Embodied Carbon & Embodied Energy in Australia's Buildings

Green Building Council Australia

thinkstep anz

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Executive Summary

This report calculates embodied carbon and embodied energy in Australia’s commercial and residential buildings

Globally, buildings are responsible for approximately 28% of total greenhouse gas (GHG) emissions and 38% of energy-related GHG emissions.[1] 26% of this is attributed to embodied carbon emissions and 74% to operational carbon emissions by the United Nations Environment Programme (UNEP).

Embodied carbon and embodied energy represent the sum of the greenhouse gas emissions (“carbon emissions”) and energy use associated with the production of materials, construction, and end of life stages of a building (Figure 1).

While operational carbon and operational energy are much more visible due to ongoing energy costs, embodied carbon and embodied energy represent the hidden impacts of buildings – impacts that are largely locked in before the building is even occupied.

The purpose of this report is to calculate the embodied carbon and embodied energy in Australia’s buildings. This report compares the 2019 baseline year to a 2050 business-as-usual scenario to show what could happen without deliberate action on embodied emissions.

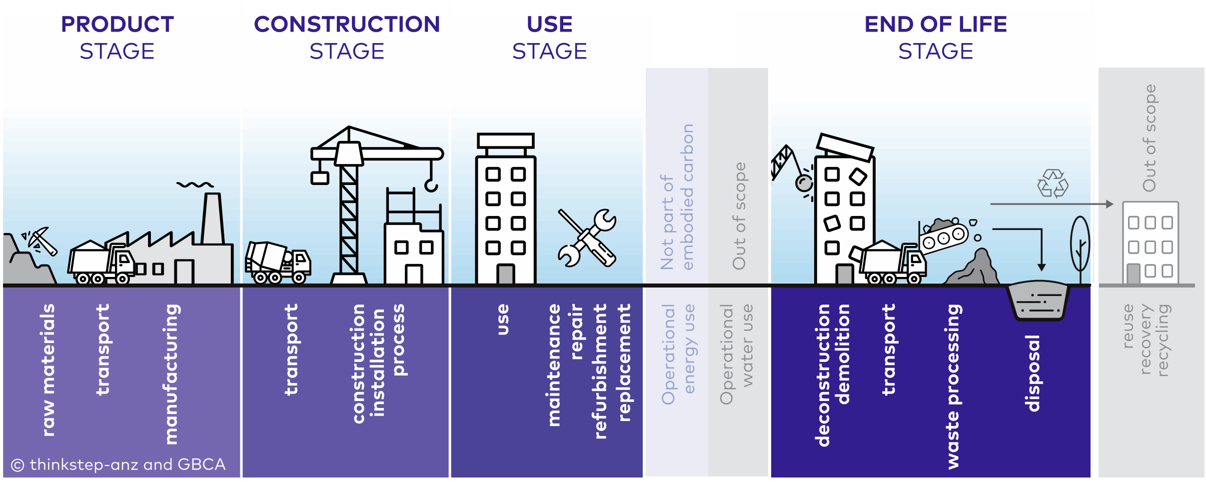

Figure 1: Scope of embodied carbon and embodied energy (WorldGBC 2019 and EN 15978:2011)

Without action, the significance of embodied carbon will grow

Over the entire Australian building stock, this report finds that the share of whole-life building carbon emissions from embodied carbon was 16% in 2019 (Figure 2). Under business-as-usual (BAU), this share is expected to climb to 85% by 2050.[2] These calculations include operational emissions from the entire building stock in 2019 and 2050, but only the embodied emissions from

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[1] Globally, buildings are responsible for approximately 38% of energy-related GHG emissions, which corresponds to approximately 28% of total GHG emissions when all emissions sources are considered. *Source:* UNEP. (2020). *2020 Global Status Report for Buildings and Construction*. Global Alliance for Buildings and Construction & UNEP: Paris.

[2] The business-as-usual (BAU) scenario in this report is designed to show what could happen by 2050 if new building construction grows in line with population forecasts and the primary focus for decarbonisation is achieving 100% renewable electricity generation by 2050. It deliberately assumes no changes in building practices from 2019, no electrification of process heat, and no carbon capture. Electricity emissions include “scope 3” GHG emissions from manufacture of photovoltaic panels, wind turbines, and other capital goods for renewable energy generation.

new builds and substantial renovations in those same years (which reflect a small percentage of the total building stock). While these figures can be seen as a proxy for building life-cycle emissions, they do not reflect the share of emissions from a single building built in 2019 or 2050.

Over time, as the electricity grid decarbonises, embodied carbon will become a greater percentage of a building's emissions profile. This is because a significant share of embodied emissions in buildings, in particular the emissions required to manufacture common building products, come from the use of process heat and from chemical reactions, meaning that they will not decrease by decarbonising electricity alone.

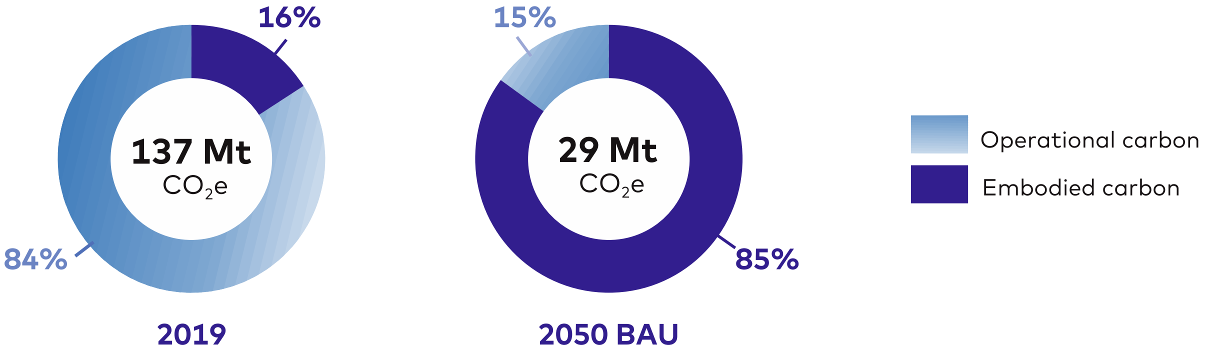

Figure 2: Carbon emissions from Australia's building stock in 2019 and 2050

Embodied energy will also grow, but its significance will become less relevant

Embodied energy in buildings is likely to almost double from 213 PJ in 2019 to 401 PJ by 2050 under a BAU scenario (Figure 3). This growth is due primarily to increasing population driving increasing construction, and to a lesser extent by the move to renewable energy.

Historically, total energy use was a good predictor of carbon emissions, given that most energy was derived from fossil fuels. However, it will become a less reliable predictor of carbon emissions as the share of renewables grows.

As time progresses, embodied carbon will become the most important metric for emissions reduction in buildings, replacing operational energy/carbon and embodied energy.

A net-zero carbon future requires a focus on embodied carbon

In 2018, the 'Trajectory for Low Energy Buildings' – Australia's national plan that sets a trajectory towards zero energy (and carbon) ready buildings – identified that buildings accounted for 18% of Australia's greenhouse gas emissions. However, this does not include the emissions generated to construct these buildings. Research has shown that in high-performance new buildings, embodied carbon represents approximately 45% of whole-life carbon emissions.[3]

There are significant opportunities to reduce embodied carbon and embodied energy in Australia's buildings. There is an urgent need for additional policy incentives to decarbonise Australia's energy supply and for investment in research and development of new materials and practices. The carbon emissions from products and materials in buildings must be driven to net zero in line with the targets of the Paris Agreement, and State and Territory emissions reduction targets.

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[3] R. Augros et al. (2019). *Guide to Low Carbon Commercial Buildings – New Build.* Low Carbon Living CRC.

This report finds that the share of Australia's national emissions caused by embodied carbon in buildings will increase from at least 3.9% in 2019 to at least 6.0% in 2050 (Figure 3). These figures are for the base building only (structure, foundation, and façade) and exclude interior fit-out, building services and all infrastructure. The share that buildings contribute to Australia's total greenhouse gas emissions approximately doubles if fit-out and buildings services are included (calculated as 48 Mt in 2019, which equates to 8.7% of Australia's carbon footprint); however, they were outside the scope of this work as they are harder to forecast accurately. As understanding of embodied carbon grows over time, the scope of analysis could be expanded to include these items.

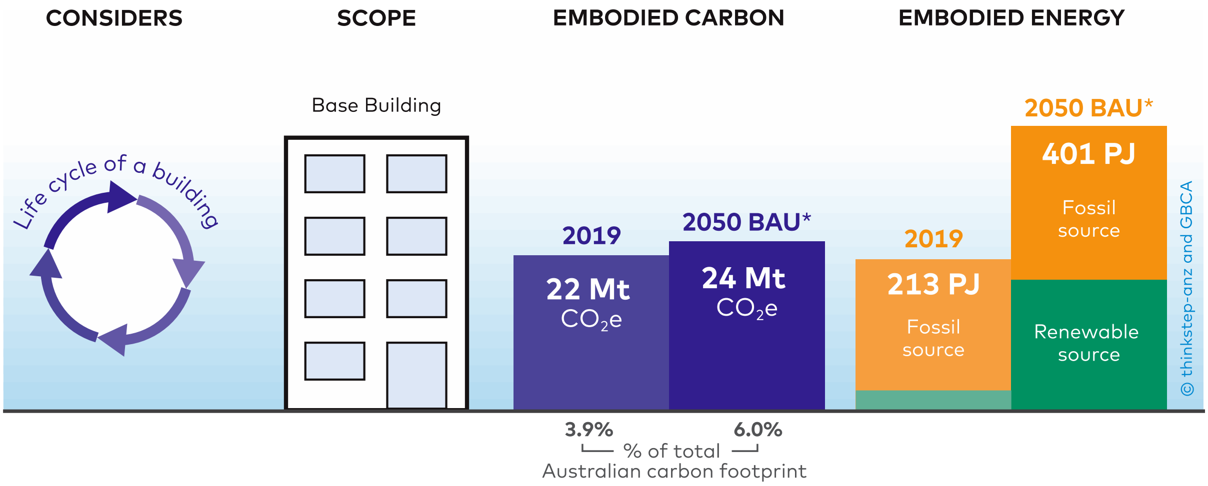

Figure 3: Embodied carbon and embodied energy in Australia's building stock

Material efficiency in the built environment plays an important role because emissions are saved immediately

Emissions reduction opportunities occur immediately as they depend on building design, material choice and manufacturing processes, not user behaviour and grid decarbonisation over time. Much of the embodied carbon is locked in as soon as the building is built.

Even a 10% reduction in embodied emissions in new commercial and residential buildings would correspond to at least 19.9 Mt CO_2e avoided between 2022 and 2030 and at least 63.5 Mt CO_2e avoided between 2022 and 2050. Making these improvements will also help to future-proof energy-intensive industries within Australia, helping to maintain their global competitiveness in a low-carbon world. The savings to 2030 are 40% higher than the predicted operational carbon emissions reductions of 14 Mt CO_2e from updating the National Construction Code in 2022 for residential buildings and 2025 for commercial buildings.[4]

Suppliers and customers both have important roles to play

Reducing a building's operational carbon emissions requires changes on-site or near-to-site (e.g., phasing out fossil fuelled heating). Decarbonising a building's embodied carbon, by contrast, requires changes in a building's supply chain.

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[4] Calculated as the sum of 6.6 Mt from residential buildings and 7.4 Mt from commercial buildings. See:
p.21 of COAG Energy Council. (2018). *Report for Achieving Low Energy Homes*.
p.10 of Energy Action and Strategy.Policy.Research (2018). *Achieving Low Energy Commercial Buildings in Australia.*

Strategies to reduce embodied carbon and embodied energy can be broadly categorised as:

- **Supply-side strategies**, which seek to improve manufacturing energy efficiency, reduce process emissions (through process substitution or through carbon capture and storage), and decarbonise energy supply (both electricity and industrial process heat). These strategies help organisations work with their supply chains to drive similar improvements for purchased goods and services.
- **Demand-side strategies**, which target low carbon products that are selected for a building, how much of each product is needed, and how construction and demolition waste is avoided (e.g., deconstruction and reuse) and managed (e.g., resource recovery). Rating tools like Green Star are already specifically targeting reductions in embodied carbon to help create market demand for low carbon products.

Importantly, both strategies are needed and are often complementary. If a product is manufactured with a lower carbon impact per unit (supply-side) and you also need fewer units (demand-side), the benefits multiply. This indicates the importance of whole supply chains working collaboratively to achieve low-carbon outcomes. Climate change is a shared problem for which we need shared solutions.

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Acknowledgements

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- Australian Aluminium Council (AAC)
- Australian Glass and Window Association (AGWA)
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- Australian Steel Institute (ASI)
- BlueScope Steel
- Brickworks
- Cement Industry Federation (CIF)
- Cement, Concrete & Aggregates Australia (CCAA)
- CSR Gyprock
- Department of Industry, Science, Energy and Resources (DISER)
- Frasers Property
- Gypsum Board Manufacturers of Australasia (GBMA)
- Hanson Australia
- InfraBuild
- Knauf Plasterboard
- Lendlease Group
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- Stockland
- USG Boral

While these organisations have assisted in the consultation and in some cases provided feedback and data, any remaining errors or omissions are those of the authors.

Introduction

Purpose

The purpose of this project was to calculate the greenhouse gas (GHG) emissions and energy embodied in the construction of Australia's buildings, both now and in 2050. For the purposes of this report, greenhouse gas emissions embodied in Australian buildings is referred to as 'embodied carbon' or 'embodied emissions'.

Unlike operational energy and emissions — which are very visible as there is an ongoing cost associated with them (e.g., utility bills) — embodied carbon and energy occur upstream of the building itself, are one-off or irregular, are largely invisible to the architect, builder or occupant, and are often locked in early in the building's life cycle and cannot be changed later.

This project was delivered by the Green Building Council of Australia (GBCA) and thinkstep-anz with funding from the Commonwealth Government through the Department of Industry, Science, Energy and Resources (DISER).

Background

Globally, buildings are responsible for approximately 35% of total energy use, 55% of electricity use, and 38% of energy-related GHG emissions (UNEP, 2020). When all sources of emissions are considered, buildings are responsible for approximately 28% of total GHG emissions (Climate Watch, 2021). Of these GHG emissions, 74% come from building operation (heating, cooling, lighting, etc.), with the remaining 26% embodied in construction products, materials, and construction processes (UNEP, 2020).

Importantly, the figures above are averages for the entire global building stock. There can be significant differences between regions and also between buildings within the same region. These differences occur due to different heating/cooling loads, different energy sources, and differences in energy efficiency measures adopted at the building level. For a code-compliant building built today in Australia, research has shown that approximately 80% of the whole-life carbon footprint of that building will be due to operational carbon, with 20% due to embodied carbon (Augros, et al., 2019). For high-performance buildings, this ratio changes to approximately 55% operational carbon versus 45% embodied carbon (Augros, et al., 2019). For ultra-efficient buildings, such as those following the Passive House standard, this ratio can change to 10% operational carbon versus 90% embodied carbon (Röck, et al., 2020).

Within Australia, the GBCA and Property Council of Australia report *Every Building Counts* (2019) included a recommendation to "Make Australia a leader in high performance building products". This could be achieved by developing a nationally coordinated strategy to achieve net zero embodied carbon and grow the availability of cost-effective low emissions building materials.

At a jurisdictional level, the NSW Government has issued a Net Zero Plan to 2030 which includes a commitment to "leading a national strategy to achieve net zero embodied carbon in building materials" (NSW Government, 2020). NSW has also established a Materials and Embodied Carbon Leaders' Alliance (MECLA) which has three key aims: "a) aggregation of demand and supply; b) knowledge sharing; and c) pre-competitive collaboration across industries.” (Waters, et al., 2020)

For operational energy/emissions, regulatory signals already exist through the National Construction Code (NCC), the Commercial Building Disclosure (CBD) Program, the National Australian Built Environment Rating System (NABERS) and the Nationwide House Energy Ratings Scheme (NatHERS). In addition, the Commonwealth Government – on behalf of all states and territories – is leading the ‘Trajectory for Low Energy Buildings’, a national plan that aims to achieve zero energy (and carbon) ready buildings for Australia (COAG Energy Council, 2018). A key tenet of the internationally recognised operational energy benchmarking pioneered in Australia is that “energy has to be measured to be managed”.

For embodied energy/emissions, the policy drivers are weaker, and a range of barriers exist starting right from the tendering process (Lendlease, 2020). While the publication of the first Low Emissions Technology Statement in 2020 is a good starting point to reduce some sources of embodied emissions in buildings (Australian Government, 2020), its focus is broader than buildings alone. More targeted action will be required going forward to fully leverage the opportunities presented by this sector.

Embodied carbon and embodied energy

What is embodied carbon?

This report adopts the World Green Building Council (WorldGBC) definition of embodied carbon as “carbon emissions associated with materials and construction processes throughout the whole lifecycle of a building or infrastructure” (WorldGBC, 2019, p. 5). Carbon emissions are calculated as the “sum of greenhouse gas emissions and greenhouse gas removals in a product system, expressed as CO_2-equivalent (CO_2e) and based on a life cycle assessment using the single impact category of climate change” (ISO, 2018).

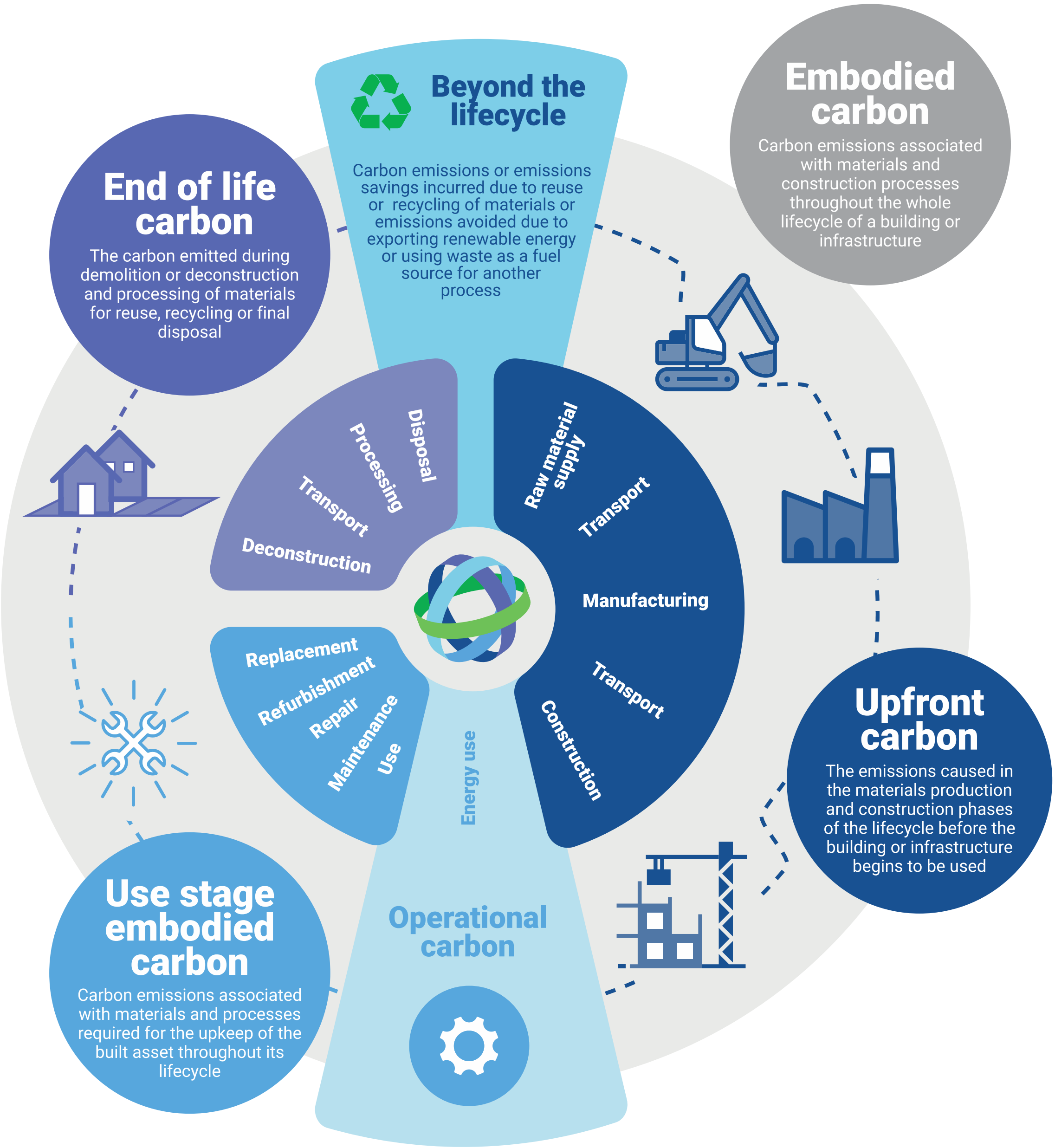


Figure 4: Embodied, upfront, use stage, and end-of-life carbon – reproduced from (WorldGBC, 2019)

Embodied carbon can be broken down into three parts (Figure 4) (WorldGBC, 2019, p. 6):

- **Upfront carbon:** “The emissions caused in the materials production and construction phases (A1-5) of the lifecycle before the building or infrastructure begins to be used.”
- **Use stage embodied carbon:** “Emissions associated with materials and processes needed to maintain the building or infrastructure during use such as for refurbishments.”
- **End of life carbon:** “The carbon emissions associated with deconstruction/demolition (C1), transport from site (C2), waste processing (C3) and disposal (C4) phases of a building or infrastructure's lifecycle which occur after its use.”

The life cycle stages included within each term are shown in Figure 5. The naming convention applied by WorldGBC follows European standards EN 15804 and EN 15978 for building products and whole buildings, respectively. Modules A1-5 focus on manufacture of the building products (A1-3), transport to site (A4) and installation (A5), modules B1-7 focus on emissions during the building’s operating life (including maintenance and repair), modules C1-4 focus on end-of-life, and module D focuses on credits for avoided production of primary (virgin) materials in future product life cycles due to recycling or reuse.

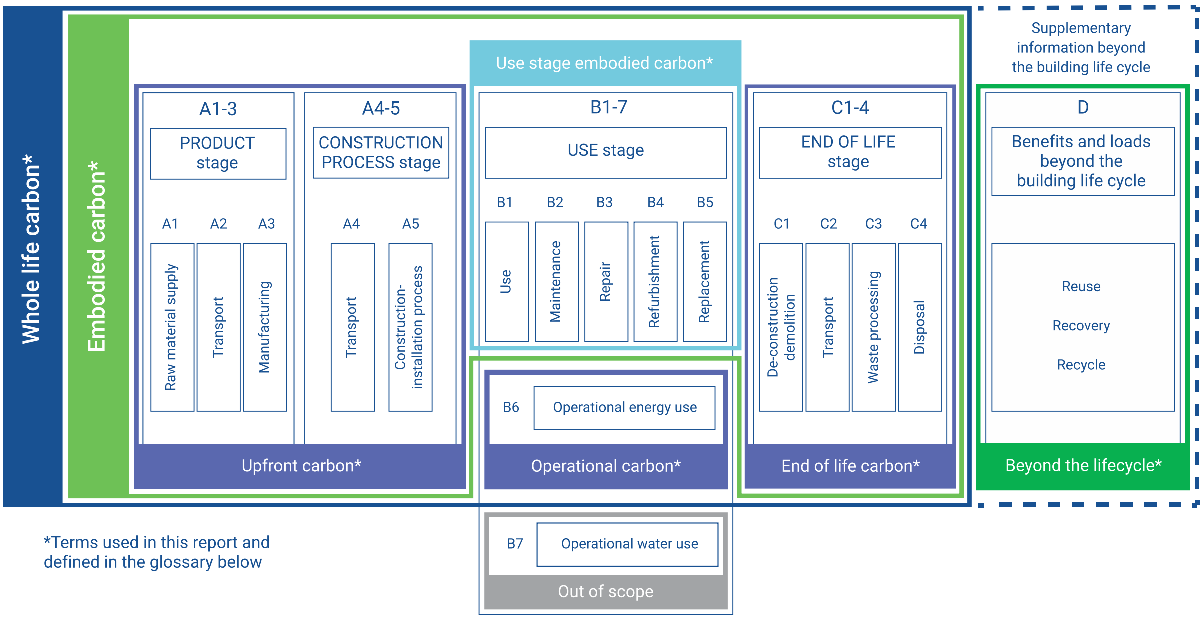


Figure 5: Terminology and related life cycle stages – reproduced from (WorldGBC, 2019)

This study reports embodied carbon using the GWP100 indicator (Global Warming Potential over a 100-year time horizon) of the Intergovernmental Panel on Climate Change (IPCC). Given that this study relies primarily on a combination of EPD and LCA data, it mixes characterisation factors from the IPCC’s Fourth Assessment Report (which was required in the original version of EN 15804 and which is still widely used today) and the IPCC’s Fifth Assessment Report (which is now common practice). This has negligible influence on the results given that most emissions from the built environment are carbon dioxide, which always has a characterisation factor of 1.

All GWP results are reported excluding biogenic carbon. Biogenic carbon is “carbon derived from biogenic (plant or animal) sources excluding fossil carbon” (IPCC, 2019).

What is embodied energy?

Like embodied carbon, embodied energy is the “energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery” (Australian Government, 2013).

In this report, embodied energy at the building level is calculated using an indicator known as Primary Energy Demand (PED) or Cumulative Energy Demand (CED). All energy figures are presented as net calorific value (lower heating value).

Importantly, it measures the use of energy in its primary form (i.e., in the natural environment) and therefore includes all losses (thermal losses, inefficiencies in solar photovoltaics, etc.) in transforming ‘natural’ energy into energy that can be used productively within the economy.

Renewable vs non-renewable energy

Embodied energy can be split into two types of primary energy demand: renewable and non-renewable energy. Non-renewable embodied energy is primary energy generated from fossil fuels. This is approximately correlated with embodied carbon (exceptions to this include carbon emissions released as part of process emissions, like in the production of cement). Renewable embodied energy is from sources which do not deplete over time (e.g., the wind and the sun).

As the Australian electricity grid decarbonises, renewable energy demand will increase, especially for materials and services which consume large amounts of electricity (like aluminium). This may lead to an increase in total embodied energy as the primary energy demand for a unit of energy consumed from solar energy is higher than the primary demand for energy consumed from fossil fuels, due to a higher inefficiency in converting available energy. This being said, the environmental relevance of ‘wasting’ energy from the sun is significantly less than the relevance of ‘wasting’ energy from fossil fuels. Due to this, renewable and non-renewable embodied energy should ideally be stated separately and not compared to each other directly.

Embodied carbon and the circular economy

The focus of this report is on embodied carbon and embodied energy; however, there is an important link to the circular economy.

The circular economy promotes circular resource use. Reused and recycled materials should (for most products) conserve at least part of the embodied carbon and energy investment in the production process by ensuring that it is amortised over a much longer time frame in use. Reused and recycled materials also reduce the demand for additional virgin materials to be produced.

An important principle of the circular economy is to keep materials in their highest form of value (Ellen MacArthur Foundation, 2021). As such, the circular economy promotes reuse over recycling, recycling over downcycling, and downcycling over landfill. In this respect, the circular economy has similarities to the waste hierarchy. In doing so, it also promotes the retention of embodied carbon and energy investments and the avoidance of virgin material impacts.

While recycling is common within the built environment, there are fewer large-scale examples of reuse. Even when recycling takes place, it may not preserve the material in its highest form of value. For example, recycled crushed concrete does help to keep this bulky material out of landfill, but it turns a high-value product (solid concrete) into a comparatively low-value product (aggregate). Given that aggregates typically make up approximately 10% of the carbon footprint of concrete made from Portland cement (based on the GaBi Databases), the remaining 90% of the impact must still be incurred to produce new concrete. A lower-carbon circular approach would be to reuse the existing concrete product, i.e., maintaining the product in its highest form of value.

Embodied carbon and the circular economy can, in many cases, both be used as drivers to achieve positive outcomes related to carbon. However, it is important to recognise that an activity can be more circular but have a higher carbon footprint than the traditional linear activity. As such, it is important to design for outcomes that are both circular and low carbon.

Calculating embodied carbon and embodied energy

Embodied carbon and embodied energy are calculated using life cycle assessment (LCA). There are three different approaches available to calculate an LCA (Suh & Huppes, 2005):

1. Bottom-up, process-based LCA (“Process LCA”)
2. Top-down economy-wide input-output LCA (“IO-LCA”)
3. Hybrids of the two (“Hybrid LCA”).

This report uses Process LCA as its baseline method. Process LCA allows many different types of products to be distinguished, but it can truncate the supply chain (“truncation error”) and typically excludes supporting functions that are not directly consumed in the production process (e.g., corporate travel and manufacture of capital goods). By contrast, IO-LCA provides infinite depth in the supply chain and infinite breadth in supporting functions (from design to sales to banking to insurance), but it can only distinguish between the number of sectors defined within the economy. The goal of Hybrid LCA is to have the best of both worlds, providing both precision and completeness.

Bottom-up, process-based LCA ("Process LCA")

The starting point for Process LCA is the unit process: a single process (typically a manufacturing process) that transforms inputs into outputs. Process LCA is the aggregation of these different unit processes to create an often-complex production chain. An inventory is compiled by summing together the resource use, energy use, and emissions incurred through every step in a product's life cycle. This inventory is then multiplied by characterisation factors (emission factors) to calculate potential impacts on the environment, such as the product's contribution to climate change.

Process LCA is the method typically used by companies to understand and reduce the impacts of their products and processes as it is highly specific to different production processes and supply chains. It is also the LCA method used for Environmental Product Declarations (EPDs).

Process LCA has the advantage of detail: it allows even small differences between products and processes to be investigated. Its key disadvantage is truncation error: Process LCA focuses on the inputs required to make a product, but it often cuts off second/third/nth-order inputs, such as the capital goods (machinery and manufacturing plant) required to manufacture the products, the fuel required by the sales and marketing team to make client visits, the energy used in office blocks, and the many professional and service industries supporting the manufacturing process.

Top-down, economy-wide input-output LCA ("IO-LCA")

Economy-wide input-output LCA (IO-LCA) starts from the direct impacts of an entire economic sector and then adds indirect impacts through trade with other sectors (i.e., from purchased goods and services). Emission intensities (e.g., kg CO_2e per $) are calculated by dividing the direct and indirect emissions by the monetary value the sector contributes to the economy.

Data required for this method includes:

1. Economy-wide input-output (IO) tables, i.e., matrices showing transactions between sectors/industries within an economy, and
2. Industry-wide emissions data corresponding to these same sectors/industries.

Equation 1 shows the method generally used to calculate IO-LCA (Carnegie Mellon University Green Design Institute, 2008), where:

- B_i = Vector of the environmental impacts of each sector per dollar of output, including direct and indirect impacts
- R_i = Vector of the direct environmental impacts of each sector per total output
- $(I – A)^{-1}$ =Total requirement matrix, also known as an inverse Leontief matrix.
- F = Vector of final demand, showing the demand of final goods and services.

$$B_i = R_i * ((I - A)^{-1} * F)$$

Equation 1: Basic formula for IO-LCA (Carnegie Mellon University Green Design Institute, 2008)

IO-LCA has the advantage of completeness: by its very nature, it includes all interactions associated with a particular activity (from direct material and energy use through to banking and insurance). As a result, it is well suited to national LCA studies where the goal is to calculate the total emissions of an activity or sector without much breakdown of the results.

Limitations of IO-LCA include:

- Resolution: IO-LCA can only distinguish between the number of sectors for which economic data and emissions are collected, which might be in the order of 100 sectors for an entire economy covering everything from fruit growing to vehicle manufacture, and professional services to utilities. This aggregation of data can lead to industries with different emissions intensities being combined into one sector. For example, in the public Australian Bureau of Statistics (ABS) IO tables, the product group “2102 – Basic non-ferrous metal manufacturing” includes the production of a wide range of metals with different emissions profiles, including aluminium, copper, and zinc.
- Imports: IO-LCA often assumes that the production of imported goods have similar emissions intensities as goods produced domestically. Multi-regional Input-Output databases such as Eora (Lenzen, et al., 2013) aim to address this limitation.
- Price homogeneity: In IO-LCA, it is necessary to assume that the prices of goods and services have are equally proportional with environmental impacts within the economy considered (in this case, Australia). Depending on the sectors defined within the economy, this might mean that all ferrous metals are defined as having the same impact, without considering differences in manufacturing process (e.g., virgin versus recycled).
- Sensitivity to irregular activities: IO-LCA is usually calculated as an annual snapshot. All activities are included, including the production of infrastructure for a given sector. However, in cases where there are only a handful of operations within a given sector, major capital expenditure in one year will disproportionately affect the impacts in that year. Rolling averages across years can help to alleviate this limitation.

Hybrid LCA

Hybrid LCA includes any method which combines both Process LCA and IO-LCA. It is designed to help avoid truncation error while also disaggregating data far enough to enable sectors to be split so that sector-specific emissions can be allocated accurately. As such, Hybrid LCA is often regarded as the gold standard for LCA (Suh & Huppes, 2005; Lenzen & Crawford, 2009; Crawford & Stephan, 2013), though others highlight that careful interpretation is the most important aspect of any LCA study due to the inherent strengths and weaknesses of all methods (Rowley, et al., 2009).

Estimating truncation error

It is only possible to estimate truncation error as there no single ‘true’ environmental footprint of a product or service – only different calculations or representations of its footprint (Ward, et al., 2018).

For Process LCA, previous estimates suggest that between 2% and 77% of total environmental impacts may be omitted by Process LCA through truncation error, depending on the sector and the environmental indicator considered (Ward, et al., 2018). Earlier estimates in the building and construction sector comparing embodied energy from Process LCA to economy-wide input-output LCA (described below) were in the order of 50% for basic steel products (Lenzen & Dey, 2000) and 69% to 77% for passive houses (Crawford & Stephan, 2013). Small truncation errors are typically found in sectors such as agriculture and transportation, where direct emissions are large and other emission sources are less relevant (Ward, et al., 2018). In the context of building products, the omission of service industries likely leads to under-counting of environmental impact by approximately 5-15% (Ward, et al., 2018). Factoring in other omissions (e.g., exclusion of capital goods for manufacturing) would further increase this estimate.

Economy-wide input-output LCA may both overestimate and underestimate the true impacts of a system (Rowley, et al., 2009; Ward, et al., 2018). Truncation error estimates for IO-LCA across all environmental indicators range between -51% to 96%. However, this overstates possible truncation errors for embodied carbon and embodied energy under IO-LCA, as the results above are for other indicators where there are likely data gaps in national pollutant inventories. Such gaps do not exist for energy and GHG emissions and so the possible range for errors is likely to be much narrower.

Differences in source and age of data

There are many different data sources available for embodied emissions. These data sources can broadly be aligned with the different LCA methods above.

It is important to recognise that not only are there differences in method, but there can also be differences in scope even within the same method (e.g., Process LCA studies with different system boundaries) and differences in the age and accuracy of the underlying data. Many LCA studies – both Process LCA and IO-LCA – rely on data sources that may be 5 to 10 years old at the time of publication. These studies are then used in future LCA studies, compounding the problem. This can become an issue in cases where a given industry is changing rapidly. For example, the Australian cement industry decarbonised by 18% from FY2011 to FY2019 (CIF, 2020). Given that cement typically makes up approximately 85% of the carbon footprint of concrete (based on the GaBi Databases) — and coupled with increased use of supplementary cementitious materials in some parts of Australia during this time — it seems quite likely that Australian concrete has decarbonised relatively significantly over the past decade.

Common sources for LCA studies are provided below.

Process LCA

Environmental Product Declarations (EPDs): EPDs provide product-specific or industry-average data for products. Data is comparable provided it follows the same Product Category Rules (PCR). The main PCR documents used for building product LCAs are European standard EN 15804 (CEN, 2019) – the sister standard to EN 15978 (CEN, 2011) whose system boundary is shown in Figure 6– and international standard ISO 21930 (ISO, 2017). There are two main EPD schemes operating in the Australian market: EPD Australasia (affiliated with ALCAS, the Australian LCA Society) and the Global GreenTag EPD Program.

Commercial LCA databases: The two main commercial databases available internationally are the ecoinvent Database and the GaBi Database. In the Australian context, other databases include the GreenBook and the database embedded within eTool, the building LCA software.

Free LCA databases: The most notable free database is the ICE (Inventory of Carbon and Energy) Database, first published by the University of Bath and now run by Circular Ecology.

Regional LCA databases: The main regional LCA database for Australia is AusLCI, run by ALCAS. Other regional databases exist for the USA, the European Union, etc.

Tool-specific databases: Certain sustainability rating tools or national bodies have created their own databases. One example in the Australian context is the Infrastructure Sustainability Council of Australia's IS Materials Calculator.

IO-LCA

The Industrial Ecology Virtual Laboratory (IELab) provides IO-LCA data for Australia. It was initially created by the University of Sydney (Prof. Manfred Lenzen) and is now managed by the University of New South Wales (led by Associate Prof. Tommy Wiedmann).

Other multi-regional databases exist, such as Eora, EXIOBASE, WIOD, GTAP, and OECD.

Hybrid LCA

The IO-LCA databases above are often used as a starting point for Hybrid LCA. There are two Hybrid LCA databases for construction products in Australia:

1. The Environmental Performance in Construction (EPiC) Database, published by the University of Melbourne (Crawford, et al., 2019).
2. The Integrated Carbon Metrics (ICM) Embodied Carbon Life Cycle Inventory Database, published by the University of New South Wales (Wiedmann, et al., 2019).

These databases use both different hybridisation approaches LCA data, which can lead to different results. EPiC uses a 'path exchange' hybrid analysis (Lenzen & Crawford, 2009), while the ICM database is an integrated analysis (Crawford, et al., 2017).

Scope of this study

Life cycle stages and modules

The scope of this study covers embodied carbon and embodied energy across the full life cycle of Australia’s buildings. It includes the following life cycle stages from EN 15978 (Figure 6):

- A1-A3: Manufacture of building products and materials.
- A4: Transportation of building products and materials to site.
- A5: Construction of buildings, including the manufacture of those products and materials which are wasted during construction and subsequent end-of-life processing.
- B1-B5: Maintenance, repair, and refurbishment of buildings.
- C1-C4: Demolition, transport of materials for reuse/recycling/landfill and disposal of those materials which are not currently recycled.
- D: Recycling credits for future product life cycles, calculated as the difference between producing one unit of recycled material and one unit of virgin material with equivalent performance. Only the net scrap is awarded a credit, meaning that scrap produced from construction and demolition waste is first ‘looped back’ to satisfy the need for recycled content (e.g., in reinforcing steel), with only the remainder being awarded a credit to prevent double counting. This approach follows EN 15804 and EN 15978.

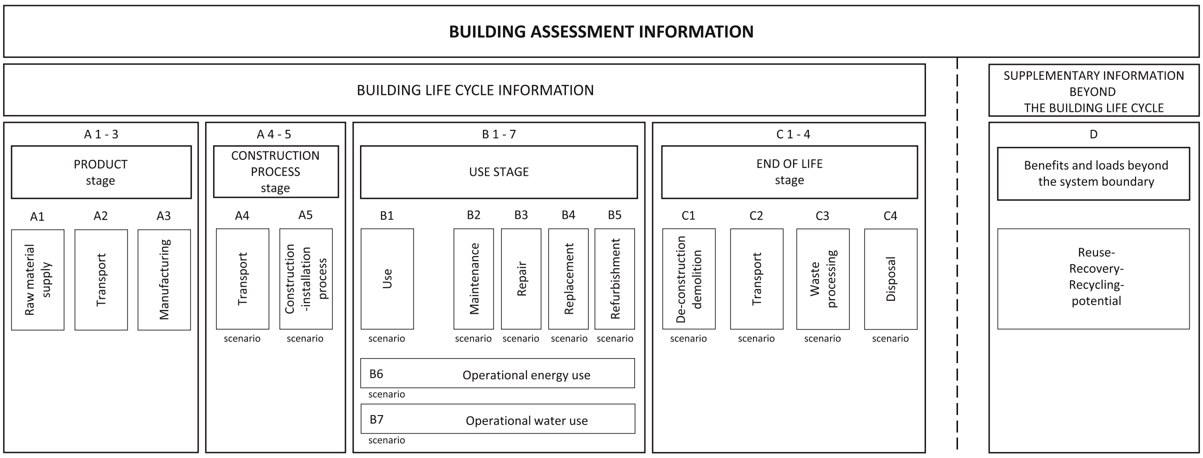


Figure 6: Building life cycle stages and modules (source: EN 15978:2011)

Reference year

Two reference years are used:

- The baseline of FY2019 (1 July 2018 to 30 June 2019).
- A forecast to FY2050 (1 July 2049 to 30 June 2050).

Importantly, each year is a snapshot in time rather than following the full life cycle of each building individually. This means that the material and carbon and energy flows entering and leaving Australia’s buildings in a single year are calculated based on construction, renovation, and demolition statistics (for FY2019) or estimates (for FY2050) for that year.

A FY2019 baseline year was chosen for this study given that the FY2020 financial year was impacted by the start of the COVID-19 pandemic and may therefore not represent recent levels of building and construction activity in the Australian economy.

Module B6 (operational energy use) is not part of this study as it is not a form of embodied carbon or embodied energy. However, results for the full building life cycle (including B6) are presented using building operational energy use modelling by ClimateWorks Australia (ClimateWorks Australia, 2020).

Building elements

The analysis in this report focuses on the structure, foundation, and envelope of buildings. This includes anything that keeps the building in shape (framing, foundations, roof framing, etc.) or separates the interior of the building from the outside (windows, doors, walls, floor) (Figure 7). It does not include the fit-out, which involves anything which makes the interior space ready for occupation (electrical wiring, HVAC systems, toilets, fire protection systems etc.). Differences in scope can have significant differences on the outcome and this should be considered when comparing between studies. Input-output LCA (like that found in Yu et. al (2017)) often looks at the structure, foundation, envelope and fit-out as it is difficult to separate the separate building elements.

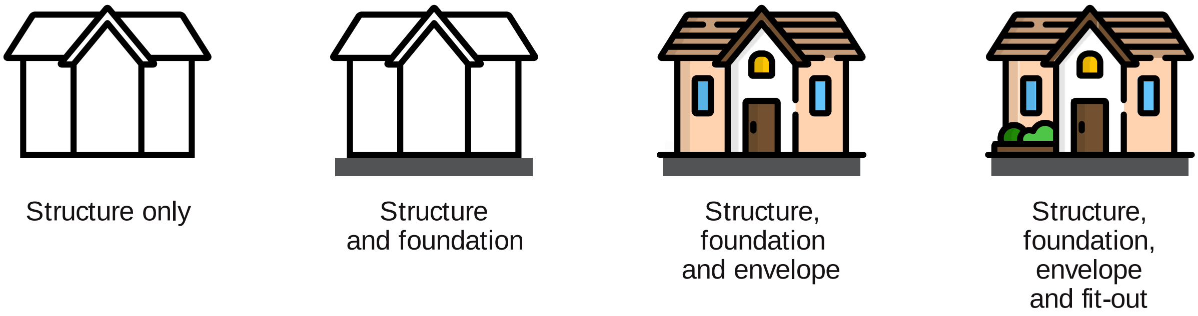


Figure 7: Coverage of building elements within the LCA

Study design

Overall approach

The approach taken in this study can be summarised in three main steps:

I. **Bottom-up hotspot assessment (Process LCA)** by scaling up the bill of quantities (BoQ) of a small pool of representative buildings (in kg per material per m^2 of floor area) to the national level using national construction statistics (in m^2 of floor area). This was multiplied by embodied carbon and embodied energy data from EPDs and past product and material LCAs. Construction waste statistics were then used to estimate losses on site, and material-specific carbon/energy factors were used for the treatment of construction and demolition waste.
This hotspot assessment has the advantage of simplicity, but it may over- or under-estimate material use at the national level if the representative buildings are not true averages of current construction practices. To help alleviate this limitation, the hotspot assessment was used to identify the top five material groups by embodied energy and/or embodied carbon, which were then analysed in further detail in step #2.

II. **Top-down material flow analysis (MFA) for the top five material categories.** The MFA was used to identify and trace raw material flows from extraction through to use in Australia's buildings. Where material quantities used in buildings at the national level were missing (due to a lack of data or to commercial sensitivity), the estimates from the hotspot assessment were used to fill data gaps. The MFA was then overlaid by national carbon and energy data per industry to calculate nationwide carbon footprint emission factors (kg CO_2e per kg of material) and embodied energy factors (MJ per kg of material) to further refine the bottom-up assessment in step #3.

III. **Refined bottom-up hotspot assessment using MFA data and supplementary data from IO-LCA.** The bottom-up hotspot assessment was then updated using the calculated economy-wide carbon/energy factors from step #2. For materials outside of the top five, the Process LCA/EPD carbon/energy factors from step #1 were used. To complete the analysis, data for the construction and demolition of buildings was added based on IO-LCA data.

Step I: Bottom-up hotspot assessment

The steps applied were as follows:

1. Forecasted the annual new-build construction and alteration rates to 2050 by building type.
2. Classified buildings into representative construction design and method.
3. Specified a bill of quantities (BoQ) for each building type.
4. Identified typical construction and demolition rates.
5. Identified embodied carbon and embodied energy data.
6. Estimated total embodied carbon and embodied energy of Australia's buildings, as follows:

   a. Material mass: Calculated by a multiplying the modelled materials used per m^2 of building constructed by the forecasted area built.
   b. Modules A1-3, B1-5 (production emissions, including repair and replacement): Calculated by multiplying the mass of each material by the respective production emission factor, then summing to get total emissions.
   c. Module A4: Calculated by multiplying the mass of the building materials by the emission factor of travelling from the final production facility to building site.
   d. Module A5: Calculated by multiplying the mass of the construction waste by the emission factors associated with the whole life cycle of this waste (production, transport to and from site, and processing at end-of-life). This value is then added to the emissions associated with building construction, calculated by multiplying a construction emissions factor by the building area constructed.
   e. Module C1-4: Calculated by multiplying ¼ of the mass of buildings materials used in construction by the emission factors for the transport and landfilling of construction waste. The ¼ was used as it is assumed that currently for every four buildings constructed in Australia, one is demolished.
7. Identified the top five building products/materials to focus on in the next step.

More detail on these steps can be found in Annex A.

Step II: Top-down MFA for the top five materials

8. Conducted a material flow analysis for the top five building materials in terms of embodied carbon and energy: concrete, steel, aluminium, clay bricks and tiles, and plasterboard.
9. Overlaid the MFA with national data on greenhouse gas emissions and energy per sector.

See Annex A and Annex B for further information.

Step III: Refined hotspot assessment using MFA and IO-LCA data

10. Updated the hotspot assessment using new carbon and energy factors from the MFA.
11. “Hybridised” these factors using data from the EPiC database (Crawford, et al., 2019). This involves replacing the Process LCA values found in EPiC with the process values calculated in this study.
12. Forecasted changes in embodied carbon and embodied energy until 2050, assuming a business-as-usual scenario where only the electricity grid decarbonises and there are no changes to process emissions or thermal energy or the BoQ composition of buildings. The electricity grid is modelled as being made up of 100% renewable energy in 2050.
13. Filled data gap for building construction, and demolition using IO-LCA data

See Annex A and Annex B for further information.

Our results

The following section shows the results of applying the steps given in the previous section to model the embodied carbon and embodied energy in Australian buildings. Unless otherwise stated, all results shown are from using the Process LCA methodology. These results are first presented as embodied carbon and energy at a national level, with later sections providing data on an average building level.

Embodied carbon at the national level

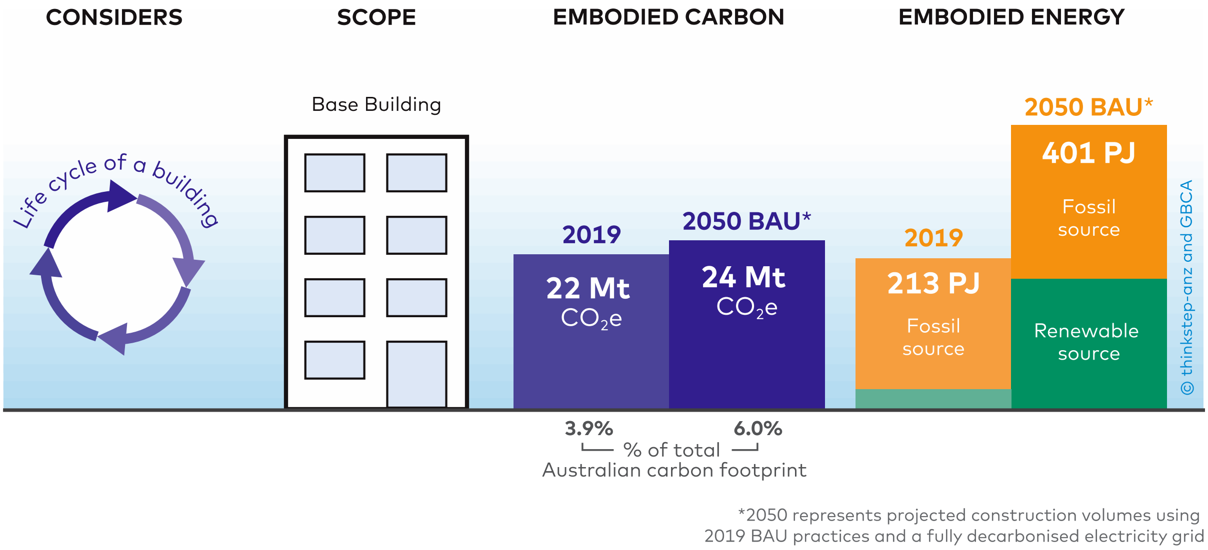


Figure 8: Embodied carbon and embodied energy in Australia's building stock using Process LCA

The calculated embodied carbon of Australian buildings in both 2019 and 2050 can be seen in Figure 8 and Table 1. While building emissions only make up a small percentage of the total emissions of Australia in 2019, this increases by about 50% (from 3.9% to 6.0%) as gross Australia emissions decrease due to the decarbonisation of other sectors and the electricity grid.

Table 1: Embodied carbon in Australian buildings (all life cycle stages excluding operation)

	Unit	2019	2050
Embodied carbon in buildings	Mt CO_2e	22	24
Total gross GHG emissions for Australia excluding LULUCF	Mt CO_2e	566	406
Embodied emissions as a % of Australia total		3.9%	5.7%

The embodied carbon in buildings, broken down by lifecycle stage, can be seen in Figure 9. The most significant contributor to emissions is upfront carbon, i.e., modules A1-5 of EN 15978 (CEN, 2011). Upfront carbon covers the production of building materials, their distribution to site and the construction of these materials into a finished building. The production of materials (A1-3) is the most significant contributor to embodied carbon overall, followed by the construction phase (A5).

The GHG emissions from the production of building materials which go to waste during construction is included in the building products life cycle stage (A1-3). This does not align with

EN 15978 and occurs due to these values being calculated as ‘top-down’, economy-wide values. This does not affect the total embodied carbon of buildings.

The recycling credit (module D) is the benefit received when the materials are recycled and made into other products after the building has reached its end-of-life. This is calculated as:

$$Recycling\ credit = E_{recycling} - E_{virgin}$$

Where:

$E_{recycling}$ = The carbon footprint of turning scrap material into useable material

E_{virgin} = The carbon footprint of producing virgin material of the same functionality

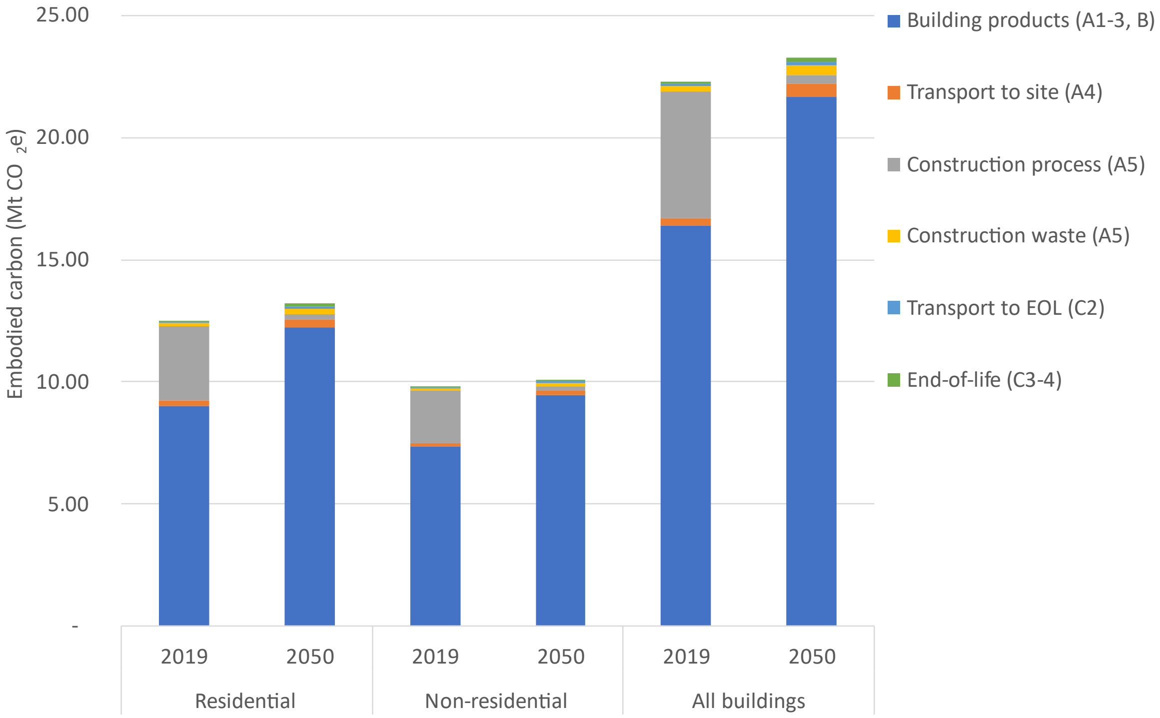


Figure 9: Embodied carbon in buildings split by life cycle stage (Mt CO_2e)

Sources of materials-related carbon emissions

Figure 10 indicates that the embodied carbon from building materials derives from three main sources: process heat, direct chemical emissions, and electricity. Decarbonising electricity will help to decarbonise building products, but embodied carbon will continue to grow without a deliberate focus on addressing these other sources of emissions.

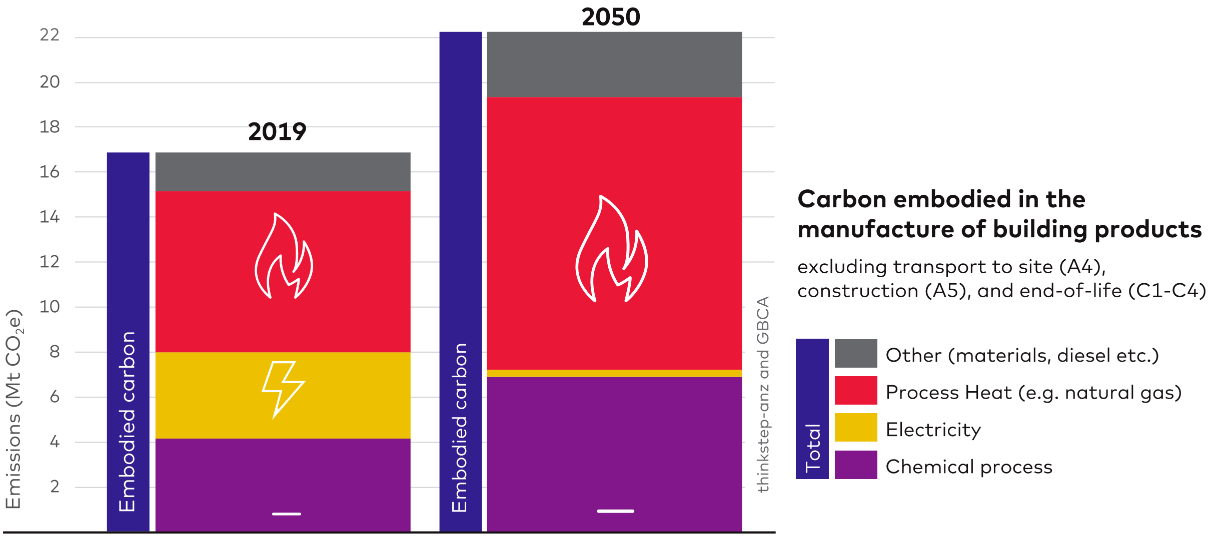


Figure 10: Sources of embodied carbon emissions from the manufacture of building products used in construction and maintenance

Embodied carbon using alternative LCA methods

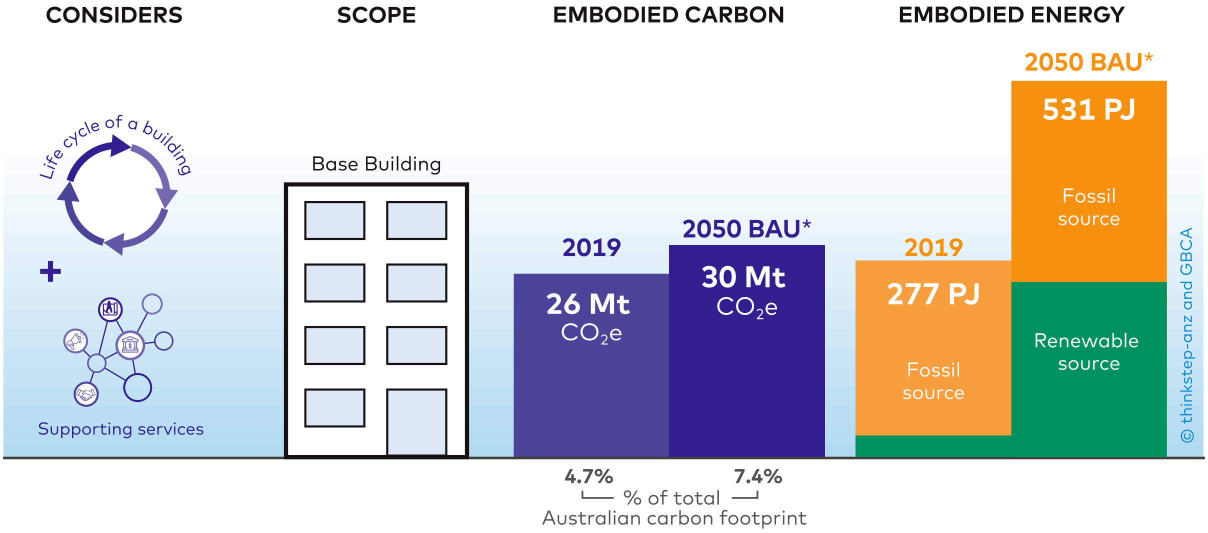
The embodied carbon of buildings, calculated by the three methods considered in this report (Process LCA, Hybrid LCA, IO-LCA) can be seen in Table 2. The results of the Hybrid LCA method are shown in Figure 11 based on the calculations described in Annex F: Hybridisation of Process LCA. IO-LCA, as presented in Figure 12, has been taken from Yu et al., (2017) and is further described on page 39.

As is to be expected, the Hybrid LCA method calculates the emissions to be between the range of the IO-LCA and Process LCA methods. Despite the decarbonisation of the grid reducing the impacts of materials, emissions from construction materials increase to 2050 due to the increase in area built annually. The Input-Output embodied carbon was not estimated for 2050 due to there being too many uncertainties and beyond the scope of this work.

Comparing the Process LCA and Hybrid LCA data, the truncation error of the Process LCA data is estimated at 24% (relative to the Process LCA). The difference between the Hybrid LCA and the IO-LCA (relative to the Hybrid LCA) of a further 88% is likely mostly explained by the difference in scope, i.e., base building only versus the whole building, including building services and fit-out (including replacement of the fit-out).

Table 2: Embodied carbon in Australian buildings, using different LCA methodology, relative to gross Australia GHG emissions

	Unit	2019	2050
Input-Output (top-down)	Mt CO_2e	48	
Input-Output relative to gross GHG emissions		8.7%	
Hybrid	Mt CO_2e	26	30
Hybrid relative to gross GHG emissions		4.7%	7.4%
Process (bottom-up)	Mt CO_2e	22	24
Process relative to gross GHG emissions		3.9%	6.0%



*2050 represents projected construction volumes using 2019 BAU practices and a fully decarbonised electricity grid

Figure 11: Embodied carbon and embodied energy in Australia's building stock using Hybrid LCA

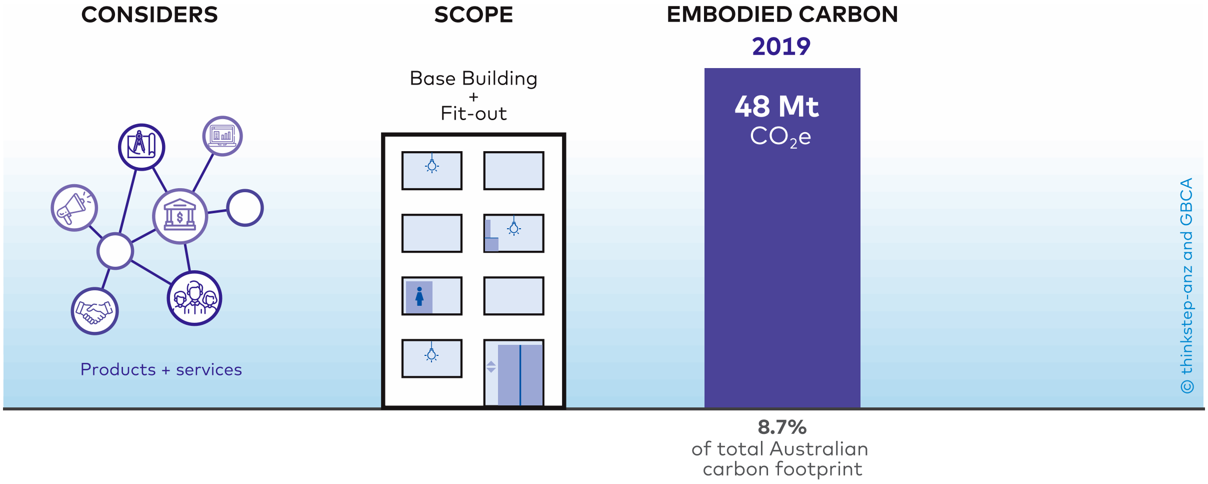


Figure 12: Embodied carbon and embodied energy in Australia's building stock using IO-LCA

The cumulative impact of improvements

Even a 10% reduction in embodied carbon in new commercial and residential buildings can cause a significant cumulative impact on greenhouse gas emissions. As seen in Table 3, a 10% reduction would correspond to at least 19.9 Mt CO_2e to 2030 and at least 63.5 Mt CO_2e to 2050. Making these improvements will also help to future-proof energy-intensive industries within Australia, helping to maintain their global competitiveness in a low-carbon world.

Table 3: Reducing embodied carbon by 10% of the modelled carbon emissions

Time period (financial year)	GHG emissions (Process LCA; Mt CO_2e)	Reduction by 10% (Mt CO_2e)	Cumulative reduction from FY22 (Mt CO_2e)
2022	20	2.0	2.0
2023	23	2.3	4.3
2024	23	2.3	6.6
2025	23	2.3	8.9
2026	23	2.3	11.2
2027	23	2.3	13.5
2028	22	2.2	15.7
2029	21	2.1	17.8
2030	21	2.1	19.9
2031	21	2.1	22.0
2032	21	2.1	24.1
2033	21	2.1	26.2
2034	21	2.1	28.2
2035	20	2.0	30.3
2036	21	2.1	32.3
2037	21	2.1	34.4
2038	21	2.1	36.5
2039	21	2.1	38.6
2040	21	2.1	40.7
2041	22	2.2	42.9
2042	22	2.2	45.1
2043	22	2.2	47.3
2044	22	2.2	49.5
2045	23	2.3	51.8
2046	23	2.3	54.0
2047	23	2.3	56.4
2048	24	2.4	58.7
2049	24	2.4	61.1
2050	24	2.4	63.5

Embodied energy at the national level

Table 4 shows the energy used in the production of Australian building materials, split into renewable and non-renewable energy. With the Australian grid predicted to become 100% renewable energy by 2050, the renewable energy demand increases by a significant amount. It should be noted that solar makes up a large portion of the modelled renewable electricity grid mix and LCA software models solar panels as 'demanding' a lot of energy due to inherent inefficiencies with the capture of sunlight and subsequent conversion to electricity. Care must be taken when comparing this value to other energy values as there is an abundance of solar energy and inefficiencies here are less significant than for other energy types.

Table 4: Embodied energy in buildings (primary energy demand) (Process LCA)

	Units	2019	2050
Total embodied energy	PJ	213	401
Non-renewable energy	PJ	191	217
Renewable energy	PJ	22	184
Total Australian energy consumption[1]	PJ	6196	7692
Construction materials energy as a % of total energy consumption	%	3.4%	5.2%

[1] The energy consumption for 2050 has been calculated based on the growth annual growth rate of the last 10 years (0.7%) continuing until 2050. It should be noted that the total energy consumption is different from the primary energy demand and does not include the inefficiencies in capturing available energy that primary energy demand does (DISER, 2020b).

Table 5 shows the embodied energy calculated using the Hybrid LCA energy data. As is to be expected, these values are higher than the embodied energy calculated using Process LCA.

Table 5: Hybrid LCA embodied energy in buildings (primary energy demand)

	Units	2019	2050
Total embodied energy	PJ	277	531
Non-renewable energy	PJ	248	284
Renewable energy	PJ	30	247

Embodied carbon and operational carbon in Australia's buildings

Figure 13 shows that embodied carbon (the blue area) in Australia's buildings will increase between 2019 and 2050 under a business-as-usual scenario as new-build construction (the black line) increases, despite electricity becoming 100% renewable by 2050. This is because embodied carbon is less directly affected by the decarbonisation of the electricity grid. During this period, operational carbon (the orange area) is forecast to decrease significantly as the electricity grid decarbonises and as fossil fuelled building heating (e.g., natural gas) is replaced with electrical heating (e.g., heat pumps). As a result, embodied carbon supplants operational carbon as the dominant source of emissions from buildings by 2036.

Table 6: Embodied and operational carbon compared to gross Australian emissions

	Units	2019	2050
Embodied carbon emissions from buildings	Mt CO_2e	22	24
Total carbon emissions from buildings (operational + embodied)[1]	Mt CO_2e	137	29
Total gross emissions for Australia excluding LULUCF	Mt CO_2e	554	406
Total building emissions as a % of Australia total	%	25%	7%
Embodied emissions as a % of total carbon emissions from buildings	%	16%	85%

[1] **Operation energy use by fuel type was taken from ClimateWorks Australia** (ClimateWorks Australia, 2020) **with fuel emission data from GaBi** (Sphera, 2020)**. This data is indicative only.**

It is important to note that this study does not show a single building over its whole life, but rather the total embodied carbon and embodied energy in all buildings built in each year, and all buildings in the building stock (old and new) in that same year. The significant operational carbon in 2019 is, therefore, largely determined by the existing stock of buildings in the market in that year, with little influence from better performing buildings constructed in 2019.

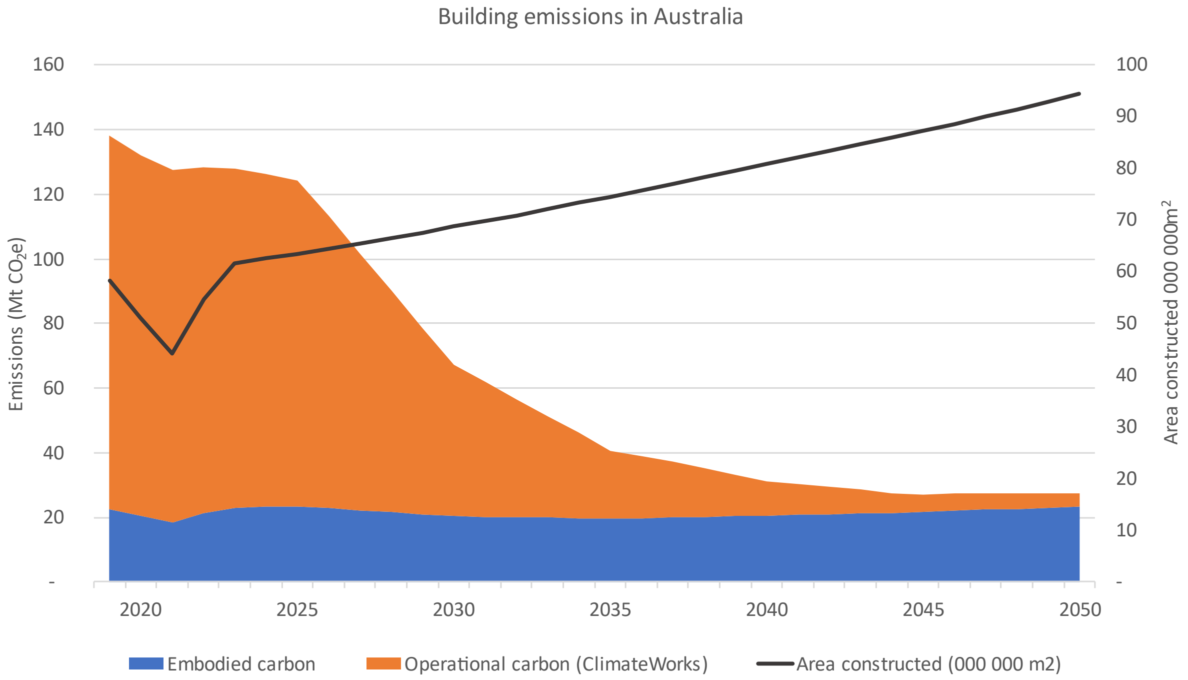


Figure 13: Embodied and operational carbon emissions in Australian buildings, with yearly area constructed

Embodied carbon per m^2 of building constructed

The embodied carbon of buildings split by building type and year can be seen in Table 7. These values include emissions from every stage of the life cycle of buildings apart from the emissions associated with the operation of the building (module B6). Table 7 shows the split of these emissions by life cycle stage, with the significant stages being the production of the materials and the emissions involved in building construction. Most of the impacts of the production of building materials which goes to waste during construction is included in the building products stage (A1-3). This occurred due to these values being calculated as a 'top-down', economy-wide value. Table 7 shows increases between 2019 and 2050 in all categories, except the construction process. The reason for this is that the construction process includes the emissions from offices of building and construction companies, and these emissions are largely due to electricity.

Table 7: Embodied carbon of buildings (A1-5, B1-5, C1-4), split by life cycle stage and building type

	Life Cycle Stage	Units	2019	2050
Residential	Building products (A1-3, B1-5)	Mt CO_2e	9.43	12.85
	Transport to site (A4)	Mt CO_2e	0.19	0.32
	Construction process (A5, C1)	Mt CO_2e	2.47	0.48
	Construction waste (A5)	Mt CO_2e	0.14	0.21
	Transport to EOL (C2)	Mt CO_2e	0.05	0.08
	End-of-life (C3-4)	Mt CO_2e	0.07	0.13
	Embodied carbon	**Mt CO_2e**	**12.3**	**14.1**
	Floor area	Million m^2	41.4	69.0
	Embodied carbon intensity	**kg CO_2e/m^2**	**298**	**204**
Non-residential	Building products (A1-3, B1-5)	Mt CO_2e	7.35	9.44
	Transport to site (A4)	Mt CO_2e	0.13	0.21
	Construction process (A5, C1)	Mt CO_2e	1.47	0.26
	Construction waste (A5)	Mt CO_2e	0.11	0.16
	Transport to EOL (C2)	Mt CO_2e	0.03	0.05
	End-of-life (C3-4)	Mt CO_2e	0.04	0.06
	Embodied carbon	**Mt CO_2e**	**9.13**	**10.2**
	Floor area	Million m^2	17.0	25.4
	Embodied carbon intensity	**kg CO_2e/m^2**	**538**	**401**
Total	Building products (A1-3, B1-5)	Mt CO_2e	16.8	22.3
	Transport to site (A4)	Mt CO_2e	0.32	0.53
	Construction process (A5, C1)	Mt CO_2e	3.99	0.75
	Construction waste (A5)	Mt CO_2e	0.24	0.37
	Transport to EOL (C2)	Mt CO_2e	0.08	0.13
	End-of-life (C3-4)	Mt CO_2e	0.11	0.19
	Embodied Carbon	**Mt CO_2e**	**21.5**	**24.3**
	Floor area	Millions m^2	58.4	94.4
	Embodied carbon intensity	**kg CO_2e/m^2**	**369**	**257**

GHG emissions per m^2 of building constructed

This section considers the GHG emissions from building materials, shown as modules A1-3 in Figure 4 and in EN 15804 (CEN, 2019). Table 8 and Figure 14 show the total GHG emissions of building materials production split by building type and year. The emissions of building materials per m^2 of floor space constructed is also shown, with the residential factor (228 kg CO_2e/m^2) being significantly lower than the non-residential factor (433 kg CO_2e/m^2). This is largely due to:

- Residential buildings being predominantly single dwelling, low rise, with timber framing making up a considerable market share.
- Non-residential typically being more often larger buildings that require more substantial foundation and structure.

Table 8: Total carbon emissions of building materials (A1-3) per m^2 of building constructed by building type (process LCA)

	Quantity	Units	2019	2050
Residential	GHG emissions	Mt CO_2e	9.43	12.8
	Floor area	Million m^2	41.4	69.0
	Building material GHG factor	**kg CO_2e/m^2**	**228**	**186**
Non-residential	GHG emissions	Mt CO_2e	7.35	9.44
	Floor area	Million m^2	17.0	25.4
	Building material GHG factor	**kg CO_2e/m^2**	**433**	**371**
Total	GHG emissions	Mt CO_2e	16.8	22.3
	Floor area	Million m^2	58.4	94.4
	Building material GHG factor	**kg CO_2e/m^2**	**287**	**236**

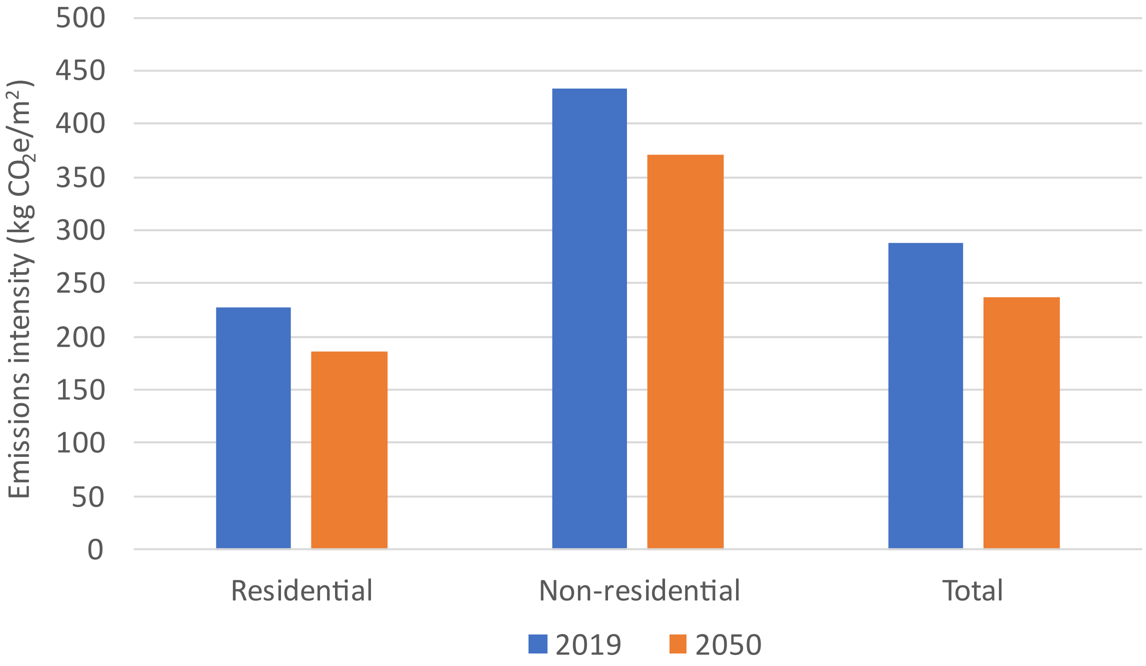


Figure 14: Carbon emissions of building materials (A1-3) per m^2 built by building type

Comparison to other studies

Thousands of building life cycle assessments (LCA) and carbon footprints (CFs) have been completed worldwide since the 1990s (CLF, 2017; Röck, et al., 2020; Yu, et al., 2017). In Australia, more than 200 building LCAs have been submitted to the GBCA to qualify for Green Star ratings – some of which apply to the base building, while others apply to the building interior only.

Several authors have compiled databases of past international building LCA studies, notably the Carbon Leadership Forum (2017) and Röck, et al. (2020). The results from these studies are compared with the results from this study on a per m^2 of gross floor area (GFA).

Carbon Leadership Forum

Figure 15 shows the carbon emissions intensity of initial building materials (modules A1-A3), by building type, based on the Embodied Carbon Benchmark Study conducted by the Carbon Leadership Forum.

The data are shown on a box and whisker chart, with the 'whiskers' showing the minimum and maximum of the included buildings, while the box shows the first, second (also known as the median), and third quartiles. Outliers have not been included in this reproduction and are not shown in the minimum and maximum. The values in the square brackets next to the building type on the x axis indicate the number of samples included for that building type in the database.

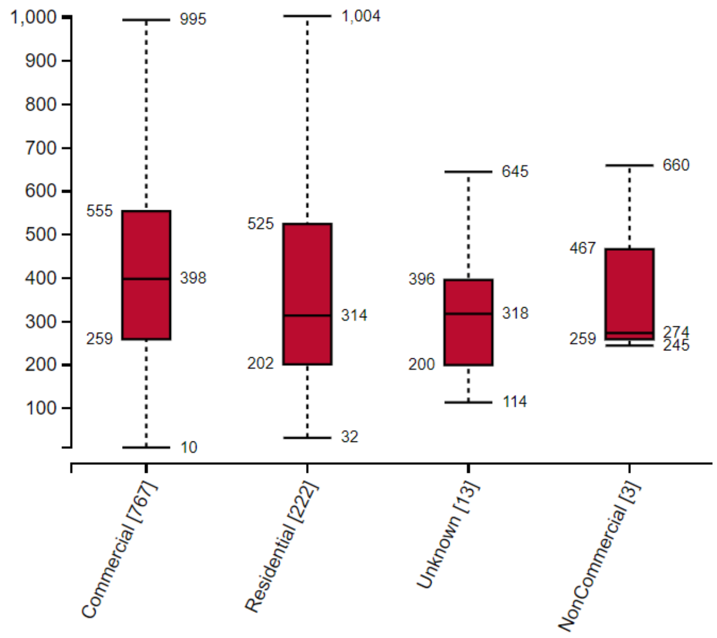


Figure 15: Carbon footprint of materials in buildings, by type (kg CO_2e/m^2) (reproduced from (CLF, 2017))

While these databases do not give a total embodied carbon figure for Australia, they can be used to estimate it. Based on the median values for the commercial and residential building types in Figure 15, Table 9 estimates a national carbon footprint of approximately 20 Mt CO_2e embodied in new-build buildings constructed in Australia in 2019. However, it is important to note that these carbon footprints cover the embodied carbon in materials for the initial building only, and do not include construction, maintenance, or end-of-life. Based on the calculations in this study, these phases of the life cycle make up approximately 25-30% of the embodied carbon of buildings. Furthermore, the buildings in the database do not necessarily represent current or Australian average construction practices (e.g., common use of timber-framing for residential buildings).

Table 9: Estimating embodied carbon in Australia's building materials in 2019, based on CLF (2017)

Type of building	kg CO_2e/m^2 (CLF, 2017)	m^2 GFA (Annex A)	Mt CO_2e
Residential	314	41,445,627	13.0
Non-residential	398	16,972,319	6.8
Total		**58,417,946**	**19.8**

Compared to the results of the average emission factor provided in the Carbon Leadership Forum (Figure 16), the carbon footprint of building materials calculated in this study for residential buildings are lower (228 vs 314 kg CO_2e/m^2). This is likely due to the use of timber framing and the high proportion of single-story dwellings with simpler foundations. The factor for non-residential buildings is comparable to the averages of the non-residential building types provided (433 vs 398 kg CO_2e/m^2 for commercial buildings and 274 kg CO_2e/m^2 for non-commercial buildings).

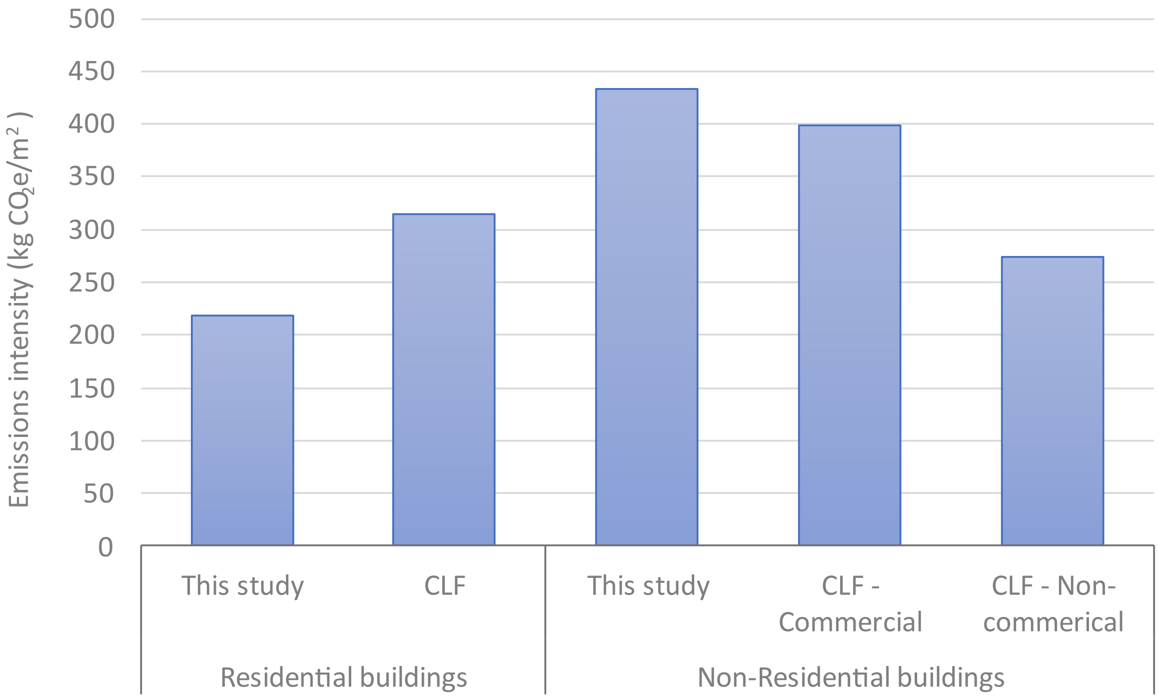


Figure 16: Comparison of the emissions intensities of this study to CLF (kg CO_2e / m^2) (CLF, 2017)

Note: This study also includes replacements and alterations (modules B1-B5) in the results, while the CLF study only includes primary building components (modules A1-A3)

Embodied GHG emissions of buildings (Röck, et al., 2020)

Röck et al., (2020) analysed over 650 LCAs of buildings globally in order to investigate how much of an impact embodied carbon has on the life cycle emissions of buildings, when operational carbon emissions are reduced due to efficiency improvements and electrification of heating systems.

The study found that for buildings following current local performance regulations, embodied carbon accounts for 20-25% of the life cycle GHG emissions, while this report calculated this value as being 16%. It is important to note that the majority of buildings studied in Röck et al., (2020) are in Europe which has different energy performance regulations, electricity grids, climate and construction practices to Australia — all of which would affect this split. Older buildings which do not meet energy performance regulations are also not considered in Röck et al., – inclusion of this would potentially lower the percentage of embodied carbon due to higher operational energy use in less energy efficient, older buildings.

Figure 20 shows the contribution of embodied carbon and operational carbon found in Röck et al., (2020) which annualises the results using a 50-year normalisation. The embodied carbon per metre squared of gross floor area (GFA) constructed can therefore be calculated by multiplying the annual embodied carbon value provided in the paper by 50. By doing this, the residential building embodied carbon intensity is calculated as 335 kg CO_2e per m^2, from an annualised figure of 6.7 kg CO_2e/m^2.a. Office buildings are calculated as having an embodied carbon value of 865 kg CO_2e per m^2 from an annualised value of 17.3 kg CO_2e/m^2.a. The average for all buildings is calculated as 364 kg CO_2e per m^2 from an annualised figure of 7.3 kg CO_2e/m^2.a.

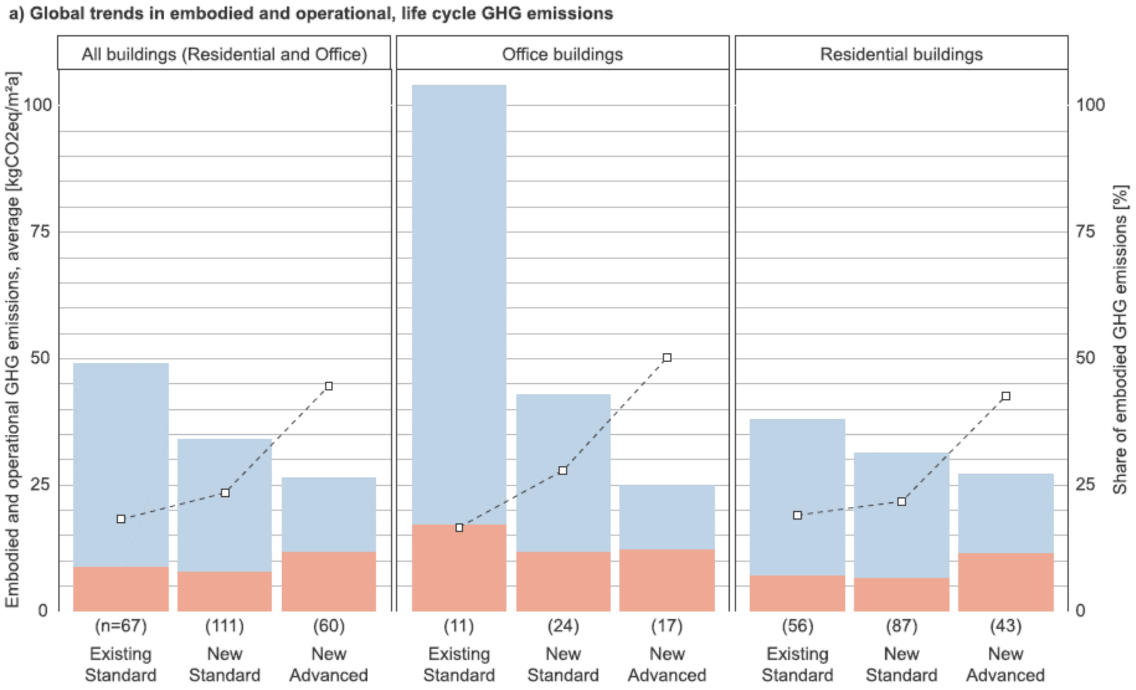


Figure 17: Annualised embodied carbon and operational carbon of global buildings (50 year normalization, gross floor area) (reproduced from (Röck, et al., 2020))

The averages for residential buildings and all buildings calculated from Röck et al. are compared to the results from this study in Figure 18. Similar to CLF, the emissions intensity of Röck et al. is higher than the results found in this study. This is likely due to the reasons mentioned previously (single-story dwellings, timber framing being common), as well as the Röck et al. analysis including some building LCAs which use IO-LCA, while the process results from this study are used as a comparison.

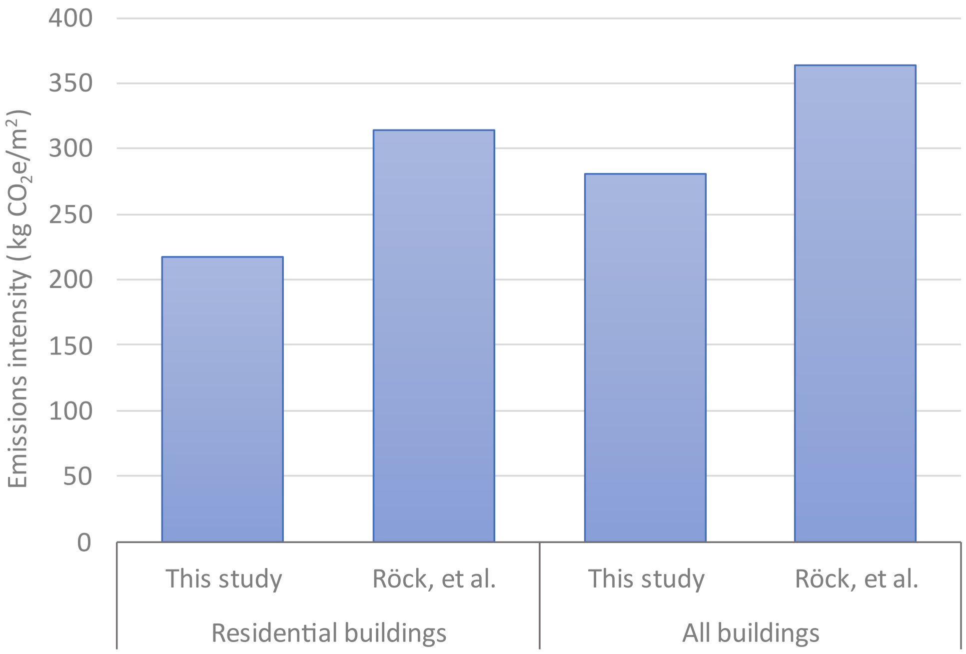


Figure 18: Comparison of the emissions intensities of this study to Röck et al., (2020) (kg CO_2e/m^2)

Economy-wide input-output LCA

Carbon footprint of the construction sector (Yu, et al., 2017)

Using an economy-wide input-output LCA approach, Yu et al. (2017) calculated the embodied carbon of Australian residential and non-residential buildings to be 21.5 Mt CO_2e and 15.1 Mt CO_2e respectively in 2013 (Table 10). This is 6.8% of Australia's gross greenhouse gas emissions in 2013 (540 Mt CO_2e) (DISER, 2021).

Given that the reference year for this report is 2019, the numbers in Yu et al. needed to be adjusted. In this study, two basic methods were used to give an approximation of this:

- **Scaling up based on Gross Floor Area (GFA) constructed.** This was done by scaling by the difference in annual new-build construction of residential and non-residential buildings between 2013 and 2019 (Table 10 and page 57). This results in the embodied carbon in 2019 being 48.1 Mt CO_2e, assuming all emissions scale linearly with built area (Table 10). This is a significant assumption, and this value is almost certainly an overestimation given the improvements in the emissions intensity of building materials in the last six years (see page 43).
- **Scaling up based on gross Australian emissions.** This was done by scaling the 2013 value by the difference in Australia's gross greenhouse gas emission (excluding LULUCF). As construction sector emissions are 6.8% of Australia's emissions in 2013, this would equate to construction emissions being 34.7 Mt CO_2e in 2019 as gross emissions have gone down between 2013 and 2019 (DISER, 2021). This assumes that construction emissions scale linearly with the rest of Australia's emissions, which is unlikely given increasing construction volumes (Table 10).

As this section is considering the difference between process LCA and IO-LCA, the maximum value of these is used as a comparison and so the adjustment based on GFA is used. Using this method shows the maximum truncation error of the Process LCA results from the IO-LCA results. The scaling used here is a limitation of this work and other methods could potentially be used, or the construction sector emissions could be recalculated using more recent Economic Input-Output tables.

Table 10: The carbon footprint of Australia's construction sector in 2013 (Yu, et al., 2017), with 2019 values estimated by this study

Sector	Unit	2013 (Yu, et al., 2017)	2019 (scaled, GFA)	2019 (scaled, gross emissions)
Australia gross emissions (excluding LULUCLF)	Mt CO_2e	597	N/A	565
Area built	million m^2	44.4	58.4	N/A
Total buildings	**Mt CO_2e**	**36.6**	**48.1**	**34.7**

The scope of Yu et al.'s analysis spans "from the extraction of raw materials (mining of limestone), the manufacturing of building products (in Australia or abroad), transport, assembly, excavations to the demolition of old buildings to make way for new ones" (Wiedmann, et al., 2017). As IO-LCA considers all monetary transactions within the economy, this analysis will consider all goods and services consumed by a sector including, for example capital goods, banking and insurance. When comparing their results to an earlier study for the year 1995, Yu et al. found that embodied carbon had increased at a significantly higher rate than direct operational carbon.

Thus, by comparing the Process LCA results from this report to the adjusted numbers from Yu et al., the embodied carbon in Australia's buildings in 2019 is likely to be between 22 and 48 Mt CO_2e. Assuming all building products and materials were manufactured locally, this accounts for approximately 3.9% to 8.9% of Australia's total GHG emissions. (Yu et al. (2017) note that imports make up only a small share of the total GHG emissions from buildings.)

Reducing embodied carbon and energy

Sources of embodied carbon and embodied energy

The carbon and energy embodied in materials comes from five sources (Table 11):

1. Stationary combustion of fuels, typically for thermal energy (e.g., natural gas, LPG).
2. Mobile combustion of fuel in vehicles (e.g., diesel, gasoline, LPG, CNG).
3. Direct process emissions (embodied carbon only).
4. Purchased energy, typically electricity.
5. Purchased goods and services – themselves a result of items 1-4 above.

Table 11: Sources of embodied carbon and embodied energy

Source	Scope (GHG Protocol)	Embodied carbon?	Embodied energy?
Stationary combustion of fuel for thermal energy / electricity generation	Scope 1	X	X
Mobile combustion of fuel in vehicles	Scope 1	(Often small)	(Often small)
Direct process emissions	Scope 1	X	N/A
Purchased electricity	Scope 2	X	X
Purchased thermal energy	Scope 2	(Uncommon)	(Uncommon)
Purchased goods and services	Scope 3	X	X

Reducing embodied carbon and embodied energy

Strategies to reduce embodied carbon and embodied energy can be broadly categorised into **supply side** and **demand side**. Supply-side strategies target the emissions sources identified in the previous section (thermal energy, direct process emissions, electricity, and purchased goods and services). Demand-side strategies target which materials/products are selected, how much of each material is needed, and how construction and demolition waste is managed. Importantly, both strategies are often complementary. If you manufacture a product with a lower impact per unit and you also need fewer units then you win twice.

Examples of supply-side strategies include:

- Energy efficiency and material efficiency projects.
- Design and supply of lightweight products.
- Process substitution to replace high-impact processes with lower-impact processes.
- Carbon capture and storage, stopping process emissions from reaching the atmosphere.
- Locating manufacturing facilities near key inputs, be this a natural resource (e.g., forest residues for renewable thermal energy), a shared resource (e.g., a regional steam plant), or a necessary product derived from another industry (industrial symbiosis).
- Decarbonisation of electricity grids through increased use of renewables.
- Decarbonisation of natural gas grids, e.g., through partial replacement of natural gas with biogas and/or injection of green hydrogen (typically up to 10%) into the grid.

- Thermal energy substitution. E.g., replacement of coal with natural gas, natural gas with biogas, or natural gas with biomass.
- Use of on-site renewables to reduce the need for purchased electricity.
- Use of biogas from landfill or anaerobic digestion of organic waste to replace natural gas.

Examples of demand-side strategies include:

- Better design to optimise material use and avoid waste generation.
- Encouraging the use of rating tools like Green Star which specifically target reductions in upfront carbon emissions.
- Material substitution, i.e., substituting a higher-impact material for a lower-impact material that serves the same function.
- Designing buildings for multi-functionality so that fewer buildings are needed overall.
- Prolonging the life of existing buildings through proper maintenance and renovation.
- Reuse of materials and/or assemblies from decommissioned buildings.
- Recycling and upcycling of materials from decommissioned buildings.

The first Low Emissions Technology Statement (LETS) (Australian Government, 2020) is an important step at the Commonwealth level to reduce supply-side emissions. In line with a recommendation of the King Review, the Government will task the Australian Renewable Energy Agency (ARENA) to work with the Clean Energy Finance Corporation (CEFC) and other relevant agencies to develop a goal-oriented program targeting a number of the priority low emissions technologies such as low emissions steel, low emissions aluminium, or energy storage.

The first LETS includes several strategies relevant to buildings:

- **Clean hydrogen** can potentially address:
    - Thermal energy emissions, but only where hydrogen is cheap enough to replace natural gas.
    - Process emissions from steel, but only if conventional blast furnaces are replaced by hydrogen direct reduced iron (a technology which is still in development).
- **Energy storage** can address electricity emissions by being able to increase the share of intermittent renewables (primarily solar and wind) in the electricity grid.
- **Low carbon materials** could conceivably cover all strategies above for the two materials it currently applies to (steel and aluminium).
- **Carbon capture and storage** addresses direct process emissions, though it is most applicable to the manufacture of ordinary Portland cement rather than steel as there are fewer stacks from which to capture the CO_2.

Voluntary drivers in the built environment to reduce embodied carbon emissions

Green Building Council of Australia's Green Star rating system is a voluntary system that is used by the built environment to demonstrate leadership in delivering sustainable buildings. In 2018, GBCA announced that upfront carbon emissions would need to be reduced by 10% compared to a typical building to achieve a rating beginning in 2020. This requirement would expand over time to require a reduction of at least 40% by 2030. After significant consultation, this approach has now been introduced and has been widely accepted by industry as appropriate best practice targets.

Progress on decarbonisation within Australia

This section contains some examples of the work currently being done to reduce embodied carbon in building products in Australia. This is not an exhaustive list and has been compiled based on public data or from conversations held with industry stakeholders.

Cement and concrete

- The GHG intensity of cement produced in Australia from Australian clinker fell 17% in the eight years from 2011/12 to 2018/19, from 0.94 kg CO_2e/kg cement to 0.77 kg CO_2e/kg cement (CIF, 2020).
- Adelaide Brighton Cement (ABC) is using Refuse Derived Fuel (mainly wood) which is taken from construction and demolition sites at its Birkenhead plant. This helps divert 200,000 tonnes of refuse from landfills per year, saving more than 12.5 million GJ of natural gas (which is a reduction of 25%) (ABC, 2020) (Adbri, 2020, p. 28). ABC hope to increase the share of alternative fuels in its South Australian kilns up to 50% within five years (Adbri, 2020, p. 24).
- Boral's cement works at Berrima currently saves approximately 30,000 tonnes of CO_2 per year through its use of alternative fuels. The plant has the goal to replace up to 30% of traditional fuel by alternative fuels (CIF, 2020). A $4.6 million grant from the NSW Government is helping to fund of a chloride bypass (Boral, 2020).
- Holcim Australia's carbon reduction strategy aims to increase the replacement of general-purpose cement with supplementary cementitious materials (SCM) such as fly ash, slag, and silica fume. (Holcim Australia, 2019).
- In 2018, Australia used 1.6 Mt of ground-granulated blast furnace slag (GGBS) (ASA, 2019) and 2.0 Mt of fly ash (ADAA, 2019) as cement replacements, corresponding to a market-wide cement replacement rate of approximately 27% (see Annex B: Detailed material flow analysis). This is quite a high rate of substitution, given that fly ash by itself would not typically be used at replacement rates above 30%.

Steel

- BlueScope Steel has achieved a 40% reduction in GHG emissions footprint at their Australian operations since 2005 and has committed to a further 12% reduction in steelmaking GHG emissions intensity by 2030 (BlueScope, 2020). However, it should be noted that basic oxygen steelmaking (BOS) is a mature technology and that opportunities for more significant reductions likely lie in increased use of recycled steel – via the electric arc furnace (EAF) route – where sufficient scrap is available (BlueScope, 2020). Novel technologies such as hydrogen direct reduced iron (DRI) or molten oxide electrolysis, which are not fully developed, are other potential sources of emissions reductions, but these come with large capital costs.
- InfraBuild have developed a new range of high-strength reinforcing steels for column fitments that have 33% less mass than that of standard fitments (Infrabuild, 2021). InfraBuild's existing EAFs will also all decarbonise as the electricity grids around them decarbonise.

Aluminium

- The GHG intensity of alumina production reduced by 19% from 2005 to 2019 due to improved yields and lower energy use. The GHG intensity of aluminium smelting (including both indirect and direct emissions) decreased by 28% during this same time period (AAC, 2020c).
- Decarbonising thermal energy for alumina production and increasing the renewable content of electricity production for aluminium smelting are likely to be the two most promising solutions to decarbonise aluminium.

Clay bricks and tiles

- Brickworks Building Products Australia currently uses biofuels, largely landfill gas and sawdust, for approximately 14% of its energy requirements across all production facilities (Brickworks, 2020). This includes either using landfill gas (which contains methane) to substitute natural gas, or by using sawdust as a primary fuel source. Brickworks has recently partnered with Murdoch University to investigate the use of hydrogen as a kiln fuel for the manufacture of clay bricks (Brickworks, 2021).
- CSR have reduced their emissions per tonne of product by 24% since 2009, achieving their ten-year target of 20%. This has partially been done through the completion of several solar projects, including a $2 million farm at PGH Bricks in South Australia, which was projected to provide approximately 25% of the plant’s electricity (CSR, 2019).

Plasterboard

Plasterboard production is a relatively mature technology. Natural gas is the major energy input, used for calcination of gypsum to Plaster of Paris and in drying the final board. Progress is being achieved at a national level through continuous improvements such as: the recycling of waste heat in the plaster mill; improved calcination equipment increasing throughput in the plant; and heat exchangers installed on dryers, saving gas consumption and collecting water, as well as increased efficiencies through plant turnover. For example, Knauf completed a new plant in Bundaberg in 2017 using the latest technology for energy-efficient manufacturing (Knauf 2019).

Decarbonisation of electricity networks

There is considerable variability in the carbon emissions intensity of electricity generation by each state and territory. The overall trend is a consistent drop in emissions from electricity generation across Australia. Emissions in the National Energy Market (NEM) for the December quarter 2020 decreased 3.9 per cent on a seasonally adjusted and weather normalised basis compared with the previous quarter.

Barriers to further decarbonisation

The comments in this section are based primarily on the views expressed by industry stakeholders during the consultation process for this report and a 2020 report by Lendlease (Lendlease 2020) which included interviews with steel, concrete, and aluminium suppliers.

Important barriers identified were:

Economic

- Capital is sunk into existing fossil fuel intensive manufacturing processes and equipment requiring very long investment horizons.
- While capital costs are a hurdle, operating costs are arguably more important. All industries considered in this report are, to greater or lesser extent, exposed to competition from imported products, or to competition from other material sectors. As a result, any change that would increase the operating costs of the manufacturer would increase their cost of production and therefore have the potential to make them uncompetitive. Changes such as a move to electrification of processes and/or using renewable hydrogen can come with a significant price premium. Eliminating the price premium is one very likely way to encourage change.

Technical performance / specifications

- In some cases, a low-carbon product behaves in a different way to the virgin product. For example, concrete with a high fraction of supplementary cementitious materials (SCM) may take longer to set and to develop its strength. While often being stronger in the long-term, use of high-SCM concretes requires better planning on the jobsite.
- Specifications favour existing materials so deviation from the norm carries business risk.

Supply

The inconsistency in the supply of biofuels can often be an issue in encouraging their uptake. These issues are not limited to biofuels however and natural gas price uncertainty in particular is an issue that many manufacturers currently face and will continue to face in the future.

- Landfill gas can vary in quality, as the moisture content and methane content can vary significantly. This results in difficulties with running kilns using landfill gas.
- Procuring wood waste from sawmills faces competition from sawmillers themselves (for use in their own kilns) as well as other fossil fuel users looking to transition. The potential of inconsistent supply is another area which concerns those looking to switch from fossil fuels.

Knowledge and perception

- Embodied carbon is a complex subject.
- Architects, specifiers, and builders have expertise and familiarity with the materials they have always used. As such, new innovations may be passed over due to the familiar response being the most appropriate.
- Embodied carbon is also only one environmental factor in procurement decisions. Some materials may offer a lower carbon impact but increase impact in other environmental impacts. For example, increased impact in terms of water consumption or biodiversity.

Lack of regulatory drivers

- Most suppliers deal in a large variety of building and construction projects (or overseas markets in the case of aluminium products) where there are no regulatory measures to encourage the use of materials with low embodied carbon.

Electricity pricing is likely to become a crucial lever for decarbonisation

While decarbonising electricity supply reduces indirect carbon emissions, low-carbon electricity also has the potential to decarbonise other sources of emissions. Important examples include electrification of industrial process heat and the use of green hydrogen to replace fossil fuels.

For its full potential to be realised, and to make investments in electrification viable, low-carbon electricity needs to be affordable. Construction product manufacturers are often competing on the global market, meaning that any significant increase in operating costs could render them uncompetitive compared to cheaper imports with lower energy costs.

For large electricity users, like aluminium smelters, the cost of electricity is significant — making up 30-40% of a smelter's expenditure (Australian Aluminium Council, 2020). Construction of new aluminium smelters are only considered in countries whose pricing is in the first quartile (lowest 25% of prices). Currently, Australia is priced in the fourth quartile (highest 25%) for electricity. These factors make Australian-made aluminium (and other products which require large amounts of electricity) less globally competitive and runs the risk of production moving offshore (Oram, 2020), potentially to locations with higher electricity grid emissions.

The Australian National Outlook (ANO) Technical Report (Brinsmead, et al., 2019) considers the cost implications associated with several modelled scenarios and a scenario of policy uncertainty. The modelling done shows that uncertainty around climate and energy policy is a driver of higher electricity system costs in the decades to 2060, which will likely be passed onto users. This is due to higher uncertainty requiring a greater return on investment for energy companies. The scenarios with the more ambitious renewable energy uptake also have lower system costs, especially in the period 2020–2030.

While high electricity prices have been an important driver of energy efficiency for decades, the need to electrify everything to help Australia and other nations achieve their commitments under the Paris Agreement is becoming more pressing. Abundant, affordable, low-carbon electricity seems likely to become one of the most important levers in the fight against climate change.

Conclusions

- Embodied carbon in buildings constructed in Australia in 2019 was at least 22 Mt CO_2e and is predicted to climb to at least 24 Mt CO_2e by 2050 if no specific action is taken on embodied emissions. This absolute increase comes despite decarbonisation of the electricity grid, with this study assuming 100% renewable electricity by 2050.

- While the absolute size of this increase is modest, embodied carbon will become an increasingly large portion of Australia's total emissions as other parts of the economy decarbonise. The embodied carbon invested in Australia's building stock in 2019 equated to at least 3.9% of Australia's total gross greenhouse gas emissions. This share is likely to grow to at least 6.0% by 2050 if no action is taken.

- The share of whole-life building carbon emissions from embodied carbon was 16% in 2019 and is expected to climb to 85% by 2050.

- Carbon emissions during the construction phase accounted for 19% of total embodied emissions of buildings in 2019 and 3% of embodied emissions in 2050. This reduction is due to the decarbonisation of the electricity grid during this time period.

- Current embodied emissions from Australia's residential buildings are lower than international averages today. Among other factors, this is likely due to the use of timber framing and the high proportion of single-story dwellings with simpler foundations.

- Current embodied emissions from Australia's non-residential buildings are slightly higher than the international average.

- There are significant reduction opportunities to reduce embodied carbon and embodied energy in Australia's buildings, which have not been included in the business-as-usual (BAU) scenario presented in this report. Additional policy incentives to decarbonise Australia's energy supply and investment in research and development of new materials and practices are urgently needed to ensure the emissions from products and materials in buildings are driven to zero in line with the targets of the Paris Agreement.

- Even a 10% reduction in embodied emissions in new commercial and residential buildings would correspond to at least 19.9 Mt CO_2e avoided between 2022 to 2030 and at least 63.5 Mt CO_2e avoided between 2022 and 2050. Making these improvements will also help to future-proof energy-intensive industries within Australia, helping to maintain their global competitiveness in a low-carbon world. The 19.9 Mt CO_2e figure compares to predicted operational carbon emissions reductions of 14 Mt CO_2e from updating the National Construction Code in 2022 for residential buildings (saving 6.6 Mt to 2030) (COAG Energy Council, 2018, p.21) and 2025 for commercial buildings (saving 7.4 Mt to 2030) (Energy Action & Strategy Policy Research, 2018, p.10).

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Abbreviations

ABCB	Australian Building Codes Board
ABS	Australian Bureau of Statistics
BF	Blast Furnace
CIF	Cement Industry Federation
CLF	Carbon Leadership Forum
DFE	Depletion of Fossil Energy resources
DFAT	Department of Foreign Affairs and Trade
EAF	Electric Arc Furnace
EPD	Environmental Product Declaration
EIO	Economy-wide input-output
GBCA	Green Building Council of Australia
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse gas
GWP	Global Warming Potential
IO	Input-Output
LCA	Life Cycle Assessment
LULUCF	Land Use, Land-Use Change, and Forestry
MFA	Material Flow Analysis
PED	Primary Energy Demand (total energy at point of extraction, including all losses)
TCNA	Tile Council of North America

Annex A: Detailed methodology

Step I: Conduct a bottom-up hotspot assessment

1. Forecast the annual new-build construction and alteration rates to 2050 by building type

This was based on historic Chain Volume building commencements from ABS combined with a future projection of completions from the Australian Building Codes Board (ABCB, 2018) to 2029 for residential buildings. To calculate the completions after 2029 (when the ABCB forecast ends) the growth rates of the past 10 years were extrapolated out until 2050. The non-residential new build construction forecast was based on Chain Volume building commencements, with an annual growth forecast taken from a report by The Centre for International Economics (CIE, 2018)

The drop in building commencements due to COVID-19 was modelled as:

- FY20/21: ¼ of the year runs at 30% capacity due to lockdowns in the first part of this year. The rest of the year runs at normal capacity
- FY21/22: Assuming a drop of 27% from the original forecast, based on Master Builders modelling in May 2020 (Master Builders Australia, 2020)
- FY22/23: Assuming volume back up to 90% of the pre-COVID forecast for FY22/23 for residential buildings and 90% of the pre-COVID (FY 18/19) value for non-residential buildings – estimated.
- FY23/24: Assuming back to forecasted rate for residential buildings and back to the pre-COVID level for non-residential buildings (ABCB, 2018)

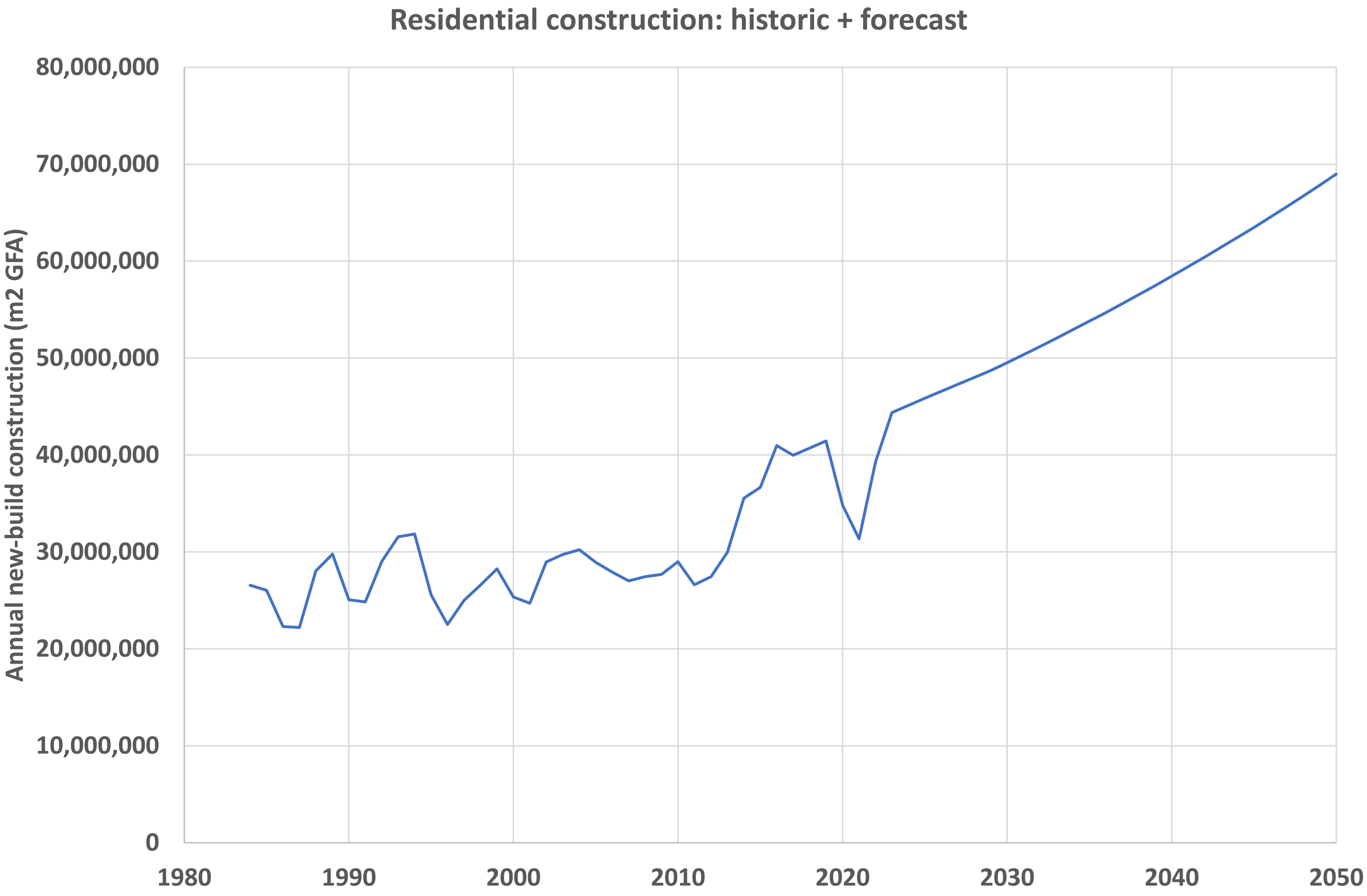

Figure 19: Residential construction historic data and forecast

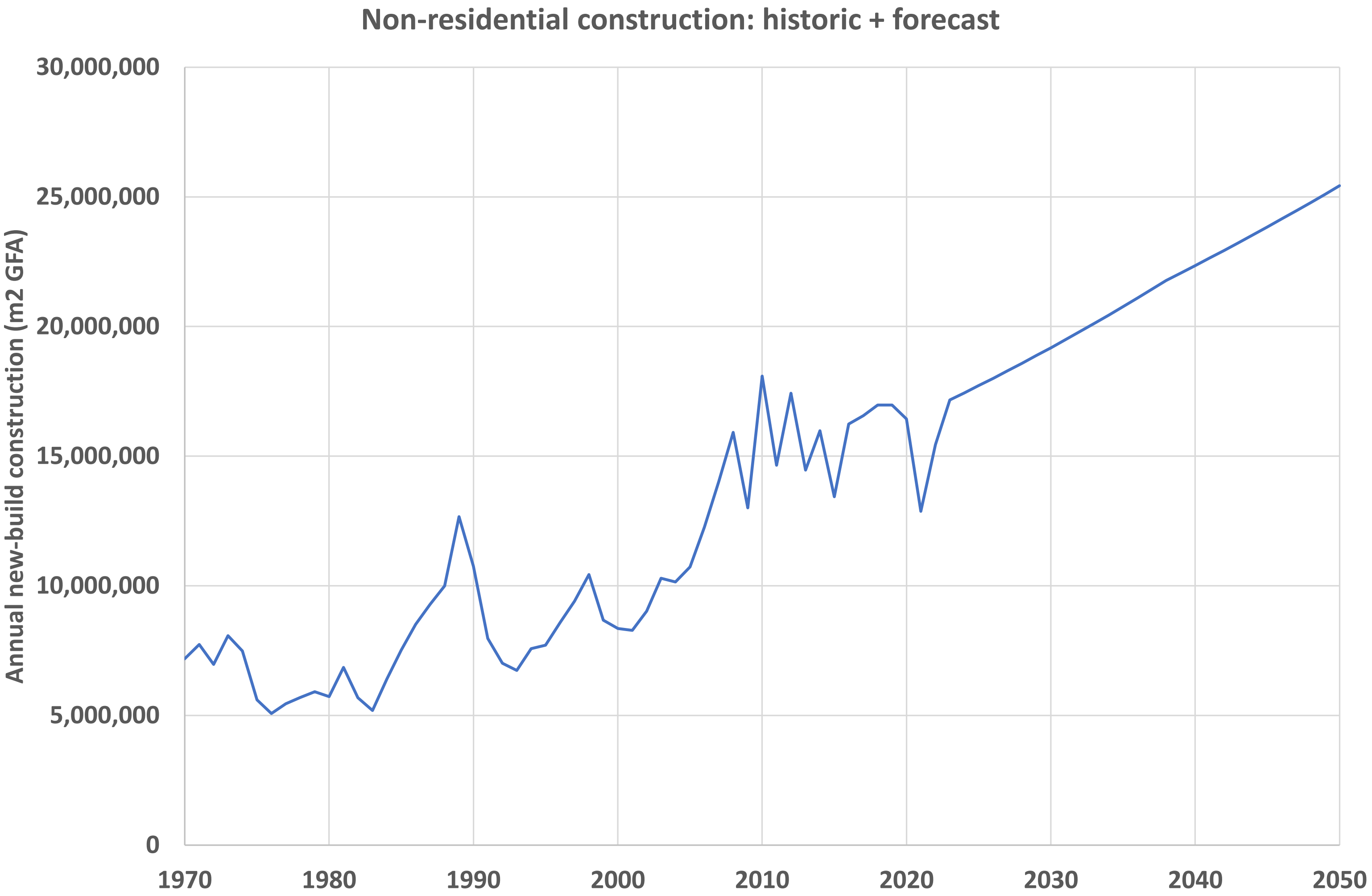

Figure 20: Non-residential construction historic data and forecast

2. Classify buildings into representative construction design and method

Residential buildings were split into two classes, following the ABCB report where the residential new build construction forecasts were sourced from (ABCB, 2018). Table 12 shows the forecasted completed area in 2019 and in 2050.

- Class 1: Standalone house
- Class 2: Other residential

Table 12: Residential floor area constructed (000,000 m^2)

Financial Year	Class 1 Floor Area	Class 2 Floor Area	Total Residential Floor Area
2019	34.0	7.43	41.4
2050	55.0	14.0	69.0

Non-residential buildings were splits into 15 classes, based on the building types provided in the ABS Building Approvals (ABS, 2020).The Building Approvals data provided the number of and the average floor area (where data was available) for non-residential building approvals in Australia across various building types, which was used to split the forecasted floor area. Table 13 and Table 14 show the split of the forecast non-residential floor area constructed in 2019 and 2050. The building type codes used were:

- Retail
- Transport
- Office
- Commercial (Other)
- Factory
- Warehouse
- Agriculture
- Industrial (Other)
- Education
- Religion
- Aged Care
- Health
- Entertainment
- Hotels
- Non-residential (Other)

Table 13: Non-residential floor area constructed (000,000 m2)

FY	Retail	Transport	Office	Commercial (Other)	Factory	Warehouse	Agriculture	Industrial (Other)
2019	2.54	0.16	2.43	0.19	0.69	5.12	0.87	0.89
2050	5.07	0.21	4.31	0.21	0.98	6.53	1.23	1.17

Table 14: Non-residential floor area constructed continued (000,000 m^2)

FY	Education	Religion	Aged Care	Health	Entertainment	Hotels	Non-residential (Other)	Total Non-residential
2019	1.42	0.05	0.40	0.17	0.73	0.68	0.62	16.97
2050	2.02	0.10	0.55	0.40	1.02	0.78	0.85	25.43

3. Specify a bill of quantities (BoQ) for each building type

The Class 1 residential building was modelled by taking the building types considered in a comparative LCA of typical Australian buildings (FWPA, 2011) and weighting the materials used in foundations, framing, roofing, walls and windows based on the current market share of construction types. The Class 2 residential building was modelled using the Life Cycle Inventory of the reference building of a comparative LCA of two multistorey residential apartment buildings (Carre & Crossin, 2015).

For the non-residential buildings, each building type was modelled using an exemplar building, which could be considered an estimate of a typical building for that class. The transport, factory, warehouse, agriculture, industrial (other) classes were modelled based on a steel warehouse building, while the office and religion categories were modelled based on typical office buildings of two different sizes, with data supplied by industry. Retail, education, entertainment and other non-residential buildings were modelled in a separate retail group. Table 15 shows the BoQ for the building types considered in this study, showing the materials as delivered to site, which includes any construction waste.

Table 15: Bill of quantities per building type (kg/m^2)

Material	Residential Class 1	Residential Class 2	Non-residential Warehouse	Non-residential Office	Non-residential Retail
Aluminium	0.92	0.89	0.33	11.25	5.79
Clay brick/tile	78.40	0.00	0.00	3.36	1.68
Concrete	439	1063	694	2165	1430
Copper	0.00	0.00	0.00	0.66	0.33
Glass	2.73	2.96	2.27	19.22	10.74
Gravel	0.00	29.82	0.00	0.00	0.00
Insulation	0.00	1.40	0.12	0.89	0.50
Paint	0.00	1.15	0.04	0.06	0.05
Wood	21.17	0.00	0.79	1.11	0.95
Plasterboard	22.05	33.64	1.65	11.90	6.77
Stainless steel	0.00	0.00	0.00	0.43	0.22
Steel	10.96	46.87	61.37	153.67	107.52
Total	**575**	**1180**	**760**	**2368**	**1564**

4. Identify typical construction and demolition rates

For the purposes of modelling, it was assumed that for every four buildings constructed in Australia, one would be demolished. This was modelled as ¼ of the mass of construction materials going to the end-of-life phase of the life cycle after use (including the end-of-life material credit).

5. Identify embodied carbon and energy data

The carbon emissions factors of the production of various building materials can be seen in Table 16. Please note that these are the factors used in the final analysis.

Table 16: GHG emission factors of building materials (kg CO_2e / kg)

Material type	2019	2050[1]	Source for 2019 factor
Aluminium	14.92	3.92	(AAC, 2020c)
Clay brick/tile	0.20	0.19	(ThinkBrick, 2018)
Concrete	0.12	0.11	MFA
Copper	4.12	4.12	(Sphera, 2020)
Glass	1.12	1.12	(Sphera, 2020)
Gravel	0.00	0.00	(Sphera, 2020)
Insulation – glass wool	1.88	1.88	(Sphera, 2020)
Paint	1.83	1.83	(Sphera, 2020)
Wood	0.23	0.23	(FWPA, 2017)
Plasterboard	0.28	0.21	Industry data
Stainless steel	3.27	3.27	(Sphera, 2020)
Steel – other	2.83	2.51	(BlueScope, 2020)
Steel – roofing & cladding	2.83	2.51	(BlueScope, 2020)
Steel – sheet	2.83	2.51	(BlueScope, 2020)
Steel – structural beams and columns	2.83	2.51	(BlueScope, 2020)
Steel – structural reinforcing	1.64	0.87	(InfraBuild, 2020a)

[1] only major materials have been decarbonised with the electricity grid

Table 17: Primary energy demand factors of building materials (MJ / kg)

Material type	Renewable energy 2019	Renewable energy 2050[1]	Non-renewable energy 2019	Non-renewable energy 2050[1]
Aluminium	42.5	275	176	51.4
Clay brick/tile	0.19	0.28	4.08	3.90
Concrete	0.01	0.02	0.61	0.56
Copper	4.48	4.48	47.6	47.6
Glass	0.89	0.89	14.0	14.0
Gravel	0.01	0.01	0.03	0.03
Insulation – glass wool	4.58	4.58	31.4	31.4
Paint	4.38	4.38	37.9	37.9
Wood	2.92	2.92	4.50	4.50
Plasterboard	1.87	7.99	4.23	2.62
Stainless steel	8.43	8.43	43.8	43.8
Steel – other	0.62	1.53	26.4	22.2
Steel – roofing & cladding	0.62	1.53	26.4	22.2
Steel – sheet	0.62	1.53	26.4	22.2
Steel – structural beams and columns	0.62	1.53	26.4	22.2
Steel – structural reinforcing	1.18	4.97	18.4	11.5

[1] only major materials have been decarbonised with the electricity grid

Module D: taken from EPDs of relevant products where available. For aluminium and copper, used recycling processes off the GaBi Life Cycle Database (Sphera, 2020). All recycling credits were static with time and not modelled as changing with the electricity grid mix changes to 2050.

6. Estimate total embodied carbon and energy and of Australia's buildings

This equations for this step are broken down into the modules of EN15084. The equations referenced and a key for this step are found below.

1. Material mass: Calculated by multiplying the modelled materials used per m^2 of building constructed by the forecasted area built, as shown in Equation 2.
2. Modules A1-3, B1-5 (production emissions, including repair and replacement): Calculated by multiplying the mass of each material by the respective production emission factor, then summing to get total emissions, as shown in Equation 3.
3. Module A4: Calculated by multiplying the mass of the building materials by the emission factor of travelling from the final production facility to building site, as shown in Equation 4.
4. Module A5: Calculated by multiplying the mass of the construction waste by the emission factors associated with the whole life cycle of this waste (production, transport to and from site, and processing at end-of-life). This value is then added to the emissions associated with building construction, calculated by multiplying a construction emissions factor by the building area constructed, as shown in Equation 5.
5. Module C1-4: Calculated by multiplying ¼ of the mass of buildings materials used in construction by the emission factors for the transport and landfilling of construction waste, see Equation 6. The ¼ was used as it is assumed that currently for every four buildings constructed in Australia, one is demolished.

$$m_{building,i} = \sum_{t=0}^{t=s} \left(a_{mass,t} \times a_{building,\mathrm{t}}\right)$$

Equation 2: Building material mass equation

$$Module\ A1 - 3 = \sum_{i=0}^{i=n} \left(m_{building,i} \times c_{material,i}\right)$$

Equation 3: Module A1-3 calculation (includes modules B1-5)

$$Module\ A4 = \sum_{i=0}^{i=n} \left(m_{building,i} \times c_{mat\ transport}\right)$$

Equation 4: Module A4 calculation

$$Module\ A5 = \sum_{i=0}^{i=n} \left((c_{area} \times a_{area}) + (m_{c\ waste,i}) \times (c_{mat\ transport} + c_{material,i} + c_{waste\ transport} + c_{waste,i})\right)$$

Equation 5: Module A5 calculation

$$Module\ C1-4 = \sum_{i=0}^{i=n} \left((\frac{1}{4} m_{building,i}) \times (c_{waste,i} + c_{waste\ transport})\right)$$

Equation 6: Module C1-4 calculation

Where:

- t = building type
- s = total number of building types
- i = building material
- n = total number of building materials
- $a_{building,t}$ = area of building type t constructed (m^2)
- $a_{mass,t}$ = mass of material in BOQ per m^2 of building type t (t / m^2)
- $m_{building,i}$ = mass of material i used in the construction of buildings (tonnes)
- $m_{c\ waste,i}$ = mass of construction waste of material i (tonnes)
- $m_{waste,i}$ = mass of demolition waste of material i (tonnes)
- $c_{material,i}$ = emission factor of material i production (t CO_2e / t material)
- $c_{mat\ transport,i}$ = emission factor of transporting material i from production facility to the building site (t CO_2e / t material)
- $c_{waste\ transport}$ = emission factor of transporting material from the building site to the end-of-life location (t CO_2e / t material)
- c_{area} = emission factor of the construction of a building per area constructed (t CO_2e / m^2 constructed)
- a_{area} = area constructed (m^2)
- $c_{waste,i}$ = emission factor of the waste processing and landfilling of material i (where applicable) (t CO_2e / t material)

7. Identify the top five building products/materials to focus on

These were identified based on embodied carbon and energy and were determined to be:

- Aluminium
- Concrete/cement
- Clay brick/tile
- Plasterboard
- Steel

While glass had the fifth highest embodied carbon for non-residential buildings, plasterboard was selected as the fifth material based on it making up a higher percentage of the residential embodied carbon that glass did of the non-residential.

Step II: Conduct a top-down MFA for the top five materials

Conduct a material flow analysis for the top five building materials.

An MFA was conducted on the top five building materials, using a mix of industry and public data.

Please refer to Annex B: Detailed material flow analysis for details.

Overlay the MFA with national data on greenhouse gas emissions and energy per material.

Using industry, public, and LCA data (Sphera, 2020), the material flows were used to calculate carbon and energy flows within each material industry.

Please refer to Annex B: Detailed material flow analysis for details.

Step III: Refine the hotspot assessment using MFA and IO-LCA data

Update the hotspot assessment using new carbon and energy factors from the MFA.

Please refer to Table 16 for carbon and Table 17 for energy factors.

Forecast changes in embodied carbon and embodied energy until 2050.

This was done assuming a business-as-usual scenario where only the electricity grid decarbonises and there are no changes to process emissions or thermal energy or the BoQ composition of buildings. The electricity grid decarbonisation was based on the 2°C Innovate Scenario from the ClimateWorks Australia Decarbonisation Futures Technical Report and was modelled in the GaBi LCI database (Sphera, 2020). The electricity grid is modelled as being made up of 100% renewable energy in 2050.

In order to model the changes in the electricity grid mix, the breakdown of the source of both energy and emissions for each material had to be calculated (split into process, thermal energy, electricity and other). The electricity portion of the energy and emissions was then adjusted based on the change in the grid mix relative to the reference year.

Fill data gaps for building construction, and demolition using IO-LCA data.

Construction and demolition data was estimated based on Yu et al (2017) which used IO-LCA to calculate the carbon footprint of the construction sector. This top-down approach calculated the emissions from construction to be 8.3% of the construction industry's embodied carbon emissions, which is 1.8 Mt CO_2e and 1.3 Mt CO_2e for residential and non-residential buildings respectively when this percentage is applied to their total emissions for the studied year of 2013 (Yu, et al., 2017). These results were then scaled based on the gross Australian emissions in 2019 and 2050 relative to 2013 values. This assumes that construction emissions will decarbonise at the same rate as the rest of Australia.

Annex B: Detailed material flow analysis (confidential)

This project included detailed material flow analysis (MFA) of five different material categories: concrete, steel, aluminium, plasterboard, and clay bricks/tiles. Given the commercial sensitivity over some of this information, these material flow analyses are not part of the public report.

Annex C: Imported building materials

This annex considers the impact of imported building materials relative to the overall impacts of building materials used in Australia. The material masses, and GWP and PED factors from the MFA were used (see Annex B) as this provided the required split of imported and domestic production. Table 18 shows the imported materials share of mass, carbon emissions, and energy demand relative to the total for Australian buildings. It shows that imported steel, concrete, and aluminium makes up a significant percentage of the carbon emissions and PED of these materials. The import share of cement & concrete mass is low due to all imports being either clinker or cement which makes up a high percentage of concrete impacts. The import share of 'other materials' was difficult to quantify due to the number of materials and products in this category, so it was estimated to be 50%.

Table 18: Import share of mass/GWP/PED in building materials used in Australia

Material	Import share of mass	Import share of GWP	Import share of PED	Source for mass import share
Clay brick/tile	1%	4%	3%	(DFAT, 2020)
Steel	35%	50%	50%	(DISER, 2016)
Cement & concrete	6%	50%	35%	(CIF, 2020)
Plasterboard	1%	1%	1%	(DFAT, 2020)
Aluminium	47%	55%	45%	Industry
Other materials	50%	50%	50%	Estimated
All construction materials	**8%**	**47%**	**39%**	

Table 19 and Table 20 provide further detail on how the import shares are calculated. Table 19 shows the GWP and PED factors of imported materials. Due to difficulties with the splitting of steel products and production route, the steel emission factor for imported steel was the same as for produced steel in the MFA. Table 20 shows the mass, GWP and PED from imported materials and calculates the import share of GWP and PED relative to all materials used in Australian buildings.

Table 19: GWP and PED factors of imported materials

Material	Imported GWP EF ($t\ CO_2e/t$)	Imported PED factor (GJ/t)
Clay brick/tile	0.61	9.82
Steel	2.57	29.4
Cement & concrete	0.85	3.70
Plasterboard	0.40	5.66
Aluminium	18.0	166
Other materials	**0.42**	**8.13**

Table 20:Calculation of GWP and PED import shares

Material	Mass of imported material (Mt)	Total material GWP ($Mt\ CO_2e$)	GWP from imported material ($Mt\ CO_2e$)	GWP Import share (%)	PED (PJ)	PED from imported material (PJ)	PED Import share (%)
Clay brick/tile	0.06	0.84	0.04	4%	16.7	0.58	3%
Steel	1.11	5.71	2.85	50%	65.5	32.6	50%
Cement & concrete	2.45	4.21	2.08	50%	26.1	9.08	35%
Plasterboard	0.01	0.27	0.00	1%	6.1	0.05	1%
Aluminium	0.1	2.17	1.19	55%	24.2	11.0	45%
Other materials	0.63	0.54	0.27	50%	10.3	5.14	50%
All construction materials	**4.33**	**13.7**	**6.43**	**47%**	**149**	**58.4**	**39%**

Annex D: Carbon emissions of material production (confidential)

The information in this annex is confidential and not part of the public communication.

Annex E: Energy used in material production (confidential)

The information in this annex is confidential and not part of the public communication.

Annex F: Hybridisation of Process LCA

To estimate the embodied carbon and energy of Australian buildings using the Hybrid LCA methodology, the Process LCA values for the five main materials were hybridised using the EPiC database (Crawford, et al., 2019). This database takes process and input-output LCA data for a given material and for splits up the entire material supply chain into a series of individual steps (nodes), in a process called a Structural Path Analysis, or (SPA) (Steps 1-4 in Figure 21). Process LCA data comes from the Australian Life Cycle Inventory Database Initiative (AusLCI) (Grant, 2016).

Direct impacts are calculated by identifying the Process LCA nodes that correspond with these impacts, while indirect impacts are calculated by taking the IO LCA data and subtracting the nodes already covered by the Process LCA (Steps 5-6 in Figure 21).

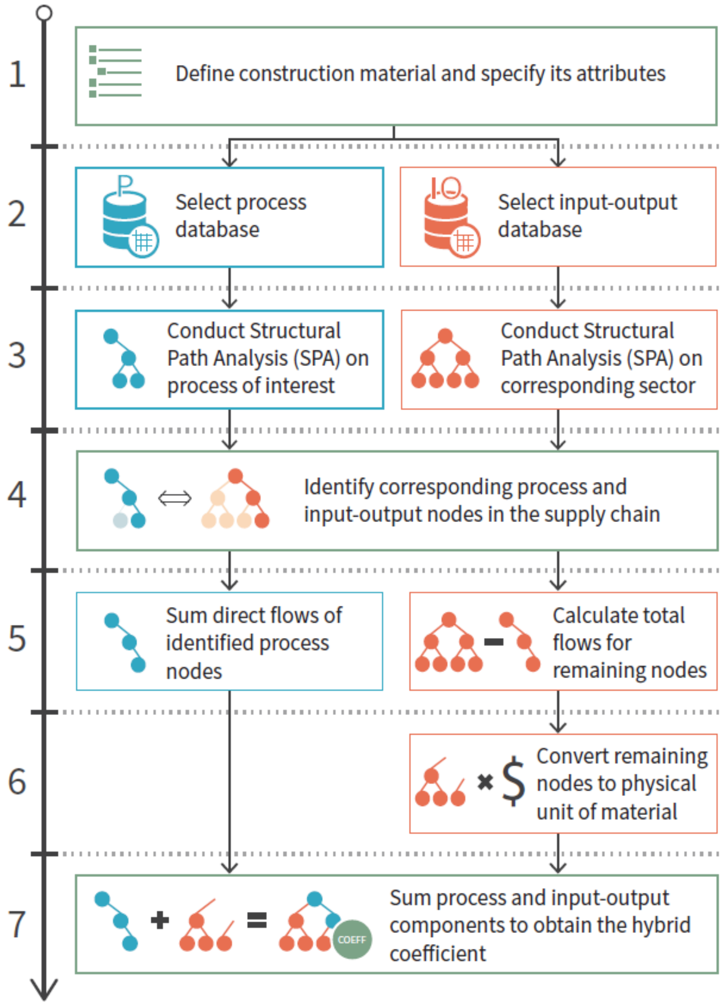

Figure 21: The hybrid approach used to create the EPiC database (Crawford, et al., 2019)

This study uses the Process LCA numbers calculated previously (Annex A: Detailed methodology) and applies factors in order to replicate the hybridisation of Process LCA data in EPiC. This approach assumes that the scope and system boundaries of the Process LCA data is similar for the values calculated in this report and those used in EPiC. The process data in EPiC (AusLCI) was not used for this report because it was last updated in 2016 (with the supplementary data from ecoinvent 2.2, which was released in 2010) and various sectors have experienced notable reductions in emissions intensities since then. This report also looks at industry average material emissions intensities, while the EPiC database provides data on a per product basis, so proxy products are used for the hybridisation, as shown in Table 21.

Figure 22 shows a graphical depiction of the removals and additions which occur in order to create the hybrid intensity found in EPiC. The steps involved in hybridising the Process LCA intensities found in this report were:

1. Subtract the removed pathways for the Process LCA (the two hatched segments in the process bar of Figure 22). This was done by calculating the percentage of the process pathways removed in EPiC and taking away the same percentage from the process intensity calculated in this report.
2. Add the IO pathways to the Process LCA (the white and shaded segments in the IO bar of Figure 22).

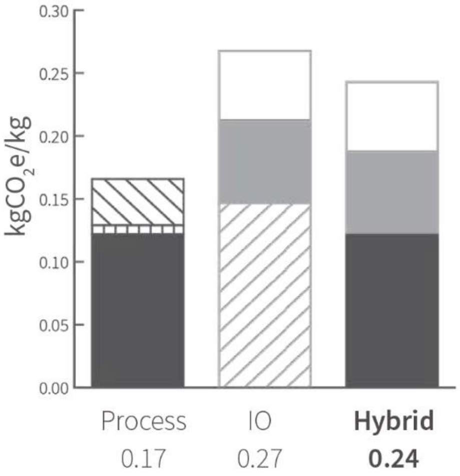

Figure 22: Coefficient breakdowns for concrete block GHG emissions (Crawford, et al., 2019)

Table 21 shows the process and Hybrid LCA GHG intensities for 2019 used in the report, with the 2050 hybrid intensities also being shown, based on the BAU scenario defined earlier in this report (the only improvement being the decarbonisation of the electricity grid).

The hybridisation factor adjustments for Portland cement were used for the concrete hybridisation, due to the EPiC hybrid concrete intensity being the same as the Process LCA intensity, which differs from Teh et al. (2017). Teh et al. considers the issue of hybridisation of cement and concrete specifically. It concludes that using Hybrid LCA increased the GHG emissions intensity by 22% for 25 MPa Ordinary Portland Cement (OPC) concrete and by 11-50% for blended cement-based concrete compared to the Process LCA values found in AusLCI (Grant, AusLCI Database Manual v1.26, 2016). The ICM Database (Wiedmann, et al., 2019) broadly aligns with this, showing an increase of between 10-20% between the hybrid and Process LCA emissions intensity, depending on the concrete mix. It is important to again state that there are inherit uncertainties with Process LCA and these are exacerbated with IO LCA and therefore Hybrid LCA.

Table 21: Process and Hybrid LCA GHG intensities used in analysis

Material type	Hybridisation data	Process LCA 2019	Hybrid LCA 2019	Hybrid LCA 2050
Aluminium	EPiC database: Aluminium bar	14.92	20.78	5.47
Clay brick/tile	EPiC database: Clay brick	0.20	0.27	0.26
Concrete	EPiC database: Portland Cement	0.12	0.16	0.15
Plasterboard	EPiC database: Plasterboard - 10 mm	0.29	0.70	0.52
Steel – flat products	EPiC database: Hot rolled structural steel	2.83	3.20	2.85
Steel – long products	EPiC database: Hot rolled structural steel	1.64	2.19	1.16

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