessments.

5.1 Literature review of the cost implications of building with low embodied carbon

One perceived barrier to designing buildings with a low carbon footprint is that this may increase the cost of development. To investigate this perception, AECOM analysed the available literature on the cost impacts of embodied carbon reduction initiatives from both a capital and operational expenditure perspective.

The literature review aims to understand and collate the available cost data within the industry and apply it to the representative set of six building typologies identified within Section 2. The review then identifies knowledge gaps in the available data and notes where further research is required.

These initial findings have informed the detailed analysis of the cost implications of designing buildings with reduced embodied carbon set out in Section 5.2.

5.1.1 Key findings

- **Limited cost data is available for low embodied carbon design:** Across different building typologies, there is limited cost data for building with reduced embodied carbon. This is likely due to the limited sharing of data and a lack of transparency and consistency in how the carbon data in particular is derived (e.g., which life cycle modules are included).

- **A current focus on capital expenditure opposed to operational expenditure:** Where data is available, it typically focuses on capital expenditure rather than operational expenditure. Capital cost studies alone often inflate the costs of net zero carbon actions, whereas life cycle cost studies, which also capture operational expenditure, can highlight opportunities throughout the whole life of a project. For example, selecting materials with a greater service life may increase capital cost, but this would enable fewer replacement cycles over a building's life, benefiting both whole life carbon and operational expenditure.

- **The variability of cost impacts by development typology and requirements:** An example study from UK Green Building Council demonstrated a cost increase of 3-7% for an office example project and 3-4% cost increase for mid-high rise residential example project, when the projects were designed in line with the LETI 2025 targets compared to a typical reference design. To achieve the LETI 2030 targets, a cost increase of 8-17% for the office and 5-6% for mid-high rise residential example project was found. In practice, the range of cost impacts is likely to be much wider depending on the specific project requirements and embodied carbon measures employed as no single design solution optimises cost and embodied carbon reductions. This is due to variances in form and function, which influence the possible costs and carbon reductions, varying supply chains and product availability, and the challenges in interrogating individual low carbon measures without considering holistically the effect that this has on the design.

- **Market maturity for low carbon alternatives:** Cost premiums associated with reduced embodied carbon are frequently associated with challenges in the current supply chains' capacity to meet the rising market demand for low-carbon construction approaches, components and materials, and associated challenges with economies of scale (8). This is typically due to the relative immaturity and low volumes of alternative low carbon construction materials; hence the costs inherently tend to be greater than those of traditional construction which benefits from greater maturity and economies of scale. However, as the low carbon industry develops, the workforce is upskilled and the demand increases for low carbon materials, the overall cost of the low carbon material or intervention should reduce.

- **The importance of early-stage interventions:** In general, early-stage intervention in the design provides greater carbon reduction and lowers the cost of the intervention. This can include exploring options for excluding unnecessary parts of the design whilst still meeting or challenging the client's requirements, such as reducing the extent of the required construction. It should be noted that although this may lead to increased project 'soft costs', such as fees arising due to increased design time from complexity and coordination requirements (9), early-stage interventions should still be prioritised.

- **Encouraging circular economy principles to benefit carbon and cost:** Reusing materials is currently less prevalent than it could be, likely due (but not limited) to challenges with availability of certifications and warranties that validate the safety and quality of secondary materials (10). The lack of experience within the industry, combined with the small specialist supply chain with relevant experience and capability, are likely to lead to increased costs and reduced implementation (11).

Overview of current carbon reduction measures and estimated cost impacts based on literature review

The published literature typically indicates an uplift in cost for designing, supplying, and installing low-carbon construction methods, technologies and materials compared to traditional carbon-intensive equivalents. However, these costs should be reduced as supply chains mature due to increased demand and the workforce is upskilled. The literature analysed also demonstrated that there is limited published cost data to explore the cost implications of alternative embodied carbon approaches properly. Greater data sharing and, transparency and consistency of cost information (e.g., common life cycle modules included) to enable robust analysis will better inform good practice and help drive the development of solutions that optimise cost and embodied carbon design.

A review of the available information and technical experience indicates several typical recommendations made during the design stages to achieve embodied carbon reductions within new build construction projects (12).

These are summarised in Table 5.1, along with their relative carbon and cost impacts and barriers to implementation.

Table 5.1. List of embodied carbon reduction interventions based on the literature review [10]

Intervention	Estimated carbon impact	Estimated cost impact	Barriers to implementation
Avoid basement constructions	Large saving possible	Major decrease	Site constraints, planning and functional space constraints.
Replacement of refrigerant with low GWP options	Large saving possible	Minor increase	Low GWP refrigerants are limited to specific system types, and currently, few commercially available options exist. There may also be higher flammability with some low-GWP refrigerants (such as R-1234ze), which should be investigated further before implementation.
Efficient design of grid spans and beam depths	Medium saving possible	Minor decrease	Space use and future flexibility.
Replace cement in concrete with Ground Granulated Blast Furnace Slag (GGBS) or Pulverised Fuel Ash (PFA)	Medium saving possible [11]	Minor increase	GGBS and recycled steel are both finite resources and should not be prioritised over building less and more efficiently (i.e., less steel and concrete in the development). Cost or availability of low carbon alternatives. Cement replacements may lead to longer curing times.
Explore the use of Electric Arc Furnace (EAF) steel in place of blast furnace steel	Medium saving possible	Medium increase	Due to current limited EAF steel production capacity in the UK, EAF steel is likely to be sourced internationally. If the UK EAF steel supply increases, then the cost impact of EAF steel should reduce.
Optimise structural design floor loadings and minimise material quantities	Medium saving possible	Minor decrease (based on the assumption that any spare load capacity is removed)	Regulations might push towards unreasonably high loads and the structural engineer may feel uncomfortable reducing uncertainty factors. With a lightweight superstructure and façade system there is a potential loss of thermal mass.

10 Whilst the carbon impact is ranked from large to small possible saving, the interventions are not in exact order of potential carbon saving as interventions will have different impacts depending on the building.

11 It is noted that EN15804+A2 requires the embodied carbon to be allocated in proportion to the value of the products (known as economic allocation) rather than using the previous approach to allocate the embodied carbon entirely to the intended product. The impact of economic allocation for supplementary cementitious materials (such as GGBS), which are converging with the price of cement, is that reported embodied carbon of the concrete increases significantly versus if the embodied carbon were not allocated based on revenue. This would therefore reduce the potential embodied carbon savings from utilising GGBS.

Intervention	Estimated carbon impact	Estimated cost impact	Barriers to implementation
Use of hybrid aluminium for façade and cladding	Medium saving possible	Minor increase	Cost implication and limitations due to fire regulations.
Adopt passive based ventilation measures	Medium saving possible	Minor decrease	Site conditions, project requirements e.g., occupant comfort levels, including thermal comfort and acoustics.
Dematerialisation (particularly of finishes)	Medium saving possible	Minor increase due to self-finishing materials e.g., timber panelling	The cost as it is different to 'business as usual' practices. Potential acoustic constraints, depending on the function of the space.
Use of high recycled content steelwork	Small saving possible	Minor increase	As demand rises for recycled products and low-carbon alternatives, so will price, potentially causing scarcity.

The cost implications of implementing different potential embodied carbon reduction measures were then investigated further and quantified within the next section. This further built upon the initial literature review described above, utilising case study buildings as the base case for each building typology, enabling marginal abatement cost curves (MACCs) to be established.

5.2 The carbon and cost implications of embodied carbon reduction measures

This section quantifies the carbon and cost impact of different embodied carbon optimisations across 5 of the 6 building typologies previously identified in Section 3.1. The building typologies modelled are low-rise residential, mid or high-rise residential, offices, industrial and education.

5.2.1 Methodology

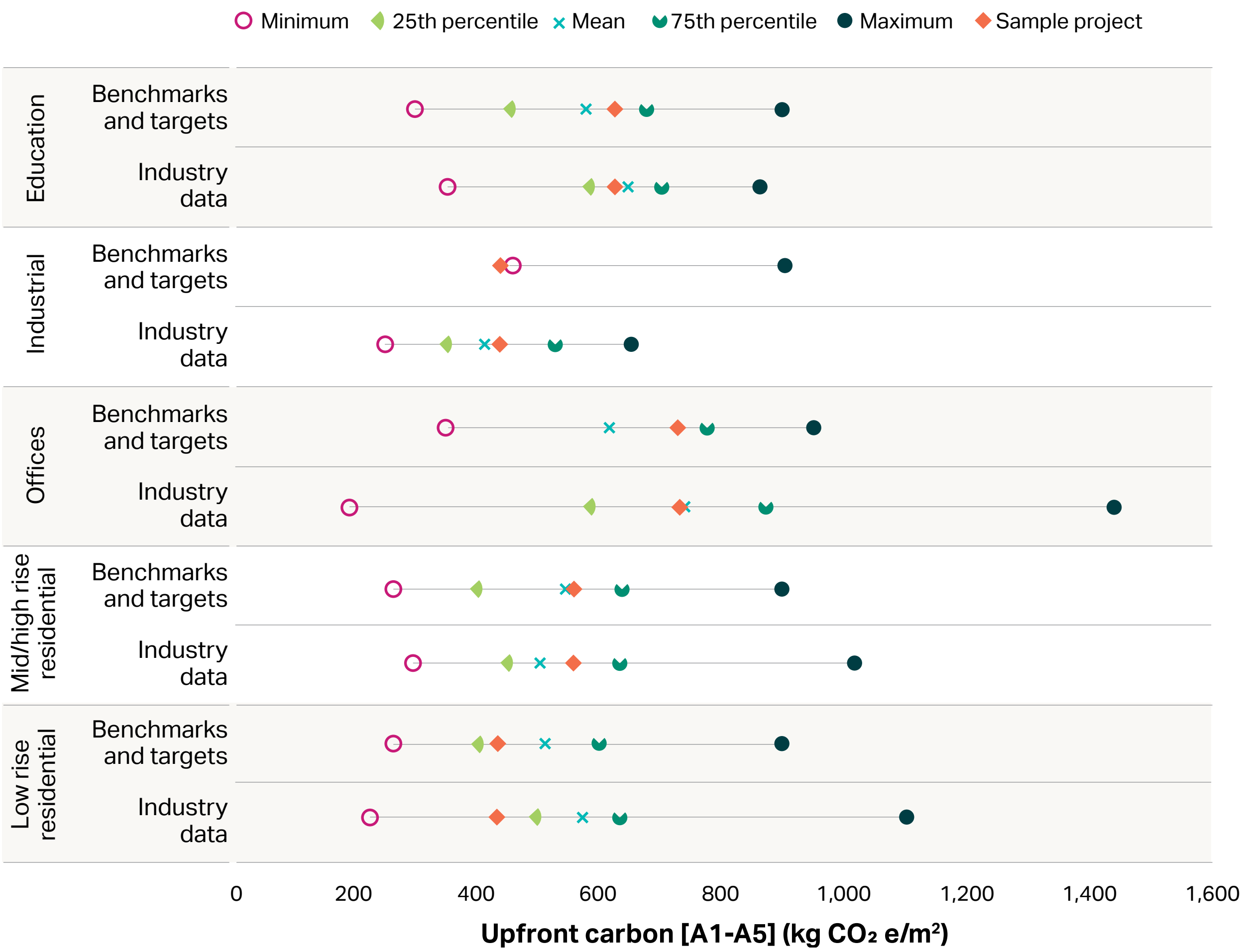
Sample building projects utilised

A series of 5 sample building projects applicable to each typology was selected to represent each building typology, and various carbon reduction measures (optimisations) were applied. This approach of using a sample building indicates the embodied carbon reductions achievable and the cost impact of measures being applied. The sample buildings were selected based on projects which reflect standard construction methods within each building typology and where sufficient data was available to underpin the analysis. However, it is acknowledged that this is likely to vary depending on the building's characteristics (e.g., size, form, function, and materiality).

Contextualising the sample projects' carbon results

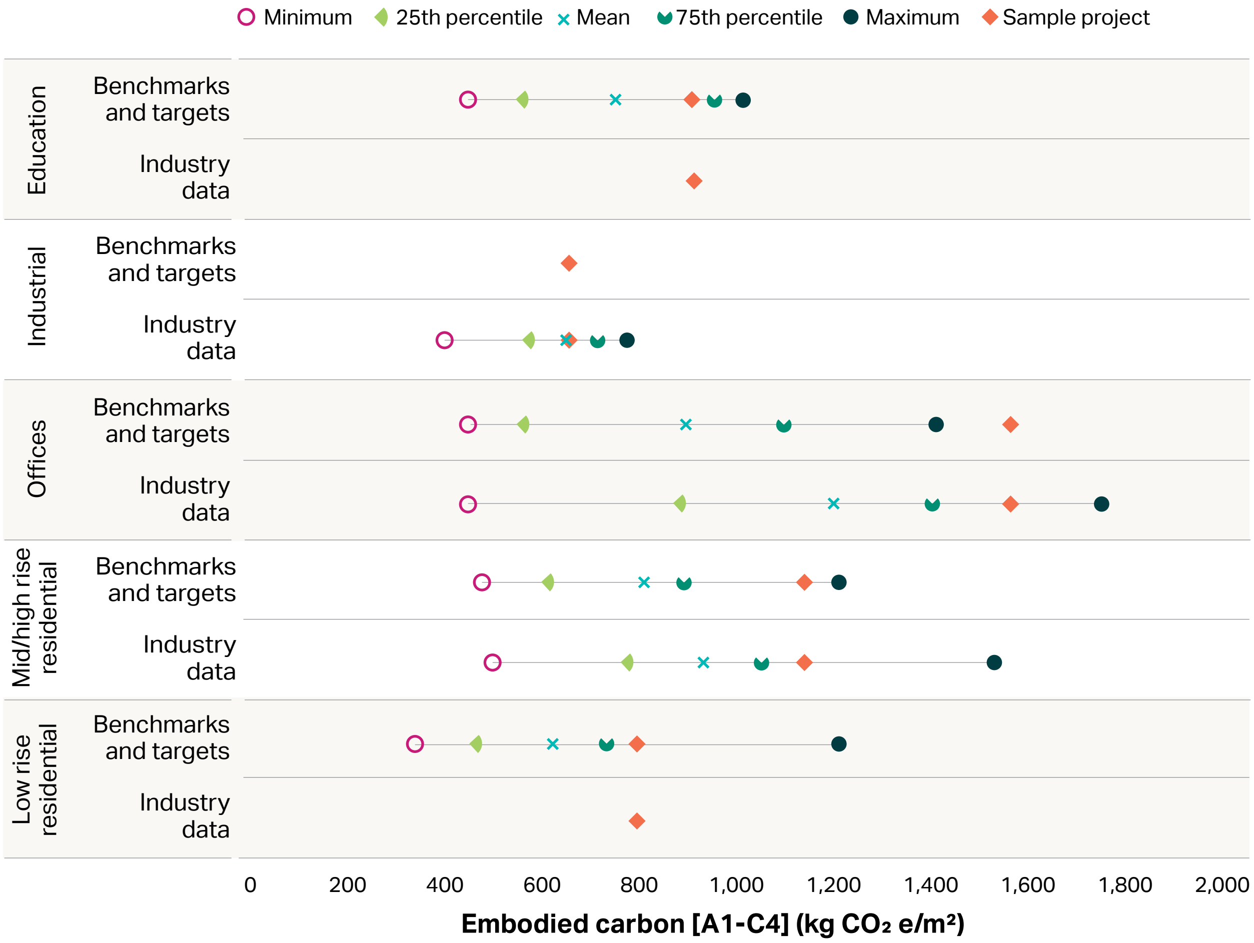
The five sample projects were assessed against the benchmark industry data to ensure they were sufficiently representative. This analysis showed that the sample projects are close to the expected mean industry data points for all typologies assessed, and therefore, they are broadly representative of the current anticipated building stock in terms of upfront carbon emissions. Figure 5.1 and Figure 5.2 demonstrate how the sample projects' upfront and embodied carbon emissions respectively compare with the anticipated variance based on benchmarks, targets, and industry data. Note that these figures only contain detail where benchmarks and targets, or industry data was available. Notably, there was minimal industry data for the embodied carbon of education buildings and low-rise residential buildings, and no embodied carbon benchmarks or targets for the industrial building typology. However, as demonstrated below, there was a much greater level of upfront carbon data available.

Figure 5.1. Comparison of the sample projects' upfront carbon results with industry data and current benchmarks and targets [12]



12 Note that there was insufficient data for the benchmarks and targets of the industrial building typology to generate a mean result.

Figure 5.2. Comparison of the sample projects' embodied carbon (modules A1-C4 exc. operational carbon) results with industry data and current benchmarks and targets



Shortlisting low upfront and embodied carbon optimisations for carbon and cost analysis

Six different optimisations were selected and quantified for each typology. These optimisations were established with the support of expert designers. Each optimisation's quantified cost and carbon impacts were then collated into Marginal Abatement Cost Curves (MACCs) to identify the most cost-effective embodied carbon optimisations. To do this, the MACCs display the total tonnage of CO_2e saved through the optimisation measures, alongside the cost per tonne of carbon saved. Please refer to Appendix D for the MACCs produced for each building typology. Note that the optimisations assessed do not include strategic design optimisations, which should be prioritised wherever possible. Strategic design optimisations include:

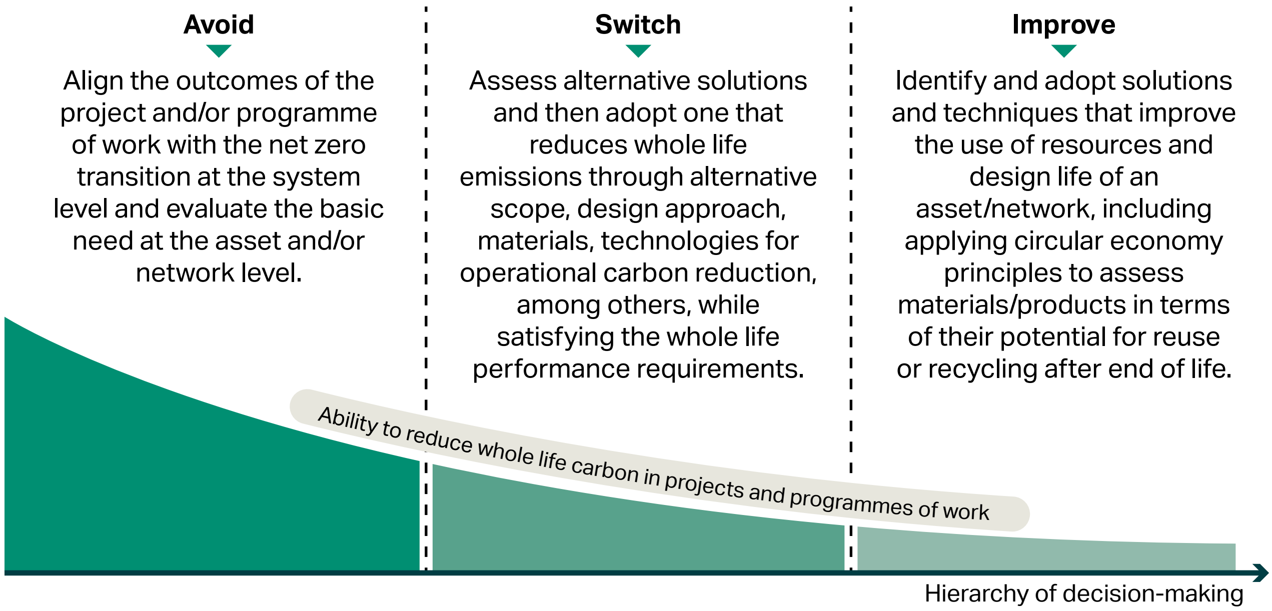
- Re-evaluating the need to construct a new building.
- Investigating alternatives such as retrofitting where possible.
- Investigating the effects of site selection on WLC and optimising the building form and Heating, Ventilation and Air Conditioning (HVAC) strategy from the early stages of a project.

5.2.2 Key findings

Strategic embodied carbon reduction measures

Fundamental design changes are a key method to achieve carbon targets and to support net zero carbon trajectories across the built environment. These include strategic design decisions which are typically undertaken at RIBA Stage 0 (Strategic Definition) and RIBA Stage 1 (Feasibility). At these early stages, there is the highest potential to reduce embodied carbon emissions, whilst also minimising or reducing cost. The cost impact of decarbonisation decisions as demonstrated within the carbon reduction hierarchy from PAS2080:2023 (13) displayed within Figure 5.3.

Figure 5.3. PAS2080:2023 carbon reduction hierarchy (13)



The potential for reducing carbon is typically greatest at the project inception. As the project progresses, the level of design detail and therefore accuracy of assessment increases, whilst the ability to influence whole life carbon diminishes. Hence, the carbon savings associated with strategic design decisions are not typically quantified. The carbon reduction hierarchy states to prioritise avoiding emissions as much as possible from project inception. For new buildings, this means evaluating the need for constructing a new building and investigating alternatives such as retrofit where possible. This would have a significant benefit for both embodied carbon and cost, provided that retrofitting a space could provide the sufficient functional requirements for the development.

In addition to following the carbon reduction hierarchy above, there are a number of key strategic design decisions which should be considered at the inception of development projects. This includes the following examples of embodied carbon reduction measures:

- **Site selection:** Site selection can have a large number of benefits for embodied carbon and cost which are predominantly associated with reduced material required but can also include emissions and cost associated with site access.

  For example, sites with poorer ground conditions may lead to the requirement for large, piled foundations which are more carbon intensive and costly than other foundation solutions such as pad foundations. Furthermore, sites which are on inclines and split-level buildings require volumes of concrete for retaining walls, leading to an increased embodied carbon within the substructure emissions.

  Within reason, these could be avoided through site selection considerations and placement of buildings on the site. A key challenge with optimising site selection is how embodied carbon can be factored into decision making at these stages. Firstly, measurement of emissions at this stage can be complex and based largely on design estimations and require tailor-made embodied carbon tools designed for early-stage optimisations. Secondly, the site selection (and/or placement of a building on a site) process often occurs before design team members or carbon consultants are involved in a project, meaning that opportunities at this stage may be missed. This highlights why a broader upskilling of the whole value chain is required, including developers and those involved in Strategic Definition (RIBA Stage 0) stage decision making.

- **Building form optimisations:** Optimising the building form can be a key way to greatly decrease both embodied carbon and operational energy emissions. Form factors are commonly used to estimate the ratio of heat loss to the heated floor space, and optimising this is one method to reduce operational energy carbon emissions (14). Buildings with a poor form factor are typically less energy efficient and therefore require additional building fabric efficiency (i.e., decreasing U-Values) to achieve required performance levels, which impacts the embodied carbon impact of the building envelope. Furthermore, simplicity of building form can decrease embodied carbon emissions, for example embodied carbon impacts can be reduced through the optimisation of the façade to floor area ratio and through removal of recessed entrances, cantilevers, and stepped façades (15). In addition to WLC benefits, optimising the building form can also reduce the total cost impact, both upfront and in-use, and should therefore be prioritised where feasible.

- **Heating ventilation and Air Conditioning (HVAC) Strategy:** In addition to providing operational energy benefits, optimising the HVAC strategy early in a project can also provide embodied carbon savings. For example, utilising passive solutions, such as natural ventilation and cooling, can reduce both operational and embodied carbon emissions, through the reduction of HVAC equipment. However, use of passive HVAC systems is not applicable to all building typologies and has potential challenges with external noise depending on the site location. Increasing the performance of a building's fabric can reduce the building's energy demand resulting in both operational and embodied carbon benefits as smaller HVAC equipment is required to meet the building's energy demand.

This is closely linked to the form factor considerations above, as an optimised building form will mean that it is easier to optimise the fabric performance, thereby reducing WLC emissions associated with the HVAC solution. Finally, system selection can support WLC reductions in emissions. It is important to consider a whole life carbon approach here, as focusing solely on operational energy could lead to an overall increase in WLC emissions when considering the embodied carbon impact of a system (16).

Decarbonisation optimisation measures explored above should be prioritised to support decarbonisation across the sector, whilst also providing cost savings. To successfully do this, a broader upskilling of the whole construction industry is required, from developers to designers, manufacturers, and contractors. Where there is wider knowledge on potential whole life carbon impacts, particularly at Strategic Definition (RIBA Stage 0) and Preparation and Brief (RIBA Stage 1) stages, carbon impacts from construction can be greatly reduced and cost benefits achieved. In addition to this broader upskilling, consistent early-stage optimisation carbon tools and consistent methodologies for calculation of emissions would increase the awareness of opportunities and the potential carbon and cost benefits from considering WLC emissions from early on in a project.

Cost-effective embodied carbon reduction measures

Further to the strategic embodied carbon reduction measures outlined above, the research also quantified the carbon reductions and cost impacts of a number of embodied carbon reduction measures. A summary of the most cost-effective embodied carbon optimisations has been produced for the optimisations analysed, identifying the typologies each measure applies to, the micro-level impacts and scalability considerations, as shown in Table 5.2.

This was derived through the Marginal Abatement Cost Curves (MACCs) developed for each building typology, with these displayed within Appendix D alongside a brief explanation of the results. The MACCs display the cost effectiveness of the embodied carbon optimisations assessed. This enables the identification of cost-effective embodied carbon optimisations, and measures which can drive down sector-wide embodied carbon emissions.

Micro-level impacts described within Table 5.2 refer to the challenges with implementing the solutions on a single building asset or development. Establishing micro-level challenges is important to understand what support can be provided to address these, with the aim of supporting the decarbonisation of embodied carbon emissions across new buildings.

The scalability describes the considerations for a broader uptake of each embodied carbon optimisation for the new buildings across the built environment. This helps to develop a comprehensive picture of how widespread carbon assessments can support the decarbonisation across the sector.

Table 5.2. Summary of the most cost-effective embodied carbon optimisations, applicable typologies, micro-impacts, and scalability considerations

Most cost-effective embodied carbon optimisations [13]	Applicable typologies	Micro impacts	Scalability
Optimised column grid in lieu of standard column grid	Mid or high-rise residential Offices Industrial Education	– Optimising the structural grid for the proposed design may limit future flexibility of the floor plate design. – Having shorter and lighter sections can be easier to crane, which can have benefits for the project timeline and cost. – Having lighter sections can decrease the required foundation quantities. – An optimised grid can reduce the façade area which has both cost and carbon benefits, however a limitation of this is the MEP requirements for underfloor space.	– An optimised column grid is easily scalable provided a structural engineer has been engaged on the project sufficiently early in a project's programme to inform this. The main limitation to the scalability of this optimisation could be future flexibility requirements of buildings.
Pad foundations based on ground conditions in lieu of pile foundations	Low-rise residential Mid or high-rise residential Offices Industrial Education	– The limited availability of ground condition information across the UK reduces the ability for structural engineers to accurately design to the specific ground conditions of the project site. A potential solution for this is to create a library of ground conditions based on the information collected for boreholes across the country.	– A key limitation to the scalability is the limited availability of relevant information of consistent quality. – A potential solution for this is to create a library of ground conditions based on the information collected for boreholes across the country.
Optimised rectangular mezzanine office layout in lieu of standard mezzanine office layout	Industrial	– Could restrict the number of users that have an interest in the mezzanine or office arrangement i.e., certain building users may prefer a C-shape mezzanine, for engagement between the office and industrial activities. – The more regular geometry and segregation between different structural typologies (long-span industrial and office) the greater the ability of future extension or modifications of existing building. It also can improve the ability to disassemble and reuse the building at end-of-life.	– As this is only applicable to specific industrial buildings, this optimisation has limited scalability across the entire UK building stock. However, depending on the geometry of the industrial building, a rectangular mezzanine should be easily implemented provided there is engagement with the developer, architect, and structural engineer.

13 Optimisations are displayed in no particular order.

Most cost-effective embodied carbon optimisations [13]	Applicable typologies	Micro impacts	Scalability
Exposed ceiling in lieu of suspended ceiling	Offices Industrial	– Additional acoustic baffles are required to ensure the acoustic properties of the office are acceptable. The quantity and type of acoustic baffles depends on the desired noise levels of the office. – As the services on the ceiling would be exposed, additional coordination of the MEP design may be required to ensure it is aesthetically pleasing.	– This can be implemented on all projects which include suspended ceilings, this limits the scalability as typically only offices and industrial buildings include suspended ceilings. – To ensure the acoustic requirements in the space are met an acoustic engineer may be required.
Hybrid Variable Refrigerant Flow (VRF) system in lieu of VRF with VRF serving Air Handling Unit (AHU) Coils	Offices Industrial	– There are potential limitations with supply as presently only one manufacturer produces a hybrid VRF system. – A hybrid VRF system requires more maintenance within the office areas. – There may be large variations in the cost of MEP systems due to the bespoke nature of their designs. – A hybrid VRF system requires more on floor space as hybrid VRF systems require expansion vessels.	– As there is only one manufacturer who currently makes hybrid VRF systems, this may impact the scalability of this system. However, the manufacturer is a large global manufacturer who has existing supply chain routes and infrastructure.
Electric arc furnace steel in lieu of blast furnace steel	Low-rise residential Mid or high-rise residential Offices Industrial Education	– There are potential supply issues due to limited number of steel works who can produce electric arc furnace steel. – Due to the limited number of available plants, storage of appropriate beams or sections for each project may be required. This can generate additional cost and coordination requirements. – There may be variations in cost due to warranties, associated contractor risks and insurance.	– Sourcing constraints associated with supply chain availability. – Effects of UK Carbon Border Adjustment Mechanism (CBAM) regulation on steel imports and the cost of this. – Fluctuating steel costs linked to energy costs.

Most cost-effective embodied carbon optimisations [13]	Applicable typologies	Micro impacts	Scalability
Reused steel in lieu of new steel	Low-rise residential Mid or high-rise residential Offices Industrial Education	– Stock matching is crucial to ensure that applicable sections are available. Timing is crucial. – For reused steel, a specific type and form of steel cannot be selected, a best match has to be used from within the inventory. – The specification is crucial, steel must be specified by performance criteria not by size or grade to enable reused steel to be used. – Steel defects (e.g., existing holes, attachment scars from shear studs, dents, and dings) may be visible. These are allowed but they need engineer input. These may also have issues for aesthetic expectations if the steel is to be exposed. – There may be variations in cost due to warranties, associated contractor risks and insurance.	– Availability of material and lack of material banks currently available in UK to enable a more consistent supply. – Broader insurance and warranty issues associated with reused steel.
Hybrid timber steel structure in lieu of steel structure	Mid or high-rise residential Offices Industrial Education	– There are potential durability and fire regulation issues associated with a hybrid timber-steel structure, depending on the building. – Fewer contractors have necessary knowledge of hybrid structures compared to steel structures which may result in a cost increase.	– Broader insurance and warranty issues associated with use of timber due to potential durability and fire regulation issues. – Limitations associated with building heights inhibits scalability. – Skills shortage across industry for timber design and constructability.
Air Source Heat Pump (ASHP) with Fan Coil Units and Mixed Mode Operation in lieu of VRF with VRF Serving AHU Coils	Mid or high-rise residential Offices Industrial Education	– Using an ASHP system enables R32 to be used, as R32 cannot be used with a VRF system due to flammability risks. – ASHP systems require additional pipework and larger fan coil units which can lead to deeper ceiling voids. – ASHP systems remove the risk of refrigerant leaks within the office space which is a present risk with VRF systems. – There may be large variations in the cost of MEP systems due to the bespoke nature of their designs.	– This is commonly used technology at commercial scale. – At a residential scale, upfront cost and skills gap of installers may limit the ability for ASHPs to be implemented.

Potential solutions to improve scalability

To address the challenges with scalability within Table 5.2, the following potential solutions were identified:

- **Sourcing constraints due to supply chain availability and supplier preference:** Due to both governmental and corporate net zero commitments, it is anticipated that more sustainable solutions should become cheaper and more accessible over time due to economies of scale. This process could be expedited through government subsidies and support of both low-carbon materials and UK-based manufacturing. Support for manufacturers in producing carbon data (such as EPDs) for new low-carbon products.

- **Warranties and insurance:** Similar to existing methods such as the mass timber insurance playbook (1), a similar insurance playbook should be created to support new and innovative materials, enabling further adoption of these across new construction whilst acknowledging and addressing insurance constraints.

- **Skills shortage, particularly for timber construction:** As noted in previous sections of this report, a general skills shortage is associated with sustainable design and construction due to the rapid increase in demand for both sustainable products and processes. Continued investment, particularly in training, is required to reduce the skills gap across the board. This includes upskilling the entire value chain, including developers, designers, manufacturers, and contractors.

- **Fire regulations:** Greater awareness of the fire regulations, and how to ensure fire safety, must be incorporated into every project with the support of a fire engineer or specialist. This should prevent blanket decisions being made and limiting the development of new forms and methods of construction.

  Fire ratings should be clearly provided for of all construction products. For smaller manufacturers, governmental support could help to ensure this is undertaken quickly and consistently.

- **Limited availability of both cost and carbon information:** Additional support is required to enable more robust and consistent carbon optioneering to be conducted throughout project stages. Refer to Section 4.3 for further detail on carbon data availability and potential actions to address this.

Macro-level considerations

In addition to the key considerations for scalability above, the following core macro-level considerations were identified:

- **Supply chain:** The UK heavily relies upon imported construction materials (17), around 80% of construction materials used in the UK are imported (18). The UK's supply chain is therefore open to risks associated with geopolitical pressures, global events, or natural disasters, on top of risks associated with domestic inflation.

- **Material flows for reused and recycled materials:** A 2023 study by Deloitte found that due to a lack of domestic recycling infrastructure the UK currently exports large amounts of recyclable waste, around 10 times more than is imported (18). This highlights how there is a large potential to utilise a greater level of recycled material within construction materials than currently happens. This can be increased through clearer communication across the supply chain regarding product sourcing to reduce potential programme delays and cost impacts.

- **Innovative and emerging materials:** There are a variety of barriers to the use of innovative and emerging materials including, but not limited to, the uncertainty of new materials, the scalability of the products at the pace required by the market, and challenges associated with supply and demand. To address this, funding should be encouraged which promotes use of innovative low carbon materials, alongside support for live trials to provide evidence of the specifications, strengths and usability of innovative materials thereby supporting their use across the industry.

The research undertaken has demonstrated how timber has an important role to play in decarbonising new construction. However, there are a number of challenges with the practical implementation of widespread timber usage, such as buildability, safety and widespread availability of skills. To better understand this, the following section explores the use of timber in more detail, analysing the national and international use of timber in construction. This is to ascertain the current barriers to increasing timber usage and the lessons that can be learned from the international markets.

5.2.3 The national and international use of timber in construction [14]

To support the built environment industry's transition to net zero, the sustainable use of timber across new buildings is an important part of decreasing sector-wide carbon emissions. Timber reduces carbon emissions due to the sequestration benefit achievable from timber building products. Sequestration benefits are typically accounted for in carbon assessments as a negative biogenic Global Warming Potential (GWP) value in accordance with BS EN 15978 and BS EN 15804. When looking to utilise timber to support decarbonisation, consideration must also be given to the end-of-life scenario of the product to ensure that benefits from sequestration are not lost. For example, if a timber product was combusted at the end of its life, carbon stored within the product would be released and therefore the carbon sequestration benefit would be lost.

14 The Timber in Construction Roadmap (20) has been published, which contains government and industry actions to support safely increasing the use of timber in construction.

The demand for natural, bio-based construction materials, such as timber, is anticipated to become more prevalent as carbon assessments become more widespread, and developments seek to meet embodied carbon targets. For example, the World Bank Group has forecast that the global demand for timber could quadruple by 2050 (19) as referenced by the timber in construction roadmap by The Department for Environment, Food & Rural Affairs (DEFRA) (20). However, expanding the use of timber in construction within the UK market is a complex task. Currently, there are a number of legislative and technical challenges with constructing new buildings from timber, which this report aims to explore further. To support a sustainable increase in timber use in construction, and to further support decarbonisation across the built environment, these challenges should be addressed.

Therefore, a qualitative review of the current state of play of the UK timber industry was undertaken to identify the key challenges in the UK market, as well as explore current initiatives and timber policies both nationally and internationally, which may be adopted to boost timber use within the UK. This included investigating fire regulations, insurance considerations, technical design and detailing, and embodied carbon and circularity considerations. The qualitative review aimed to inform MHCLG on possible methods for sustainably increasing timber usage to drive down embodied carbon emissions in new buildings.

Challenges and considerations for expanding timber usage in UK construction

The following areas were identified as being the key challenges and considerations for expanding timber in construction in the UK:

- **Expanding the UK's commercial forestry:** Expanding commercial forestry requires considerations related to the tree species intended for use in construction. If new species are brought in from abroad, their technical properties (used for design) will need to be established for the UK market first. Additionally, sustainable forestry principles must be embedded in any future commercial forestry expansion to ensure the protection of biodiversity and limit to mass tree disease spread.

- **Increase availability and robustness of information on fire performance:** There is currently a lack of robust information about the fire performance of mass timber products. As a result, current best practice recommends that, where use of mass timber is suitable, this is appropriately encapsulated with a fire resisting boarding system such as plasterboard. It is recommended that a targeted programme of fire testing and experimentation, in collaboration with relevant experts in the field, is undertaken to obtain a better understanding of fire dynamics in timber compartments, with particular focus on self-extinction and external flaming and fire spread.

- **Address insurance market concerns:** The UK insurance market is often reluctant to underwrite mass timber projects. Their primary concerns are water ingress, combustibility, construction quality control and record keeping. Existing initiatives, such as the Mass Timber Insurance Playbook have successfully addressed this challenge during the design stages. When it comes to preventing moisture buildup within the timber, as well as record keeping, the Mass Timber Insurance Playbook discusses practical examples of systems which could be applicable to address these issues both from an insurance standpoint, as well as structural performance generally.

Technical design and competency considerations for expanding timber usage in UK construction

From a technical design standpoint, this study has identified a few areas which require further consideration, particularly around increasing the technical competency of the UK designers:

- **Current structural design codes:** The current timber structural design code (Eurocode 5) does not cover mass timber structures, such as Cross Laminated Timber (CLT). The lack of official guidance has led to this becoming a specialist service, with few engineers holding the necessary knowledge to carry out the full structural designs. A new version of Eurocode 5 is expected to be released soon, which is expected to detail design guidance of mass timber elements such as CLT. Once the new version is released, it will be necessary to fast-track the knowledge-building phase, which can be achieved through up-skilling programmes supported by both government and professional institutions.

- **Increasing industry skillsets for timber construction:** There is an existing knowledge gap of Structural Engineers understanding fire. Structural Engineers will need to be more knowledgeable in fire protection systems and their limitations, as well as the structural performance in a fire limit state. Clear scope and professional competence levels may need to be re-defined to fill this skills gap.

- **Increasing publicly available testing data:** On a product and systems level, timber is predominantly a proprietary product, with elements and embedded connections performance and capacity locked away by the private market's Intellectual Property. The lack of publicly available physical testing data is a major barrier to upskilling more structural engineers in designing with timber. To overcome this challenge, it is recommended to invest in and support physical testing (of both products and systems), and to pool that information to inform design standards and guidance.

Embodied carbon considerations of timber

When undertaking embodied assessments of structures containing timber elements, steps should be taken to ensure accuracy and consistency in the reporting. This includes:

- **A consistent methodology and reporting of sequestered carbon:** Clearly identifying a consistent methodology for reporting of carbon sequestration, i.e., carbon stored within bio-based building materials (such as timber). This is to mitigate the gamification of results for timber products, where embodied carbon benefits from sequestration may be lost at end-of-life, depending on the end-of-life scenario. For example, if timber is combusted at end-of-life, carbon sequestration benefits would be lost as the carbon stored is released to the atmosphere. This highlights the importance of re-use or re-purposing timber at end-of-life should be prioritised and explored from the outset when looking to build in timber. This also highlights that without consistency in the methodology, different end-of-life scenarios may be applied, leading to the potential gamification of embodied carbon results.

Lessons learned from the international approach to timber in construction

Following a review of international approaches to timber in construction, the following key findings and lessons learned were identified:

- **Building regulations:** The latest revision of the American International Building Code includes allowances for exposed, partially exposed, and fully encapsulated timber. These are significantly greater (in terms of height limit) and those recommended by the STA design guidance in the UK and differentiate between sprinklered and un-sprinklered buildings.

- **Open-source databases for timber construction materials:** For example, Germany has an online open-source database of timber construction materials (21), components and component connections covering thermal, acoustic, fire and ecological performance levels, released by accredited testing institutes. Datasheets available from this site are generally accepted as proofs of compliance by building authorities (21).

- **Incentivise the use of low carbon materials:** This could potentially include an embodied carbon taxation which can be regularly reviewed and increased with time. For example, the Netherlands has a taxation to heavily polluting industries, currently set at €30/tonne of CO_2 and set to increase over time. Such interventions result in more carbon-intensive materials becoming more expensive to use, therefore incentivising the use of natural and lower-carbon alternatives. This may also include providing financial incentives for meeting a certain embodied carbon target, or for using bio-based materials.

- **Increasing timber usage in new public buildings:** Publicly funded timber construction projects and/or adopting a quota of timber usage in new public buildings. For example in Finland, the Government's wood building programme aims to build public buildings in timber. Furthermore, in 2020 the French Government announced that all new public buildings are to be built using at least 50% timber or other natural materials. This law was implemented in 2022 impacting the construction of all publicly financed buildings.

- **Supporting building circularity:** Enabling or supporting research and development in circular economy. To support this, the Netherlands has developed a Circular Dutch economy by 2050 roadmap which includes actions and projects which are to be implemented between 2019 and 2023 across different construction sectors. Additionally, Amsterdam aims to be fully circular by 2050. They developed the CircuLaw, which is a knowledge platform aimed at identifying opportunities in the current law and regulations which would support the transition to circular economy through policy intervention.

- **Improving timber supply chains:** Working with and supporting the forestry industry to boost the timber supply chain. For example in France, the forestry industry is investing in decarbonising the construction sector, through the Timber Construction Ambition Plan setting strategic commitments to develop training, employment, investment, Research and Development, development of the French wood supply chain, sustainable forest management, material cost reduction and recycling of timber.

Overall, expanding the use of timber in construction within the UK market is a complex task. This section has summarised the primary barriers the UK is currently facing, relating to the supply chain, legislation, and technical competency, and has provided recommendations for further research and example initiatives which may be expanded to help overcome these challenges.

The next section considers the cost to business of carbon assessments being adopted more widely.

5.3 The impact on business of carrying out carbon assessments

In addition to the cost impacts of utilising low carbon construction methods and materials, there is a cost impact to businesses for undertaking carbon assessments themselves. To better understand this impact, a questionnaire was issued to the UK built environment industry to gather information on the current state of carbon assessments being undertaken in the UK. In conjunction with the questionnaire, a workshop was held with a steering group consisting of developers to gain a greater understanding of the impacts to business of widespread carbon assessments.

The objectives of the exercise were to understand:

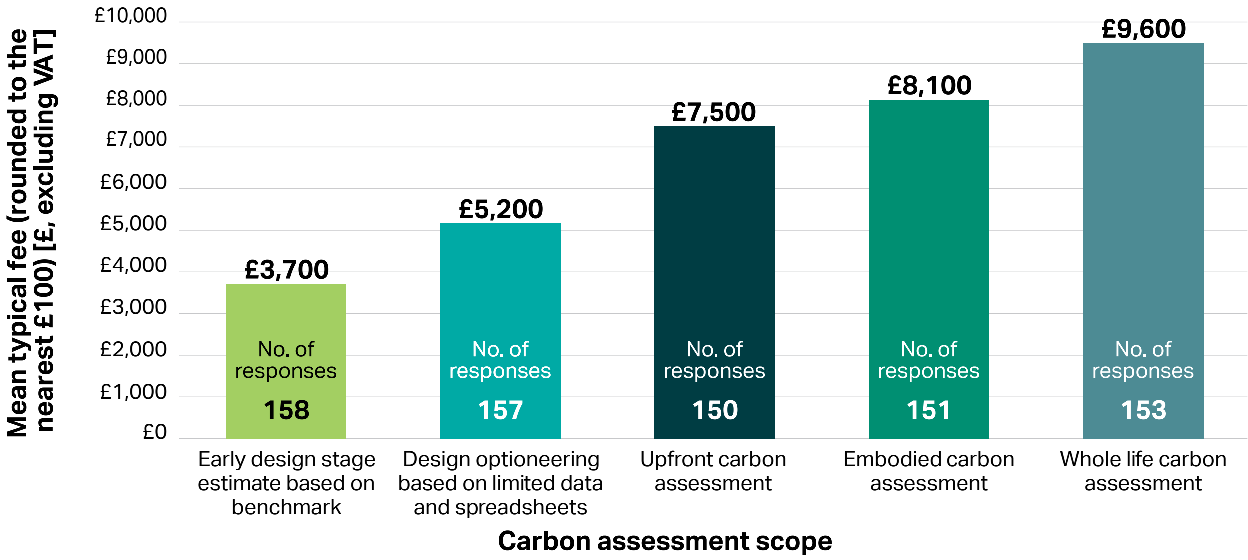
1. The costs associated with carbon assessments depending on the level of assessment and when the assessment is undertaken in relation to the project work stages.
2. The effect carbon assessments have on project programmes.
3. The most significant drivers, barriers, and risks to undertake carbon assessments.
4. The variation in uptake of carbon assessments on a national level.

5.3.1 Key findings

Costs associated with undertaking different types of carbon assessment

The industry questionnaire provided an indication of the costs associated with the scope of assessment undertaken as illustrated in Figure 5.4.

Figure 5.4. Estimated fee of undertaking carbon assessments based on assessment scope



The results within Figure 5.4 show that as the carbon assessment scope expands, typical fees increase, with the most common response for early design stage estimates being £0 to £3,000 and the most common response for whole life carbon assessments being more than £15,000.

This is expected as a wider scope requires more time to complete. Although Figure 5.4 shows an increase in fee in line with increasing assessment scope, responses were received for all fee bands across all assessment scopes. A large proportion (433 respondents, 33%) of respondents selected 'don't know' for expected typical fees and a further 8% of respondents selected "prefer not to say". This could be because they are not involved in the fee process or are not exposed to this information.

Costs associated with undertaking embodied carbon assessments by sector type

The average cost to undertake an embodied carbon assessment per sector type for different project gross internal areas is demonstrated by the industry questionnaire results displayed in Table 5.3.

Table 5.3. Mean typical fees (excluding Value Added Tax (VAT), rounded to nearest £100) for embodied carbon assessments by project size and sector. [15] [#] indicates number of responses

Sector type	Less than 500m²	500m² - 1,000m²	1,000m² - 5,000m²	5,000m² - 10,000m²	10,000m² - 20,000m²	More than 20,000m²	Sector mean
Industrial	NA [0]	£10,500 [1]	£4,500 [4]	£8,500 [3]	£12,500 [6]	£13,000 [6]	**£10,400** [20]
Other	£1,500 [1]	£10,500 [2]	£7,500 [1]	£15,000 [1]	£14,300 [2]	NA [0]	**£10,500** [7]
Energy + utilities	£1,500 [1]	NA [0]	NA [0]	NA [0]	£9,000 [2]	£14,100 [5]	**£11,300** [8]
Transportation	NA [0]	£7,500 [1]	£4,500 [1]	NA [0]	£8,500 [3]	£10,900 [8]	**£9,600** [13]
Healthcare	NA [0]	£10,500 [1]	£3,000 [4]	£9,500 [3]	£5,700	£10,400 [10]	**£8,000** [12]
Leisure	£1,500 [1]	£4,500 [3]	£4,500 [3]	£7,100 [7]	£11,500 [3]	£13,500 [3]	**£7,700** [20]
Government	£1,500 [1]	£10,500 [1]	£5,300 [4]	£1,500 [2]	£7,000 [6]	£11,400 [10]	**£8,000** [24]
Commercial	£3,000 [2]	£4,500 [5]	£3,600 [10]	£6,400 [17]	£7,500 [15]	£11,000 [38]	**£8,100** [87]
Retail	NA [0]	£4,500 [2]	£2,500 [3]	£6,600 [7]	£6,200 [7]	£9,400 [12]	**£7,100** [31]
Residential	£2,500 [6]	£2,100 [5]	£5,700 [13]	£7,700 [19]	£6,800 [13]	£9,700 [23]	**£7,100** [79]
Education	£1,500 [1]	£5,500 [3]	£3,300 [5]	£6,300 [12]	£7,000 [12]	£10,000 [13]	**£7,000** [46]
Sports	£1,500 [1]	£1,500 [1]	£1,500 [1]	£3,000 [2]	NA [0]	£9,800 [4]	**£5,600** [9]
Size mean	**£2,100** [14]	**£5,300** [25]	**£4,300** [49]	**£6,900** [73]	**£7,800** [74]	**£10,700** [132]	**£7,800** [367]

The largest project type cost would be an energy and utilities building of a GIA greater than 20,000 m², and the least costly projects are those who have a GIA less than 500 m² and are either for education, government, leisure, energy and utilities, sports, or 'other' sectors.

15 Average fees have been taken from ranges. For those who selected Healthcare only, 3no. responses were received: 2no. respondents typically have projects more than 20,000 m² and 1no. respondent typically has projects 5,000 to 10,000 m². Only 1 respondent selected healthcare, government, and education. This respondent typically has projects of 500 to 1,000 m². Therefore, as multiple sectors could be selected but only single areas and single fees could be selected, the area and fees for healthcare and Government projects of 500 to 1,000 m² may be based on Government projects.

The questionnaire results show that the costs associated with completing carbon assessments at each RIBA stage of work varies greatly between respondents based on the building typology and, the size and location of the organisation. In addition, a large proportion of respondents did not know the fees required for the different scopes of assessments. The responses received from the industry questionnaire indicate the cost of completing carbon assessments can vary greatly due to the building typology, building size (floor area), or building location.

The effect carbon assessments have on project programmes

When asked about programme delays, the number of respondents who said that there are no impacts (160 respondents, 42%) is only marginally outweighed by the number of respondents who stated that there are delays due to carbon assessments (189 respondents, 50%). For those who stated there are programme delays, the main reason given is that carbon assessments can delay design decisions. Many respondents (63 respondents, 17%) stated that carbon assessments need to be undertaken early in the project programme to mitigate delays on design decisions and to have the largest impact on reducing embodied carbon. Similarly to the fees greatly varying between respondents, so does the number of days required to complete carbon assessments. Respondents stated that carbon assessments can take between 1 day to more than 21 days.

The most significant drivers to undertake carbon assessments

The industry questionnaire indicated there are a wide range of drivers for undertaking carbon assessments, the major driver being net zero target achievement, followed by planning policy. The steering group suggested the primary drivers were third-party sustainability standards, scope 3 emissions reporting, and industry benchmarks and targets (these drivers were identified by questionnaire respondents, but they were not frequently mentioned).

The most significant barriers to undertake carbon assessments

The main barriers identified to undertaking carbon assessments based on findings from the questionnaire included a lack of a significant driver on a particular project and insufficient information being provided to the carbon modeller, which includes estimated material quantities at design stage and a general lack of guidance.

The most significant risks to undertake carbon assessments

The greatest perceived risk of not undertaking carbon assessments correctly is that an organisations' Environmental Social Governance (ESG) goal may not be achieved. The next highest perceived risk was not responding to planning policy.

Common themes

Several commonalities were found from general comments from respondents throughout the questionnaire. There was consensus that standardisation of carbon assessment methodology, scope, and carbon values is required, and the costs associated with carbon assessments are heavily dependent on the size and complexity of the project. Furthermore, the steering group highlighted the requirement for a general upskilling of the entire industry to better address embodied and whole life carbon emissions across the built environment. It was suggested that this could be supported by wider industry training on carbon assessments, alongside instilling more consistent feedback loops following project completion on how best to reduce carbon emissions across both their portfolios and wider industry.

The next section expands upon the project-level impacts discussed above to consider the potential national-level economic impacts of widespread carbon assessments.

5.4 Sector-wide economic impacts of widespread carbon assessments

A study was completed to understand the built environment industry's current capacity to undertake carbon assessments should these become widespread under a range of demand scenarios, as well as understanding the overall economic impact of widespread carbon assessments.

To understand this impact, the estimated annual demand of carbon assessments was calculated based on current annual building completions in England and the current availability of competent carbon assessors to undertake these assessments was estimated.

The sector-wide economic impact consists of the costs associated with completing carbon assessments in addition to the costs associated with training people to be a competent carbon assessor, in addition to the economic benefits. This economic analysis uses historic building data for England to estimate the demand for carbon assessments and therefore, this analysis does not consider the future demand for carbon assessments based on the predicted building completions in the coming years.

5.4.1 Key findings

Methodology

To estimate the annual cost of carbon assessments across England, four demand scenarios were calculated using the following:

1. Data from Energy Performance Certificates (EPC) lodgements from 2018 to 2023.
2. The cost for assessments per building typology (identified in Section 2).
3. The results of the industry questionnaire explained in Section 4.1.
4. A bottom-up analysis estimating the cost and time to produce different types of carbon assessments across different building typologies.

The four demand scenarios are based on the floor area and number of dwellings for non-domestic and domestic developments respectively: low (large developments only), medium, high, very high (all developments). These are detailed within Table 5.4.

Table 5.4. Estimated average annual demand for carbon assessments across various scenarios

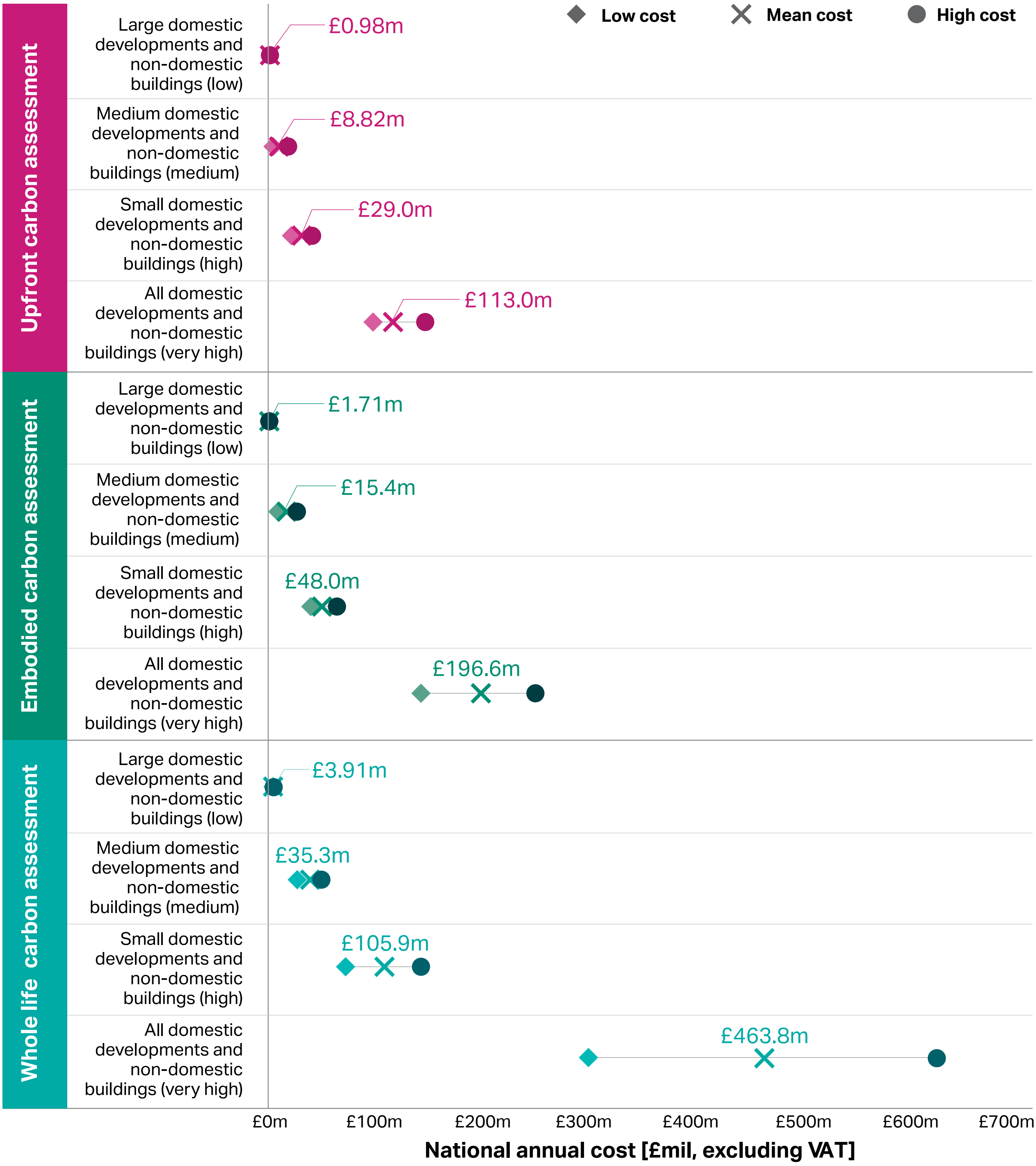
Demand scenario	DOMESTIC Building/ development size [No. of dwellings]	DOMESTIC No. of assessments per year	NON-DOMESTIC Area [m²]	NON-DOMESTIC No. of assessments per year	Total number of assessments per year
Low	≥150	27	≥10,000	168	196
Medium	≥50	281	≥1,000	1,493	1,773
High	≥10	3,879	≥500	2,065	5,945
Very high	All	20,376	All	4,765	25,141

In addition to the cost of carbon assessments themselves, the total availability of carbon competent carbon assessors was estimated. This was based on responses from a second industry questionnaire and historic training data provided by training providers. This assumes that to be deemed competent, an assessor must have undertaken some form of LCA training, either internally within their organisation or externally via a training provider. The availability of competent carbon assessors was then compared against the demand for carbon assessments to ascertain any deficits in the total number of carbon assessors required, in addition to the total cost of training sufficient carbon assessors to meet the demand.

Annual economic impact of widespread carbon assessments under a range of scenarios

The estimated annual total cost of carbon assessments is demonstrated in Figure 5.5 across the range of demand scenarios displayed in Table 5.4.

Figure 5.5. **Estimated national annual costs for carbon assessments based on the demand scenarios for carbon assessments**



As the demand for carbon assessments increases so does the annual cost however, the change in cost from a high to a very high demand scenario results in a large cost uplift with the maximum annual cost of widespread WLCAs estimated to be £628.5m. This trend is shown across the three types of carbon assessments included in this analysis: upfront carbon assessment, embodied carbon assessment, and WLCA. This is largely down to the cost and number of carbon assessments required for low-rise residential developments included within these scenarios.

Once residential developments of 10 dwellings or more require carbon assessments (High Demand), the number of annual carbon assessments increases substantially. It should be noted that tools are being developed, such as by the Future Homes Hub (FHH), that are free to use and will theoretically support a reduction in carbon assessment cost of low-rise residential building in particular. Therefore, the costs associated with the low-rise residential sector may be more likely to fall over time. Furthermore, as the market matures and the construction industry gains experience undertaking carbon assessments, standardisation will improve and time requirements may reduce which should, in time, reduce the overall cost of carbon assessments.

Supply and demand analysis for number of competent carbon assessors

There is currently no list of 'competent' carbon assessors, or indeed an agreed definition for what requirements comprise a 'competent' or 'suitably qualified' carbon assessor. A formal definition would help create an accurate assessment of the number of competent carbon assessors and therefore, the content and detail of carbon assessor training can be tailored specifically to meet the formal definition. This could be linked to years of experience, a professional institution and/or via a consolidated training programme and subsequent examination, demonstrating competency.

Due to the lack of a consistent definition for competency, the current number of carbon assessors was estimated based on data from an industry questionnaire and data provided from external training providers. This included undertaking sensitivity analysis to estimate the percentages of those who have undertaken training that are competent and the percentage of those who continue delivering carbon assessments after completing training. Based on this analysis, it is estimated that the lower estimated number of trained, competent, and active carbon assessors in the UK is circa. 80no., with the higher estimated number being circa. 330no. based on the sensitivity analysis undertaken.

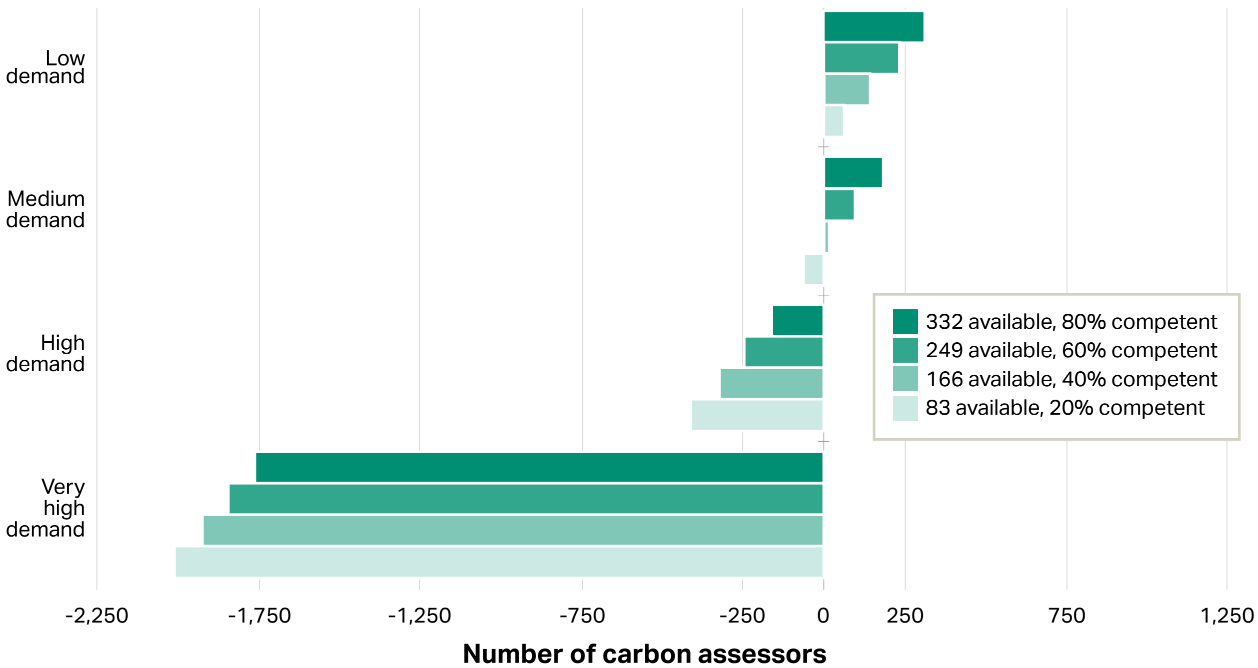
The current demand for competent carbon assessors is based on the estimated demand (Low, Medium, High, Very High) for carbon assessments annually as well as the number of carbon assessments a single full-time employee (FTE) can complete in a year which can vary from assessor to assessor.

Based on AECOM's experience, the most representative scenario of industry currently is that approximately 10% of externally trained and 20% of internally trained assessors continue working in carbon assessments, with a single carbon assessor able to complete 12no. carbon assessments in a single year. This is based on the assumption that the majority of assessors trained have undertaken a short course to understand the carbon process but wouldn't necessarily undertake carbon assessments themselves following this. This highlights the need for a formal definition of 'suitably qualified' carbon assessor, and linked training requirements to meet this definition.

However, the volume of people undergoing training courses (regardless of whether they continue completing carbon assessments currently) does indicate that the market is suitably adaptable to cope with increasing demands of carbon assessments.

The most likely representative scenario is shown in Figure 5.6, which demonstrates that there is currently estimated to be a sufficient number of carbon assessors for the majority of the low and medium demand scenarios modelled, although it is cautioned that this result is based on limitations and uncertainty within the economic analysis. Furthermore, it is likely that where drivers for undertaking carbon assessments increase, the number of carbon assessors would also increase. It is recommended that methods to explore increasing the competency of carbon assessors are investigated alongside methodologies being developed to assess and track the number of competent carbon assessors as noted above.

Figure 5.6. Number of competent carbon assessors required to meet the demand for carbon assessments for the most likely number of trained assessors and number of assessments completed by 1 FTE



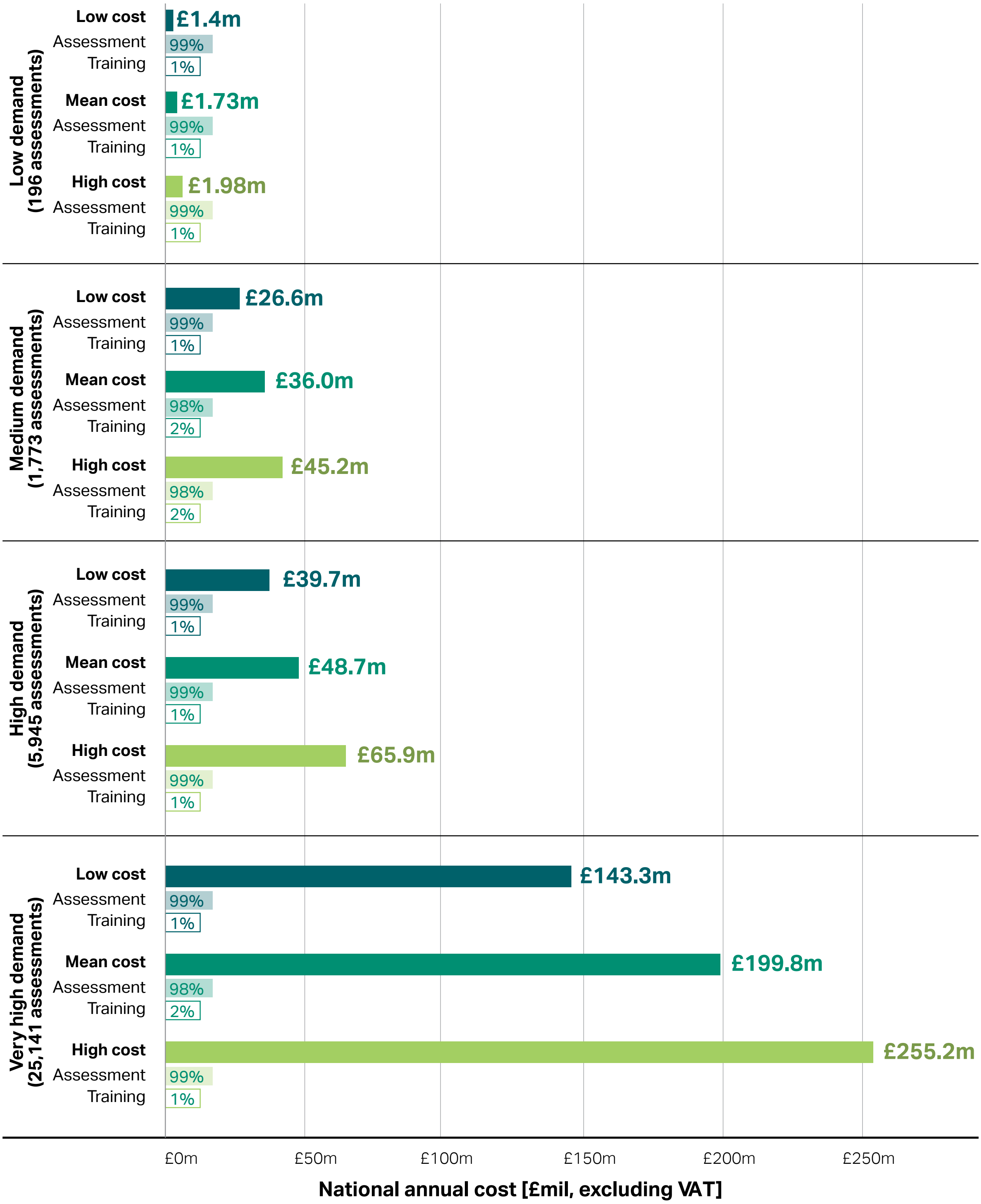
The training costs associated with meeting the demand for competent carbon assessors is expected to range from £0 to £2.46million. This significant range in cost is due to the uncertainty in the demand for carbon assessments and the uncertainty in the number of available competent carbon assessors. As explored in the section below, this is a small percentage (less than 2%) of the overall economic impact compared with the annual cost impact of undertaking carbon assessments.

Overall Economic Impact

The sector-wide economic impact of widespread carbon assessments is the combination of the costs of carbon assessments plus the cost of training to meet the demand. Overall, the cost of undertaking assessments is expected to account for the majority of the total cost.

The estimated sector wide economic impact will vary depending on the building typology being assessed, the annual number of carbon assessments required, the cost of undertaking a single carbon assessment, and the type of carbon assessment being undertaken. Figure 5.7 demonstrates the overall national annual impact of widespread embodied carbon assessments.

Figure 5.7. Overall economic impact of widespread embodied carbon assessments for low, medium, high, and very high demand, and low, mean, high cost



Economic benefits

The introduction of widespread carbon assessments can support a reduction in the total embodied carbon emissions from UK construction, which has an associated cost benefit with the Green Book supplementary toolkit estimating the value for carbon as £134/tCO_2e for the low scenario and £269/tCO_2e for the central scenario (22). This means that the cost benefit of reducing carbon may offset the cost of introducing carbon assessment requirements. However, further research is required to establish the cost benefit of reducing industry-wide embodied carbon across new buildings through a range of carbon reduction scenarios that are deemed to be achievable.

The adoption of widespread carbon assessments will result in additional upfront costs to property developers. However, cost savings can be made through carbon reductions achieved by lean building design. In addition, widespread carbon assessments will not only help to reduce embodied carbon associated with buildings but will increase the demand for 'Green Jobs' [16] and further skilled carbon assessors, thereby increasing employment and opportunities for people to up-skill into an emerging market. By providing an incentive for skills for green jobs such as carbon assessors, this can protect against economic decline in other sectors of the economy. Overall, the widespread adoption of carbon assessments will improve carbon literacy and help reduce the embodied carbon emissions associated with the construction sector in England. Additionally, skilled professionals can offer consultancy services to international clients, advising them on best practices for reducing embodied carbon in construction materials, and extending the life of buildings. There is a potential opportunity for the UK to position itself as a hub for expertise in sustainable construction and infrastructure and to influence global policies and standards related to carbon assessments. These services can generate revenue for the UK economy while promoting sustainable practices globally.

5.5 Cost and economic impacts conclusion

The published literature typically indicates an increase in cost for designing, supplying, and installing low-carbon construction methods, technologies and materials compared to traditional carbon-intensive equivalents. However, these costs should reduce as supply chains become more mature due to increased demand, and the workforce is upskilled. In addition, there are a number of cost-effective decarbonisation measures which can support a reduction in embodied carbon across the new construction sector. Furthermore, by optimising the implementation of strategic embodied carbon reduction measures at RIBA Stage 0 (Strategic Definition) to RIBA Stage 2 (Concept Design), both embodied carbon and cost savings can be made.

16 Green jobs have two main components: First, they are decent, fair, and meaningful jobs, and second, they are jobs which reduce negative environmental impacts. Subsequently, green jobs are defined by the International Labour Organisation (ILO) as jobs that 'help reduce negative environmental impact ultimately leading to environmentally, economically, and socially sustainable enterprises and economies (37).

This includes building less (e.g., analysing options for retrofitting) and embedding carbon into the decision-making process to inform the site selection, building form, and HVAC strategy.

Following a detailed quantification of the carbon reductions and cost impacts, the following cost-effective decarbonisation measures were identified (in no particular order):

- CLT structure in lieu of brick and block structure.
- Linoleum in lieu of carpet.
- Calcium sulphate RAF in lieu of a typical RAF product.
- ASHP with fan coil units and mixed mode operation in lieu of VRF with VRF serving AHU coils.
- Pad foundations in lieu of pile foundations, where ground conditions allow.
- Electric arc furnace steel in lieu of blast furnace steel.
- Reused steel in lieu of virgin steel.
- Timber structural insulated panels.

In addition to the cost of different decarbonisation solutions, the cost of undertaking carbon assessments was investigated. This detailed the average cost of undertaking different types of carbon assessment based on market research. This indicated the following average costs per assessment type:

- Early design stage estimate based on benchmarks: £3,700 (158 responses).
- Design optioneering based on limited data and spreadsheets: £5,200 (157 responses).
- Upfront carbon assessment: £7,500 (150 responses).
- Embodied carbon assessment: £8,100 (151 responses).
- WLCA: £9,600 (153 responses).

Despite the averages shown above, the industry questionnaire results showed that the costs associated with completing carbon assessments at each work stage varies greatly between respondents likely due to the building typology, as well as the complexity and size of the development. It is also noted that tools are being developed, such as by the Future Homes Hub (FHH), that are free to use and will theoretically support a reduction in carbon assessment cost of low-rise residential building in particular. Furthermore, as the market matures and the construction industry gains experience undertaking carbon assessments, standardisation will improve and time requirements may reduce which should, in time, reduce the overall cost of carbon assessments.

Further to the cost of assessments per development, the sector-wide economic impact was estimated based on the costs for completing carbon assessments and the additional costs associated with training new carbon assessors where required to meet the demand. The estimated sector-wide economic impact of widespread carbon assessments shows that the cost of undertaking assessments is expected to account for the majority of the total cost.

Widespread carbon assessments can help to reduce embodied carbon nationally. The Green Book supplementary toolkit estimates the value of carbon as £269/tCO_2e [17] (2). This means that the cost benefit of reducing carbon may offset the cost of introducing carbon assessment requirements. However, further research is required to establish the cost benefit of reducing industry-wide embodied carbon across new-buildings through a range of carbon reduction scenarios that are deemed to be achievable.

In addition, one of the positive effects of implementing widespread carbon assessments is the creation of jobs within the English construction sector which in turn will aid in economic growth and stability in England. In addition, the widespread adoption of carbon assessments will improve carbon literacy within the English construction sector meaning England can position itself as a hub for expertise in sustainable construction and infrastructure within international markets.

17 Based on the central scenario.

6. Recommended approaches to remove barriers to measuring and reducing embodied carbon

The recommendations below are possible approaches identified by AECOM to remove barriers to measuring and reducing embodied carbon based on the research summarised above [18].

6.1 Typologies and benchmarks

The key recommendations from Section 3 are as follows.

Defined building typologies

The analysis outlines a set of six building typologies which should be prioritised for reducing embodied carbon due to their anticipated embodied carbon impact nationally, the availability of carbon data within these sectors, and the carbon impact per development. These are: low-rise residential; mid or high-rise residential; commercial offices; industrial; education; and 'other' buildings. Through defining building typologies, benchmarks, targets, and carbon reduction strategies can be established across different sector-types. In addition, through defining their characteristics (as per Appendix C), greater comparability and certainty can be provided within carbon assessment data, helping to decarbonise each sector type. It is noted that the typologies listed within this research should be seen as an initial list of typologies, which AECOM recommends should expand as greater levels of carbon data become available.

Benchmarks and targets for typologies

The research shows that there is greater levels of carbon data available in the commercial, residential, and education sector but other sector typologies presently have much more limited data available. However, there is still a need to ensure that benchmarks and targets are sufficiently robust. This includes ensuring that the scope of data underpinning benchmarks and targets is consistent to maintain data quality.

18 It should be noted that these are not Government recommendations, nor are they formal recommendations to government or industry.

Furthermore, streamlining carbon data collection via the development of consistent reporting templates would greatly improve the quality and availability of carbon assessment data. This is particularly important for those building typologies which currently have less data available, such as the industrial building typology.

Functional units

There is an absence of data surrounding the use of functional units (e.g., floor area) and how representative they are of the absolute embodied carbon impact of buildings. It is therefore recommended that further research into the effect that functional units may have on both carbon assessment results and the design of buildings in the event of widespread carbon assessments (see Section 7.1).

Scope of carbon assessments

To ensure consistency across the industry when understanding and reporting embodied carbon, it is recommended that three scope elements of carbon are consistently clearly defined. They are the applicable building types, the building element category scope and the BS EN 15987 life cycle modules that are covered by the benchmarks and targets. By declaring these three elements, accurate comparisons between benchmarks and targets and project data can be made.

6.2 Uncertainty and consistency

The key recommendations from Section 4 are as follows.

Standardising modelling approach

The uncertainties analysed and the ability to artificially alter results creates a high level of uncertainty within carbon assessments of developments, which is then translated into uncertainty within national carbon assessment datasets. Further consistent guidance is recommended to standardise modelling approaches and reporting of carbon assessments to reduce uncertainty and potential gamification.

Better quality data for specific elements

To improve consistency within carbon assessments, AECOM recommend that a national carbon dataset is created based on existing carbon data available. This may comprise generic carbon factors to utilise to drive consistency within carbon assessments undertaken and help to mitigate the differences between the results of different carbon tools.

In addition, it is recommended that the generation of product and manufacturer specific carbon data (such as EPDs, CIBSE TM65 assessments, etc.) are coordinated with planned policies to enable the further generation of consistent carbon data. This could include developing systems to support manufacturers in developing carbon data and collating this data centrally to inform generic UK-based carbon databases.

The detail within the carbon data collated may also be staggered by the size of company, to ensure that small and medium-sized enterprises are not adversely affected.

In the short term, create interim methodologies, such as how CIBSE TM65 is working for building services products, to reduce the gaps in data availability. Development of low-cost LCA tools should be explored for use by SMEs to ensure that cost is less of a barrier to generating carbon data. In addition, consistent guidance could be developed to support consistency in how carbon tools generate generic carbon factors.

Carbon tools

Guidance on how to use carbon tools consistently is required to reduce the variations in the method of inputting data and the results they produce. This includes limiting variations in: the scope of the tools; the underlying datasets; the modelling approaches; and the assumptions used.

A consistent methodology for both public and private carbon tools to follow should be created. It is recommended that this includes defined levels for each of the following elements to ensure consistency across results produced:

- EN 15978 life cycle module scope.
- Building element categories scope.
- Assumptions.

A third-party verification process of the tools should be created to ensure that they are robust. This could include a third-party validating the following elements of carbon tools:

- The data sources.
- That the calculations are complete in line with the chosen methodology.
- Confirm the scope of the module and building element category.
- Confirm the assumptions used.
- Verify the output format.

It is recommended that work is done with industry to increase access to carbon tools. One method to increase access may be through supporting free to use carbon tool solutions to ensure widespread access to carbon tools, particularly for small and medium enterprises.

Data tracking of carbon assessment datasets

Three levels of data tracking have been recommended within this research, which are aiming to increase the value of carbon assessment datasets and encourage improvement within them: a minimum practice, standard practice, and a best practice approach. Moving from a minimum to best practice approach results in a more valuable dataset however, greater resource is required to compile the data. Establishing a consistent carbon assessment scope aims to improve consistency across carbon assessment datasets while making it easier to interrogate the data within them.

Having a data driven approach to embodied carbon reductions is key to support the UK's decarbonisation aspirations. Carbon assessment datasets enable the tracking of building carbon assessments across a large range of projects, with the aim of using this data to inform decision making and further decarbonisation opportunities throughout the value chain. Carbon assessment datasets are also useful for developing future benchmarks, targets, or legislation.

To streamline data entry into carbon assessment datasets, it is recommended that a consistent reporting mechanism is developed and standardised across industry. This may include tracking key fields outlined within Section 4.5 alongside the carbon data to support the contextualisation of this within datasets.

6.3 Cost and economic implications of carbon assessments

The key recommendations from Section 5 are as follows.

Upskilling of the construction industry

Significant opportunities exist to reduce carbon impacts at the Strategic Definition (RIBA Stage 0) and Preparation and Brief (RIBA Stage 1) stages. A broader upskilling of the whole construction industry is recommended to capitalise on these opportunities, along with the creation of consistent early-stage optimisation carbon tools and consistent methodologies for the calculation of emissions at early design stages.

Sourcing constraints of low-carbon materials

Governmental and corporate net zero commitments should ensure that more sustainable solutions become cheaper and more accessible over time due to economies of scale. This process could be expedited through government subsidies and support of both low carbon materials and UK-based manufacturing. Support could also be provided for manufacturers in producing carbon data (such as EPDs) for new low carbon products.

Warranties and insurance

Similar to existing methods, such as the mass timber insurance playbook (1), a similar insurance playbook should be created to support new and innovative materials, enabling further adoption of these across new construction whilst acknowledging and addressing insurance constraints.

Skills shortage, particularly for timber construction

The general skills shortage associated with sustainable design and construction could be rectified through continued investment, mainly through training. This includes upskilling the entire value chain, including developers, designers, manufacturers, and contractors.

Improve the availability of both cost and carbon information for low embodied carbon solutions

Greater transparency of the cost impacts of decarbonisation measures would greatly support the industry in highlighting cost-effective methods for reducing embodied carbon emissions. This includes giving the industry the tools to make strategic decisions from project inception to reduce embodied carbon and cost.

Create policy incentives for timber use in construction

As summarised by other countries' approaches, timber use in construction can be positively incentivised by policies at local and national level.

Industry training programme on carbon assessments and decarbonisation across the built environment

The whole industry needs to be upskilled in order for WLC to be more accurately quantified in order to address embodied carbon across the built environment. This should include wider industry training on WLCAs, alongside providing more consistent feedback loops following project completion on how best to reduce WLC across both their portfolios and the wider industry.

Definition of competent carbon assessors

It is recommended that an agreed definition of what requirements comprise a 'competent' or 'suitably qualified' carbon assessor be created. This could be linked to years of experience, a professional institution, a consolidated training programme, and subsequent examinations demonstrating competency. A list of 'competent' carbon assessors can then be created along with carbon assessor training explicitly tailored to meet the formal definition.

7. Further research

Typically, carbon assessments undertaken currently primarily focus on the potential GWP benefit achievable from different decarbonisation optimisation measures.

7.1 Functional units

Carbon assessment data across the industry currently focuses on reporting emissions in $kgCO_2e/m^2$ GIA and tCO_2e units. Displaying results utilising a functional unit, such as per m^2 GIA, is beneficial as this enables a comparison of results across developments. However, this can produce misleading results due to the artificial benefits of having a more significant area weighting decreasing the per m^2 GIA embodied carbon figures. Focussing solely on $kgCO_2e/m^2$ GIA as the primary metric for reporting emissions may accidentally lead to an increase in building sizes, as typically smaller buildings are more likely to be penalised using an area weighting due to their smaller GIA. This challenge is highlighted when undertaking embodied carbon comparisons of different building form optimisations, whereby decreasing the absolute tCO_2e may increase or have a negligible effect on the $kgCO_2e/m^2$ figures due to reductions to the building footprint.

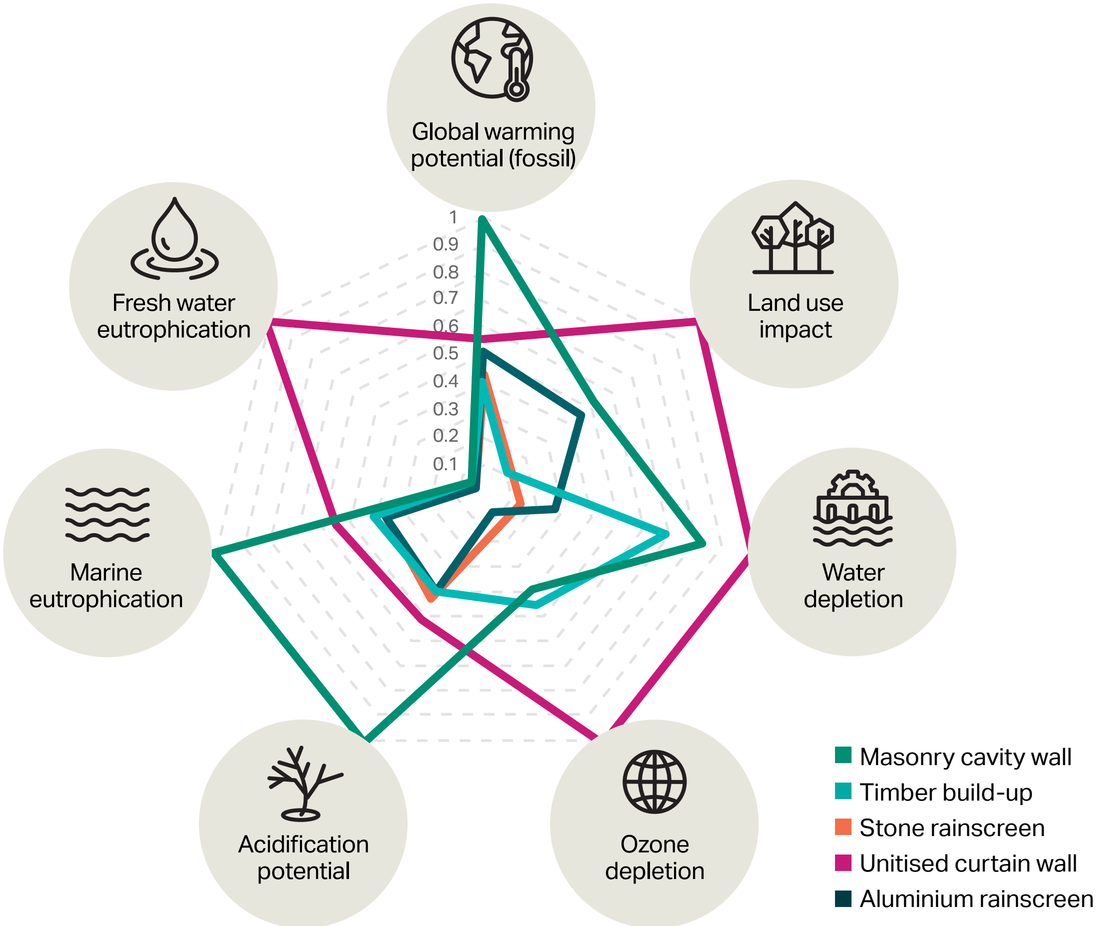
It is therefore recommended that alternative functional units are investigated to mitigate the potential downsides of using a per m^2 GIA metric displayed above and to mitigate against gamification of results. Alternative functional units may include the $kgCO_2e$ per number of occupants or number of per number of classrooms (for education building types). This will vary by building typology, providing a challenge when comparing building typologies against one another. Therefore, the research may also include an investigation of how use of two alternative functional units could mitigate these effects and support accuracy and transparency in reporting of emissions.

7.2 Further environmental impact categories

Typically, carbon assessments undertaken currently primarily focus on the potential GWP benefit achievable from different decarbonisation optimisation measures. However, there is a risk that the environmental impact from further environmental impact categories (such as acidification, ozone depletion potential, or eutrophication) may not be factored in by focusing solely on GWP. For a full list of further impact categories, please refer to Appendix F.

Further research is required to better understand the relationship between GWP and further environmental impact categories across building element types and materials, and how this links to common low decarbonisation solutions. For example, Figure 7.1 highlights how the environmental impact of different categories may vary. Better understanding this will help to mitigate the risk of accidental environmental damage caused by focusing solely on GWP emissions. Understanding these risks will enable holistic decision-making, whilst reducing broader environmental impacts as well as global warming potential.

Figure 7.1. Comparison of five façade systems and their relative environmental impact across seven impact categories, with one representing the largest impact in each category (23)



8. Conclusion

Overall, the widespread measurement and reduction of embodied carbon in new buildings will not only help achieve net zero aims but also help to increase employment in green jobs and give people the ability to up-skill in an emerging market. The research has shown that there are a number of practical, technical and economic considerations for measuring and assessing embodied carbon in new buildings, which have been summarised below.

Technical considerations for measuring and reducing embodied carbon in new buildings

It is recommended that key building typologies are established and defined, which can in turn act as a focal point for targets and benchmarks. This is with the aim of supporting further embodied carbon reductions across the industry through comparisons to carbon assessment data and benchmarks and targets across each building typology. The research also demonstrated the variances in current benchmarks and targets, and the current data underpinning these. This highlights the need for greater consistency across the industry in terms of the scope of benchmarks and targets, and the embodied carbon figures themselves.

To increase the robustness of both benchmarks and targets, and carbon assessment data, uncertainty within carbon assessments should be addressed. Currently, the analysis shows that there is uncertainty within carbon assessments from the data inputs to carbon models, different methodologies and assumptions leading to scope differences, variations within carbon tools, and variations across different datasets. This report has outlined a series of recommendations to address this uncertainty and increase the robustness of carbon assessments. Addressing uncertainty enables more robust financial decision-making for funding projects and implementing embodied carbon reduction measures across the built environment. The analysis also outlined how carbon assessment datasets can support reductions in embodied carbon emissions and upskill the industry across the value chain.

AECOM's key recommendations from the research to address technical challenges can be summarised into four areas of focus as follows:

- Standardising the modelling approach and assumptions to drive consistency within carbon assessments.
- Drive consistency within generic carbon data and improving carbon data quality and availability.
- Drive consistency within carbon tools to mitigate variations in results between them.
- Refine and instil tracking of carbon assessment data to drive continual improvement across the value chain.

Practical considerations for measuring and reducing embodied carbon in new buildings

In addition to the technical challenges and opportunities above, there are a number of practical considerations for implementing carbon reduction measures within new buildings. The research undertaken identified a series of micro-level challenges and opportunities for implementing low embodied carbon reduction measures. In addition, the scalability of embodied carbon reduction measures was investigated, with routes to address these challenges outlined. Addressing the scalability of decarbonisation solutions is key to ensuring that supply chains are sufficient for the decarbonisation opportunities to be successfully implemented within developments.

Further to the above, the practical challenges of building with timber were investigated in detail. This included the technical design challenges and current industry competency for building in timber. In addition, one of the current barriers to greater timber development is the concerns within the insurance market, whereby insurers are commonly reluctant to underwrite mass timber projects. There are also presently practical constraints with the public availability of testing data, which acts as a major barrier for upskilling the industry in designing with timber.

AECOM's key recommendations from the research to address the practical challenges can be summarised into four areas of focus as follows:

- Upskilling the whole construction industry in low carbon design and designing with timber.
- Addressing challenges within the insurance market for new and innovative materials and timber in construction.
- Increasing the data availability of cost and carbon data for decarbonisation solutions.
- Creating policy incentives for low carbon design measures, including the use of timber in construction.

Cost and economic considerations for measuring and reducing embodied carbon in new buildings

The research undertaken established the cost and economic impacts of widespread carbon assessments. This included detailing the costs of carbon reduction measures, and identifying where there are easy wins that can support decarbonisation across the sector. In addition, the cost of undertaking different types of carbon assessments was ascertained through an industry questionnaire. This found that the average cost of carbon assessments is £7,500 for an upfront carbon assessment, £8,100 for an embodied carbon assessment, and £9,600 for a WLCA. However, it was noted that these costs vary considerably within the responses received, likely based on the building typology, as well as the size and complexity of the development.

Of the decarbonisation solutions assessed, the most cost-effective optimisations were found to be:

- Optimised column gird in lieu of standard column grid.
- Pad foundations based on ground conditions in lieu of pile foundations.
- Optimised rectangular mezzanine office layout in lieu of standard mezzanine office layout.
- Exposed ceiling in lieu of suspended ceiling.
- Hybrid Variable Refrigerant Flow (VRF) system in lieu of VRF with VRF serving Air Handling Unit (AHU) coils.
- Electric arc furnace steel in lieu of blast furnace steel.
- Reused steel in lieu of new steel.
- Hybrid timber steel structure in lieu of steel structure.
- Air Source Heat Pump (ASHP) with fan coil units and mixed mode operation in lieu of VRF with VRF serving AHU coils.

In addition to the cost impacts of widespread carbon assessments per development, the sector-wide economic costs were estimated. This research included undertaking supply and demand analysis to establish whether there are a sufficient number of carbon assessors to meet a range of demand scenarios. This analysis demonstrated that under the low and medium demand scenarios analysed, there was deemed to be a sufficient number of carbon assessors in all but one scenario (based on the sensitivity analysis undertaken). Where additional carbon assessors are required across the high and very high demand scenarios, it was estimated that the cost of training additional carbon assessors is minor compared to the cost of undertaking assessments themselves.

Further research recommended

The research undertaken identified two primary areas of further study that would benefit from greater analysis and detail. This included further recommended research on:

- **Functional units:** Carbon assessment data is currently typically represented using the functional unit of per m^2 GIA, to normalise global warming potential results enabling comparability across developments. However, this may lead to artificially benefitting larger developments and penalising smaller developments, which would likely have a lower absolute embodied carbon, due to the differences in area. Therefore, to mitigate this effect, it is recommended that alternative functional units are investigated. For example, this may include calculating and reporting the carbon emissions per occupant, or per internal volume, depending on the building typology. Reporting results against two functional units would therefore mitigate the potential negative impacts of solely utilising a per m^2 GIA metric. However, further research is required to define alternative functional units for different typologies, and to provide robust carbon data displayed using alternative functional units.
- **Additional impact categories:** Currently, carbon assessments undertaken primarily focus on the global warming potential impacts, and there is less focus or understanding of further environmental impact categories (such as acidification, ozone depletion potential, eutrophication, etc.). Further research is required to better understand these impact categories and ensure that risks of other environmental impacts are not accidentally worsened by a sole focus of reducing global warming potential emissions. Understanding these risks will enable holistic decision-making, whilst reducing broader environmental impacts as well as global warming potential.

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Appendix A : Acronyms and abbreviations

Abbreviation or term	Definition
AHU	Air Handling Unit
ASBP	The Alliance for Sustainable Building Products
ASHP	Air Source Heat Pump
BECD	Built Environment Carbon Database
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Methodology
BS	British Standard
CBAM	Carbon Border Adjustment Mechanism
CLT	Cross-Laminated Timber
DEFRA	The Department for Environment, Food & Rural Affairs
DLUHC	Department for Levelling Up Housing & Communities
EAF	Electric Arc Furnace
EC3	Embodied Carbon in Construction Calculator
EN	European Standard
EPC	Energy Performance Certificates
EPD	Environmental Product Declaration
ESG	Environmental Social Governance
FES	Future Energy Scenario
FF&E	Furniture, Fittings, and Equipment
FHH	Future Homes Hub
FTE	Full-Time Employee
GGBS	Ground Granulated Blast-Furnace Slag
GHG	Greenhouse Gas
GIA	Gross Internal Area
GLA	Greater London Authority

Abbreviation or term	Definition
GWP	Global Warming Potential
HQM	Home Quality Mark
HVAC	Heating, Ventilation and Air Conditioning
HVRF	Hybrid Variable Refrigerant Flow
ICE	Inventory of Carbon and Energy
ISO	International Organisation for Standardisation
KG	Kilogram
LCA	Life-Cycle Assessment
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environment Design
LETI	Low Energy Transformation Initiative
MACC	Marginal Abatement Cost Curve
MEP	Mechanical, Electrical and Public Health/Plumbing
MHCLG	Ministry of Housing, Communities and Local Government
NIA	Net Internal Area
NRM	New Rules of Measurement
PAS	Publicly Available Specification
PFA	Pulverised Fuel Ash
PT	Post Tensioned
RAF	Raised Access Floor
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
SFS	Steel Framing System
SIPs	Structural Insulated Panels
VAT	Value-Added Tax
VRF	Variable Refrigerant Flow
WLC	Whole Life Carbon
WLCA	Whole Life Carbon Assessment

Appendix B : Definitions

Term	Definition
Biogenic global warming potential	GWP-biogenic accounts for GWP from removals of CO_2 into biomass from all sources except native forests, as transfer of carbon, sequestered by living biomass, from nature into the product system declared as GWP-biogenic. This indicator also accounts for GWP from transfers of any biogenic carbon from previous product systems into the product system under study. Biogenic GWP refers to the carbon that is absorbed from the atmosphere by plants and animals.
Building element category	Grouped building elements into categories such as foundations, superstructure, envelope and building services [19] in line with reporting mechanisms and standards such as RICS.
Building typology	Classification of buildings based on their function, form, and construction.
Carbon assessment	A generic term covering all carbon assessment types detailed within this report, including upfront carbon assessments, embodied carbon assessments, and WLCAs.
Carbon database	A repository of information containing data on the carbon emissions associated with the use and production of various products and services.
Carbon sequestration	The phenomenon of carbon dioxide being stored in biomass such as timber, delaying its release into the atmosphere.
Carbon tool	Tools for conducting carbon assessments
Construction stage (RIBA Stage 5) [20]	Construction stage covers the manufacturing, construction, and commissioning activities relating to the asset or building.
Design stage (RIBA Stage 3 to 4) [20]	Design stage covers the spatial, technical, and detailed design of the proposed asset or building.
Early-stage design (RIBA Stage 0 to 2) [20]	Refers to the identification of the business case and strategic brief, the development of project objectives and the preparation of concept design. Early-stage design stage covers the strategic and conceptual design of the proposed asset which includes feasibility studies and designing to meet building regulations.
Embodied carbon	Embodied carbon emissions are the total emissions associated across the lifespan of the building excluding operational energy (module B6) and water (module B7). This includes emissions from raw material extraction through to end-of-life stage. This is commonly called a cradle-to-grave analysis.
Embodied carbon benchmark	An embodied carbon benchmark provides a comparative metric to assess carbon emissions associated with an asset or building, typically split by metrics such as building typology m^2, etc.

19 As defined by RICS Whole life carbon assessment for the built environment, 2nd Edition
20 As defined by the RIBA Plan of Work, 2020

Term	Definition
End-of-life scenario	The proposed disposal and processing method of a material once it is no longer installed in the assessed building. End-of-life scenarios can include the following: landfill, incineration, recycling, and reuse.
Environmental Product Declaration (EPD)	An Environmental Product Declaration (EPD) transparently reports objective, comparable and third-party verified data about products and services' environmental performances from a life cycle perspective [21].
Functional unit	Functional units refer to the normalisation of results to enable great comparison. For the purposes of this report, 'functional unit' more specifically refers to a unit metric of a primary function of a building used to illustrate the embodied carbon impact of a building. For example, embodied carbon per m^2 gross internal area, or kg CO_2e/m^2 GIA.
Generic carbon data	Non-manufacturer or product specific carbon data. It is typically derived from LCI databases and localised project locations.
Generic carbon factors	These are carbon emissions factors (see above) that are not based on any manufacturer-specific data and are instead aggregates of pre-existing information.
Global warming potential fossil	GWP-fossil accounts for GWP from greenhouse gas (GHG) emissions and removals to any media originating from the oxidation or reduction of fossil fuels or materials containing fossil carbon by means of their transformation or degradation (e.g., combustion, incineration, landfilling, etc.). This indicator also accounts for GWP from GHG emissions e.g., from peat and calcination as well as GHG removals from carbonation of cement-based materials and lime.
Impact category	The impact category refers to the type of environmental effect that is the subject of a life cycle assessment (LCA). Global warming potential (GWP) is an example of an impact category. Other categories include, but are not limited to; water eutrophication, human toxicity, ozone depletion, biodiversity, etc.
Life cycle assessment [22]	Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle.
Life cycle impact assessment (LCA)	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
Life cycle inventory	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

21 As defined by the International EPD System
22 As defined by BS EN ISO 14044:2006

Term	Definition
Life cycle module	A breakdown of an asset's life cycle into stages and modules, whereby some modules are broken down further into sub-modules. An example of a module is the product stage. The product stage deals with the carbon impacts attributable to cradle-to-gate processes: raw material extraction and supply, transport, and manufacturing. This subsection provides additional details to assist in calculating the carbon impacts for these stages.
Module D	Module D represents the potential benefits and loads beyond the system boundary. The benefits demonstrated in module D align with circular economy principles. For example, exported energy that is used on another project outside the boundary of the project in question, or the carbon benefits of recycling materials at end-of-life (the carbon savings from which fall within the scope of the project that uses the materials).
Normalise	The multiplication of a series, function, or item of data by a factor that makes the norm or some associated quantity.
NRM1 and NRM3	NRM1 and NRM3 refer to the RICS New Rules of Measurement categorisation systems, which provide a categorisation method for building elements. NRM 1 is the Order of Cost Estimating and Cost Planning for Capital Building Works, and NRM3 is the Order of Cost Estimating and Cost Planning for Building Maintenance Works.
NRM Level 1, Level 2, and Level 3	NRM Level 1, Level 2, and Level 3 refer to the level of detail and granularity within each NRM category. For example, Level 1 may refer to '2. Superstructure', Level 2 may refer to '2.1 Frame' and Level 3 may refer to '2.1.1 Steel Frames'.
Operational carbon	The carbon emissions arising from all operational energy and operational water consumed by an asset in use, over its life cycle [23]. This is represented by modules B6 (operational energy) and B7 (operational water) from standard BS EN 15978.
PAS 2080	An international standard for the management of infrastructure carbon.
Reference study period	The standard period covered by a carbon assessment. Allows for comparability between carbon assessments.
Replacement period	The period of time after which a product that has been installed in a building is removed, disposed, and replaced by a new product.
Service life	The intended life, in years, of an asset or material.
System boundary or product system	Defines the unit processes to be included in the assessment model. This ensures that impacts, particularly for recovery and use of recovered material, are not double counted. Based on BS EN 15804, it is set when the end-of-waste state is reached.
Upfront carbon	Upfront carbon emissions are the emissions associated with the product and construction stages of the life cycle modules as defined in BS EN 15978:2011.

23 As defined by RICS Whole life carbon assessment for the built environment, 2nd Edition.

Term	Definition
Value chain	All organisations and stakeholders involved in creating, operating, and managing assets including developers, design teams, manufacturers, and contractors.
Whole life carbon (WLC)	Whole life carbon (WLC) emissions are the total emissions associated across the lifespan of the building.
Carbon modeller	The person undertaking the modelling of the construction materials comprising the structure and other element categories of a building to assess its carbon impact.
WLCA	A whole life carbon assessment (WLCA) is the calculation and reporting of the quantity of carbon impacts expected throughout all life cycle stages of a project, but also includes an assessment of the potential benefits and loads occurring beyond the system boundary.

Appendix C : Summary of characteristics of agreed building typologies

This section confirms the functional and form characteristics of each building typology.

C.1 Low-rise residential

Building function	Building form
Buildings intended for private occupation, providing habitable spaces for occupants. Typically for single families. Includes buildings no greater than three storeys.	**Minimum GIA requirements** [1] – Ranges from 50m² – 121m² for single storey to three storey dwellings respectively. – Ranges from 39m² – 138m² for single storey to three-storey dwellings respectively. **Floor-to-ceiling heights** [2, 3] – A minimum of 2.3m across 75% of relevant floor area. – A minimum 2.5m is required for at least 75% of the gross internal area (GIA) of each dwelling. Preference is for 2.6m in particular for ground floor dwellings. **Storey height** [1] – Typically, no greater than three-storeys, as houses taller than this will require the provision of a protected staircase combined with a domestic sprinkler system. **Glazing ratios** [4] – Large and wide full-height windows are avoided in habitable rooms (particularly in bedrooms) where the risk of being overlooked and/or overheating is high.

Low-rise residential sources:

1 Metric Handbook: Planning and Design Data, Pamela Buxton, Taylor & Francis Group,2021.
2 Technical Housing Standards, Nationally Described Space Standard, Department for Communities and Local Government, March 2015.
3 Metric Handbook: Planning and Design Data, Pamela Buxton, Taylor & Francis Group,2018
4 Housing Designs Standard, Greater London Authority, June 2023.

C.2 Medium and high-rise residential

Building function	Building form
Buildings providing a separate and self-contained premise constructed or adapted for use for multi-residential purposes and forming part of a building from some other part of which it is divided horizontally. This includes buildings greater than three storeys. Can be privately or publicly owned	**Stair cores** [1] – Provisions for second stair cores in new Residential buildings more than 30 meters. **Flat configurations** [2] – Internal travel distance of more than 9m, from the entrance door to any point of accommodation, should have a cellular layout around an internal fire protected hallway. – Open plan layouts are feasible if sprinkles are provided. **Sound insulation** [3] – All flats must provide reasonable sound resistance between party walls. – Common internal parts of the building containing flats or rooms for Residential purposes require design and construction to prevent more reverberation around the common parts. – Minimum airborne sound insulation and sound insulation is 45dB for walls, floors, and stairs for purpose-built flats. – Maximum impact sound insulation is 62dB for floors and stairs for purpose-built flats.

Medium and high-rise residential sources:

1 Government proposes second staircases to make buildings safer, Department for Levelling Up, Housing & Communities, December 2022.
2 Metric Handbook: Planning and Design Data, Pamela Buxton, Taylor & Francis Group,2021.
3 Resistance to Sound: Approved Document E, Ministry of Housing, Communities & Local Government, 2015.

C.3 Commercial offices

Building function	Building form
A place of business where professional duties is undertaken, people do non-manual work professional, commercial, or bureaucratic work. An office can include the following spaces: – Private offices – Shared offices – Open offices	**Floor depth** [1] Where building depths are usually measured as either 'glass-to-core' or 'glass-to-glass: – A glass-to-core dimension of 9 to 12 m allows room for cellular office space or open plan plus circulation and storage. – A glass-to-glass dimension of 13.5 to 18 m allows two or three zones of office, circulation, and support space. **Glazing** [2] – A deep plan building as one where a window core is typically 6 to 13.5 m. Window-to-window or atrium is 15 to 21 m. – A shallow plan building as one where window-to-core is typically 6 to 7.5 m window-to-window or window-to-atrium is 12 to 15 m. **Storey height (finished floor to underside of ceiling)** [2] – New build typically 2.6 to 2.8 m. – New build deep floor plan (e.g., spaces more than 18m in depth) typically 2.8 to 3.2 m. **Floor plates and configurations** [2] – Landlord efficiency (the ratio between Net Internal Area (NIA) and GIA) should be 84–87% in mid- to high-rise or 90% in low-rise buildings. **Tenant efficiency** [1] – Expressed as the ratio between Usable Area and NIA, should be 85% or above. **Structural loading** [2] – The BCO recommends 2.5 kN/m^2, with hardened areas for extra weight of up to 7 kN/m^2 but says that institutions demand ranges of 3 to 4 kN/m^2. **Planning and partition grids** [1] – A 1.35 m grid allows 2.7 m wide minimum office enclosures (relatively rare in the UK). – A 1.5 m grid allows 3 m wide offices that are much more common and have the additional advantage of relating well to 600 mm building components. This grid is much used in office planning in the UK.

Commercial offices sources:
1 Metric Handbook: Planning and Design Data, Pamela Buxton, Taylor & Francis Group,2021.
2 BCO Guide to Specification, British Council for Offices, 2019.

C.4 Industrial (including industrial storage)

Building function	Building form
A building enclosure and site within which goods are manufactured, assembled, stored, or shipped.	**Building dimensions** [1] – Typically, regular structure (optimally 2:1 to 3:1 ratio length: width) to maximise usable area and facilitate extension. – Minimum internal clear height of the building is 6 m. – Intensive manufacturing recommends a minimum clearance height of 7.5 m (for automated picking etc.). – Minimum height for main vehicle entrance doors for ground level loading is 5 m. – Distribution facilities internal clear height ranges from 12 m to18 m. **Grid spacing** [1] – Most economic primary grid spacing ranges from 6 m to 7.2 m. – Total office and welfare accommodation typically is equivalent to 10% of 1000 m^2 floor area, and 5% for floor areas more than 10,000 m^2. **Structural load** [1] – Within economic constraints, the building should be design for heaviest likely loads. – Ideally points loads of 36kN. – For dense storage, 30kN/m^2 distributed loading. **Fire precautions** [2] – If the building is fitted with sprinklers throughout, there is no need to compartmentalise. – The building should be compartmentalised, each compartment no larger than 20,000 m^3 and no higher than 18 m. – In high bay buildings (up to 35 m) automatic sprinkler systems must be installed.

Industrial sources:

1 Metric Handbook: Planning and Design Data, Pamela Buxton, Taylor & Francis Group,2018

2 Fire Safety: Approved Document B, Department for Levelling Up Housing and Communities, Ministry of Housing, Communities & Local Government, 2022.

C.5 Education

Building function	Building form
Education of students from first year primary education to final year secondary education or sixth form college for both state and private schools.	**Ventilation** [1] – Night-time cooling via exposed thermal mass – Earth tubes – Borehole cooling – Mixed mode cooling **Fire safety** [2] – Minimum number of escape routes and exits from a room, tier, or storey. (see table below) **Areas and space types** [3] (24) – BB103 provides guidance on area sizes for different space types within schools and net capacity. **Acoustic conditions** [4, 5] – Each space in a school building should be designed and constructed against appropriate acoustic conditions and the insulation against noise disturbance is appropriate to the space's intended use.

Maximum no. persons	Minimum no. escape routes or exits
60	1
600	2
More than 600	3

Education sources:

1 Metric Handbook: Planning and Design Data, Pamela Buxton, Taylor & Francis Group,2021.
2 Building Bulletin 100: design for fire safety in schools, Department for Education, 2014.
3 Building Bulletin 103:design for fire safety in schools, Department for Education, 2018.
4 Resistance to Sound: Approved Document E, Ministry of Housing, Communities & Local Government, 2015.
5 Building Bulletin 93: acoustic design of schools - performance standards, Department for Education, 2014.

Note:
There is government guidance available for public schools, which is based on the number of occupants however, there are no minimum requirements for schools. The guidance for schools is largely governed by fire safety. There is no government guidance for private schools due to the bespoke nature of buildings typically used for private schools.

C.6 'Other' buildings

Building function	Building form
Buildings where the function is not covered by Sections C.1 to C.5.	– Buildings whereby the form characteristics are not directly covered by Sections C.1 to C.5.

Note:
Where building typologies are mixed-use, the primary function type should be referred to. If the primary function is not contained within Sections C.1 to C.5, then the development can be classified under 'other buildings'.

Appendix D : Uncertainties explained

Uncertainty	Definition
Consistency of building element category scope between carbon assessments	The main sources of variation within the building element categories in carbon assessments are due to: – The scope of the project e.g., fit-out or shell and core. – Modelling tool or software used. – Drivers for undertaking assessment e.g., sustainability certifications or planning. – Amount of information modelled for each building element category. The scope of a project may mean that certain building element categories will not be included for example, within a shell and core carbon assessment, the RICS NRM1 building element category 4 Fittings, Furnishings and Equipment (FF&E) would be out of scope. A further source of uncertainty within building element category scope is due to variation in the scope of modelling for building element categories including, but not limited to, temporary works, MEP, and external works. A large source of uncertainty is also due to the inconsistency of the proportion of building materials modelled per building element category. This means that BS EN 15978 may not be followed in its requirement to model 95% of the cost by building element category. This may therefore lead to the underreporting of embodied carbon emissions within the building. This uncertainty is anticipated to be greater for early-stage applications.
Scope of life cycle modules reported	Uncertainty may be created where different scopes of carbon assessment are compared against one another. Different guidance documentation mandate the reporting of different life cycle modules, and frequently use differing terminology. This can create further uncertainty when WLC or embodied carbon values produced in line with one set of guidance is compared against the output of a different guidance document e.g., BREEAM v6.1 Mat 01 criteria compared to RICS.
Basis of data at different stages underpinning carbon assessments	Carbon modelling requires a minimum level of material quantity and material specification information. As with any analysis, the quality and completeness of information is directly proportional to the reliability of the results of carbon assessments. The root of this uncertainty predominantly lies in the large variations in the Level of Detail (LOD) and Level of Information (LOI) available within each RIBA stage where carbon assessments are being carried out, which directly affecting the reliability of the results. Due to these inherent variances, carbon assessments carried out during the early RIBA stages rely more on assumptions, 'rules of thumb', and averages to address the gaps in the detail or information available. Since there is no cohesive guidance available for these assumptions in the industry currently, carbon modellers risk making assumptions which are either too generic or alternatively too detailed, thereby increasing the likelihood of deviation from the actual as-build design. In addition, at a specific design stage, there can be differences in the LOD and LOI available to the carbon modellers as inputs into the carbon assessment, which creates more uncertainty. For instance, a Building Information Model (BIM) may not be updated to the LOD of a Cost Plan within a RIBA stage. Some carbon models may streamline the process at early design stages, where the LOD or LOI is limited, and focus on assessing the building structure or envelope in more detail (25).

Uncertainty	Definition
Inconsistencies in transport emissions (module A4) reported	In theory, this uncertainty should only affect RIBA stages 2-4 as at post completion, information should be available about the transportation emissions of products. Whereas at early-stage design specifications have not been produced so sourcing of materials cannot be known. To address the uncertainty generated by the large variation in the transport assumptions used during design due to the lack of transport information, some carbon assessment guidance documents have default transport scenarios for UK projects which covers materials manufactured locally, nationally, in Europe, and globally. At post construction, there should be little to no uncertainty in the transport emissions reported however this is dependent on the quality of the information inputted into the model and the ability of the carbon modeller to interrogate the information received and input this correctly. Current guidance states that transport distances should be updated to represent the actual distances travelled for post construction assessments however, there are a limited number of readily available post-construction carbon assessments and so there is little evidence that this is implemented in practice.
Inconsistencies in construction emissions and construction wastage rates	During construction, significant resources are used throughout the programme however the energy and resources associated with an asset are not thoroughly documented. This makes it difficult to report these emissions accurately within post-construction assessments. In addition, the lack of data, means that it is challenging to create reasonable assumptions to calculate construction emissions during design stage. Due to this, there are currently varying assumptions within different guidance documents and carbon tools for estimating construction emissions at the design stage.
Misreporting and misrepresentation of biogenic and sequestered carbon	The interchanging of the terms biogenic and sequestered carbon results in the misreporting of each. Biogenic carbon can be sequestered carbon, but sequestered carbon is not exclusively biogenic. The misclassification of sequestered carbon leads to the misreporting of carbon emissions particularly at product stage. As per industry best practice, the impact of sequestered carbon should be excluded from product stage reporting and reported separately. The wide variety of carbon assessment tools and datasets available on the market report biogenic and sequestered carbon with varying levels of transparency. It is noted that some do not have the ability to separate out sequestered carbon.
Reporting of building services – challenges and availability of services information	Historically, EPDs and other forms of LCA data have been difficult to produce for building services because of the number of constituent parts within MEP equipment and the flexible nature of component sourcing within the industry. There is a lack of EPDs surrounding building services equipment therefore, a manual self-certify calculation methodology (Chartered institute of Building Services Engineers (CIBSE) Technical Memorandum (TM) 65) was developed to improve the quantification of embodied carbon associated with building services.

Uncertainty	Definition
Reporting of building services – mis-categorisation or omission of refrigerant leakage	There is variation between how refrigerant leakage is accounted for in different industry databases, and between the assumptions made at design stage and the actual in-use refrigerant leakage. This may therefore lead to misreporting or omission of refrigerant leakage from carbon assessments. One method used to tackle the misreporting of refrigerant leakage is to reduce the variation in the refrigerant leakage rates used in carbon assessments. CIBSE defined different refrigerant leakage rates for different categories of systems to address this issue. Of the literature reviewed to generate the refrigerant leakage rates, the date of publication of the sources ranges from 1991–2018. It does not appear that in-use figures have been incorporated within the refrigerant leakage guidance documents currently available which demonstrates why there is discrepancy between the assumed refrigerant leakage rates and what happens in-use.
Inconsistent use stage (module B) modelling assumptions – use (module B1)	During the building's life, natural processes impact the absorption and release of greenhouse gas (GHG) occurs. This includes refrigerant leakage (analysed above) and concrete carbonation however, both processes are often not accounted for accurately in module B1 of carbon assessments. Depending on the modelling used and modeller's assumptions, the potential carbon benefit of concrete carbonation may be recorded differently. Some tools automatically account for this process whereas for others, the modeller must manually add the impact of concrete carbonation into the model. It should be noted that the by-product of the carbonation process is water which can cause corrosion of reinforced steel in reinforced concrete components.
Inconsistent use stage (module B) modelling assumptions – maintenance (module B2) and repair (module B3)	Module B2 assesses the GHG emissions associated with maintenance activities which includes any products used to enable maintenance and cleaning, as well as energy and water used as part of these activities [24]. Module B3 assesses the GHG emissions associated with any unexpected repairs that are outside of maintenance activities such as damage to façades due to an extreme weather event. There is limited guidance on accounting for modules B2 and B3 emissions and only high-level assumptions based on upfront carbon emissions are available. Furthermore, carbon tools may default these values to zero, meaning that manual assumptions may have to be added. This may therefore lead to omission of these modules in carbon assessment models. This issue is typically limited to life cycle modules B2 and B3.

24 Refer to BS EN 15804 (28) for the full definition of what is included in Modules B2 and B3.

Uncertainty	Definition
Inconsistent use stage (module B) modelling assumptions – replacement (module B4)	Module B4 assesses the GHG emissions associated with the installation of new products including the upfront emissions as well as activities needed to enable replacement. This includes any products used to enable replacement, as well as energy and water used as part of these activities. Due to the varied application contexts and in-use conditions across embodied carbon models, there is uncertainty in the service life and replacement rates of building components or systems (26). The assumed product service lives are often not representative of how a product is used in a building as some products last much longer than expected and other products are replaced more frequently. For example, at design stage, it is difficult to know the future circumstances of a leased building and therefore, difficult to assess the in-use stage emissions precisely. In addition, for building services equipment, service life is determined based on hours of operation instead of the number of years since installation. The replacement of building components will be dependent on their differing lifespans, therefore generic assumptions may not be representative (27). The industry has a range of definitions for building element 'lifetime' and 'service life', which though unavoidable, creates inconsistency across assessments. The definition is also dependent on the scope of the final user (carbon modeller, building designer etc.) (26). In this case, consistent definitions for building elements or systems which have the most significant impact on the final carbon assessment result should be prioritised. Many modelling tools allow for replacement periods to be changed manually to be more representative of the assessed building. Although this enables replacement emissions to be more precise for the individual projects, it makes comparing with other projects difficult as they may use generic assumptions built into the modelling tool. Moreover, there is disparity in the level of detail considered for a building element's service life.
Effects of localisation	To use EPD or generic region-specific data from other regions, a compensation factor is applied to a product based on the comparison of grid emissions factors from the data's origin country and the target country. The compensation factor applied may artificially inflate or deflate the product carbon factor, meaning that the raw data (both generic and EPD data) may not match the model outputs. This will also affect some building materials much more than others, with this disproportionately affecting materials with greater electrified processes within their manufacturing process. There is inherent uncertainty with the application of localisation factors as the grid emissions factors used and compared against may not always be the latest emissions factors for the countries in question. This may lead to greater uncertainty when calculating the compensation factor itself. Localisation may be effective when used at an early stage to inform higher-level analysis where less information is available. However, as the project progresses and more detail is known on product sourcing, localisation should, in theory, not be applied. Presently, there is little guidance on this and as such the use of localisation may vary across projects, therefore increasing uncertainty in large scale carbon assessment datasets. Furthermore, when localisation is applied, it is typically applied to localise data to the site of the proposed development which is undertaking carbon calculations (for example the UK). Whereas the products sourced may still be imported and therefore carbon emissions factors would be inaccurately reported.

Uncertainty	Definition
Inconsistent end-of-life (module C) modelling assumptions	Module C accounts for GHG emissions arising from decommissioning, stripping out, disassembly, deconstruction, and demolition operations, as well as from transport, processing, and disposal of materials at the end-of-life of the project. As module C is predicting how materials will be processed in decades time, there is inherent uncertainty already. Furthermore, some projects estimate end-of-life emissions based on assumptions informed by project-specific information, whilst other projects use default end-of-life assumptions. There is therefore an inconsistency in the assumptions behind end-of-life emissions. Overall, the default end-of-life assumptions is highly generalised and are therefore subject to inherent uncertainty. The default end-of-life assumptions do not necessarily provide an accurate representation of the emissions associated with module C, as they can overstate or understate emissions compared to when calculated using project specific information. However, often times detailed information on the end-of-life scenario of a project is not sufficiently known at the time when a carbon assessment is developed, meaning that default assumptions need to be applied in the absence of other available information. The default end-of-life assumptions are based on current statistics which provide the best available estimate for absent data. However, in the long term demolition methods will evolve, and associated activities decarbonise, the accuracy of the default factors may reduce. There is limited data available to carbon modellers to inform module C, therefore the results are typically dependent on the assessor's assumption of the default end-of-life scenarios provided (27).
Scope of operational energy	Operational energy calculations are required to calculate the operational carbon emissions for life cycle module B6. However, there are a variety of operational energy calculations methodologies, all of which greatly vary in scope. Part L building regulations may be used to underpin the operational carbon emissions in some WLCAs. However, this may overlook any benefits from different controls, heating programmes, or setpoint adjustment that would be displayed within CIBSE TM54: Evaluating operational energy use at the design stage (2022) calculations. The use of CIBSE TM54 would also enable further reporting of the unregulated energy emissions, which can represent a large proportion of overall operational energy. Further to the above, the new RICS 2nd Edition WLCA guidance is specific that "the results of Part L 2021 calculations must not be used under any circumstances", with the justification that are "not a prediction of energy consumption" (3). Instead, the latest RICS WLCA guidance recommends the use of CIBSE TM54, NABERS, or ASHRAE 90.1 'Energy Standard for Buildings' to estimate the operational energy. This new guidance is more prescriptive, which will work to minimise the uncertainty within the operational carbon module. However, the methods outlined may not presently be standard in terms of operational energy calculation methodologies and may therefore have additional costs. This may hinder adoption of these operational energy calculation methodologies at a macro-level.

Uncertainty	Definition
Effects of decarbonisation – embodied carbon	Decarbonisation in embodied carbon, when applied to carbon assessments, affects the use stage (module B) and end-of-life stage (module C) results. This includes grid decarbonisation as well as future replacement products which may have lower embodied carbon due to improved processes and increased product availability. When predicting use stage and end-of-life emissions, current guidance documents typically require reporting of embodied carbon emissions without including the effects of grid decarbonisation. Both BS EN 15978:2011 (28) and BS EN 15804 (29) exclude the reporting of embodied carbon decarbonisation to limit the uncertainty influencing the results of WLCAs (30). The 1st Edition WLCA guidance from RICS (30) encourages the reporting of decarbonised figures, although this is optional. The new 2nd Edition RICS WLCA guidance (3) goes a step further and asks to report both with and without decarbonisation. Furthermore, where embodied carbon results are reported inclusive of grid decarbonisation, the method of decarbonisation applied may not always be consistent or clear, which would therefore affect the overall carbon assessment results. The current approach of most guidance documents to either reporting carbon assessment results exclusive of grid decarbonisation or reporting both inclusive and exclusive of decarbonisation enables consistency and minimises uncertainty in carbon assessment results. However, this may not be an accurate depiction of the use stage and end-of-life stage emissions. There is further potential uncertainty when considering grid decarbonisation associated with imported products and how this is addressed. Furthermore, the effects of decarbonisation may also affect the underlying figures for upfront carbon.
Effects of decarbonisation – operational carbon	As the grid decarbonises, emissions associated with operational energy (module B6) are anticipated to reduce. The rate at which these emissions are anticipated to reduce varies depending on the Grid's Future Energy Scenarios (FES) (31), leading to inherent uncertainty in the reporting of decarbonised operational energy over the assumed 60-year reference building lifespan [25]. Similarly to the embodied carbon decarbonisation section above, the current consensus in the industry is to report operational carbon results excluding grid decarbonisation, with WLCA results inclusive of grid decarbonisation reported separately and typically optional. The difference between reporting operational carbon results including and excluding grid decarbonisation can alter the proportions of embodied carbon and operational energy within a building, affecting key design decisions.

25 This is typical across the industry based on RICS WLCA guidance, BREEAM v6 LCA guidance, and GLA WLCA guidance.

Uncertainty	Definition
Demolition emissions	There can be variation in how demolition emissions are reported, due to modelling constraints as well as practical constraints. Modelling constraints refers to the different assumptions used to model demolition emissions based on guidance documents and/or data within carbon tools. In terms of practical constraints, there can be uncertainty in who has ownership of the demolition emissions depending on when demolitions occurs and therefore whether demolition is categorised as pre or post construction demolition. Some buildings may therefore report varying demolition emissions as a result of timing of ownership rather than any variation in the actual demolition emissions. In addition, uncertainty may arise if a separate contactor is hired for demolition as demolition emissions may be accounted for as the contractor's emissions, but in practice, these emissions are still related to the embodied carbon of the development. To address this, the RICS WLCA 2nd Edition guidance states that "emissions from any demolition that has already occurred via a previous site owner or event must still be considered within the scope of the WLCA and reported in A5.1, if demolition occurs within three years of the sale or new proposal".
Assumed building lifespans	Presently, carbon assessment calculations undertaken in the UK tend to use an assumed reference service life (RSL) of 60 years (30) (32). It is noted that this varies across international based documentation although is relatively consistent across carbon assessments undertaken for UK projects. There may be uncertainty built into this assumed 60-year RSL for UK projects. For example, most new buildings fall under Category 4 of BS EN 1990 (Eurocode 0), with a 50-year period of use as intended by the designer before potential replacement (33). Presently in the UK, demolishing buildings before their design life ends has been common resulting in approximately 50,000 demolitions each year (34). This highlights a broader issue in relation to building less to reduce WLC emissions, as per the PAS2080:2023 decarbonisation hierarchy (35). Some building typologies may wish for the design life and/or RSL of buildings to align with proposed lease periods. This may lead to a longer or shorter RSL which would affect the reporting of use stage emissions. This disparity between design life, RSL, and actual lifespan and its impact on WLCAs is a broader issue which requires further consideration. Although it may be atypical for a building's reference service life to be over 100 years or higher, this may lead to further uncertainty within the WLC model. This is not only due to a higher uncertainty in use stage assumptions, but also due to how global warming potential (GWP) is calculated over a 100-year period. This means that for developments with a RSL of over 100 years, GWP emissions may be inaccurate for any years beyond the 100-year reference period of GWP. This may disproportionately affect some greenhouse gases (GHG) with lifespans greater than 100 years and affect the use stage (module B) and end-of-life stage (module C) results.

Uncertainty	Definition
Contingency factors	One of the methodologies proposed to address uncertainty associated with the RIBA Stage is the use of contingency factors, as suggested by the RICS WLCA 2nd Edition guidance (3). Within this guidance, contingency factors are applied based on three factors: 1. The stage of a project. 2. Carbon data uncertainty. 3. Material quantity uncertainty. Prior to the release of the updated RICS WLCA 2nd Edition guidance, there were few carbon assessment methodologies which included contingency factors and as such it is anticipated that the application of contingency factors in existing data varies based on the carbon assessor. Artificially inflating carbon factors to provide an embodied carbon contingency may be a useful measure to reduce uncertainty, however, may also be misleadingly utilised to report WLC savings through project stages where contingency factors should in theory reduce.
Global warming potential and GWP separation	Global warming potential (GWP) quantifies the expected global warming impact of GHGs, reported in equivalent carbon dioxide emissions, associated with an asset typically over a 100-year period. GWP is the most commonly used factor to assess the environmental impact of an asset over its lifetime. GWP can be separated into its constituent parts: – GWP-Fossil. – GWP-Biogenic. – GWP-Land Use and Land Use Change (LULUC). However, the overall GWP is often reported by itself, and the impact is not split into its constituents which help garner further information on the environmental impact. It may not always be possible to report GWP in its three constituent parts, as this depends on the dataset and/or modelling tool used. This potentially leads to reduced flexibility to compare GWP impacts between buildings.
Other impact categories reported	Outside of GWP, there are several other environmental impact categories that quantify the change in the Earth's atmospheric layers, quality of land and water, availability of resources, and impact on humans. Each category or indicator has their own functional unit so cannot be directly compared to one another. It is noted that at present, not all datasets include the other impact categories. In addition, where these are included in datasets, alternative units may be used for the same impact categories, hindering comparability of the results of other impact categories.

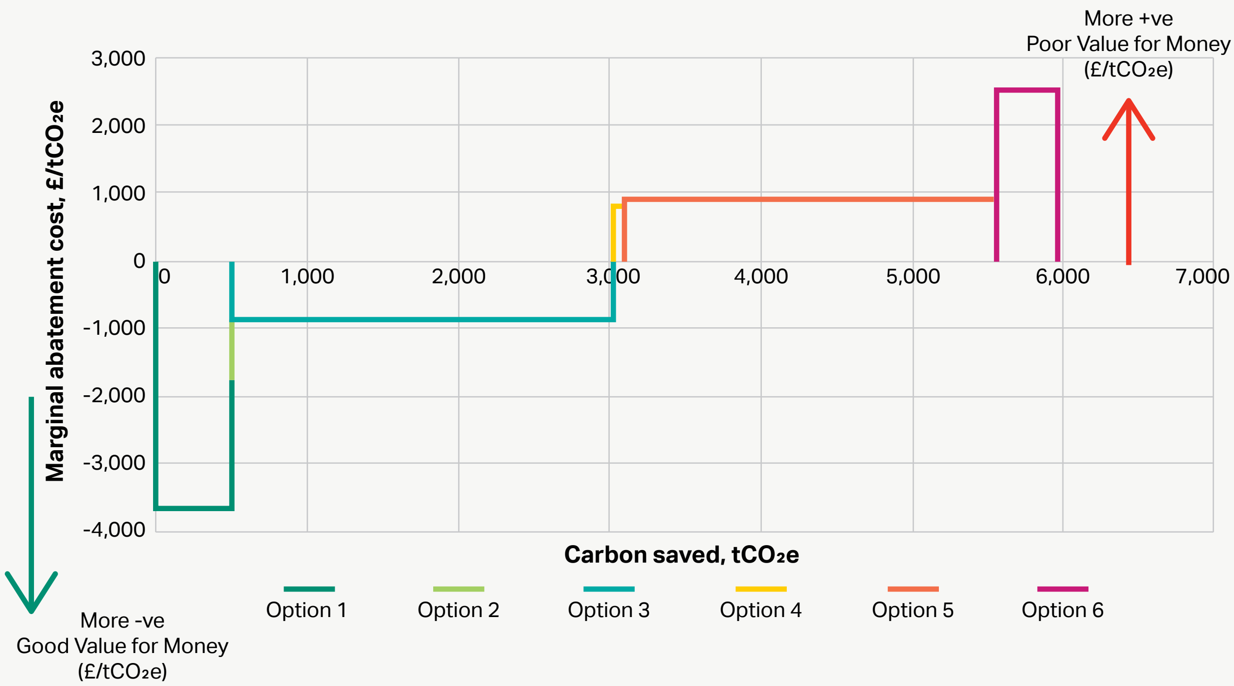
Appendix E : The carbon and cost implications of embodied carbon reduction measures – marginal abatement cost curves

E.1 Quantified embodied carbon optimisation solutions

Each shortlisted embodied carbon optimisation solution has been analysed in terms of the carbon reductions achieved across the life cycle stages, the marginal abatement cost curve (MACC), the micro-level impacts, and a summary of the total impacts. All savings have been calculated based on the difference per module. The percentage differences shown in the following section are the percentage differences across the whole building rather than per building element.

The diagram below depicts how MACC can demonstrate cost-effectiveness for carbon savings achieved. On the x-axis the wider the bar the more carbon saved. On the y-axis a negative value represents good value for money and a positive value represents poor value for money.

Figure 10.1. Example marginal abatement cost curve (MACC) [26]



26 Note that this example MACC is utilising dummy data.

E.2 Low-rise residential

Figure 10.2 demonstrates that when looking at upfront carbon, changing to a CLT structure is both the most effective in reducing carbon and requires the least amount of financial input. The switch to use of CLT structure and rendered façade provide relatively good value for money. The natural slate and heat pump with underfloor heating optimisation however, in terms of the upfront carbon saved, are the least cost-effective options of those analysed.

Legend for Figures 10.2 and 10.3

- Heat pump with underfloor heating in lieu of heat pump with radiators
- CLT structure in lieu of brick and block structure
- Rendered façade in lieu of handset brick façade
- Double glazed timber and aluminium windows in lieu of double glazed UPVC windows
- Clay board in lieu of plasterboard
- Natural slate roof in lieu of fibre cement roof

Figure 10.2. MACC of the low-rise residential upfront carbon optimisations

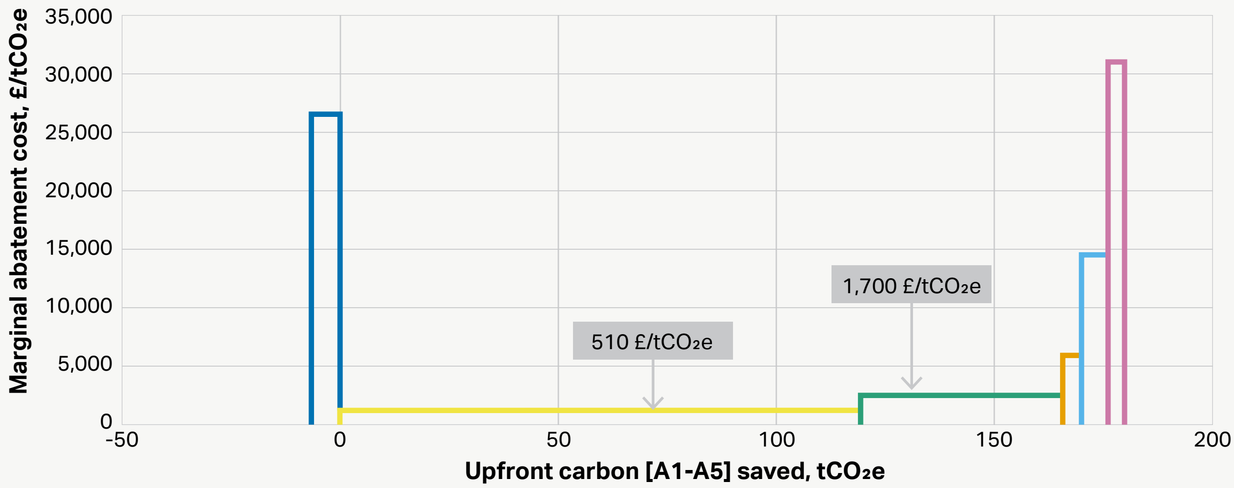
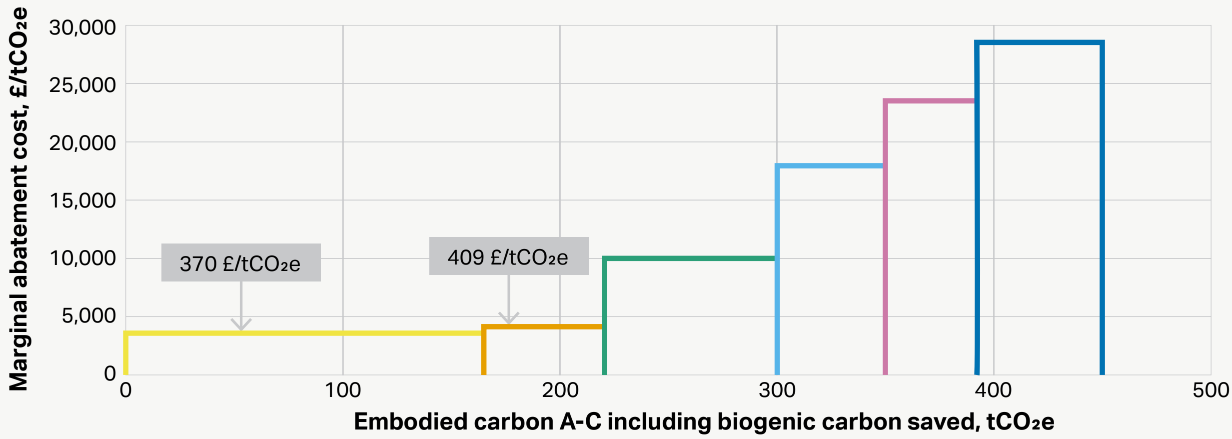


Figure 10.3 shows that when considering the embodied carbon savings including biogenic carbon, the carbon savings for the natural stone and heat pump with underfloor heating are more comparative to the other optimisations however it is still an expensive optimisation.

Figure 10.3. MACC of the optimisations for low-rise residential embodied carbon including biogenic carbon



E.3 Mid or high-rise residential

Figure 10.4 demonstrates how, for upfront carbon, the cost of the switch from refrigerant R32 to R290 is very high and the carbon impact is minimal as refrigerant emissions are associated with modules B1 and C1. It should be noted that the costs associated with the refrigerant change include replacement of the units and is not just a change of the refrigerants due to limited cost information. Figure 10.5 shows the upfront carbon impact of the optimisations excluding refrigerant R290 in lieu of refrigerant R32 to better show the cost and carbon impacts of the other optimisations.

Legend for Figures 10.4, 10.5 and 10.6

- Rainscreen cladding using brick slips in lieu of brick wall
- Linoleum in lieu of carpet
- PT slabs in lieu of conventional slabs
- Natural Hydraulic Line (NHL) floor screed in lieu of cement screed
- Pre-cast concrete panel in lieu of brick wall
- Refrigerant R290 in lieu of refrigerant R32

Figure 10.4. MACC of the mid or high-rise residential upfront carbon optimisations

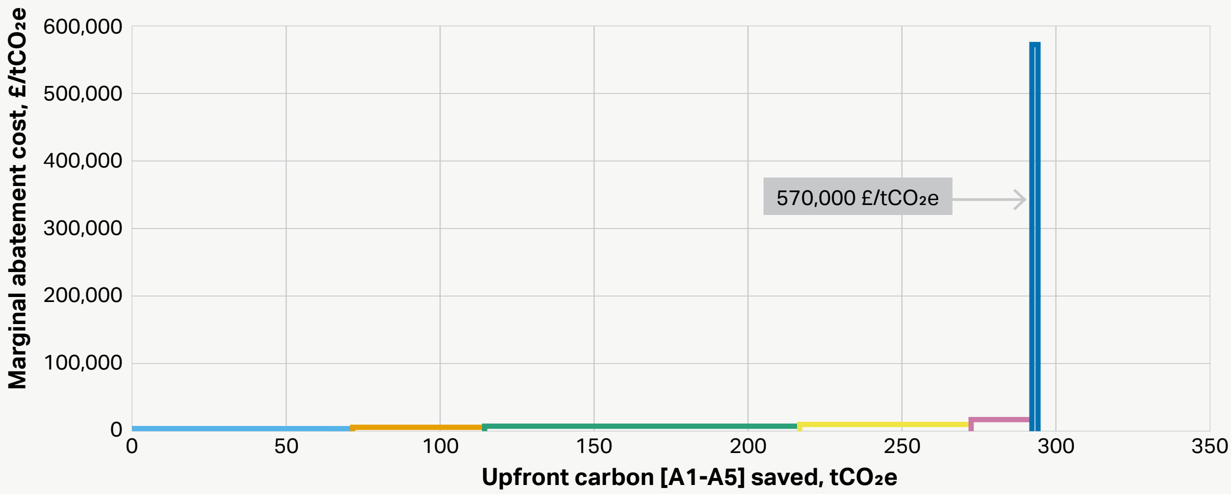


Figure 10.5 shows that although PT slabs have the greatest upfront carbon impact of the options assessed, the most cost-effective upfront carbon optimisations is the use of rainscreen cladding.

Figure 10.5. MACC of the mid or high-rise residential upfront carbon optimisations excluding refrigerant R290 in lieu of refrigerant R32

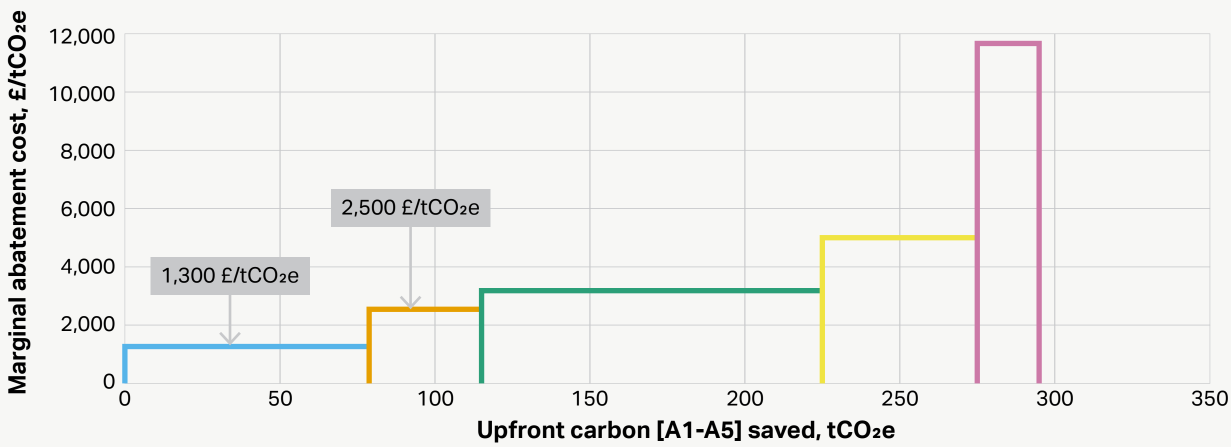
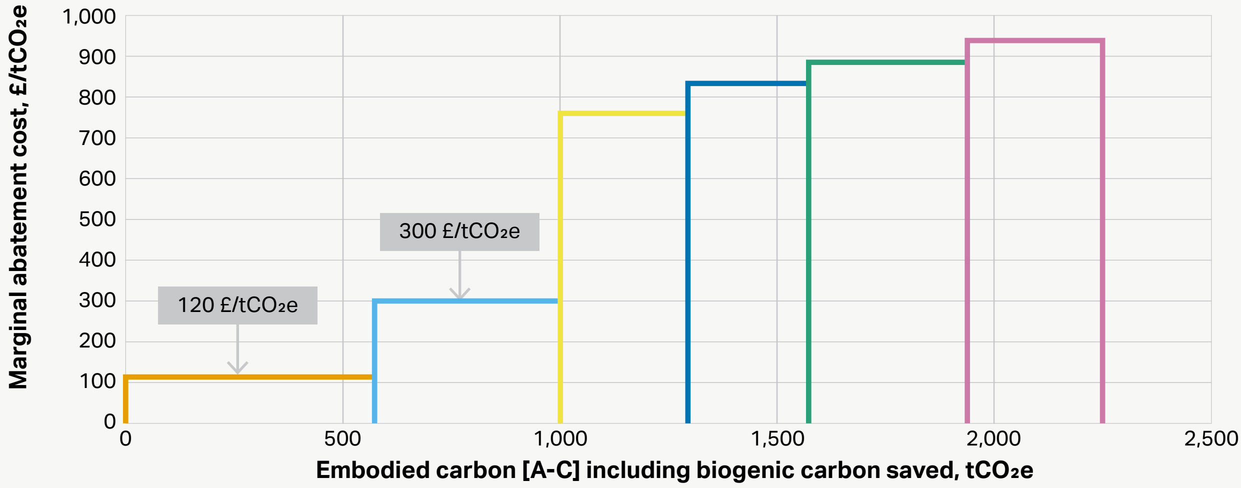


Figure 10.6 demonstrates the use of linoleum is the most cost-effective optimisation and produces the largest embodied carbon saving.

Figure 10.6. MACC of the optimisations for mid or high-rise residential embodied carbon including biogenic carbon



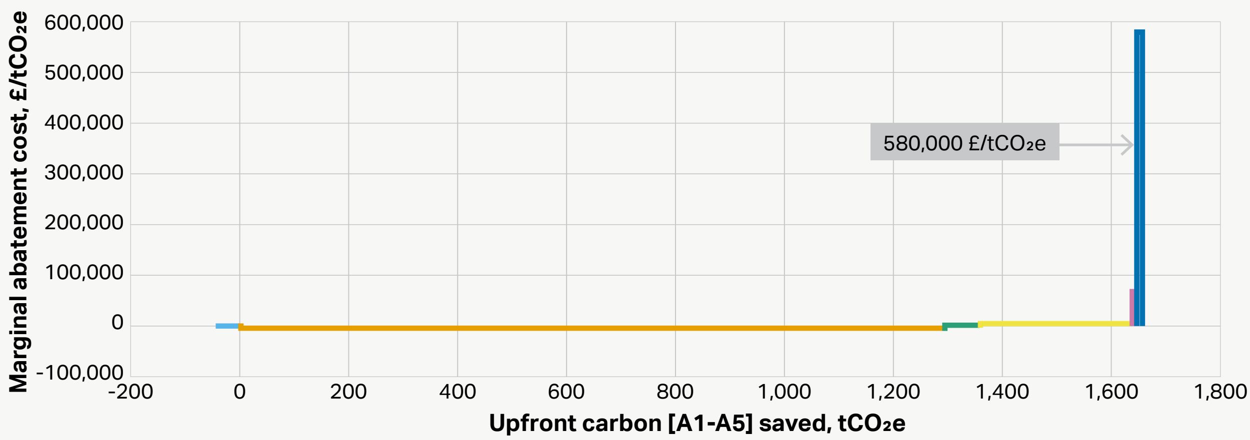
E.4 Offices

Figure 10.7 demonstrates how, for the sample office, replacing the aluminium framed curtain wall with a hybrid timber aluminium curtain wall has a high upfront cost and generated limited upfront carbon savings.

Legend for Figures 10.7, 10.8 and 10.9

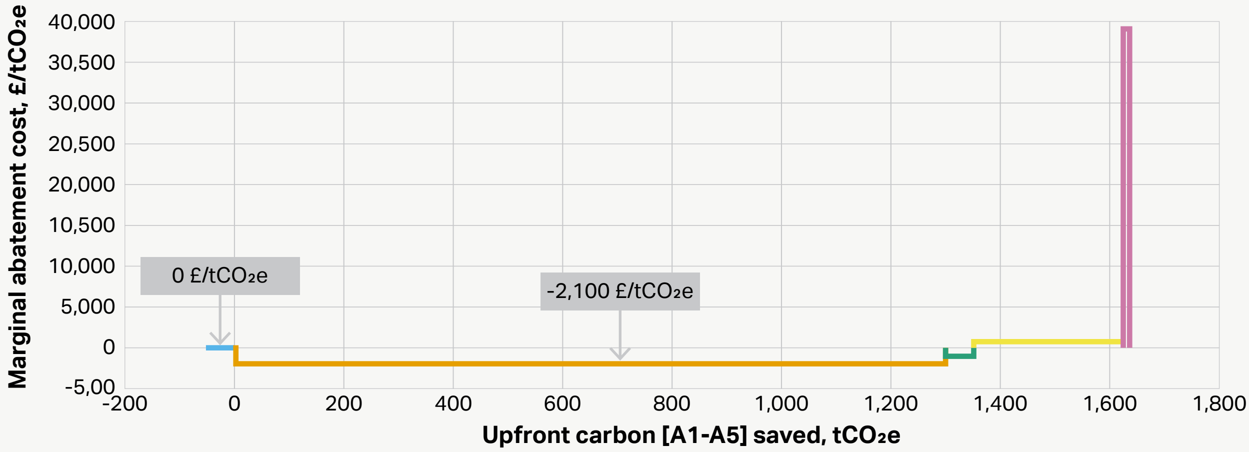
- Hybrid VRF in lieu with VRF Serving AHU coils
- Optimised column grid in lieu of standard column
- Exposed ceiling in lieu of suspended ceiling
- New calcium sulfate RAF in lieu of new Kingspan RMG 600 RAF
- ASHP with fan coil units and mixed mode operation in lieu of VRF serving AHU coils
- Hybrid timber aluminum curtain wall in lieu of aluminium framed curtain wall system, double glazed

Figure 10.7. MACC of the office upfront carbon optimisations



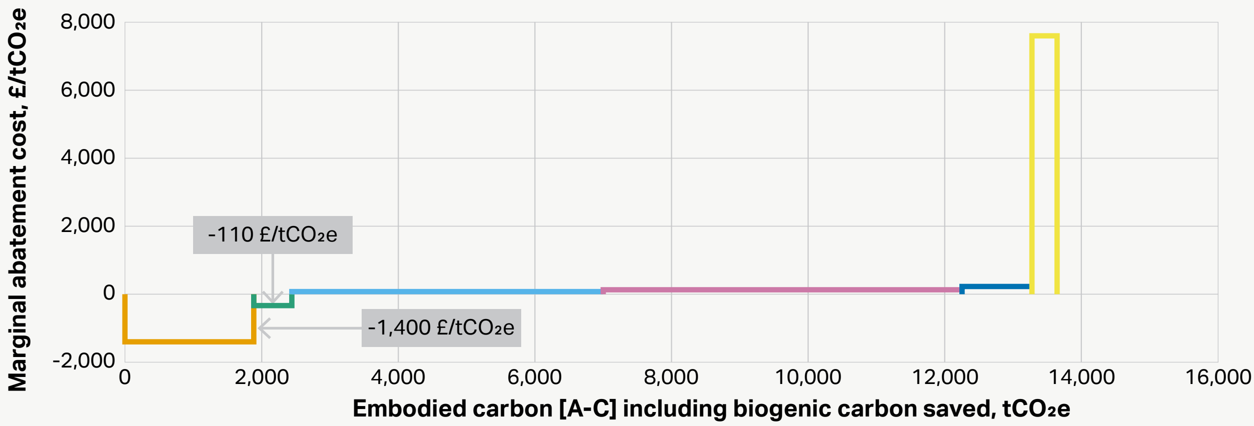
[Figure 10.8](#) shows the upfront carbon optimisations without the hybrid timber solution to enable the impact of the optimisation to be seen. This demonstrates that for upfront carbon, the optimised column grid produces a carbon and cost saving, due to less material being required.

Figure 10.8. MACC of the office upfront carbon optimisations excluding hybrid timber or aluminium curtain wall



[Figure 10.9](#) shows that the cost impact of the hybrid Variable Refrigerant Flow (VRF) system is deemed to be negligible, and the embodied carbon savings provided are larger than all other options except for the use of Air Source Heat Pumps (ASHPs) with Fan Coil Units (FCUs), which also provides a cost-effective solution to reducing embodied carbon.

Figure 10.9. MACC of the optimisations for the offices embodied carbon including biogenic carbon



E.5 Industrial

Figure 10.10 and Figure 10.11 demonstrate how both use of pad foundations and optimisation of the mezzanine results in a cost reduction because both optimisations have a reduction in material quantity. Of the optimisations that result in a cost uplift, the use of electric arc furnace steel is the most cost-effective in terms of upfront and embodied carbon.

Legend for Figures 10.10 and 10.11

- Pad foundations based on ground conditions in lieu of pile foundations
- Optimised rectangular mezzanine office layout in lieu of standard mezzanine office layout
- Electric arc furnace steel in lieu of blast furnace steel
- Hybrid timber steel structure in lieu of steel structure
- Optimised column grid and internal space height in lieu standard column grid and internal space layout
- Composite stonewool panel in lieu of Kingspan PIR façade

Figure 10.10. MACC of the industrial upfront carbon optimisations

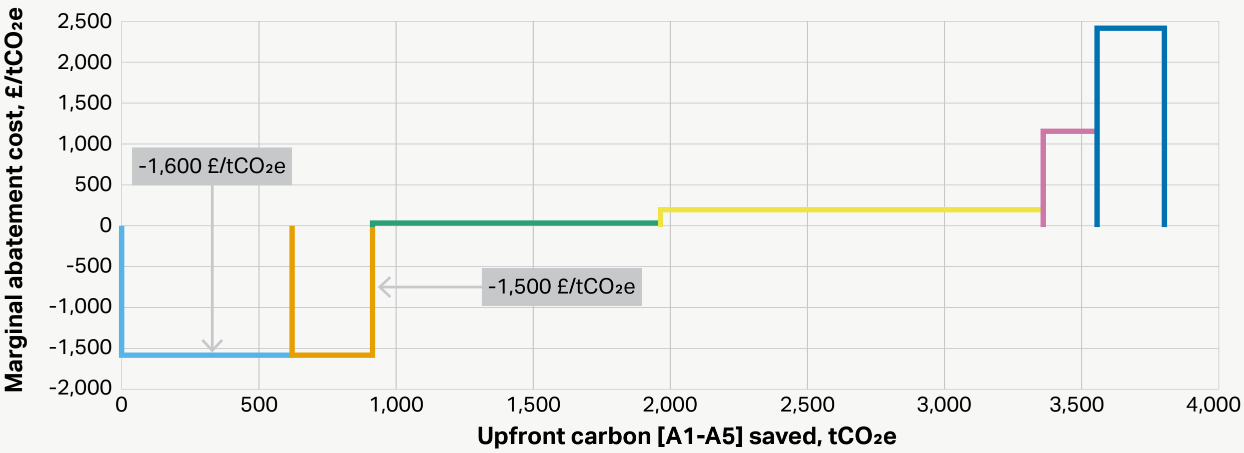
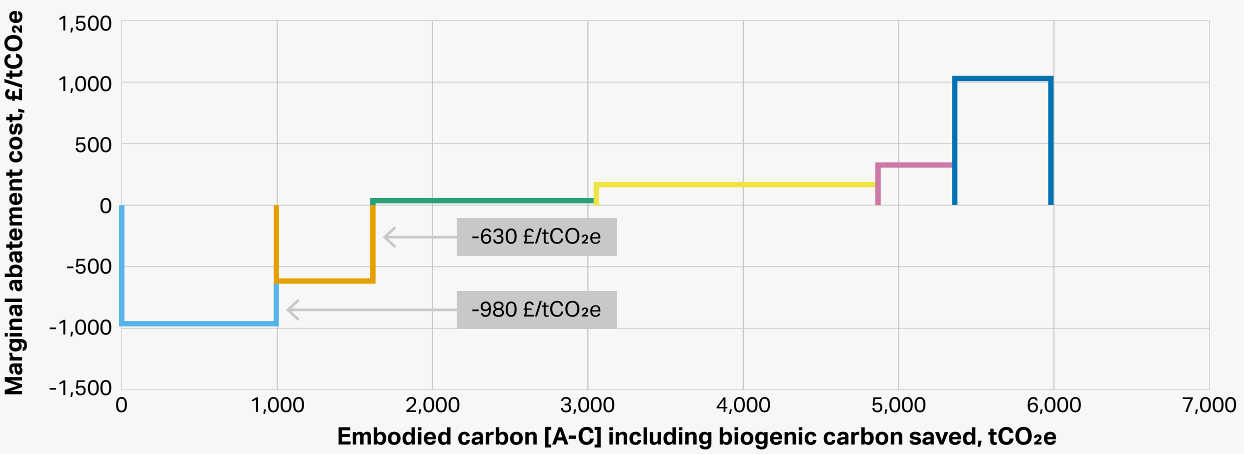


Figure 10.11. MACC of the optimisations for the industrial embodied carbon including biogenic carbon



Electric arc furnace steel may need to be stored, especially for larger projects, to bridge the gap between steel manufacturing and supply and project requirements. This can have both implications on cost and project programme. The cost of storage could not be quantified and so has not been included in the upfront costs within this report. Project experience has shown that the storage costs can be significant depending on the amount of steel required and how the requirements line up with the manufacturing programme and the other project commitments of the steel works.

E.6 Education

Figure 10.12 demonstrates how, for upfront carbon, the switch from centralised to a decentralised hot water system is an expensive solution with little carbon benefit. The cost of the switch however can vary depending on the size and layout of the building. In order to understand the impact of the other optimisations, Figure 10.13 shows the upfront carbon excluding the hot water system optimisation.

Legend for Figures 10.12, 10.13 and 10.14
- Reused steel in lieu of steel
- Structural insulated panels in lieu of brick structure
- Timber internal wall structure in lieu of SFS internal wall structure
- Timber ground floor slab in lieu of concrete ground floor slab
- End grain wood flooring in lieu of polyflor floor covering
- Decentralised hot water in lieu of centralised

Figure 10.12. MACC of the education upfront carbon optimisations

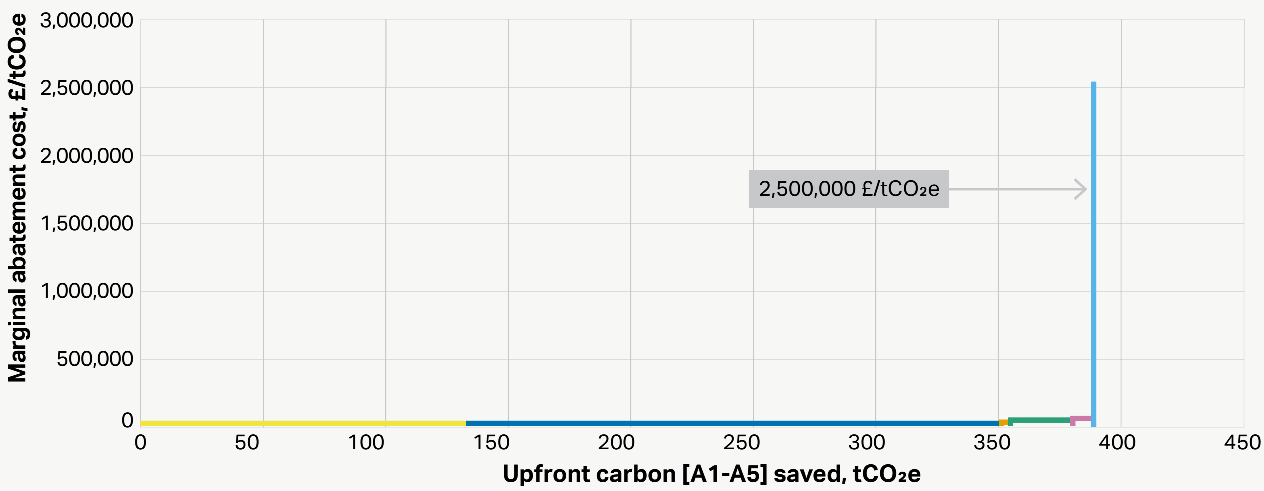


Figure 10.13 and Figure 10.14 show how reused steel is the most cost-effective optimisation, for both upfront and embodied carbon. The second most cost-effective option is the use of structural insulated panels. The use of a timber ground floor slab was found to be the least cost effective option for embodied carbon savings, due to the cost of the materials which are required for the timber ground floor slab.

Figure 10.13. MACC of the education upfront carbon optimisations excluding the direct hot water optimisation

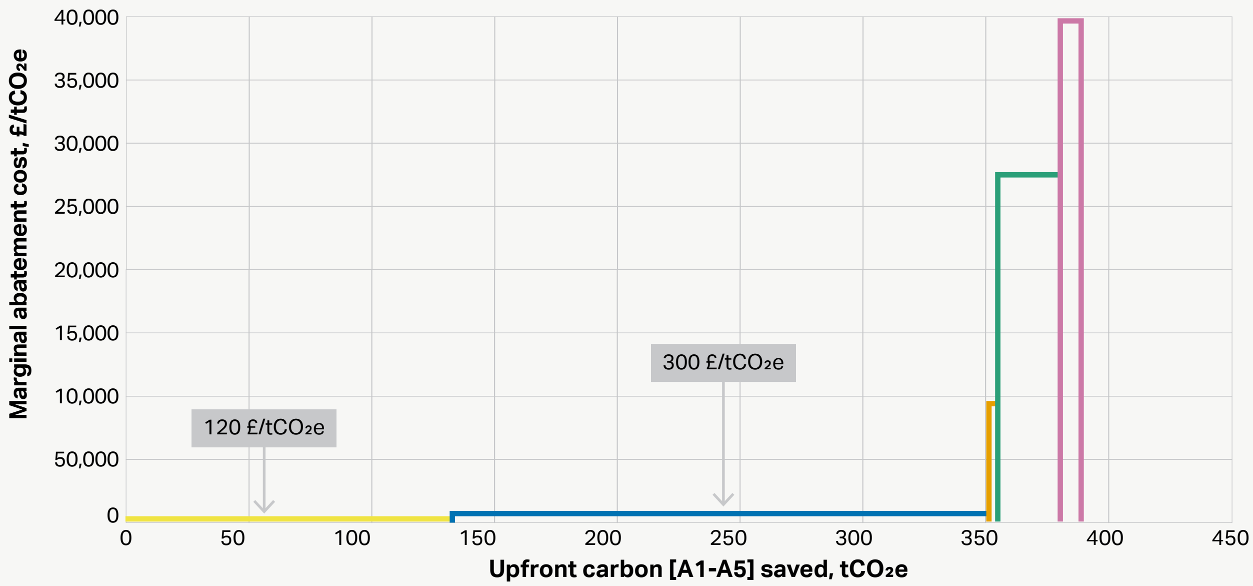
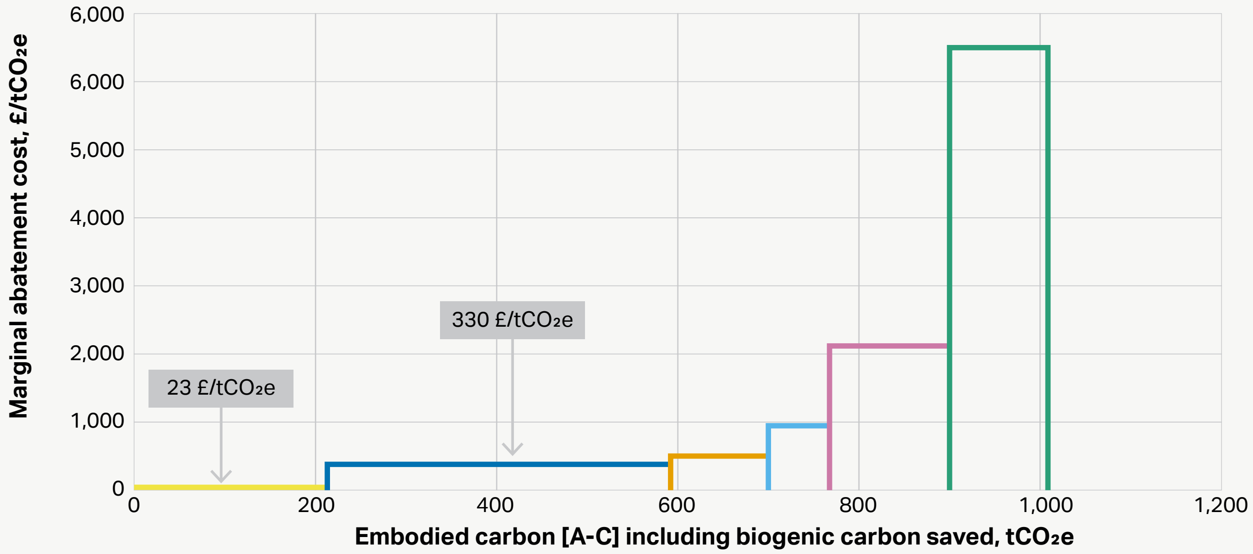


Figure 10.14. MACC of the optimisation for education embodied carbon including biogenic carbon



Appendix F : Further impact categories

In addition to Global Warming Potential (GWP), there are also a series of further impact categories that should be noted as defined by the Environmental Profiles Methodology 2008 (36). These are explained further within Table 10.1. The impact of these categories is typically less tracked within carbon assessments or carbon assessment datasets. It should also be noted that not all the impact categories explored in this section are mandatory within environmental product declarations (EPDs).

Table 10.1. Description of further impact categories (36)

Category [units] [27]	Description
Acidification potential [kgSO_2 eq]	The acidification potential is an impact category used in life cycle assessment (LCA) to assess the potential of a product or process to contribute to acidification of the environment. Acidification can have negative effects on ecosystems, including soil degradation, reduction of biodiversity, and harm to aquatic life. The acidification potential is calculated by multiplying the mass of emitted acidic substances by their respective characterization factors, which represent their contribution to acidification. Characterisation factors vary depending on regional or local conditions.
Eutrophication potential [kgPO4 eq]	Eutrophication potential is a measure of the potential of a product or process to contribute to eutrophication of the environment. Eutrophication is a process where excess nutrients in water bodies can lead to overgrowth of algae, disrupt ecosystems, and harm aquatic organisms. Eutrophication potential in LCA is quantified by calculating the potential of a product or process to release nitrogen and phosphorus into the environment and multiplying it by characterisation factors. Characterisation factors represent the potential of released nutrients to cause eutrophication and are determined based on environmental fate, effects, and local conditions.
Ozone depletion potential [kgCFC11 eq]	Ozone depletion potential (ODP) is an impact category used in LCA to evaluate the potential of a substance to deplete the ozone layer in the Earth's atmosphere. The ODP of a substance is expressed as a ratio relative to a reference gas (CFC-11), with higher values indicating a greater potential to deplete the ozone layer. Human-made chemicals such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons are the main cause of ozone depletion.
Formation of ozone of lower atmosphere (photochemical ozone creation) [kgC_2H_4 eq]	The formation of ground-level ozone is an impact category in LCA used to evaluate the potential of a substance to contribute to harmful air pollution. Ground-level ozone is formed when nitrogen oxides (NOx) and volatile organic compounds (VOCs) react in the presence of sunlight. The impact of ground-level ozone is measured in terms of its potential to cause respiratory problems and other health impacts in humans, as well as damage to crops, forests, and ecosystems. The impact category is typically assessed in LCA studies using metrics such as photochemical ozone creation potential (POCP).

27 It should be noted that the unit for the further impact categories may vary depending on the underlying LCA dataset used.

Category [units] [27]	Description
Depletion of non-renewable energy [MJ]	Depletion of non-renewable energy is an impact category in LCA that assesses the potential of a product or process to contribute to the depletion of finite energy resources. Metrics like cumulative energy demand or net energy ratio are used to measure the impact of energy depletion. The aim of considering this impact category is to identify sustainable alternatives that reduce dependence on non-renewable energy sources and promote the use of renewable energy sources such as solar, wind, and hydro power. It helps to quantify the environmental impact associated with the consumption of finite energy resources and identify sustainable alternatives.
Water extraction [m^3 of water extracted]	Water extraction highlights the potential damage that over-extraction from rivers and aquifers can cause. This includes all water extraction except: – Seawater. – Water extracted for cooling or power generation and then returned to the same source with no change in water quality. – Water stored in holding lakes on site for recirculation. – Rainwater collected for storage on site.
Mineral resource extraction [tonnes of minerals extracted]	This indicator relates solely to resource use and is based on the Total Material Requirement (TMR) indicators as used by the European Union. The indicator calculates the total resource use associated with any use of non-energy, abiotic materials within the EU, wherever the resource occurs.
Ecotoxicity to freshwater and land [kg 1, 4-DB]	Ecotoxicity potential provides a method for describing fate, exposure, and the effects of toxic substances on the environment.
Nuclear waste [mm^3 of spent fuel, high and intermediate level radioactive waste]	This indicator assesses radioactive wastes which may require storage for more than 10,000 years or more due to their radioactivity.
Waste disposal [tonne of solid waste]	This indicator is an absolute measure of the mass of any waste that is disposed of in landfill or incinerated.
Fossil fuel depletion [tonnes of oil eq]	This indicator is an absolute measure based on the energy content of the fossil fuel used.

Appendix G : Contributors

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Peter Milway	Milway Consulting Limited	– The Impacts to Business of Carrying Out Carbon Assessments – The Sector-Wide Economic Impacts of Widespread Carbon Assessments

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