

Embodied water in construction

Robert Crawford



Cover image. Wunggurrwil Dhurrung Aboriginal Community Centre by Gresley Abas Architects in collaboration with Gregory Burgess Architects (Image: Peter Bennetts).

Abstract

Water is necessary for human survival, but it is also a key ingredient in the production of construction projects. Increasing water scarcity means that we must reduce water use and improve water efficiencies across all human activities, including within the construction industry. While the operational use of our buildings accounts for 12% of global water use, embodied water now represents most of the water used across the building life cycle. This note explains the concept of embodied water in the context of construction and the different methods that can be used to quantify the water embodied in construction projects. It provides embodied water data for common construction materials in Australia and uses a residential case study to demonstrate the steps involved in calculating embodied water and identifying strategies for its reduction.

What is embodied water?

Embodied water is the amount of water needed to produce, maintain, and dispose of a product. This is also known as a product's water footprint. It includes the water needed across all stages of production, from growing and harvesting, or mining raw materials, transporting these materials, processing them, manufacturing products or components, and assembling the final product. It also includes the water associated with the repair, replacement, or refurbishment of products throughout their life, as well as the water needed for end-of-life processes, such as disassembly, transport and disposal. See Project life cycle stages for an overview of these associated stages and activities in the context of a building.

Background

Australia is the driest inhabited continent on Earth. Our rainfall is highly variable and only 9% of it flows into rivers (Green and Moggridge 2021). Climate change is further exacerbating this rainfall variability, as well as increasing the frequency and severity of droughts and floods throughout the country. This will continue to influence an already vulnerable water supply, in a country that is in the top 10 water consumers per capita in the world (OECD 2022).

It can be argued that water is never consumed, rather, it evaporates and falls later elsewhere as precipitation. However, once evaporated or removed from the system, it can be considered consumed as we cannot rely on it falling as rain in the same upstream catchment. A litre of water in a pipe is much more available to us than a cloud hovering several kilometres somewhere above the ocean.

Australia's water consumption

The total water distributed in Australia for consumptive use is approximately 9000 GL per annum (ABS 2021). Figure 1 shows the proportion of water consumption by sector. Agriculture accounts for the highest consumption per year, at 50%. Other industries, including electricity production and mining account for another 30%. Households account for approximately 20% of distributed water consumption, which is used for building operation and maintenance as well as for occupant activities.

To help maintain sustainable water access for current and future generations, designers must understand the effects of design and construction decisions on water demand. Consideration must be given to the effect of design decisions on whole-of-life water use,

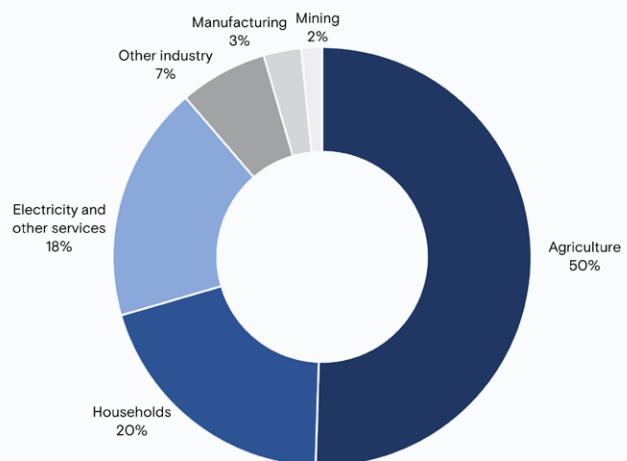


Figure 1. Distributed water consumption by sector, Australia 2019-20. Source data: ABS (2021).

or the water used across the entire life of a building. This aligns with Australia's National Standard of Competency for Architects (NSCA) (AACA 2021), by focusing on designing projects that minimise the use of natural resources, use water sustainably, and utilise information from life cycle assessments to inform these decisions.

Construction water consumption

Construction projects use water during their construction and throughout their use.

During the construction process, water is used for activities such as mixing concrete, drilling, piling, dust suppression, cleaning and demolition. This is known as the direct water of construction, or Scope 1, as often referred to in greenhouse gas (GHG) emissions accounting.

During the use of a building, water is used for building operation, such as in cooling systems, but also by occupants for cooking, showering/bathing, washing and garden watering.

Over recent decades considerable effort has been placed on reducing building operational water use, not least due to the Millennium drought that occurred from 1997 to 2010. Significant reduction in building operational water use has been achieved through behavioural change, regulations, building certification schemes, water restrictions and technology/water efficiency improvements. Less, but not insignificant effort has also been made to reduce construction-related water use. However, an increasing population has offset much of these savings.

Compounding this issue is the growing awareness that water use during the construction process and operation of buildings is only a small proportion of the water used throughout their life. In addition to these water demands, buildings and other construction assets are responsible for water consumed across other sectors of the economy. The products and services used in construction projects demand water themselves, which is embodied in the construction projects in which they are used. This water is a major part of the indirect water of construction, which includes Scope 2 water inputs, covering the water associated with supplying the direct water used on site, including losses, and Scope 3 water inputs, covering all other upstream water inputs across the construction supply chain.

Project life cycle stages

The embodied water of a construction project, including water used across the various stages of the project life cycle, is typically categorised according to International Standard EN 15643 (CEN 2021) (Figure 2), and calculated according to International Standard EN 15978 (CEN 2011). Water is used directly in construction activities (A5). However, indirect water use, ie water consumed in other sectors, including agriculture (eg fibres for carpets and textiles), and industry (eg steel, concrete and electricity), for products and services used in construction, represents a much larger proportion of a construction project’s embodied water. The total water intensity (embodied water) of Australia’s construction sectors ranges from 5-10 L per dollar of construction activity (Crawford et al. 2019).

Measuring embodied water

Measuring the embodied water of a construction project is a complex task. Every project is a combination of many materials, each with a production history and a contribution to the project’s embodied water. Embodied water can also vary for the same type of product because the source of materials and the manufacturing process can vary between manufacturers.

Life cycle assessment

Embodied water is often calculated using life cycle assessment (LCA). LCA is a tool used to evaluate the environmental effects associated with a product or service, across its entire life cycle, encompassing all stages depicted in Figure 2. It considers a range of environmental indicators and the guidelines and requirements for conducting an LCA are provided by the International Organization for Standardization (ISO) in ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b). Data gathered within an LCA can be used to identify low embodied water products as well as identifying water demand hotspots within specific production processes or projects.

Within this LCA framework, there are several methods available for quantifying embodied water: process analysis, input-output analysis and hybrid analysis, as discussed below. The accuracy and completeness of any embodied water value depends on the method chosen. This means that some caution is required when using embodied water values from different sources to ensure that the values are comparable.

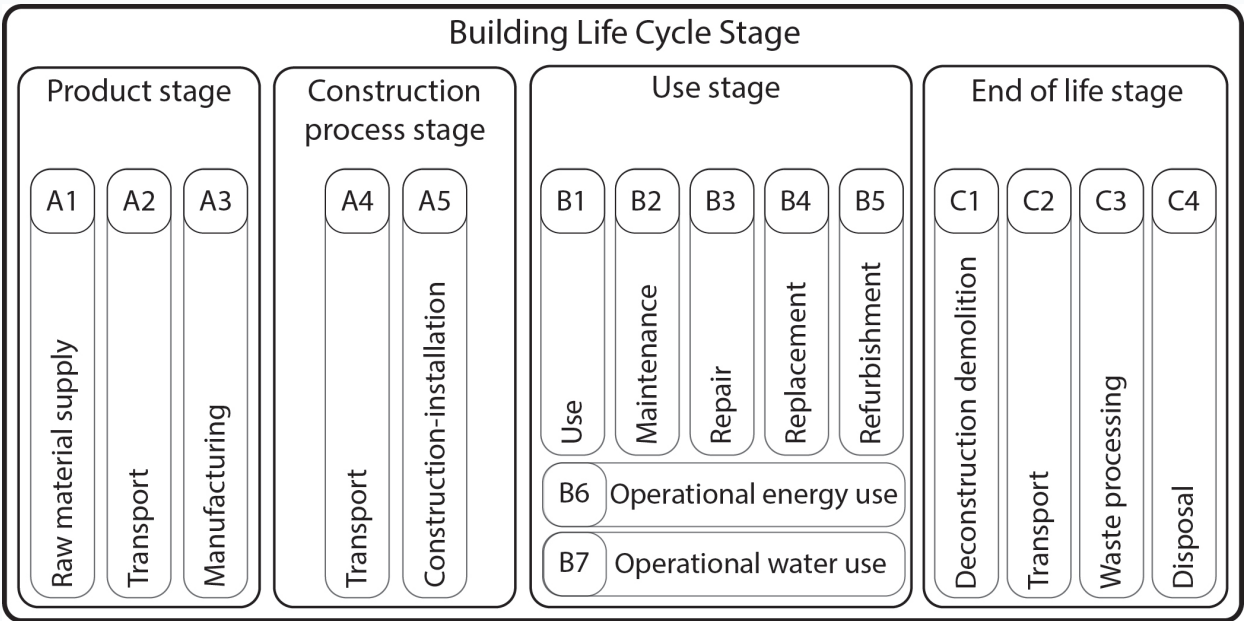


Figure 2. Building life cycle stages. Source: Adapted by author from CEN (2021).

Process analysis

In a process analysis, embodied water is determined by collecting data directly from the source of production or use (eg mine, factory or construction site). This data may include water usage, raw material quantities, costs or equipment specifications. The data is then converted to a total embodied water value for a defined functional unit (eg cubic metre or tonne of material, square metre of a building, or a whole building). This approach is the most widely used as the data collected is highly product specific. However, a key limitation of this approach is the time and cost involved in collecting the data. This means that many of the processes associated with a product are not included, or generic data is used.

Process data may vary widely between sources, even for similar materials, due to different manufacturing processes, production efficiencies and transport distances. Research has shown that on average, this approach underestimates the embodied water of construction materials by 58% (Crawford et al. 2022). The most common exclusions are minor raw material inputs, water used higher up in the supply chain, and water use associated with providing supporting services to the companies involved in production and transportation of materials (such as finance, marketing and research and development). Process analysis is best used for Scope 1 and Scope 2 water calculations.

Process-based embodied water data is available from a range of sources, including the Australian National Life Cycle Inventory Database (AusLCI) (ALCAS 2019), OzLCI (The Evah Institute 2019) and the majority of industry Environmental Product Declarations (EPDs) according to ISO 14025 and EN 15804.

Input-output analysis

An input-output analysis combines sector-based economic data with data from national water accounts to create environmentally extended input-output (EEIO) data. The use of data covering all activities within the economy enables a much more comprehensive coverage of the processes and other inputs needed in the production of materials, including their embodied water. The typical exclusions of a process analysis, such as water associated with producing minor raw materials, and providing supporting services to the companies involved in production and transportation of materials, are included. While input-output analysis

provides a more comprehensive coverage of the total embodied water of a product compared to a process analysis, the data relates to the average product from each economic sector. Therefore, it is difficult to reliably distinguish between the embodied water of materials or other products within the same sector or compare between products from different sectors. The generic nature of EEIO data can also affect the reliability of embodied water values when used to represent specific products. However, EEIO data is particularly useful for Scope 3 water calculations that are extremely difficult to calculate any other way.

In Australia, the Industrial Ecology Virtual Laboratory (IELab) provides data and tools for modelling embodied water using input-output analysis (Baynes et al. 2018).

Hybrid analysis

A hybrid analysis combines process- and input-output analysis to maximise the specific benefits of each approach. Several different hybridisation techniques are available (Crawford et al. 2018), with process data integrated into or supplemented by input-output data. Embodied water calculations based on this approach benefit from the reliability of data on specific materials or products afforded by a process analysis, and the ability to fill the data gaps inherent in a process analysis with the use of input-output data. This improves consistency and comparability between products as all data is based on a much more complete and consistent coverage of production processes.

The reliability of hybrid embodied water data for a product can vary based on the proportion of input-output data used. However, studies have shown that the benefits of this approach outweigh its limitations, especially where availability or coverage of process data is limited (Agez et al. 2020; Majeau-Bettez et al. 2011). Hybrid data also has the benefit of being highly disaggregated, enabling detailed analysis of a product's production processes, and related embodied water inputs. This can be useful for identifying embodied water hotspots, and guiding selection decisions or embodied water reduction efforts across the supply chain.

In Australia, the EPiC Database provides hybrid embodied water data for many common construction materials (see Figure 3 for an example of the data provided).

kg

Hot rolled structural steel

Steel is a ferrous metal and is an alloy of iron and carbon, as well as potential other elements. It has a very high tensile strength. Steel has been used in the construction industry for over a century.

The core material for making steel is iron, which is found in iron ore. Iron is extracted from iron ore in blast furnaces through the smelting process, while controlling for the content of carbon. The molten steel is usually further processed before being cast for its final use.

Steel is commonly used in the construction industry, mainly as a structural material. Hot rolled structural steel is used to produce a range of structural elements, such as reinforcement bars, I-beams and railroad tracks.

Category Metals

Type Steel

Functional unit kg

Specific heat 490 J/(kg·K)

Density 7 850 kg/m³

Common uses

Reinforcement bars, beams, railroad tracks

Process name

Steel hot rolled (custom)

Input-output sector

Structural Metal Product Manufacturing

Further information

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Material variations

Hot rolled structural steel

Steel reinforcement bar - 6 mm dia.

Steel reinforcement bar - 8 mm dia.

Steel reinforcement bar - 12 mm dia.

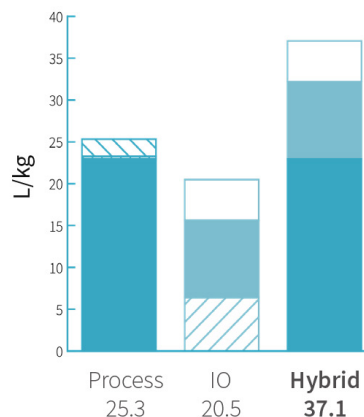
Unit	Energy (MJ/unit)	Water (L/unit)	GHG emissions (kgCO ₂ e/unit)
kg	38.8	37.1	2.9
m	8.6	8.2	0.6
m	15.3	14.6	1.1
m	34.5	32.9	2.6

TOP THREE INPUTS

44.8% Steel, converter, low-alloyed, at plant/RER U/ AusSD U

17.1% Hot rolling, steel/RER U/ AusSD U

3.8% Basic Non-Ferrous Metal Manufacturing



WATER

37.1
L/kg

Figure 3. Edited extract view of material data for hot rolled structural steel from the EPiC Database. Source: Crawford et al. (2019).

Environmental Product Declarations (EPDs)

Embodied water values for specific products can be found within a manufacturer's environmental product declaration (EPD). EPDs disclose a range of environmental data associated with a product, and typically cover stages A1-A3 (as per Figure 2). Embodied water values are categorised under the 'Use of net fresh water' impact category and measured in cubic metres of water per unit of product. EPDs for construction products are generally produced in accordance with EN 15804 (CEN 2019), with process analysis typically used for data collection. The two main sources for EPDs for Australian products are EPD Australasia (EPD Australasia 2022) and Global GreenTag (GGTI 2022). The relevance of EPDs to specific products is one of their key advantages over more generic data, but EPDs do suffer from inconsistency, limited transparency and data quality issues (Moré et al. 2022; Waldman 2020), which can limit their usefulness for comparison between products and their reliability in identifying water demand hotspots.

Source of data for each life cycle stage

The source of data for measuring embodied water across each of the life cycle stages of a building will often vary. The typical source of data for each of the main life cycle stages includes:

- **Product stage (A1-A3)** – This stage relates to the production of materials and products used within a building project, including raw material supply, transport and manufacturing processes. Embodied water data is often sourced from life cycle inventory (LCI) databases or EPDs that provide coefficients for specific building materials and products, based on either of the three methods described above.
- **Construction process stage (A4-A5)** – This stage includes the transport of products from factory gate to final construction site, removal of waste materials, as well as the on-site construction processes. Limited data is available on the embodied water associated with this stage. Total water intensities of the construction sectors based on input-output analysis (eg Crawford 2022a, 2022c), combined with the project cost can be used to estimate embodied water for this stage. Process data is also available for the water associated with different transport modes.
- **Use stage (B2-B5)** – This stage includes the maintenance, repair, replacement and refurbishment of products used for the initial construction. Associated embodied water is usually measured using the same product-specific inventory data/coefficients as for the product stage. Data or assumptions on the frequency of these activities is needed to determine total embodied water demand over the life of a project (see Rauf (2016:156) for building material service life values).
- **End-of-life stage (C1-C4)** – This stage involves deconstruction or demolition, transport, processing and disposal of products and materials at the end of the project's physical life. This stage is a small contributor to the life cycle embodied water of a construction project. As such, limited data exists on this stage. Process or input-output data can be used to measure the embodied water for the individual activities involved, using transport distances, material quantities or input-output intensities of specific economic activities (such as waste processing or transport).

Types of water

This isn't whether the water is flavoured, sparkling or still, but instead refers to the source and quality of the water.

Green water is precipitation that is stored in the ground and taken up by plants. Blue water is surface or groundwater and is used to produce products, in buildings, and as drinking water. Grey water is wastewater discharged from an activity, such as showering, washing or a production process.

While standards exist for measuring the embodied water of a product according to these different water types (Hoekstra et al. 2011), in reality it can be difficult to find data that differentiates between the different types of water.

Embodied water coefficients

Embodied water coefficients for construction materials can be used to measure the embodied water associated with stages A1-A3 and B2-B5 of the project life cycle (as per Figure 2). Typical embodied water coefficients for some building materials are given in Table 1. A more extensive list is available as part of the EPiC Database (Crawford et al. 2019).

Materials should usually not be compared based on these values alone as this is not an appropriate basis for decision making. A tonne of timber and a tonne of steel are not interchangeable in the context of a building or building element. Instead, the embodied water of materials should be compared in relation to the amount needed for a particular building element or at the whole project level.

Material	Unit	Embodied water (L/unit)
Aluminium - extruded	kg	182
Aluminium foil insulation	m ²	33.8
Autoclaved aerated concrete (AAC)	kg	8.4
Carpet - nylon	m ²	1149
Cellulose insulation	kg	20.5
Ceramic tile	kg	15.2
Clay brick	kg	1.8
Concrete block	kg	3.7
Concrete 25 MPa	m ³	4196
Concrete 25 MPa - 30% fly ash	m ³	4028
Cross laminated timber (CLT)	m ³	8608
Fibre cement sheet	kg	19.8
Glass - flat	kg	32.2
Glass - toughened	kg	30.2
Glasswool insulation	kg	40.7
Hardwood - air dried	m ³	19,110
Hardwood - kiln dried	m ³	25,332
Laminated veneer lumber (LVL)	m ³	18,025
Melamine coated MDF board 16 mm	m ²	283
Paint - solvent-based	m ²	14.7
Paint - water-based	m ²	16.1
Plasterboard 10 mm	m ²	85.6
Plywood	m ³	23,083
Polystyrene (EPS)	kg	841
Softwood - air dried	m ³	13,091
Softwood - kiln dried	m ³	13,181
Steel - hollow section	kg	45.2
Steel - structural	kg	37.1
Steel - corrugated sheet	kg	73.4

Table 1. Embodied water values for a selection of construction materials. Source: Crawford et al. (2019).

Embodied water of common building assemblies

Comparing embodied water values at the assembly level can be a useful way of informing design decisions, as whole assemblies are generally interchangeable. This section provides embodied water values for a range of typical residential building assemblies (Table 2). Further details of the assemblies can be found in Crawford (2022b).

A life cycle approach

The choice of building materials and components should aim to reduce water use over a building's life cycle. This means considering the embodied water of the building, both for initial construction and ongoing repair, replacement, and refurbishment, as well as its operational water, for use in cooling systems, bathrooms, laundries, kitchens and gardens.

An increase in embodied water may be warranted if it leads to greater savings in operational water.

For example, installation of rainwater tanks or greywater recycling systems will increase the embodied water of a project but will generally lead to considerably greater savings in a building's operational water use.

Embodied water for assembled floors	Embodied water (L/m ²)
Elevated timber floor	2333
110 mm concrete slab-on-ground, raft	1504
110 mm concrete slab-on-ground, waffle pod	5762
Embodied water for assembled walls	Embodied water (L/m ²)
Brick veneer wall, timber frame	890
Brick veneer wall, steel frame	1096
Cavity clay brick wall	1194
Cavity concrete block wall	1647
Concrete block veneer wall, timber frame	1143
Corrugated steel wall, timber frame	714
Hardwood weatherboard wall, steel frame	2093
Hardwood weatherboard wall, timber frame	1888
Polystyrene wall, timber frame	1365
Reverse brick veneer wall, timber frame	1320
Single skin AAC block wall, plasterboard lining	2369
Embodied water for assembled roofs	Embodied water (L/m ²)
Concrete tile pitched roof, timber frame, plasterboard ceiling	814
Terracotta tile pitched roof, timber frame, plasterboard ceiling	749
Corrugated steel sheet roof, timber frame, plasterboard ceiling	861
Corrugated steel sheet roof, steel frame, plasterboard ceiling	1083

Table 2. Embodied water values for a selection of residential building assemblies.

Case study

This section shows a breakdown of the life cycle embodied water for a detached house, with results shown in Figures 5 and 6. It provides an example of how embodied water data can be used to quantify the embodied water of a construction project, and how this information can be used to identify opportunities for reducing embodied water. The case study is a single storey detached brick veneer house of 202 m² (Figure 4). It comprises three bedrooms, two bathrooms, laundry, open plan area including living, kitchen and dining, formal lounge, and a garage. The house is designed to meet the minimum energy efficiency standards for Melbourne at the time of writing, including minimum thermal performance requirements. It is constructed

on a reinforced concrete slab, with timber framed walls and roof, concrete tile roof cladding, single glazed timber windows, and carpet and ceramic tile floor coverings.

Product stage (A1-A3)

Material quantities for the house were derived from architectural drawings. These can also easily be extracted from digital models, assuming each material has been specified. Each element of the house must be separated into individual materials for which an embodied water coefficient is available. Material quantities were multiplied by their respective embodied water coefficient from the EPiC Database. The total embodied water of the house for this stage was 2527 kL (12.5 kL/m²). This is equivalent to more than five times the total volume of the house.

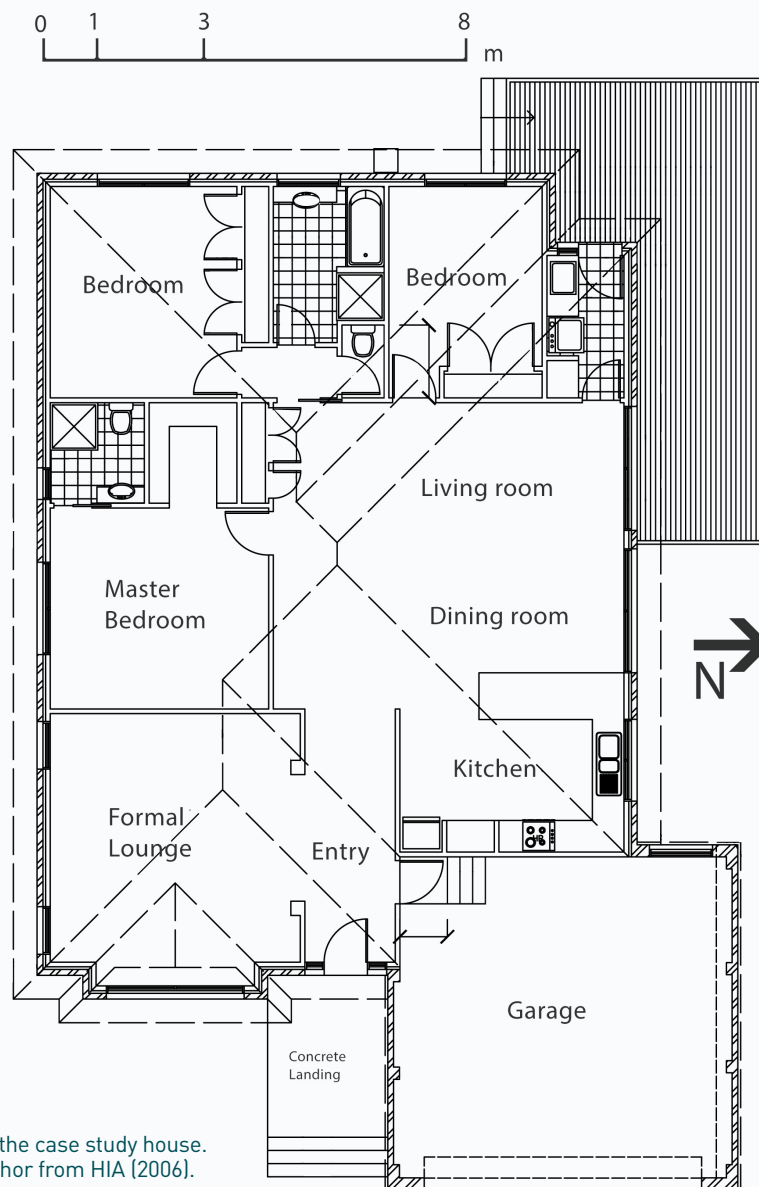


Figure 4. Floor plan of the case study house.
Source: Adapted by author from HIA (2006).

Construction process stage (A4-A5)

Due to limited process data for this stage, and to ensure all Scope 1 to 3 water inputs are included, input-output data has been used to determine the associated embodied water for transport and construction activities for the initial construction of the house. The sum of direct water requirements of the four transport sectors required by the Australian Residential Building Construction sector (0.119 L/\$) was multiplied by the construction cost of the house (\$214,257 in 2015 terms) to give a total embodied water value of 25.5 kL for A4. The direct water intensity of the Australian Residential Building Construction sector, of 1.56 L/\$, was multiplied by the total construction cost of the house to give a total embodied water demand of 335 kL for A5. While the use of input-output data maximises the inclusion of water demands for this stage, being national average data, it's much less reliable than process data specific to the house would be.

Use stage (B2-B5)

Embodied water associated with maintenance, repair, replacement and refurbishment, also known as recurrent embodied water, was determined based on values for material service life from Rauf (2016), and assumed frequency of maintenance and repair. Quantities of materials required for this stage over a 50 year period, the average life of a building of this type, were multiplied by embodied water coefficients from the EPiC Database. Total embodied water of the house for this stage was found to be 1691 kL (8.4 kL/m²). Embodied water associated with transport and construction activities for this stage were calculated

as per the construction process stage above, resulting in an additional 17.3 kL and 249 kL of embodied water, respectively.

Due to a lack of data and issues with predicting embodied water of activities many decades into the future being inherently problematic, an embodied water value for the end-of-life stage was not calculated.

The remaining embodied water not shown in Figures 5 and 6 is for minor materials (eg fixings, wiring) as well as the services required to support the construction activities (eg banking, insurance, communications). These additional water demands account for 38% of the total life cycle embodied water of the house (1858 kL).

Reducing embodied water

In the case study house discussed above, concrete and timber products represent the largest contributors to the initial embodied water (see Figure 6). The water associated with the construction process is also significant. From a life cycle perspective, frequent replacement of internal finishes, including paint and carpet, results in these elements accounting for the largest proportion of embodied water (see Figure 5).

By calculating the embodied water of a project at the material and element level, water hotspots can be easily identified, and strategies can be prioritised for reducing embodied water across the project life cycle.

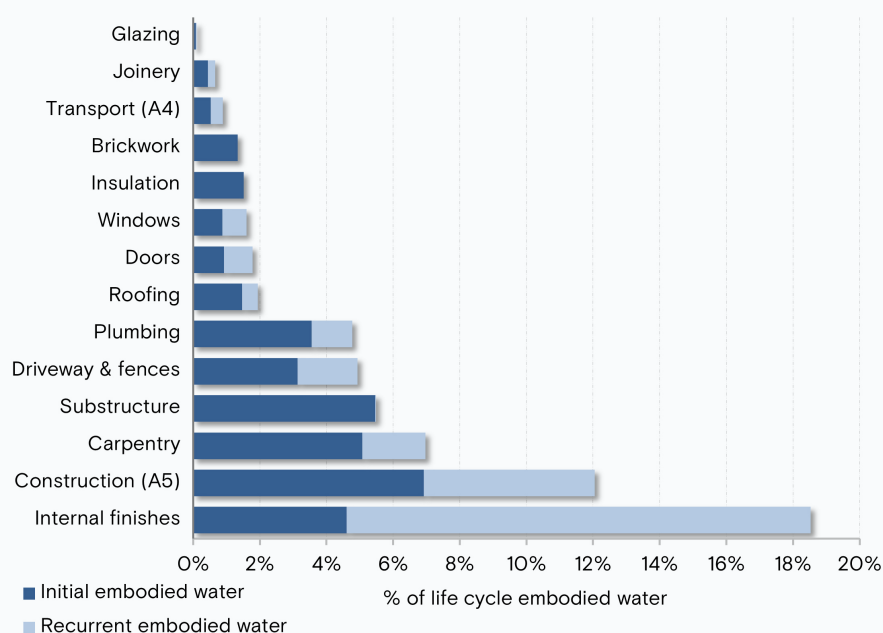


Figure 5. Embodied water of the house over 50 years, by element. Note: Totals do not sum due to the exclusion of minor materials and non-material inputs.

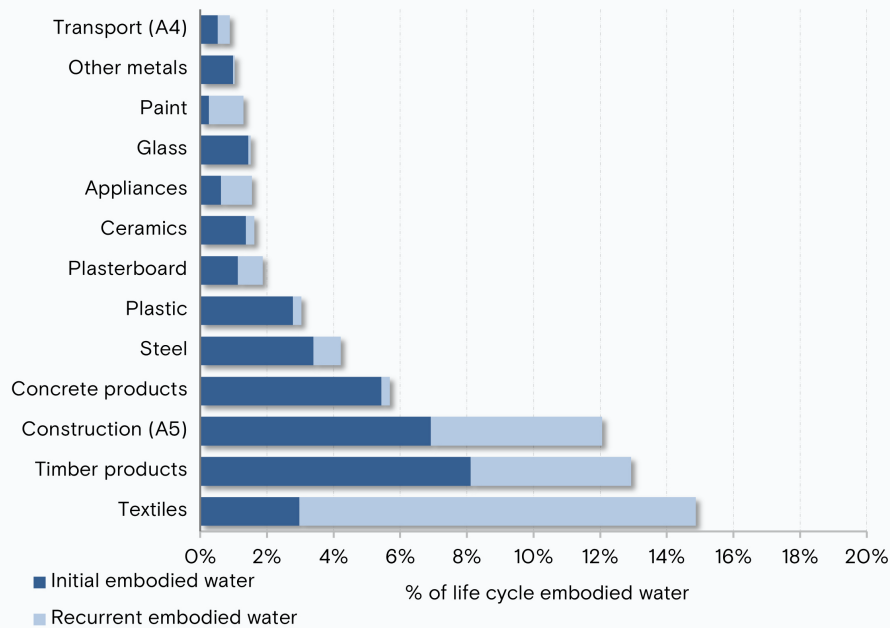


Figure 6. Embodied water of the house over 50 years, by material. Note: Totals do not sum due to the exclusion of minor materials and non-material inputs.

This case study shows that while opportunities exist for reducing the initial embodied water of a project (such as reducing the quantity of materials used or considering alternatives to concrete and timber products), it is important to also consider recurrent embodied water as additional opportunities for achieving substantial embodied water reductions may arise. In this case, removing or substituting the carpet or paint with alternative or longer-lasting products may be viable options.

Strategies

Many of the strategies for optimising embodied water, apply also to improving the broad environmental performance of construction projects. These include:

- Dematerialise - avoid the use of materials where possible, by designing out redundancy, and rationalising building area and elements.
- Use low embodied water materials and products, but consider life cycle implications.
- Source materials and products from manufacturers that have water-efficient production practices, prioritising local manufacturers.
- Specify materials and products that have been used previously, have high recycled content, and have high reuse or recyclability potential.
- Specify durable, long-lasting materials and products.
- Avoid short-lived materials and products that require regular replacement or maintenance.

- Reduce construction waste, using standardised designs and components to provide an immediate embodied water saving.
- Design for adaptability and disassembly to encourage maximum use of materials and products.

Reuse and recycling

Reuse of construction materials and products can save a substantial amount of the water needed for producing virgin materials. Often, only a small amount of water is needed for the 'making good' of previously used materials.

Embodied water savings from the recycling of materials is often less than for reuse, with the embodied water needed for reprocessing varying considerably between materials.

While the specification of materials that have the potential for reuse or recycling is strongly encouraged, given the large uncertainty associated with the construction project end-of-life stage (timing, waste diversion and disposal practices), projects utilising materials and products with this potential for reuse and recycling should not have their embodied water discounted. However, future projects in which these materials and products are used will benefit from having had a fraction of their embodied water allocated to a previous project.

Conclusion

This note has introduced the concept of embodied water and demonstrated its significance in the context of construction projects using a case study. The water embodied in the construction process as well as high volume and frequently replaced materials is significant. Consideration of water use across the entire project life cycle is critical, also ensuring that in the optimisation of embodied water, operational water use is not unnecessarily increased. Likewise, when designing for optimising operational water use, the embodied water should be considered, to ensure the net effect of design decisions is positive, and that ongoing life cycle water savings are achieved. The data provided in this note enables designers and the construction industry to evaluate project decisions from a holistic perspective and better understand the whole-of-life water implications of these decisions.

It is also critical that designers consider other environmental impacts associated with design decisions. There is considerable alignment between data sources, assessment methods and reduction strategies between GHG emissions, water and other environmental concerns. However, while knowledge gained from other assessments, such as those focussed on GHG emissions or energy, can provide insight into important areas for reducing embodied water demand across the construction supply chain, it has been shown that sometimes key hotspots can change considerably depending on the environment flow or impact being considered.

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