Sustainable Cities and Society 113 (2024) 105702

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Towards net-zero embodied carbon: Investigating the potential for ambitious embodied carbon reductions in Australian office buildings

William Craft [a,*], Philip Oldfield [a], Gerard Reinmuth [b,c], Damian Hadley [d], Scott Balmforth [b], Anh Nguyen [b]

[a] School of Built Environment, University of New South Wales, Kensington 2052, NSW, Australia
[b] Terroir, Chippendale 2008, NSW, Australia
[c] School of Architecture, University of Technology Sydney, Ultimo 2007, NSW, Australia
[d] Cantilever, Newtown 2042, NSW, Australia

ARTICLE INFO

Keywords:
Embodied carbon
Net zero
Net zero embodied carbon
Low carbon design
Life cycle assessment
Office building
Timber construction

ABSTRACT

Embodied carbon is recognised as a major contributor to building-related greenhouse gas (GHG) emissions. In response, ambitious targets have been posed to reduce embodied carbon in the built environment, including the aspiration of 'net-zero embodied carbon'. This research uses a life cycle assessment (LCA) methodology to explore the magnitude of embodied carbon reductions viable within a multi-storey office building in Australia. It compares a typical building with more ambitious design scenarios to determine if net-zero embodied carbon is feasible in the current context and how design, material and methological decisions impact this. The results show that upfront embodied carbon reductions of 17–45% are achieveable with ambitious design and material changes, including a full timber structure, hybrid timber-aluminium façade, reduced columns grids, straw insulation, and more. However, the magnitude of reductions is highly influenced by material data sources and methodology. Net-zero embodied carbon was achievable when considering biogenic emissions stored in timber and other biomaterials, although only temporarily, for a period of up to 19 years. In response, we propose a new term 'temporal net-zero embodied carbon' to identify the point in time during a building's life cycle when it can no longer be considered a temporary carbon sink. The paper concludes by highlighting the opportunties and challenges temporal net-zero embodied carbon presents in terms of transparency and reliability of metrics, the need for consistent approaches to measurement and benchmarking, and the challenges of achieving large-scale embodied carbon reductions in the office sector.

1. Introduction

The scientific basis for climate change is well established with robust evidence showing the way humanity has, and continues, to live is causing irreversible and widespread damage to the life-supporting systems we rely upon (Armstrong McKay et al., 2022; IPCC, 2023; Rockström et al., 2023). Despite recently increased climate pledges and targets to meet the Paris Climate Agreement's aim of limiting global warming to 1.5 °C, the world's current trajectory is likely to result in around 2.7 °C of warming by the end of the century (Lenton et al., 2023; Meinshausen et al., 2022; UNEP, 2023). A large contributor to this is the buildings and construction sector, which accounts for 37% of global energy and process-based carbon dioxide (CO_2) emissions and is not on track to reduce emissions sufficiently by 2050 (UNEP, 2022). As a result, there are concerted efforts to reduce the built environment's greenhouse gas (GHG) emissions through research, policy, design, and technology. In many parts of the world, these efforts are now increasingly focused on reducing *embodied carbon emissions*. This is due to a growing awareness that embodied carbon is a major contributor to building-related GHG emissions both at present, and especially in the future, as electricity grids decarbonise and building operational efficiencies improve (GBCA & thinkstep-anz, 2021; Schmidt et al., 2020).

Embodied carbon can be defined as the GHG emissions that are associated with materials and construction processes throughout the whole life cycle of a building or piece of infrastructure (WGBC, 2019). Recent studies have shown that embodied carbon can account for up to 50–75% of a building's life cycle carbon emissions (RICS, 2017; Robati et al., 2021; Schmidt et al., 2020). However, without urgent and

* Corresponding author.
E-mail address: w.craft@unsw.edu.au (W. Craft).

https://doi.org/10.1016/j.scs.2024.105702
Received 26 March 2024; Received in revised form 3 July 2024; Accepted 23 July 2024
Available online 25 July 2024

substantial action, it is estimated that embodied carbon could represent 85% of the total GHG emissions of Australian buildings by 2050 (GBCA & thinkstep-anz, 2021). In response, there is a significant and growing body of research on the importance of embodied carbon in buildings and strategies to reduce it (Circle Economy, 2023; Häkkinen et al., 2015; Pomponi & Moncaster, 2016; Pomponi et al., 2018; Prasad et al., 2023; Robati et al., 2021; WBCSD & Arup, 2023; WGBC, 2019). Emerging from this research are national and international targets with typical goals of a 40–65% reduction of embodied carbon by 2030 and 'net-zero embodied carbon' by 2040–2050 (Architecture, 2023; Prasad et al., 2023). Many call for substantive action immediately. For instance, a recent study by the World Business Council for Sustainable Development and Arup argues that we can and should reduce embodied carbon by 50% in all new buildings *now* (WBCSD & Arup, 2023).

In response to these targets, there has been a rapid increase in the frequency of embodied carbon calculations throughout academia and industry practice (De Wolf et al., 2017). This has been supported by the development of globally recognised standards to guide life cycle assessments (LCA) [(European Committee for Standardization (CEN), 2011; RICS, 2017; ISO, 2006a; ISO, 2006b)]. More recently, the regulation of embodied carbon emissions has also started to emerge, for example in France, the Netherlands and the Nordic countries (Röck et al., 2023). But 'net-zero embodied carbon' remains a relatively new concept, and there is a notable gap in studies that quantitatively and methodologically interrogate what it means and how it can be achieved at the building scale, if at all. This study addresses this gap by investigating the feasibility of net zero embodied carbon through design, material, methodological and supply chain considerations, and the temporal dimensions associated with it.

1.1. Towards net-zero embodied carbon buildings

In 2019, the World Green Building Council released a report titled 'Bringing embodied carbon upfront', which importantly defined the term 'net-zero embodied carbon' as:

> "A net zero embodied carbon building (new or renovated) or infrastructure asset is highly resource efficient with upfront carbon minimised to the greatest extent possible and all remaining embodied carbon reduced or, as a last resort, offset in order to achieve net zero across the lifecycle" (WGBC, 2019).

Although the importance of embodied carbon is acknowledged in most definitions of net-zero buildings (Lützkendorf et al., 2015), net-zero embodied carbon is rarely an explicit goal or outcome of building LCAs. Of the studies that do consider net-zero embodied carbon, many tend to be based on sector-wide decarbonisation pathways with higher degrees of uncertainty (Allen et al., 2022; Watari et al., 2024). For the limited studies at the individual building scale that have claimed net-zero, and even net-negative embodied carbon figures, there are three key factors that must be carefully considered.

First is the extent to which carbon offsets are relied upon. The Science Based Targets initiative (SBTi) have defined 'net zero' as reducing absolute GHG emissions in alignment with a 1.5 °C scenario with any residual emissions offset, and 'carbon neutral' as counterbalancing GHG emissions with carbon offsets without substantial (or any) emission reductions (Tarrant, 2021). For example, using current Australian residential building practices, a typical 230 m^2 family home will require planting over 8000 trees to offset its embodied carbon emissions (Schmidt et al., 2020). Beyond nature-based carbon offsets, Grinham et al. (2022) showed that over a service life of 100 years it was possible to offset a low-rise building's whole-of-life embodied carbon emissions of 488 $kgCO_2e/m^2$ through on-site renewable energy generation under specific grid decarbonisation scenarios. Luo (2022) investigated the feasibility of offsetting the embodied carbon emissions associated with a building retrofit through the anticipated energy and carbon savings from these retrofit measures. Most notably perhaps, Ng et al. (2016) demonstrated that through extensive on-site renewable energy generation, Hong Kong's 'Zero Carbon Building' was able to offset the operational and embodied carbon emissions of its 50-year lifespan. Yet for multi-storey buildings and dense urban contexts with decarbonising electricity grids, the feasibility of such approaches decreases significantly.

Secondly, how biogenic carbon is accounted for can significantly influence a building's reported embodied carbon emissions. Some studies suggest that biogenic carbon can enable buildings to be effective carbon sinks (Arehart et al., 2021; Churkina et al., 2020), and achieve net-zero and net-negative embodied carbon outcomes. For instance, the embodied carbon of Canadian homes has been calculated to range from 758 $kgCO_2e/m^2$ for high material carbon intensities, to −84 $kgCO_2e/m^2$ (negative) for the best available materials and those that store carbon (Magwood et al., 2021). Besana and Tirelli (2022), while acknowledging the potentially misleading negative values associated with biogenic carbon, show that a reuse project can almost offset its upfront embodied carbon emissions from its biomaterials. Other researchers find negative embodied carbon figures "deeply problematic", since any biogenic carbon stored in building materials is only temporary and should therefore be reported separately (Butler & Simmonds, 2024).

Thirdly, there can be considerable variation in how life cycle assessment (LCA) methodologies are applied (Pomponi & Moncaster, 2018). In addition to the treatment of biogenic carbon, large differences in embodied carbon results can arise from the scope of the study (i.e. upfront embodied carbon, whole-of-life embodied carbon, etc.), building inclusions and exclusions (i.e. whether finishes and services are included), and life cycle inventory data sources (i.e. process, input-output, or hybrid data sources). This variability in embodied carbon results is well documented (Bahramian & Yetilmezsoy, 2020; Pan & Teng, 2021; Prasad et al., 2023; Simonen et al., 2017) and in some cases has been proven to change embodied carbon results by a factor of 10 or more (Moncaster et al., 2018).

In sum, limited research examines if net-zero embodied carbon is feasible at the building-scale (particular for multi-storey buildings), and how design, material and supply chain considerations, as well as different LCA methodological choices and data sources impact this. This research directly responds to this gap in the context of the Australian office building sector by seeking to answer the following three questions:

1. What magnitude of embodied carbon reductions are currently possible in the Australian office building sector?
2. How do embodied carbon methodology and data sources influence the measurement and size of these reductions?
3. Can net-zero embodied carbon be achieved, and what factors influence this?

2. Methodology

2.1. Office case study scenarios

This study uses a case study office building in Australia called the 'Launceston St Lukes Timber Tower' to investigate the above research questions. The office building was completed in 2024 and has 8 storeys above ground with a small basement escape pathway. It has a rectangular plan shape with a gross floor area (GFA) of approximately 1000 m^2 per floor and includes the partial retention of an existing low-rise building's roof, floor and walls within the ground level. The building's core, ground and first floors have a reinforced concrete (RC) structure, and the remaining floors above consist of cross-laminated timber (CLT) floor slabs with glue-laminated timber (GLT) columns and beams. This as-built office building is consistent with current best practice in low-carbon office building design in Australia and is therefore defined as the 'best practice' (BP) scenario for this study. A detailed building information modelling (BIM) model was provided by the project design team to enable comprehensive material quantities to be determined. The high level of detail within the BIM model enabled the inclusion of a broader scope of building elements than typically reported in many LCAs, including building services (mechanical, plumbing, electrical and fire) and interior finishes (Hoxha & Jusselme, 2017; Kiamili et al., 2020; Pan & Teng, 2021). However, office fit-out and furniture were not included.

From this BP scenario, an alternative office case study scenario was developed to reflect more conventional construction in Australia. This involved redesigning the structure as an RC frame with increased building foundations to accommodate the heavier building, assuming the adaptive reuse elements at ground were new and not reused and adding in typical finishes such as suspended ceilings. The structural and material properties for these changes were informed by a structural engineer and the typical specifications of mid- to high-rise office building construction outlined by the Green Building Council of Australia's upfront carbon emissions calculation guide (GBCA, 2022). This scenario is defined as the 'typical' (TY) scenario for this study.

An initial embodied carbon analysis was first conducted for the BP scenario. This allowed the authors to identify the main contributors to embodied carbon and develop strategies to reduce them through a series of design workshops. For example, the building's structure was found to be a major contributor, which resulted in a redesigned timber structure with a reduced grid, enabling the removal of the substantial GLT beams. In addition, a lightweight timber frame was used as the primary structure for the upper three floors, replacing the mass-timber elements. The building's façade was also found to be a major contributor to embodied carbon, so alternative low-carbon materials such as straw insulation and a timber-aluminium hybrid curtain wall system were sourced. These design strategies that go beyond 'best practice' in Australia were consolidated into what is referred to as the 'stretch' (ST) scenario for this study.

The key functional building characteristics such as the window-to-wall ratio (WWR) and gross floor area (GFA) of these three case study scenarios were kept as similar as possible to ensure comparability. However, this study also defined three stretch 'sub-scenarios' to maximise the embodied carbon reductions by adjusting some of these characteristics. The first stretch sub-scenario (ST-W) involved reducing the window-to-wall ratio (WWR) from 60% to 40%, which is more aligned with low-carbon building design strategies (WBCSD & Arup, 2023). For example, a comprehensive study by Gauch et al. (2023) found that a lower WWR not only reduces embodied carbon but also reduces a multi-storey building's heating and cooling loads for all climates. This was defined as a sub-scenario, as the three main scenarios (TY, BP and ST) were established on the basis that changes would not impact operational emissions. The second stretch sub-scenario (ST-R) involved maximising reused and recycled building materials. This comprised of reusing structural steel and hardwood finishes from other projects and recycled aluminium profiles and steel reinforcement (see Appendix, Table A.3). The third stretch sub-scenario (ST-C) is a combination of these two sub-scenarios. All case study scenarios and sub-scenarios for this study are shown in Fig. 1, and a summary of their key structural, design and material differences is provided in Table 1.

As the BP scenario is based on an as-built office building, it complies with the regulatory context of Australia, the state of Tasmania, and the City of Launceston. It is also designed specifically for the cool temperature climate of Launceston. All office building scenarios were therefore established within this same regulatory and climatic context. For example, the total R-value for the roof insulation was set at R3.7 (upward), to comply with the minimum requirements of the National Construction Code of Australia for climate zone 7, with this maintained through all scenarios.

2.2. Calculating embodied carbon emissions

The life cycle of a building is typically divided into five key stages and 17 modules in accordance with the European Standard EN 15978 (European Committee for Standardization (CEN), 2011). This study includes modules A to D but does not include the carbon emissions associated with refurbishing the building (B5) and its operational energy use (B6) and water use (B7) (Fig. 2). This study focuses on the embodied carbon impact of each case study scenario, which is determined by its global warming potential (GWP) and measured in kilograms of carbon

Fig. 1. Schematic and artistic visualisation of the TY, BP and ST scenario and sub-scenarios.

Table 1
Key building characteristics of the office case study scenarios.

Building Characteristics	Best Practice (BP)	Typical (TY)	Stretch (ST)	Stretch WWR (ST-W)	Stretch Reuse (ST-R)	Stretch Combined (ST-C)
Number of storeys above ground	8	8	8	8	8	8
Total gross floor area (GFA)	8064 m^2	8064 m^2	7908 m^2 *	7908 m^2 *	7908 m^2 *	7908 m^2 *
Total estimated building mass	646 kg/m^2	1068 kg/m^2	379 kg/m^2	426 kg/m^2	379 kg/m^2	426 kg/m^2
Window-to-wall ratio (WWR)	60%	60%	60%	40%	60%	40%
Structural system	Substructure: concrete Superstructure: mass timber-concrete hybrid	Substructure: concrete Superstructure: concrete	Substructure: concrete Superstructure: mass timber and lightweight timber upper storeys	Substructure: concrete Superstructure: mass timber and lightweight timber upper storeys	Substructure: concrete Superstructure: mass timber and lightweight timber upper storeys	Substructure: concrete Superstructure: mass timber and lightweight timber upper storeys
Structural column grid	6 m x 9 m	6 m x 9 m	3.6 m x 6 m	3.6 m x 6 m	3.6 m x 6 m	3.6 m x 6 m
Cement replacement	20–30%	0%	20–30%	20–30%	20–30%	20–30%
Curtain wall system	Double-glazing, aluminium mullions	Double-glazing, aluminium mullions	Double-glazing, timber-aluminium hybrid mullions	Double-glazing, timber-aluminium hybrid mullions	Double-glazing, timber-aluminium hybrid mullions	Double-glazing, timber-aluminium hybrid mullions
Façade insulation material	Glasswool	Glasswool	Straw	Straw	Straw	Straw
Retention of existing building materials on-site	Yes	No	Yes	Yes	Yes	Yes
Use of recycled and reused materials from other sites	No	No	No	No	Yes	Yes

[*] The minor difference in GFA for the stretch scenario and sub-scenarios is due to the spatial reconfigurations needed from changing the structural column grid and the increased thickness of the straw-insulated external walls.

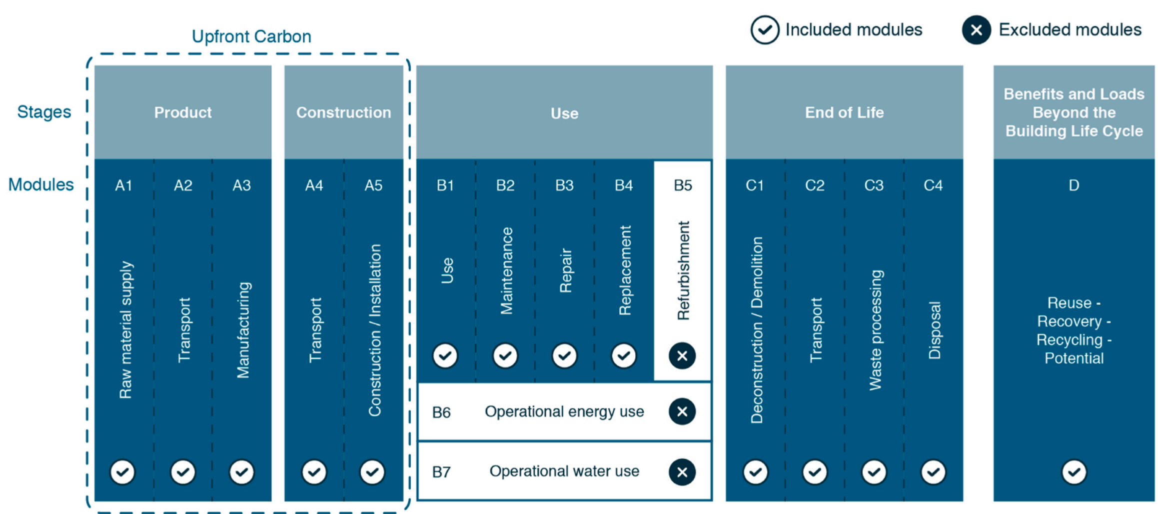

Fig. 2. Whole life carbon assessment modules included in this study, as defined by EN 15978 (European Committee for Standardization (CEN), 2011).

dioxide equivalent ($kgCO_2e$). The whole life cycle embodied carbon emissions for the case study scenarios were calculated using Eq. (1), which is adapted from Robati et al. (2021) and aligns with the RICS 'Whole life carbon assessment for the built environment' methodology (RICS, 2017).

$$E_{em} = \sum_{i=1}^{n} \Big((Q_i \times E_{i.pd}) + \big(M_i\big((D_{i.truck} \times E_{i.truck}) + (D_{i.ship} \times E_{i.ship}) + (D_{i.rail} \times E_{i.rail})\big) + \big(Q_i((W_i \times E_{i.el}) + E_{i.cn} + E_{i.umr})\big)\big)\Big) \times \frac{L_t}{L_i} + (Q_i \times E_{i.el}) \tag{1}$$

Where:

- E_{em} is the whole of life embodied carbon emissions of the case study scenarios (in $kgCO_2e$). This study considers the impacts of 139, 133 and 110 materials (or components where appropriate) in the BP, TY and ST scenarios respectively ($n = 139$, 133 and 110).
- i is the building material or component for each scenario (see Appendix, Tables A.1-A.3).
- Q_i is the quantity of the ith building material or component (see Appendix, Tables A.1-A.3).
- $E_{i.pd}$ is the product stage (A1-A3) embodied carbon value ($kgCO_2e$/unit) using process-based or hybrid-based life cycle inventory sources for the ith building material or component (see also Section 2.3: 'Life cycle inventory data sources').
- M_i is the mass in tonnes (t) of the ith building material or component.

- $D_{i.truck}$ is the travelling distance (km) the *i*th building material or component was transported by truck from the supplier to the construction site (see Appendix, Table D.1).
- $E_{i.truck}$ is the embodied carbon emissions ($kgCO_2e$/tkm) associated with transporting the *i*th material or component by truck. Process-based and hybrid-based fuel conversion factors for different sized trucks were used from AusLCI (2023) and Lenzen (1999) respectively.
- $D_{i.ship}$ is the travelling distance (km) the *i*th building material or component was transported by ship from the supplier to the construction site.
- $E_{i.ship}$ is the embodied carbon emissions ($kgCO_2e$/tkm) associated with transporting the *i*th building material or component by ship. In this study we have assumed a constant fuel conversion factor for container ships of 0.0161 $kgCO_2e$/tkm for the process-based analysis, which is taken from DEFRA (2022), and 0.03 $kgCO_2e$/tkm for the hybrid-based analysis, which is taken from Lenzen (1999).
- $D_{i.rail}$ is the travelling distance (km) the *i*th building material or component was transported by rail from the supplier to the construction site. Rail transportation was only considered for suppliers that were in close proximity to freight train lines.
- $E_{i.rail}$ is the embodied carbon emissions ($kgCO_2e$/tkm) associated with transporting the *i*th building material or component by rail. In this study we have assumed a constant fuel conversion factor for rail transportation of 0.024 $kgCO_2e$/tkm for the process-based analysis, which is taken from AusLCI (2023), and 0.07 $kgCO_2e$/tkm for the hybrid-based analysis, which is taken from Lenzen (1999).
- W_i is the typical on-site construction waste percentage for the *i*th building material or component taken from GBCA (2022) or relevant process-based life cycle inventory sources (see Appendix, Table B.1). The construction waste factor associated with prefabricated elements and engineered timber was assumed to be 0% in this study, as this is included in the product stage (A1-A3) embodied carbon emissions of the building material or component (RICS, 2023).
- $E_{i.cn}$ is the embodied carbon emissions ($kgCO_2e$) associated with the on-site construction equipment that is required to construct the building. In this study, the recommended value of 40 $kgCO_2e/m^2$ from RICS (2023) is used in all scenarios.
- $E_{i.umr}$ is the embodied carbon emissions ($kgCO_2e$) associated with the use (B1), maintenance (B2) and repair (B3) of the *i*th building material or component. The scope of this LCA only included a process-based analysis for these life cycle stages due to lack of available hybrid data.
- L_t is the total lifespan in years of the building for all scenarios, which was assumed to be 60 years (RICS, 2017).
- L_i is the lifespan in years of the *i*th material or component. When a material or component's lifespan exceeded the 60-year building lifespan, the lifespan ratio $\left(\frac{L_t}{L_i}\right)$ is equal to 1. The building material or component lifespan's were taken from RICS (2017) (see Appendix, Table C.1) or from their associated reference service life specified in the EPD where possible. Where this was not possible, industry averages for the service life of specific materials were used.
- $E_{i.el}$ is the embodied carbon emissions ($kgCO_2e$) associated with the end-of-life (C1-C4) embodied carbon emissions for the *i*th building material or component. The scope of this LCA only included a process-based analysis for these life cycle stages. Where end-of-life impacts were not reported in the specific process-based life cycle inventory sources, similar product or sector wide values were used. Transportation distances to end-of-life (C2) facilities were project-specific.
- Benefits and loads beyond the building life cycle (D) are reported separately to whole-of-life (A-C) embodied carbon emissions as per (RICS, 2017). This was calculated by multiplying the quantity of the *i*th building material or component with their associated embodied carbon value ($kgCO_2e$/unit) for reuse, recycling and recovery loads or benefits. The scope of this LCA only included a process-based analysis for this life cycle stage.

The functional unit of an LCA is the quantified performance of a product system for use as a reference unit (ISO, 2006a), and as such becomes the basis for comparing the embodied carbon emissions of the case study scenarios. The functional unit defined in this study is 1 m^2 of gross floor area (GFA) of an Australian office building. All embodied carbon emissions presented in this study are therefore normalised per square metre of GFA (i.e. $kgCO_2e/m^2$ GFA).

2.3. Life cycle inventory data sources

A life cycle inventory (LCI) outlines the inputs and outputs associated with building materials or products and can be established by using a process, hybrid or environmentally-extended input-output analysis (EEIOA) (Crawford et al., 2018). A process-based LCI itemises each specific input and output for a given step in producing a product. This is the method used for Environmental Product Declarations (EPDs). An EEIOA-based LCI is based on far broader economic transactions between industry sectors, and a hybrid-based LCI is a combination of these two approaches. In Australia, the Environmental Performance in Construction (EPiC) database (Crawford et al., 2019) is a commonly used hybrid LCI database for building materials.

The benefits and limitations of EPDs and hybrid-based databases like EPiC are well documented. For example, EPDs can rely on inconsistent data sources and methods, vary in system boundaries and are not particularly transparent, which makes selecting and comparing appropriate products potentially problematic (Crawford et al., 2022; Gelowitz & McArthur, 2016). However, EPDs are third-party verified documents of specific building products which can be beneficial to informing detailed design and material choice decisions for practitioners (Gelowitz & McArthur, 2016). Conversely, it is suggested that the EPiC database provides a more comprehensive calculation of embodied carbon emissions, avoiding truncation errors associated with EPDs, that is methodologically consistent, transparent and can save time and costs associated with conducting an LCA. But EPiC data is generic at a national level, and thus cannot be used to compare materials from different suppliers (Crawford & Stephan, 2022; Crawford et al., 2022). Temporally, the EPiC database provides a relative improvement to previous material coefficient databases that are considerably out of date (Crawford et al., 2022), whereas EPDs typically have only a 5-year lifespan, with the number of emerging EPDs showing exponential growth in recent years (Anderson, 2023). However, the EPiC database only considers the product stage (A1-A3) and excludes use (B) and end-of-life (C) data whereas EPDs can vary in system boundaries. Changes to EN 15804 in 2019 (European Committee for Standardization (CEN), 2019) now requires newer EPDs to include end-of-life (C) and module D emissions, but transportation (A4), construction (A5) and use (B) stages remain optional (Anderson & Moncaster, 2022).

EPDs, primarily from the EPD Australasia (EPD Australasia, 2023) and EPD International (EPD International, 2023) systems, and the EPiC database were used separately in this study to quantify and compare the embodied carbon emissions for the case study scenarios. This is because in Australia, embodied carbon calculations typically use either EPDs or the EPiC database. The choice of which LCI method to use can be influenced by a range of factors such as data availability, the LCA's scope, which embodied carbon tool is used, the building type or an LCA expert's preference. Importantly, two key sustainable building performance programs in Australia—the Building Sustainability Index (BASIX) and the National Australian Built Environment Rating System (NABERS)—are integrating embodied carbon calculations into their scope. BASIX is a mandatory policy requirement for all new residential buildings and major renovations in the state of New South Wales, which from October 2023 requires the calculation of embodied carbon. NABERS ratings are a legal requirement for all commercial buildings over 1, 000m^2 at the point of sale or lease, which at present focusses on operational emissions, but is in the process of expanding to embodied carbon ratings also. While both systems permit the use of both EPDs and EPiC, BASIX has developed a material index for product stage (A1-A3) embodied carbon calculations that prioritises the use of data from EPiC (NSW Government, 2023), and NABERS has established a framework for upfront (A1-A5) embodied carbon calculations that prioritises the use of data from EPDs (Vickers et al., 2022). This study conducts a comparative analysis of each case study scenario using EPiC and EPDs to quantify the variability in potential embodied carbon reductions and highlight the key implications of using these different LCI data sources for building-scale LCAs. Alternative options beyond EPDs and EPiC were not considered in this study as these data sources are the only two integrated into emerging Australian embodied carbon regulatory frameworks. By limiting the study to EPDs and EPiC, this ensures the results of this study, and their implications, are relevant and practical for the Australian building and construction industry.

To ensure an accurate comparison, this study investigates the variability between EPDs and EPiC in embodied carbon reductions for the upfront embodied carbon (A1-A5) of each case study scenario only (since EPiC data for B, C and D is unavailable). However, the ST-R and ST-C are excluded from this analysis as recycled and reused material coefficients are not available in the EPiC database. Where some building materials and components were not available or limited from the EPD Australasia and EPD International systems, additional EPDs from other systems as well as product environmental profiles (PEP) were used. Published data generated using the Chartered Institution of Building Services Engineers (CIBSE) TM65 embodied carbon tool for building services (CIBSE, 2021) was also used to determine the embodied carbon of some building services and equipment. As the EPiC database primarily reports the embodied carbon of materials and not products, breakdown material percentages of building products were taken from relevant EPDs to calculate the product stage (A1-A3) impacts of components using EPiC where possible. This means the EPiC figures may be less complete in terms of material quantities than the EPD data due to the large scope of complex building components included in this study.

To address some of the key limitations associated with using EPDs, this study also calculated the embodied carbon of the case study scenarios using a range of equivalent product EPDs. To do so, the ten most impactful products or materials in relation to their contribution to each scenario's upfront (A1-A5) and whole life (A-C) embodied carbon emissions were first identified (following the methodology of (RICS, 2023)) (see Appendix, Tables E.1-E.6). For each of these key products and materials, appropriate alternative EPDs were identified based on typical material sources for Australian buildings (e.g. concrete EPDs only within close proximity to building site, whereas GLT EPDs include manufacturers from Australia, Europe and New Zealand) and data availability. The lowest and highest embodied carbon products or materials were then used to recalculate the upfront and whole life embodied carbon for each case study scenario, providing an upper and lower range for measurements.

2.4. Biogenic carbon sequestration and storage

Bio-based construction materials have the potential to be carbon neutral as they absorb carbon from the atmosphere through plant photosynthesis, which converts carbon dioxide into biomass. This is then released at the end of the material's life through decomposition or combustion (Robati & Oldfield, 2022). Accordingly, there is a growing interest and appetite for bio-based construction materials (e.g. timber, straw, hemp, bamboo, etc.) in the built environment. This has also led to the emergence of the idea that buildings can be 'carbon sinks', providing temporary, but long-term storage of carbon emissions (Arehart et al., 2021). However, the ways in which carbon is sequestered (and subsequently stored and released) by construction materials and how this is accounted for is an area of inconsistency in building LCAs, and can significantly influence embodied carbon results and outcomes. For example, the whole-of-life embodied carbon emissions of particleboard was found to range between -692 kgCO_2e/m^3 to 433 kgCO_2e/m^3 due to differences in life cycle methodology and end-of-life scenarios (Garcia & Freire, 2014). Additionally, Rasmussen et al. (2021) showed that the embodied carbon values of structural wood EPDs can vary by a factor of two due to differences in material density and end-of-life scenarios. Another challenge when accounting for the biogenic carbon of bio-based construction materials in LCAs is that they can belong to multiple systems (e.g. the forest, the building, the energy industry, the landfill site), all of whom can claim the benefit of carbon capture (Hoxha et al., 2020). While this remains a complex challenge spanning across the entire supply chain, there are two major accounting methods that are used to avoid the double counting of biogenic carbon in building LCAs: traditional and dynamic approaches.

The traditional or static LCA approach assumes that any carbon sequestered and stored by bio-based construction materials will be equivalent to its end-of-life release of biogenic carbon. This traditional approach is further classified into two subcategories. Biogenic carbon is either ignored in the building LCA (the '0/0′ approach) or it is reported as 'negative emissions' in the product and construction stages (A) with equivalent positive emissions at the end of its life (C) (the '$-1/+1'$ approach). The dynamic LCA approach uses time-dependant life cycle inventories that accounts for the timing of these emissions (Arehart et al., 2021; Levasseur et al., 2013). However, a comparison between static and dynamic methods found that dynamic carbon accounting can potentially shift burdens between upfront and future emissions, and risk reducing the importance of strategies such as designing for disassembly and reuse, and maintenance-free buildings (Andersen et al., 2024).

As the $-1/+1$ approach is used by EN 15804+A2 (European Committee for Standardization (CEN), 2019) (i.e. EPDs), this method is used for all embodied carbon calculations in this study (unless documented otherwise). However, EPDs for timber products in Australia and New Zealand use a variation of the $-1/+1$ approach that reports negative biogenic carbon emissions in life cycle stage A, but the end-of-life emissions are determined by the specific end-of-life scenario (incineration, recycling/reuse and landfill) (Ouellet-Plamondon et al., 2023). Importantly, when a landfill end-of-life scenario is used, timber building components can report net-negative biogenic carbon emissions. That is, not all emissions stored in the timber products are measured as leaving the system at the end-of-life. This is based on research that has shown that only a very small fraction of the timber will degrade over timespans as long as 500 years, and therefore will only release a small percentage of the biogenic carbon it has captured (Wang et al., 2011). To investigate the impact of this end-of-life variability, this study calculated the whole-of-life embodied carbon emissions for all case study scenarios using both approaches. Where relevant, '$-1/+1$ (Recycling)' is used to refer to the standard $-1/+1$ method where all end-of-life emissions are released or passed onto the next building, and '$-1/+1$ (Landfill)' is used to refer to the variation of the $-1/+1$ method with a landfill end-of-life scenario for Australian and New Zealand timber EPDs.

While it is possible to manually calculate the biogenic carbon content of biomaterials (RICS, 2023), this study used the biogenic carbon values reported in EPDs. EN 15804+A2 compliant EPDs require biogenic carbon values to be reported separately as 'global warming potential (biogenic)' for each relevant life cycle stage. These values were used following the calculation methodology outlined in Section 2.2.

3. Results

3.1. Upfront embodied carbon

Fig. 3 shows the upfront (A1-A5) embodied carbon emissions for all case study scenarios using EPiC and EPD data. These results are segmented by LCA modules to show the breakdown of product stage (A1-A3), transportation (A4) and construction (A5) emissions. The

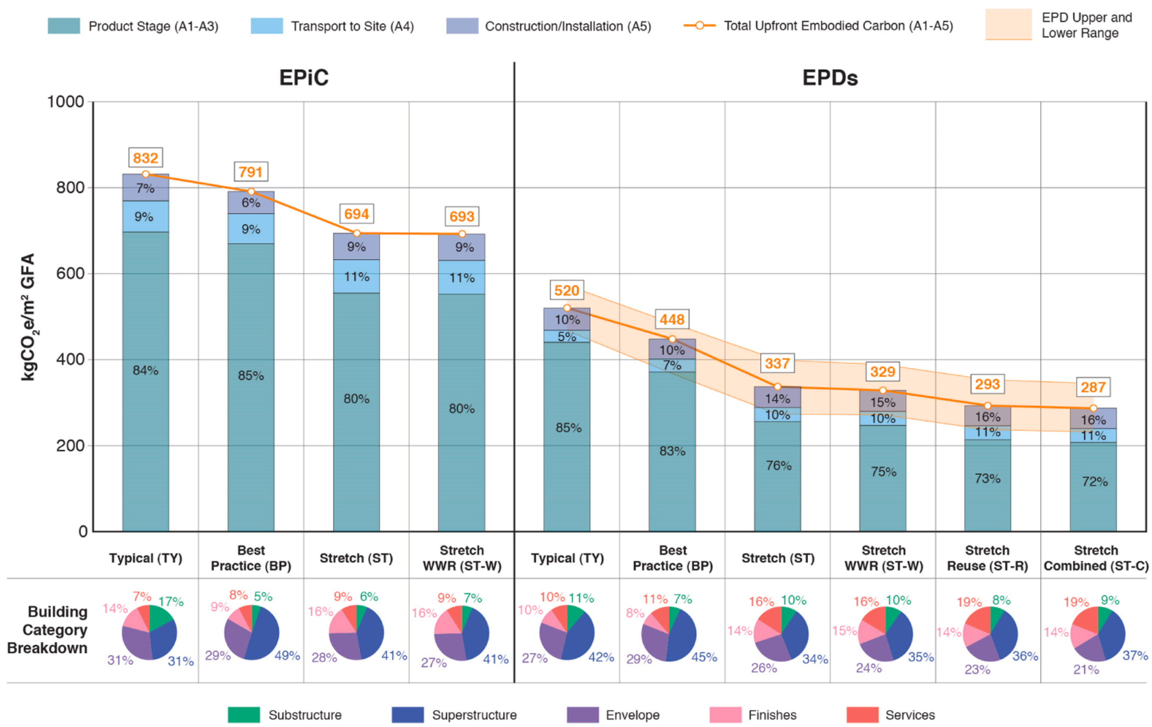

Fig. 3. Upfront (A1-A5) embodied carbon emissions for all case study scenarios using EPiC and EPD data.

upfront embodied carbon results using EPiC were 60–111% higher as compared to EPDs. Using EPiC, the upfront embodied carbon emissions of the ST-W scenario (693 kgCO$_2$e/m^2) achieved a 17% reduction from the TY scenario (832 kgCO$_2$e/m^2). However, using EPDs, the upfront embodied carbon emissions of the ST-W scenario (329 kgCO$_2$e/m^2) achieved a 37% reduction from the TY scenario (520 kgCO$_2$e/m^2). The lowest upfront embodied carbon achieved was the ST-C scenario using EPDs, with a figure of 287 kgCO$_2$e/m^2, which is a 45% reduction from typical (Fig. 3). Reductions beyond this to meet more ambitions targets (for example, <225 kgCO$_2$e/m^2 for LETI *A+* office buildings (London Energy Transformation Initiative)) would therefore seem highly challenging in the current Australian building industry. Upfront embodied carbon is mostly influenced by product stage (A1-A3), which accounted for between 72% and 85% of the embodied carbon emissions across all scenarios and LCI data sources (Fig. 3). However, as the quantity of low-carbon materials increases in the ST scenario and sub-scenarios, the relative importance of decarbonising transportation and construction activities increases. A breakdown of the upfront embodied carbon results by building category shows that with these larger quantities of low-carbon materials, the relative importance of decarbonising the building's services also increases (Fig. 3).

In general, the variability of the upper and lower EPD range increased for the ST scenario and sub-scenarios with larger quantities of timber products and decreased for the TY scenario with predominantly concrete products. For example, the TY scenario's upfront embodied carbon using EPDs ranged between 467 kgCO$_2$e/m^2 (−10%) to 573 kgCO$_2$e/m^2 (+10%), whereas the ST-C scenario ranged between 232 kgCO$_2$e/m^2 (−19%) to 345 kgCO$_2$e/m^2 (+20%) (Fig. 3).

A multi-storey building's structure is typically the largest contributor to its upfront embodied carbon emissions (Gauch et al., 2023). Fig. 4 shows the product stage (A1-A3) embodied carbon emissions of the structural building elements for the TY, BP and ST scenarios using EPiC and EPD data. The product stage embodied carbon of the timber-concrete hybrid structure of the BP scenario was 20% less than the all-concrete frame of the TY scenario using EPDs, but actually increases by 8% when using EPiC. This is due to the higher hybrid-based embodied carbon coefficients for timber in the EPiC database,

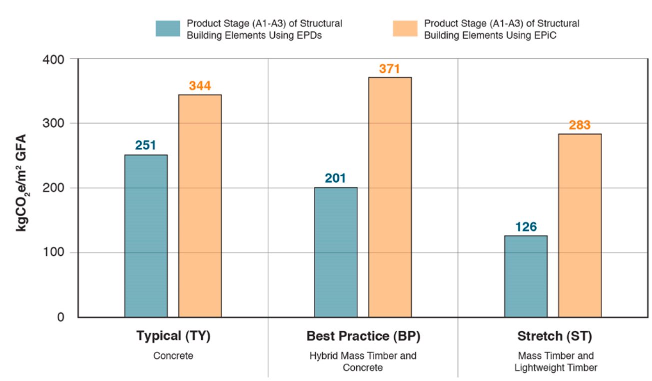

Fig. 4. Product stage (A1-A3) embodied carbon emissions of the structural building elements for the TY, BP and ST scenarios using EPiC and EPD data.

especially for the glue-laminated timber beams (GLT is 1,718 kgCO$_2$e/m^3 in EPiC and approximately 200–400 kgCO$_2$e/m^3 using EPDs). However, using an all-timber structure with reduced grid dimensions in the ST scenario provides product stage embodied carbon savings of 24% and 18% as compared to the BP and TY scenarios respectively using EPiC. Using EPDs, the all-timber structure of the ST scenario achieved more substantial embodied carbon reductions of 37% and 50% compared to the BP and TY scenarios respectively (Fig. 4).

3.2. Whole-of-life embodied carbon

Fig. 5 shows the whole-of-life (A-C) embodied carbon emissions divided by LCA modules for all case study scenarios using EPD data (EPiC data is not available for stages B and C, and so is excluded from the analysis here). The ST-C scenario had the lowest whole-of-life embodied carbon emissions of 530 kgCO$_2$e/m^2, which is 42% less than the TY scenario (918 kgCO$_2$e/m^2). Like the upfront embodied carbon results, the variability of the upper and lower EPD range across the whole building life cycle increased for the ST scenario and sub-scenarios with

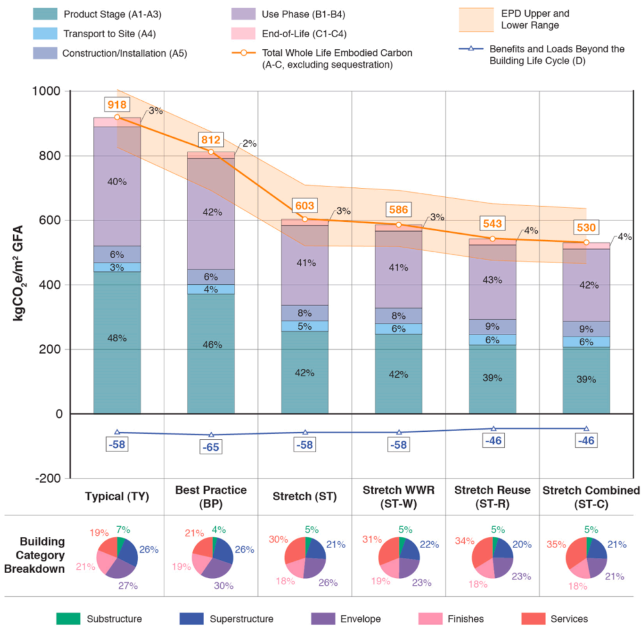

Fig. 5. Whole-of-life (A-C) embodied carbon emissions for all case study scenarios using EPD data.

larger quantities of timber products. The ST-C scenario's whole life embodied carbon ranged between 482 kgCO$_2$e/m^2 (−12%) to 654 kgCO$_2$e/m^2 (+19%), and the TY scenario ranged between 825 kgCO$_2$e/m^2 (−10%) to 1,003 kgCO$_2$e/m^2 (+9%) (Fig. 5). Importantly, as the quantity of low-carbon and reused materials increases with the ST-R and ST-C scenarios, the use phase (B1-B4) outweighed the product stage (A1-A3) in the breakdown of whole-of-life embodied carbon emissions. This is primarily due to replacing building materials (stage B4) across the 60-year lifespan of the building. A breakdown of the whole-of-life embodied carbon results by building category shows that as the quantity of low-carbon materials increases in the ST scenario and sub-scenarios, the building services become the largest contributor to the whole life embodied carbon, responsible for up to 35% of emissions (Fig. 5).

Fig. 6 shows the detailed design changes between the case study scenarios and the associated embodied carbon changes across the building's whole life. The most effective single strategy for reducing embodied carbon is replacing the floor finishes from carpet to hardwood for the ST scenario, which resulted in a whole-of-life (A-C) reduction of

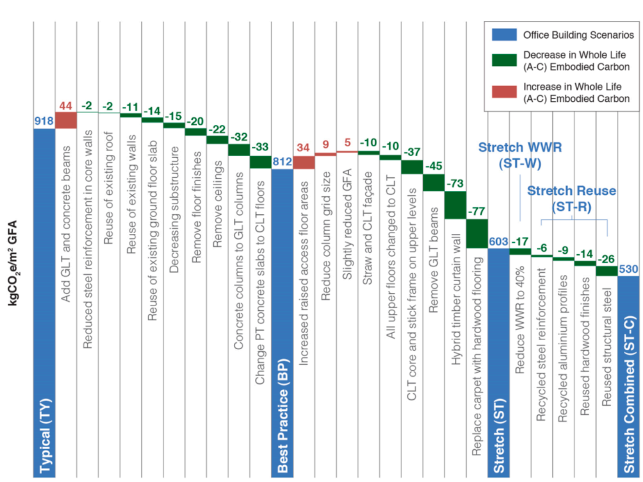

Fig. 6. Waterfall diagram showing the embodied carbon (A-C) impact of individual design and material changes across the case study scenarios using EPD data.

77 kgCO$_2$e/m^2. This is a direct result of a relatively high product stage emissions and the short lifespan of carpet flooring, which was assumed to be replaced every ten years. Changing from aluminium mullions to a timber and aluminium hybrid mullion for the ST scenario achieved a whole-of-life embodied carbon reduction of 73 kgCO$_2$e/m^2. Another key design change with high embodied carbon savings was the removal of GLT beams in the BP scenario by using a smaller column grid of 3.6 m x 6 m. Although this change required more GLT columns resulting in an additional 9 kgCO$_2$e/m^2, the removal of the GLT beams reduced the whole-of-life embodied carbon by 45 kgCO$_2$e/m^2.

3.3. *Timber end-of-life scenarios*

Fig. 7 shows the embodied carbon, biogenic carbon and subsequent net embodied carbon emissions of each case study scenario when timber is either recycling or landfilling at the end of its life. As outlined in Section 2.4, the recycling end-of-life scenario represents the −1/+1 biogenic carbon accounting method aligned with EN 15804+A2, whereas the landfill scenario represents the −1/+1 variation used in Australia and New Zealand timber EPDs, with some emissions considered 'stored' in the landfilled timber. When biogenic carbon is included (i.e. net embodied carbon emissions) and Australian and New Zealand timber products are landfilled, large whole-of-life embodied carbon reductions are possible as not all carbon stored in the timber and counted as a negative emission in the product stage (A1-A3) is released at the end of life. For example, the ST-C scenario has a net embodied carbon of 550 kgCO$_2$e/m^2 when the timber recycled at the end-of-life stage, but a far lower 295 kgCO$_2$e/m^2 when the timber is landfilled (Fig. 7).

3.4. *Net-zero embodied carbon*

Fig. 8 shows the net whole life embodied carbon (including biogenic carbon) for all case study scenarios with the upper and lower EPD range. While many LCA standards now require biogenic carbon to be reported separately, it is included here to investigate if net-zero embodied carbon is feasible for the case study scenarios. We propose the term 'temporal net-zero embodied carbon' to emphasise that even if net zero is achieved, it is only temporary (although often long-term), and that any carbon stored in the materials will leave the system at the end of the building's life (all scenarios in Fig. 8 use the −1/+1 method, aligned with EN 15804+A2). Using the lower EPD range, temporal net-zero embodied carbon for the ST-R and ST-C scenarios was achievable for 19 years; that is the carbon stored in the building materials was higher than the embodied carbon emitted for that period (Fig. 8). The buildings cease being 'net-zero embodied carbon' when the emissions due to maintenance, repair, replacement and end-of-life activities increase embodied carbon beyond that stored in the biomaterials.

4. Discussion and conclusions

4.1. *Are net-zero embodied carbon buildings feasible?*

One of the questions motivating this study was 'can we achieve net-zero embodied carbon?' In the context of an office building in Australia, the answer was found to be both yes and no. The no answer is straightforward in the sense that no case study scenario was able to achieve net-zero embodied carbon emissions for either its upfront emissions, nor for the entire 60-year lifespan. The yes answer is more complex and relies on both design and methodological choices and assumptions. In this study, net-zero embodied carbon could only be achieved *temporarily*, as emissions from upfront and in-use phases eventually outweigh any carbon stored in the building materials. We have proposed a new term 'temporal net-zero embodied carbon' to reflect this, and to identify the point in time during a building's life cycle when it can no longer be considered a temporary carbon sink.

Achieving temporal net-zero embodied carbon relies upon reducing

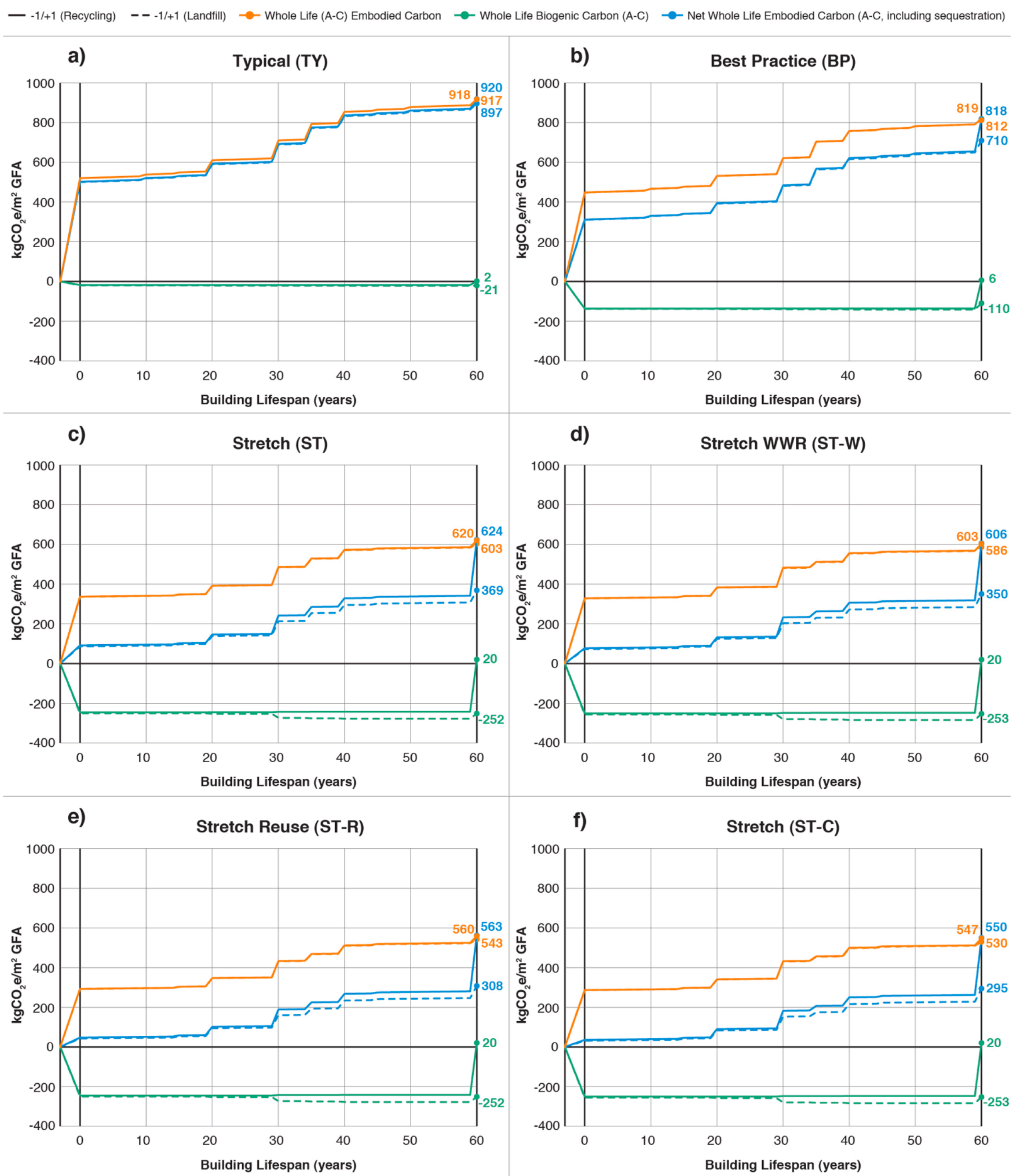

Fig. 7. Whole-of-life (A-C) embodied carbon emissions showing the impact of the −1/+1 (recycling) and −1/+1 (landfill) timber end-of-life scenarios for the (a) TY; (b) BP; (c) ST; (d) ST-W; (e) ST-R; and (f) ST-C scenarios.

upfront carbon emissions and maximising carbon storage by using bio-based building materials such as timber or straw. However, this is potentially problematic as it could in theory encourage practitioners to increase quantities of bio-based materials in buildings to 'offset' the impact of other materials, instead of out of functional necessity. To illustrate this, consider the following; if the CLT floor thickness for the ST-C scenario using the lower EPD range was doubled from 250 mm to 500 mm, the building temporal net-zero embodied carbon increases from 19 years to 39 years, even though its upfront embodied carbon [A1-A5] would increase from 232 $kgCO_2e/m^2$ to 258 $kgCO_2e/m^2$. If this same scenario also used the landfill end-of-life scenario as documented in Australian timber EPDs, its temporal net-zero embodied carbon increases further to 54 years of the building's 60-year lifespan. To avoid this, most LCA standards and guides state that any biogenic carbon must be reported separately. However, the analysis here shows that with 'creative accounting' (Butler & Simmonds, 2024), ambitious embodied carbon performance metrics can be reported that could be considered misleading.

Another key factor influencing net-zero embodied carbon in this study was the replacement of building elements after their useable lifespan (B4). As shown in Fig. 5, these are a significant contributor to the whole-of-life embodied carbon emissions of all scenarios. This study assumes that the replacement of future building elements will have the same embodied carbon impact as they currently have now, as per established methodologies (RICS, 2023). However, the embodied carbon of materials will likely fall in future years, due to the decarbonisation of energy sources and supply chains. The replacement embodied carbon emissions in this study are therefore likely to be an

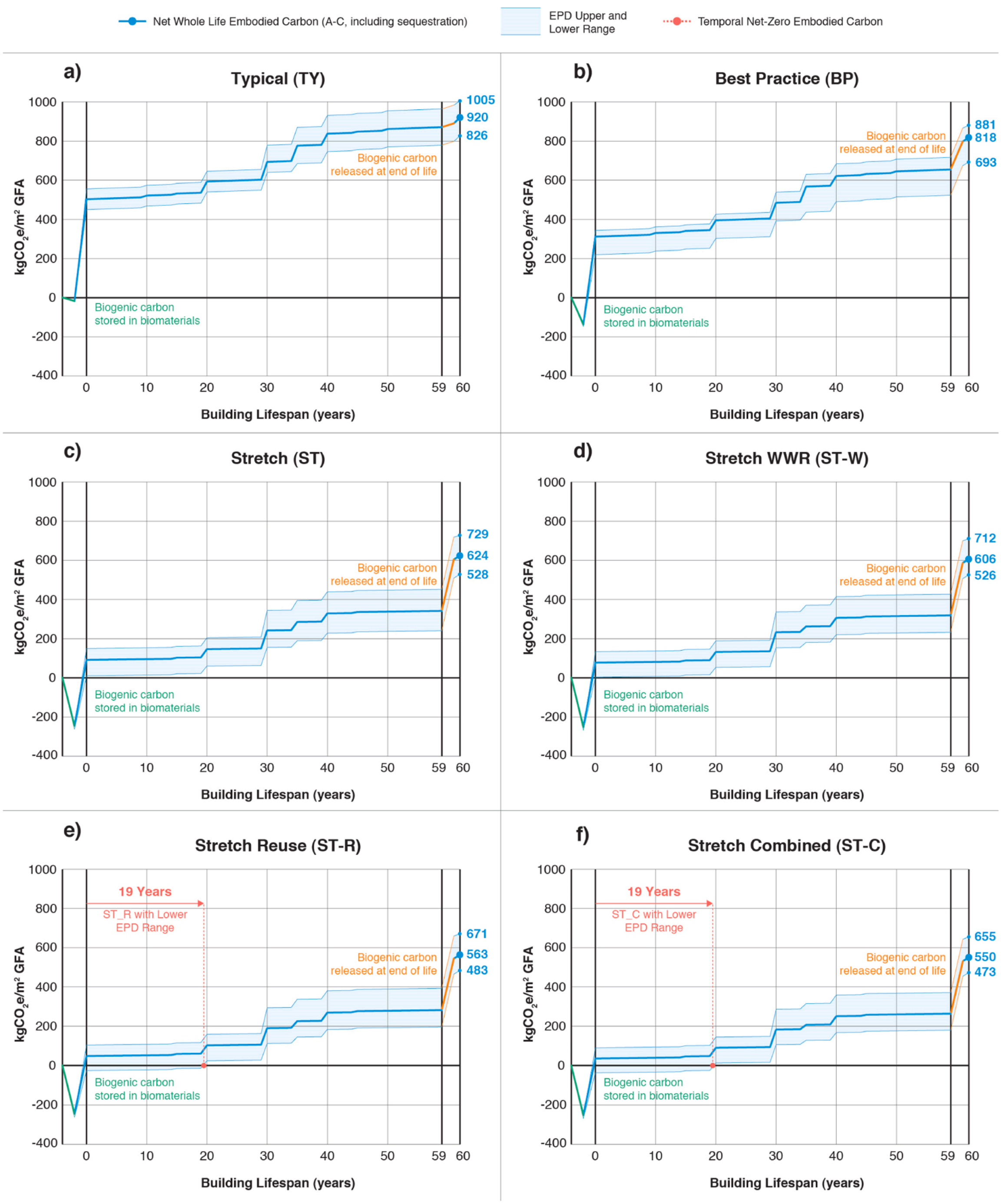

Fig. 8. Whole-of-life (A-C) net embodied carbon emissions showing the upper and lower EPD range for the (a) TY; (b) BP; (c) ST; (d) ST-W; (e) ST-R; and (f) ST-C scenarios, and using the −1/+1 approach for biogenic emissions (the green line shows product stage biogenic carbon storage, and the orange line shows end-of-life biogenic carbon release). Periods of temporal net-zero embodied emissions against the lower range of EPDs are highlighted in red.

overestimation. This could result in temporal net-zero embodied carbon durations increasing further. Dynamic LCA can be considered an appropriate methodology to account for decarbonising supply chains, but conversely it has been criticised as underestimating these emissions and potentially risking shifting the focus away from the use stage and end-of-life emissions (Andersen et al., 2024). Alternatively, a new methodology developed by RICS provides decarbonisation pathways and guidance for both operational emissions and future material usage in LCAs (RICS, 2023). The Science-Based Targets Initiative (SBTi) also provide a decarbonisation pathway aligned with a 1.5 °C future for construction (Den et al., 2023), which could be used to inform the integration of future decarbonisation in LCAs. Shanbhag and Dixit (2024) highlights the importance of considering future weather and energy consumption changes alongside these decarbonisation pathways. Regardless, there is a need to refine and harmonise existing building LCA methodologies to better consider the decarbonisation of future material supply chains into the calculation of these recurring or replacement emissions.

It is proposed that temporal net-zero embodied carbon could be further developed alongside conventional embodied carbon reporting metrics to support decarbonisation goals within the building and construction industry. Separate reporting of biogenic carbon is critical, but on its own it can be hard to determine for how long biogenic emissions are stored in a building's life cycle, when it is released, and the broader carbon implications of this. The ability of temporal net zero embodied carbon to document the changing nature of emissions *over time* (as shown in Fig. 8), can clearly and effectively illustrate the temporal considerations of carbon sequestration, storage, and release. It could also increase the transparency and reliability of net-zero or net-negative embodied carbon claims as the industry moves towards this ambitious net-zero embodied carbon target.

4.2. Embodied carbon methodology and data source implications

Another major objective of this study was to investigate the impact of different methodologies and data sources on embodied carbon reductions. Most notably, the upfront embodied carbon emissions of the case study scenarios were found to be 60–111% higher when using the hybrid-based EPiC database compared to the process-based EPD data. A major difference between these LCIs is the significantly higher embodied carbon values for timber products in the EPiC database. This study has shown that the switch from a concrete structure to an engineered timber structure could reduce building-scale embodied carbon using some metrics (EPDs) but increase emissions using others (EPiC). This is particularly important in Australia, since the BASIX Materials Index for residential embodied carbon calculations prioritises EPiC data and the NABERS embodied carbon methodology prioritises EPD data for commercial buildings. This could lead to industry pursuing concrete structures in the residential sector, and timber systems in the commercial sector to achieve the lowest embodied carbon outcomes. It is therefore critical that practitioners understand the fundamental differences between different embodied carbon datasets, and the benefits and limitations of each when designing for low embodied carbon buildings.

The biogenic carbon accounting methodology was also found to have a significant impact on embodied carbon reductions. For the ST scenario and sub-scenarios with large quantities of timber, changing the end-of-life outcome to landfilling for these timber elements reduced the whole-of-life net-embodied carbon emissions by over 40%. However, this is only possible when using timber EPDs from Australia and New Zealand, as many EPDs and datasets from around the world use either the '$0/0'$' or '$-1/+1'$' method (Ouellet-Plamondon et al., 2023), for which there is always a balance of embodied carbon stored and released across a building's life. This posed an interesting conundrum as the BP scenario, which was based on the as-built case study office building, sourced timber from both Australian and European manufacturers. While the $-1/+1$ approach was used for consistency in this study (unless otherwise noted), following the EPDs directly would mean that if Australian timber is sourced and landfilled there would be a large quantity of carbon stored and reported as a benefit for the building. But if European timber is imported and landfilled, any carbon stored within this timber is assumed to be passed on and cannot be claimed by the building. As many multi-storey buildings have global supply chains, this reinforces the need for a more consistent approach with clearly defined boundaries for building LCAs regarding biogenic carbon accounting.

Furthermore, any apparent 'carbon benefit' of landfilling timber elements could have adverse effects on building design and sustainability outcomes. This could see practitioners prioritise the landfill of timber elements at the end of the building's life, rather than design for deconstruction and reuse of these elements. This would be at odds with established frameworks where reuse and recycling are preferred to disposal (European Commission, 2021).

4.3. Embodied carbon reductions in the office sector

This research also quantified the magnitude of embodied carbon reductions currently possible in Australian office buildings. Firstly, it shows a simple switch from concrete to timber may not provide major embodied carbon savings *on its own*. Existing studies have suggested embodied carbon reductions of building structures in the order of 34–84% are possible with a switch from concrete to timber (Skullestad et al., 2016). Here, we found structural emissions reduced by 20% when using EPDs (a reduction of 50 $kgCO_2e/m^2$) but an increase of 8% using EPiC data (an increase of 27 $kgCO_2e/m^2$). This is due not only to the higher timber figures in the EPiC database, but also the detailed documentation of steel connection plates used in the timber structure, which increased the structural embodied carbon. However, when combined with a reduction of grid dimensions, and the use of lightweight timber on the upper three floors, structural embodied carbon reductions, as compared to an RC frame, were more substantive—a 50% reduction using EPDs (125 $kgCO_2e/m^2$) and an 18% reduction using EPiC (61 $kgCO_2e/m^2$). This supports existing research that reducing floor spans can provide substantive embodied carbon savings (WBCSD & Arup, 2023), and puts the emphasis on architects, structural engineers and developers to move away from 'column-free' office designs.

Most focus on embodied carbon reductions in both literature and policy is centred on upfront emissions (modules A1-A5) (WBCSD & Arup, 2023). This study shows that savings in the order of 35% are achievable using EPDs, and 17% using EPiC. More substantive reductions above 40% were possible using EPDs, but only when quite radical design and material substitutions were made. As such, meeting the 40% reduction proposed by the WGBC by 2030 (WGBC, 2019) may be a challenge in the Australian office building sector. However, such targets are dependant on the 'baseline' against which reductions are made. In this study, a conventional concrete-framed office building was used (the TY scenario), which provided an upfront embodied carbon of 520 $kgCO_2e/m^2$. While such a figure is consistent with global norms (Lützkendorf et al., 2015), the Green Building Council of Australia suggest 500 $kgCO_2e/m^2$ would equate to a 'low embodied carbon' commercial building, while 1,000 $kgCO_2e/m^2$ would be a 'high embodied carbon' commercial building (GBCA, 2023). In this sense, the 'benchmark' of this study could already be considered relatively 'low carbon', due to its compact form and efficient post-tensioned slab structural solution. This highlights the need for robust embodied carbon benchmarks for different building typologies, such that relative reductions can be quantified and compared consistently (Prasad et al., 2023).

In terms of absolute figures, the lowest upfront embodied carbon found was 693 $kgCO_2e/m^2$ using EPiC and 287 $kgCO_2e/m^2$ using EPDs. These figures were largely achieved through design and material changes to the building's structural system, envelope and interior finishes. Further reductions beyond these figures would likely be challenging in the current market for new build offices. This reinforces the need for greater levels of adaptive reuse and retrofit to achieve substantive embodied carbon reductions (WGBC, 2019).

4.4. Limitations and future work

The limitations of this study primarily relate to the availability of data. There was a relatively limited number of EPDs available in Australia, which meant that EPDs for some building components were found only in countries with higher renewable energy mixes than Australia (e.g. Sweden, Finland, etc.). Local products could therefore have higher overall impacts than these materials, despite the international transportation (A4) emissions used in this study. Future studies could integrate additional LCI databases beyond EPDs and EPiC to address this data availability challenge, and further explore the variability in embodied carbon outcomes as documented here. Integrated industry-led embodied carbon databases such as the 'Built Environment Carbon Database' in the UK (BECD, 2024) and 'Product Aware' in Australia (Architects Declare, 2024), are also emerging to address data availability challenges.

While this study provided an EPD range to address data uncertainties, future work could also seek to address a wider range of uncertainties. For example, the updated RICS methodology includes a whole life cycle assessment uncertainty factor, which accounts for potential discrepancies arising from data reliability, a building's project phase, and the accuracy of material quantities (RICS, 2023). An example of these uncertainty factors is provided in the Appendix (Table F.1), using the best practice scenario.

Given the high embodied carbon contributions of material replacements identified here, and the high fit-out churn rates reported in Australian offices (Forsythe, 2017), future office building LCAs should seek to integrate complete fit-outs and furniture into their scope. The post-COVID hybrid work environment could also enable further research into a broader range of workplace and cultural scenarios to reduce embodied carbon emissions in the office sector, beyond those achieved here, such as reducing building floor area to account for more hot-desking and hybrid working.

Lastly, this study has investigated the embodied carbon reductions in Australian office buildings within current material, design and supply chain paradigms. However, carbon emissions are cumulative with defined carbon budgets to limit future global warming. Therefore, global, national and sectoral carbon allocation methods could be integrated into future building LCA research to investigate whether the magnitude of embodied carbon reductions are aligned with a 1.5 °C trajectory. Research in Denmark has proposed a methodology (Reduction Roadmap, 2022) that could be used to achieve this.

Funding

This work was supported by an Innovation Connections Grant from the Australian Department of Industry, Science and Resources (grant number ICG002422) and funding from Terroir.

CRediT authorship contribution statement

William Craft: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Philip Oldfield:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Gerard Reinmuth:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Damian Hadley:** Writing – review & editing, Resources, Investigation, Conceptualization. **Scott Balmforth:** Writing – review & editing, Supervision, Resources, Conceptualization. **Anh Nguyen:** Writing – review & editing, Visualization, Investigation, Conceptualization.

Declaration of competing interest

Research Support: William Craft and Philip Oldfield report financial support was provided by Terroir. **Relationships**: There are no additional relationships to disclose. **Patents and Intellectual Property:** There are no patents to disclose. **Other Activities**: Gerard Reinmuth, Scott Balmforth and Anh Nguyen were involved in the architectural design and realisation of the Launceston St Lukes Timber Tower, through their roles at Terroir.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge St. Lukes Health, Commercial Project Delivery, Fairbrother and Engineering Solutions Tasmania for support with building information used in the study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.105702.

References

Allen, C.., Oldfield, P.., Teh, S. H., Wiedmann, T.., Langdon, S.., Yu, M., & Yang, J. (2022). Modelling ambitious climate mitigation pathways for Australia's built environment. *Sustainable Cities and Society, 77*, Article 103554.

Andersen, C. E.., Hoxha, E.., Rasmussen, F. N.., Sorensen, C. G.., & Birgisdottir, H.. (2024). Temporal considerations in life cycle assessments of wooden buildings: Implications for design incentives. *Journal of Cleaner Production*, Article 141260.

Anderson, J.. (2023). Reducing embodied carbon in the built environment: The role of environmental product declarations. *STEM | engineering & innovation* (p. 235). The Open University.

Anderson, J.., & Moncaster, A.. (2022). Embodied carbon, embodied energy and renewable energy: A review of environmental product declarations. In *Proceedings of the Institution of Civil Engineers - Structures and Buildings* (pp. 1–12).

Architects Declare, Product Aware, 2024. https://www.productaware.com.au/. (Accessed 24 June 2024).

Architecture 2030, The 2030 Challenge for Embodied Carbon, 2023. https://www.architecture2030.org/2030_challenges/embodied/. (Accessed 30 November 2023).

Arehart, J. H.., Hart, J.., Pomponi, F.., & D'Amico, B.. (2021). Carbon sequestration and storage in the built environment. *Sustainable Production and Consumption, 27*, 1047–1063.

Armstrong McKay, D. I.., Staal, A.., Abrams, J. F.., Winkelmann, R.., Sakschewski, B.., Loriani, S.., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science, 377*(6611), eabn7950.

AusLCI, The australian national life cycle inventory database (AusLCI) v1.42, 2023. https://auslci.com.au/index.php/EmissionFactors. (Accessed 2 August 2023).

Bahramian, M.., & Yetilmezsoy, K.. (2020). Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). *Energy and Buildings, 219*, Article 109917.

BECD, Built environment carbon Database, 2024. https://carbon.becd.co.uk/. (Accessed 24 June 2024).

Besana, D.., & Tirelli, D.. (2022). Reuse and retrofitting strategies for a net zero carbon building in milan: an analytic evaluation. *Sustainability, 14*(23), 16115.

Butler, J.., & Simmonds, A.. (2024). Much Ado about nothing: Is zero carbon construction actually possible?. *Passive House + Sustainable Building* (pp. 62–65). Dublin, Ireland: Temple Media Ltd.

Churkina, G.., Organschi, A.., Reyer, C. P. O...., Ruff, A.., Vinke, K.., Liu, Z.., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability, 3*(4), 269–276.

CIBSE, TM65 Embodied carbon in building services: A calculation methodology, 2021.

Circle Economy. (2023). *The Circularity Gap Report 2023* (pp. 1–64). Amsterdam: Circle Economy.

Crawford, R.., Stephan, A.., & Prideaux, F.. (2019). *Environmental Performance in Construction (epic) database*. Melbourne: The University of Melbourne.

Crawford, R.., Stephan, A.., & Prideaux, F.. (2022). The EPiC database: Hybrid embodied environmental flow coefficients for construction materials, Resources. *Conservation and Recycling, 180*, Article 106058.

Crawford, R. H.., Bontinck, P. A.., Stephan, A.., Wiedmann, T.., & Yu, M. (2018). Hybrid life cycle inventory methods – A review. *Journal of Cleaner Production, 172*, 1273–1288.

Crawford, R. H.., & Stephan, A.. (2022). Comparison of embodied greenhouse gas emissions data from environmental product declarations and the EPiC database: Implications for material selection. In P. Izadpanahi, & F. Perugia (Eds.), *55th International Conference of the Architectural Science Association* (pp. 177–188). ANZAScA.

DEFRA, Greenhouse gas reporting: conversion factors 2022, 2022. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022. (Accessed 2 August 2023).

Den, X. L., Caspani, M., Steinmann, J., Ryberg, M., & Lauridsen, K. (2023). A 1.5°C pathway for the global buildings sector's embodied emissions: pathway development description. *Science Based Targets*.

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings, 140*, 68–80.

EPD Australasia, EPD Australasia, 2023. https://epd-australasia.com/. (Accessed 15 May 2023).

EPD International, The International EPD System, 2023. https://www.environdec.com/home. (Accessed 15 May 2023).

European Commission, Waste Framework Directive, 2021. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en. (Accessed 15 March 2024).

European Committee for Standardization (CEN), EN 15978: 2011: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, 2011.

European Committee for Standardization (CEN). (2019). EN 15804:2012+A2:2019: Sustainability of construction works. Environmental product declarations. *Core Rules for the Product Category of Construction Products*.

Forsythe, P.. (2017). Quantifying the recurring nature of fitout to assist LCA studies in office buildings. *International Journal of Building Pathology and Adaptation, 35*(3), 233–246.

Garcia, R.., & Freire, F.. (2014). Carbon footprint of particleboard: A comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. *Journal of Cleaner Production, 66*, 199–209.

Gauch, H. L.., Dunant, C. F.., Hawkins, W.., & Cabrera Serrenho, A.. (2023). What really matters in multi-Storey building design? A simultaneous sensitivity study of embodied carbon, construction cost, and operational energy. *Applied Energy, 333*, Article 120585.

GBCA, thinkstep-anz, Embodied carbon and embodied energy in Australia's buildings, 2021.

GBCA, Upfront carbon emissions calculation guide - interim: guidance on calculation methods for the upfront carbon emissions and life cycle impacts credits, 2022.

GBCA, A practical guide to upfront carbon reductions: For new buildings and major refurbishments, 2023.

Gelowitz, M. D. C., & McArthur, J. J.. (2016). Investigating the effect of environmental product declaration adoption in LEED® on the construction industry: A case study. *Procedia Engineering, 145*, 58–65.

Grinham, J.., Fjeldheim, H.., Yan, B.., Helge, T. D.., Edwards, K.., Hegli, T.., & Malkawi, A. (2022). Zero-carbon balance: The case of HouseZero. *Building and Environment, 207*, Article 108511.

Häkkinen, T.., Kuittinen, M.., Ruuska, A.., & Jung, N.. (2015). Reducing embodied carbon during the design process of buildings. *Journal of Building Engineering, 4*, 1–13.

Hoxha, E.., & Jusselme, T.. (2017). On the necessity of improving the environmental impacts of furniture and appliances in net-zero energy buildings. *Science of The Total Environment, 596-597*, 405–416.

Hoxha, E.., Passer, A.., Saade, M. R. M...., Trigaux, D.., Shuttleworth, A.., Pittau, F.., Allacker, K., & Habert, G. (2020). Biogenic carbon in buildings: A critical overview of LCA methods. *Buildings and Cities*.

IPCC, Summary for Policymakers, Climate Change 2023. (2023). Synthesis report. In *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–34). Geneva, Switzerland: IPCC.

ISO. (2006a). *ISO 14044:2006 Environmental Management – Life Cycle Assessment – Requirements and Guidance* (pp. 235–248). Geneva, Switzerland: International Organization for Standardization.

ISO. (2006b). *ISO 14040:2006 Environmental management – Life Cycle Assessment – Principles and Framework* (pp. 235–248). Geneva, Switzerland: International Organization for Standardization.

Kiamili, C.., Hollberg, A.., & Habert, G.. (2020). Detailed assessment of embodied carbon of HVAC systems for a new office building based on BIM. *Sustainability*.

Lenton, T. M.., Xu, C., Abrams, J. F.., Ghadiali, A.., Loriani, S.., Sakschewski, B.., Zimm, C., Ebi, K. L., Dunn, R. R., Svenning, J. C., & Scheffer, M. (2023). Quantifying the human cost of global warming. *Nature Sustainability, 6*(10), 1237–1247.

Lenzen, M.. (1999). Total requirements of energy and greenhouse gases for Australian transport. *Transportation Research Part D: Transport and Environment, 4*(4), 265–290.

Levasseur, A.., Lesage, P.., Margni, M.., & Samson, R.. (2013). Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *Journal of Industrial Ecology, 17*(1), 117–128.

London Energy Transformation Initiative, Defining and aligning: Whole life carbon & embodied carbon, LETI.

Luo, X. J. (2022). Retrofitting existing office buildings towards life-cycle net-zero energy and carbon. *Sustainable Cities and Society, 83*, Article 103956.

Lützkendorf, T.., Foliente, G.., Balouktsi, M.., & Wiberg, A. H.. (2015). Net-zero buildings: Incorporating embodied impacts. *Building Research & Information, 43*(1), 62–81.

Magwood, C.., Ahmed, J.., Bowden, E.., & Racusin, J. D.. (2021). Achieving real net-zero emission homes: embodied carbon scenario analysis of the upper tiers of performance in the 2020 Canadian national building code. *Builders for Climate Action*.

Meinshausen, M.., Lewis, J.., McGlade, C.., Gütschow, J.., Nicholls, Z.., Burdon, R.., Cozzi, L., & Hackmann, B. (2022). Realization of Paris agreement pledges may limit warming just below 2 °C. *Nature, 604*(7905), 304–309.

Moncaster, A. M.., Pomponi, F.., Symons, K. E.., & Guthrie, P. M.. (2018). Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system. *Energy and Buildings, 173*, 389–398.

Ng, T. S. K., Yau, R. M. H., Lam, T. N. T., & Cheng, V. S. Y. (2016). Design and commission a zero-carbon building for hot and humid climate. *International Journal of Low-Carbon Technologies, 11*(2), 222–234.

NSW Government, State Environmental Planning Policy (Sustainable Buildings) 2022, 2023. https://legislation.nsw.gov.au/view/whole/html/inforce/current/epi-2022-0521. (Accessed 1 December 2023).

Ouellet-Plamondon, C. M.., Ramseier, L.., Balouktsi, M.., Delem, L.., Foliente, G.., Francart, N.., Garcia-Martinez, A., Hoxha, E.., Lützkendorf, T., Nygaard Rasmussen, F., Peuportier, B., Butler, J., Birgisdottir, H., Dowdell, D., Dixit, M. K., Gomes, V., Gomes da Silva, M., Gómez de Cózar, J. C., Kjendseth Wiik, M., Llatas, C., Mateus, R., Pulgrossi, L. M., Röck, M., Saade, M. R. M., Passer, A., Satola, D., Seo, S., Soust Verdaguer, B., Veselka, J., Volf, M., Zhang, X., & Frischknecht, R. (2023). Carbon footprint assessment of a wood multi-residential building considering biogenic carbon. *Journal of Cleaner Production, 404*, Article 136834.

Pan, W.., & Teng, Y.. (2021). A systematic investigation into the methodological variables of embodied carbon assessment of buildings. *Renewable and Sustainable Energy Reviews, 141*, Article 110840.

Pomponi, F.., De Wolf, C.., & Moncaster, A.. (2018). *Embodied Carbon in buildings: Measurement, Management and Mitigation* (p. XXII). Cham, Switzerland: Springer, 512.

Pomponi, F.., & Moncaster, A.. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management, 181*, 687–700.

Pomponi, F.., & Moncaster, A.. (2018). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews, 81*, 2431–2442.

Prasad, D.., Kuru, A.., Oldfield, P.., Ding, L.., Dave, M.., Noller, C.., & He, B. (2023). *Delivering on the Climate Emergency: Towards a Net Zero Carbon Built Environment*. Singapore: Palgrave Macmillan Singapore.

Rasmussen, F. N.., Andersen, C. E.., Wittchen, A.., Hansen, R. N.., & Birgisdóttir, H.. (2021). Environmental product declarations of structural wood: A review of impacts and potential pitfalls for practice. *Buildings*.

Reduction Roadmap, Reduction Roadmap: Preconditions and Methodologies, 2022.

RICS, Whole life carbon assessment for the built environment, 2017.

RICS, Whole life carbon assessment for the built environment, 2023.

Robati, M.., & Oldfield, P.. (2022). The embodied carbon of mass timber and concrete buildings in Australia: An uncertainty analysis. *Building and Environment, 214*, Article 108944.

Robati, M.., Oldfield, P.., Nezhad, A. A.., Carmichael, D. G.., & Kuru, A.. (2021). Carbon value engineering: A framework for integrating embodied carbon and cost reduction strategies in building design. *Building and Environment, 192*, Article 107620.

Röck, M.., Balouktsi, M.., & Ruschi Mendes Saade, M.. (2023). Embodied carbon emissions of buildings and how to tame them. *One Earth, 6*(11), 1458–1464.

Rockström, J.., Gupta, J.., Qin, D.., Lade, S. J., Abrams, J. F.., Andersen, L. S.., Armstrong McKay, D. I., Bai, X., Bala, G., Bunn, S. E., Ciobanu, D., DeClerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T. M., Loriani, S., Liverman, D. M., Mohamed, A., Nakicenovic, N., Obura, D., Ospina, D., Prodani, K., Rammelt, C., Sakschewski, B., Scholtens, J., Stewart-Koster, B., Tharammal, T., van Vuuren, D., Verburg, P. H., Winkelmann, R., Zimm, C., Bennett, E. M., Bringezu, S., Broadgate, W., Green, P. A., Huang, L., Jacobson, L., Ndehedehe, C., Pedde, S., Rocha, J., Scheffer, M., Schulte-Uebbing, L., de Vries, W., Xiao, C., Xu, C., Xu, X., Zafra-Calvo, N., & Zhang, X. (2023). Safe and just Earth system boundaries. *Nature, 619*(7968), 102–111.

Schmidt, M.., Crawford, R. H.., & Warren-Myers, G.. (2020). Quantifying Australia's life cycle greenhouse gas emissions for new homes. *Energy and Buildings, 224*, Article 110287.

Shanbhag, S. S.., & Dixit, M. K.. (2024). A review of evolving climate and energy economy trends to enhance the dynamic life cycle assessment of buildings. *Sustainable Cities and Society, 111*, Article 105560.

Simonen, K.., Rodriguez, B. X.., & De Wolf, C.. (2017). Benchmarking the Embodied carbon of buildings. *Technology | Architecture + Design, 1*(2), 208–218.

Skullestad, J. L.., Bohne, R. A.., & Lohne, J.. (2016). High-rise timber buildings as a climate change mitigation measure – a comparative lca of structural system alternatives. *Energy Procedia, 96*, 112–123.

P. .Tarrant, Net-Zero Jargon Buster - a guide to common terms, 2021. https://sciencebasedtargets.org/blog/net-zero-jargon-buster-a-guide-to-common-terms. (Accessed 13 March 2024).

UNEP, 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, Nairobi, 2022.

UNEP, Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again), Nairobi, 2023.

Vickers, J.., Sullivan, N.., Davies, A.., Kogileru, T.., & Wouters, T. (2022). *Embodied emissions technical report*. NABERS.

Wang, X.., Padgett, J. M.., De la Cruz, F. B.., & Barlaz, M. A.. (2011). Wood biodegradation in laboratory-scale landfills. *Environmental Science & Technology, 45*(16), 6864–6871.

Watari, T.., Yamashita, N.., & Serrenho, A. C.. (2024). Net-zero embodied carbon in buildings with today's available technologies. *Environmental Science & Technology, 58*(4), 1793–1801.

WBCSD, Arup, Net-zero buildings: Halving construction emissions today, 2023.

WGBC, Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon, 2019.