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The effect of data age on the assessment of a building's embodied energy

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Abstract: Data used to quantify the embodied energy of a building, known as life cycle inventory (LCI) data, varies widely in temporal relevance. The energy associated with construction material production and building construction changes regularly due to improvements in manufacturing and construction processes, and energy mix and intensity. Older LCI data may not be representative of the current industry. Due to the time and costs involved in compiling LCIs, many studies rely on outdated data, yet no studies have considered the effect of data age on the analysis of a building's embodied energy. A reliable embodied energy value is critical to ensure energy reduction efforts have been effective. This study compares the life cycle embodied energy of a typical Australian house using data from a 2010 and 2019 LCI database, compiled using an identical technique. The 2019 data lead to a 27.7% decrease in life cycle embodied energy. This reveals that the age of data may have a considerable effect on the value of a building's embodied energy, indicating that LCI data should be regularly updated to respond to changes in manufacturing and construction processes as well as energy mix and intensity.

Keywords: Embodied energy; Life cycle assessment; Life cycle inventory; Buildings; Data age.

1. Introduction

Our built environment, the buildings and infrastructure of our towns and cities, contribute more than any other single sector to global energy use (36%) and greenhouse gas (GHG) emissions (39%) (IEA, 2019). Energy use and GHG emissions have continued to increase, and in 2018, they reached record highs, up 7% from 2010 levels, despite global efforts to reduce them. Improvements to building envelopes and building energy systems have offset some of the growth in building-related energy demand and GHG emissions in recent years. However, they have continued to rise due to increasing demand for electricity. Global population growth and rising living standards will put further pressure on energy demand and GHG emissions, fuelled largely by an expected threefold increase in air conditioning use by 2050 (IEA, 2018). Buildings thus represent one of the most important and cost-effective options for mitigating global energy demand and GHG emissions (IPCC, 2014).

Historically, reducing energy demand associated with heating and cooling, hot water, cooking and appliance use has been the focus of global building-related energy and GHG emissions reduction efforts.

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However, embodied energy associated with the manufacture of building materials accounts for around a third of all building-related GHG emissions (Adams *et al.*, 2019) and up to 97% of a building's total life cycle GHG emissions (Chastas and Theodosiou, 2016). As buildings head towards net-zero operational energy and GHG emissions, their embodied energy and emissions will become even more significant. In response to this, the World Green Building Council (Adams *et al.*, 2019) has called for a 40% reduction in construction-related embodied GHG emissions by 2030 and net zero embodied GHG emissions by 2050.

A detailed, well-informed understanding of the embodied energy implications of a building project, especially during the design phase, based on reliable data and a comprehensive analysis, is crucial in our efforts to reduce a building's life cycle embodied energy demand. This understanding is usually informed with the use of software-based life cycle assessment tools or using simplified calculations based on embodied energy coefficients of construction materials. However, the quality of the data used, particularly in terms of geographic and temporal relevance, can vary greatly. Some of the key reasons why the embodied energy associated with the production of construction materials may vary include differences in manufacturing processes, variation in production efficiencies, quantity and treatment of waste, regional differences in fuel mix, and transport distances. These differences can be further exacerbated with the passing of time. This means that the older the data, the less likely it is to be representative of the energy associated with current material production. Despite this, many decision-makers continue to rely on data from sources that are several decades old (for example, Lawson (1996) and Alcorn (2003)).

There have been no studies that have looked at the effect of the use of this older data on the value of a building's embodied energy and the subsequent implications for building design and construction decision-making. Even the international standard for conducting life cycle assessments (International Organization for Standardization (ISO), 2006) places little emphasis on data age. The only reference to data age within this standard is in the specification of data quality requirements. The requirement here is that if 'a study is intended to be used for comparative assertions intended to be disclosed to the public', the age of data must be addressed. The standard does not however further define how this is to be addressed, but leaves this decision to the discretion of the individual. Therefore, the aim of this study was to assess the effect of LCI data age on the embodied energy of a building.

2. Research approach

This section outlines the approach used to assess the effect of LCI data age on a building's embodied energy. This includes a comparison of LCI data from 2010 and 2019 databases as well as a comparison at the material, element and whole building level for a case study house.

2.1. Life cycle inventory databases

To minimise the effect of different methods for compiling LCI data on the findings, and restrict the comparison to the age of the data alone, LCI data compiled using an identical approach was compared. In order to maximise the completeness of an LCI, a hybrid approach is recommended (Crawford, 2011; Majeau-Bettez *et al.*, 2011). Therefore, this study focuses on a comparison of hybrid LCI data. Several methods can be used to produce hybrid LCIs, as reviewed by Crawford *et al.* (2018). This study compares LCI data compiled using the Path Exchange method for hybridisation. This technique was first developed by Treloar (1998) and formalised by Lenzen and Crawford (2009). The two databases compared were released in 2010 and 2019 and contain LCI data for materials in the form of coefficients, providing embodied energy data in GJ per unit of material for a range of materials. The main difference between databases is that the 2010 version uses LCI data from the mid-1990s, while the 2019 version relies on LCI data from the last decade. A summary of the key attributes of both databases is provided in Table 1.

Table 1: Key attributes of the hybrid life cycle inventory databases.

Database name	Database of embodied energy and water values for materials	Environmental Performance in Construction (EPiC) Database
Year of release	2010	2019
Reference	Crawford and Treloar (2010)	Crawford *et al.* (2019)
No. of materials	58	284
Hybridisation technique	Path exchange hybrid analysis (manual)	Path exchange hybrid analysis (semi-automated, based on Stephan *et al.* (2018))
Input-output data	Based on 1996-97 input-output tables (ABS, 2001), 106 sectors + fixed capital	Based on 2014-15 input-output tables (ABS, 2017a), 114 sectors + fixed capital
Process data	Based on AusLCI data (ALCAS, 2011) and others from the 1990s	Based on AusLCI data (ALCAS, 2011) with ecoinvent2.2 (2010) shadow database (4,531 processes, 2015 version)
Flows (units)	Energy (GJ per kg/m^2/m^3/no.) Water (kL per kg/m^2/m^3/no.)	Energy (GJ per kg/m^2/m^3/no.) Water (kL per kg/m^2/m^3/no.) GHG emissions (kgCO$_2$-e per kg/m^2/m^3/no.)

2.2. Comparison of 2010 and 2019 hybrid coefficients

Comparison of material embodied energy coefficients from the 2010 and 2019 databases was performed in order to establish key differences. As the 2019 database contains a larger number of materials, only a selection of common construction materials contained within the 2010 database were compared. The change in coefficient values between the two databases was determined.

2.3. Effect of data age on building embodied energy

To determine the effect of the age of LCI data on the embodied energy of a building, the embodied energy of a case study house (see Section 2.4) was quantified. The life cycle energy of the case study house was quantified using the coefficients contained within the 2010 and 2019 databases. A bill of material quantities (BoQ) was extracted from construction documentation, including drawings, specifications and schedules. Each material quantity (Q_m) was then multiplied by its respective 2010 and 2019 hybrid embodied energy coefficient (EEC_m). In order to account for on-site construction wastage and thus the need to order more materials than will end up in the project, a wastage factor (W_m) was applied (see Wainwright and Wood (1981); CSIRO (1994) for a list of common wastage factors). The resultant values provide the embodied energy for each material within the house, which when summed provide the material-based total embodied energy (EE_h) for the house, in GJ.

In a hybrid analysis, any minor material or non-material-related energy (e.g. materials not included in the BoQ, direct energy associated with on-site activities or site-support activities such as financing, machinery and equipment) are accounted for using pure input-output data. This is a unique characteristic of the Path Exchange hybrid approach and accounts for processes and related energy demand not typically included in similar studies. This energy, for the processes referred to as *other items*, is determined by subtracting the total input-output-based flows associated with the material production processes for the materials contained within the BoQ (TER_m) (this data is extracted from a pure input-output model) from the total input-output-based energy requirement of the relevant economic sector, *n* (TER_n), in this case *Residential Building Construction*. This input-output component needs to be scaled to the level of the house by multiplying it by the cost of the house (C_h) (Equation 1).

$$EE_h = \sum_{m=1}^{M}\left(Q_m \times EEC_m \times W_m\right) + \left(TER_n - \sum_{m=1}^{M} TER_m\right) \times C_h \tag{1}$$

The recurrent embodied energy associated with replacement of materials and maintenance of the house throughout its assumed life of 50 years was calculated using Equation 2, as outlined in Crawford *et al.* (2016).

$$REE_h = \sum_{m=1}^{M}\left[\left[\frac{POA}{SL_m} - 1\right] \times \left[\left(Q_m \times EEC_m \times W_m\right) + \left(TER_n - TER_m - NATER_m\right) \times C_{m,h}\right]\right] \tag{2}$$

Where REE_h is the recurrent embodied energy of the house, *h* in GJ; *POA* is the period of analysis, in years; SL_m is the service life of the material *m,* in years; $NATER_m$ is the total energy requirement of all input-output pathways not associated with the installation or production process of material *m* being replaced, in GJ/AUD, e.g. pathways representing concrete production when replacing aluminium; and $C_{m,h}$ is the cost of the material *m* in AUD in the house, *h*. Other variables are the same as in Equation 1. Once the initial and recurrent embodied energy of the house were calculated using both 2010 and 2019 hybrid coefficients, the results were compared at a material, elemental and whole building basis.

2.4. Case study description

A typical suburban three-bedroom single-family house was chosen as the case study (Figure 1).

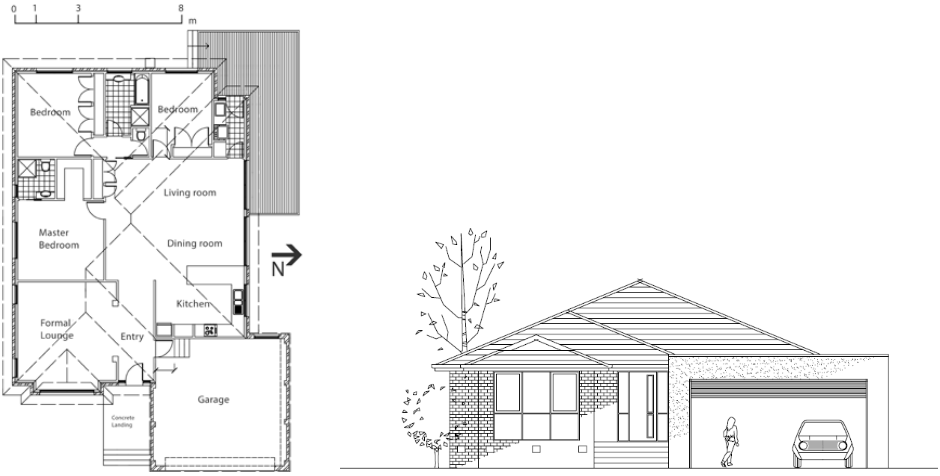

Figure 1: Floor plan and front elevation of the case study house.

This house was developed by the Housing Industry Association (HIA) as a representative sample of new Australian houses for costing purposes. The brick veneer house has a net conditioned floor area of 135.4 m² (when modelled according to the Australian Nationwide House Energy Rating Scheme technical guidelines and zoning protocols) and a gross floor area of 202 m². This house is representative of housing in Australia, where more than 70% of all dwellings are detached houses (ABS, 2017b).

3. Results and Discussion

This section compares a selection of the embodied energy coefficients contained within the 2010 and 2019 databases, followed by the results of the embodied energy analysis of the case study house using the 2010 and 2019 databases. The embodied energy of the house is compared on a material and element basis. This is followed by a discussion of the influence of each database on the overall embodied energy of the house and broader implications for the use of this data.

3.1. Embodied energy coefficient comparison

This section compares the embodied energy coefficients from the 2010 and 2019 databases for a selection of common construction materials. Figure 2 shows the percentage change in the 2019 coefficients compared to the 2010 coefficients. This shows that the majority of coefficients decreased in value for the 2019 database, with a small number increasing. This decrease is most likely to be due to an overall increase in the energy efficiency of manufacturing, year on year. Also, the proportion of process data to input-output data for a specific material can have a considerable effect on its hybrid embodied energy coefficient. The coefficients contained within the 2019 database integrate significantly more detailed process data compared to those within the 2010 database. Process data tends to reflect far more accurately the energy demand associated with the relevant industrial processes for manufacturing specific materials. Where limited process data is available for a specific material, a high proportion of the coefficient is represented by input-output data. If the total embodied energy requirement of the input-output sector representing the material underestimates the embodied energy of the material, then the resultant coefficient will likely be lower than in reality (as for *aluminium*, *cement mortar*, *clay brick* and *timber* in the 2010 database, for example). In this situation, as more process data is included, the coefficient increases, as has happened with the 2019 data for these materials (see Figure 2). However, if the input-output data overestimates the embodied energy for a material, adding more process data will likely reduce the coefficient. This is what has happened with the 2019 data for *paint* and *glass*, for example. One way in which an overestimation can occur with the use of input-output data is related to the cost of the material. The use of input-output data relies on the use of material costs and the resultant embodied energy coefficient is directly proportionate to the cost of the material (see Equation 1). This is a limitation of the use of this data, as often cost is not directly proportionate to energy use. However, research has shown that the use of input-output data in this way is much better than just excluding the embodied energy not covered by the available process data (Crawford, 2008; Pomponi and Lenzen, 2018). If material costs are overestimated, this can artificially inflate the embodied energy coefficient of a material. Despite this, as Crawford (2008) has shown, input-output data can be a good representation of process data, but this does not usually diminish the importance of using process data where it is available as it is usually more representative of reality. This means that while coefficients for materials have fluctuated both up and down between 2010 and 2019 databases, it is most likely that the 2019 values are more representative of reality given the much higher proportion of process data used (29% v 43%).

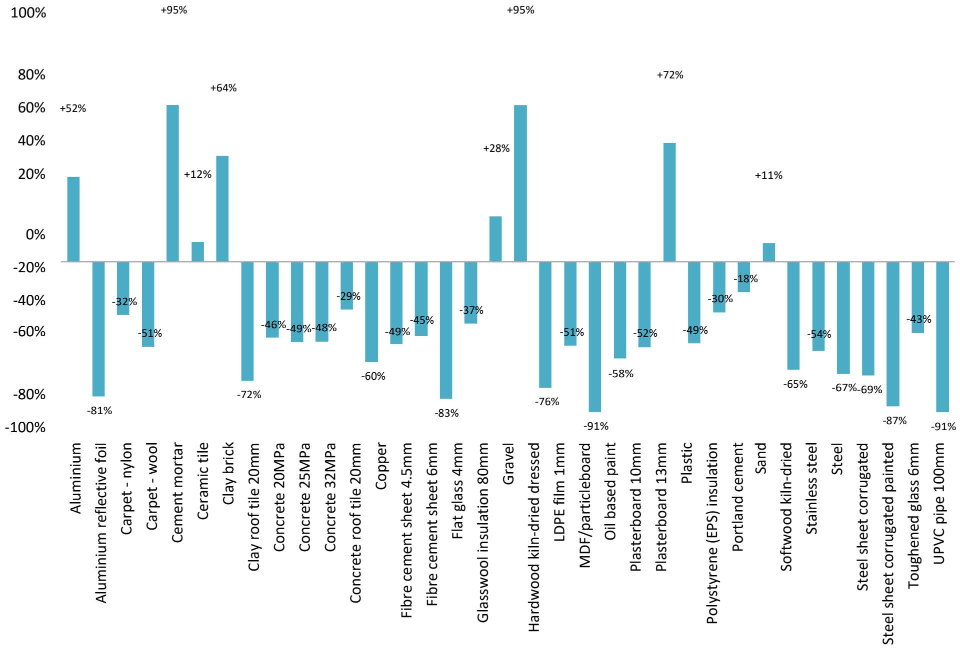

Figure 2: Percentage change in embodied energy coefficients for the 2019 database, compared to the 2010 database.

3.2. Life cycle embodied energy of the case study house

The life cycle embodied energy of the case study house decreased by 27.7% when using the 2019 database, compared to the older database. This reflects the general decrease in coefficient values for the newer database. Table 2 provides the breakdown of the embodied energy by database and life cycle stage (initial construction and material replacement). The initial embodied energy is higher than the recurrent embodied energy due to the use of more energy-intensive materials, with a longer life span, many of which are not replaced during the life of the house (e.g. concrete slab, brick walls).

Table 1: Life cycle embodied energy of the case study house over 50 years, by life cycle stage.

Indicator	2010 database	2019 database	Relative difference
Initial embodied energy (GJ)	2,536 (12.6 GJ/m²)	1,987 (9.8 GJ/m²)	-21.6%
Recurrent embodied energy (GJ)	2,091 (10.3 GJ/m²)	1,360 (6.7 GJ/m²)	-35%
Life cycle embodied energy (GJ)	4,627 (22.9 GJ/m²)	3,347 (16.6 GJ/m²)	-27.7%

3.3. Life cycle embodied energy comparison of case study materials

The total life cycle embodied energy of individual materials within the case study house varies considerably between 2010 and 2019 databases (Figure 3). For example, the life cycle embodied energy of *ceramics* did not change significantly (+12.7%), while the life cycle embodied energy associated with *paint* fell by 91%. The only materials that saw an increase in their total embodied energy were *ceramics* and *timber*, reflective of the increase in their embodied energy coefficient in the 2019 database compared to the 2010 version. In addition to this, the ranking of materials from highest to lowest contribution to the embodied energy of the house changed. Based on the 2010 database, *steel*, *carpet, timber, paint* and *appliances* were the top five contributors to the life cycle embodied energy. For several of these materials (*carpet, paint and appliances*) this was predominately due to their recurrent embodied energy demand due to their relatively frequent replacement. With the 2019 database, this ranking changed to *timber, carpet, steel, concrete* and *ceramics*. Timber ranked higher using the 2019 database due to an increase in the embodied energy coefficient of all timber materials and a considerable decrease in the embodied energy coefficient of steel products. Likewise, the shift from *paint* and *appliances* in the top five materials to *concrete* and *ceramics* was due to a considerable decrease in the embodied energy coefficient of *paint* and *appliances.*

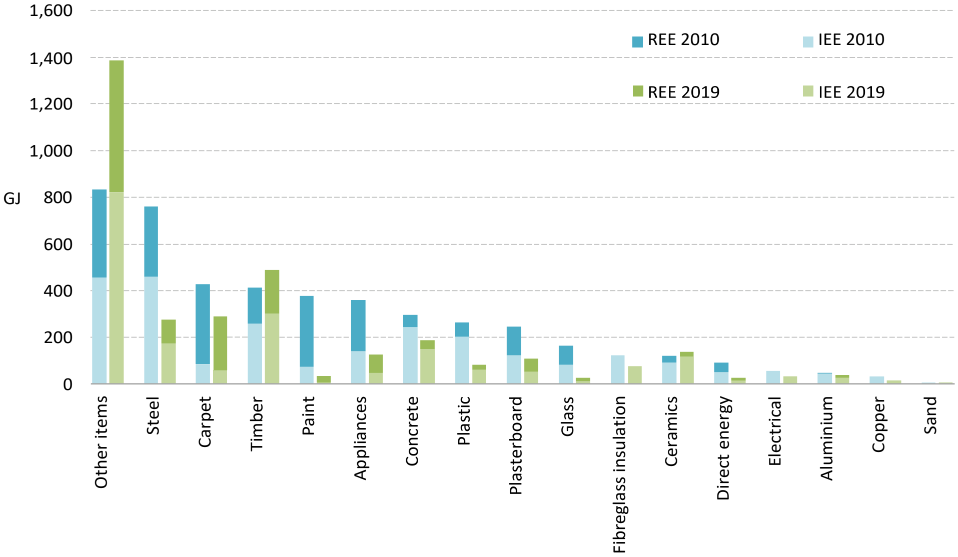

Figure 3: Initial and recurrent embodied energy of the case study house, using 2010 and 2019 databases, by material. IEE: initial embodied energy; REE: recurrent embodied energy.

3.4. Life cycle embodied energy comparison of case study elements

Figure 4 shows the life cycle embodied energy of the case study house by element, based on the 2010 and 2019 databases. As per the material level, the embodied energy of most elements within the house varies considerably depending on whether the 2010 or 2019 database is used. The total life cycle embodied energy for each element is considerably lower with the use of the 2019 database, with the exception of *walls.* The reason for the 31.5% increase here is due to the increase in the embodied energy coefficient for *bricks* and *timber* in the 2019 database, which was also evident in Figure 2 and 3.

For all other elements, the reduction in embodied energy ranges from 39.1% to 75.3% with the use of the 2019 database.

The ranking of elements from highest to lowest contribution to the embodied energy of the house changed only due to the increase in embodied energy for the *walls* element. Based on the 2010 database, *finishes, driveway and fences, substructure, plumbing* and *windows and doors* elements were the top five contributors to the life cycle embodied energy. The embodied energy of the *finishes* element was highest due to the recurrent embodied energy demand from the replacement of *paint* and *carpet*, in particular. Using the 2019 database, this ranking changed to *finishes, walls, driveway and fences, substructure* and *plumbing.*

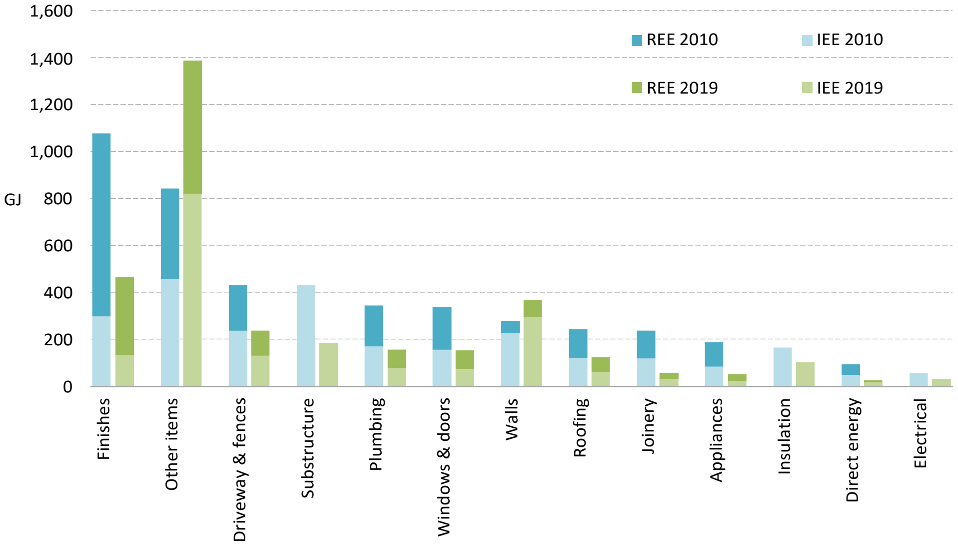

Figure 4: Initial and recurrent embodied energy of the case study house, using 2010 and 2019 databases, by element. IEE: initial embodied energy; REE: recurrent embodied energy.

The *other items* shown in Figure 3 and 4 represent the minor materials not included as part of the main materials quantified within the case study house as well as non-material inputs required in the construction and on-going refurbishment/repair of the house (e.g. construction equipment or services to support the builder, such as insurance, finance, marketing etc.). These *other items* represent 833 GJ, or 18% of the total life cycle embodied energy of the house using the 2010 database, and 1,387 GJ or 41% of the total life cycle embodied energy of the house using the 2019 database. While these items were not included in the material and element rankings discussed above, they nonetheless account for a higher proportion of the embodied energy of the house than any single material. The significant increase in these *other items* from the older to newer data is due to the fact that the energy intensity of the *other items* in GJ/AUD has remained almost identical (2010: 0.0036 GJ/AUD; 2019: 0.0039 GJ/AUD), while the building’s cost has increased by 51%, due to inflation. This indicates that the energy intensity of the *Residential Building Construction* sector has reduced within the last several decades, by a total of 41% according to the input-output data used to compile the two databases (from 0.01 GJ/AUD to 0.006 GJ/AUD). This is due to improvements in the energy efficiency of the construction process as well as the industrial processes associated with other organisations within the construction supply chain. Despite this considerable increase in the embodied energy of *other items*, it is not as significant as the reduction in embodied energy across all other materials, thus leading to a net reduction in the life cycle embodied energy of the house.

4. Conclusion

The aim of this study was to assess the effect of LCI data age on the embodied energy of a building. Embodied energy coefficients from two databases, compiled using an identical approach, were used to quantify the embodied energy of a case study house. In general, coefficients were found to have decreased from the 2010 to 2019 database. The key reasons for this include improvements to manufacturing practices and efficiencies and an increase in the proportion of process data used to compile each coefficient, further improving their overall reliability. When applied to the case study house, at a whole building level, increases in the embodied energy of the *timber, ceramics* and *other items* were not enough to offset decreases in the embodied energy of all other materials within the case study house. This meant that the total life cycle embodied energy of the house decreased by a total of 27.7% with the use of the 2019 database compared to the older data. Regardless of the database used, *steel*, *carpet* and *timber* remained the most significant contributors to the embodied energy of the house, which means that reducing the embodied energy of these materials is important regardless of the age of the data used. While this study provides the first insight into the effect of LCI data age on the analysis of a building’s embodied energy, further analysis is needed, covering a broader range of building types and scenarios. While the findings of this study would likely be just as relevant to other environmental flows, such as GHG emissions, this should also be a focus of further research.

The field of LCA and associated data availability and quality continues to be an area in which further development is needed. This study shows that access to comprehensive and reliable data has improved over recent decades. It has also highlighted the need to ensure data is regularly updated in response to the changes to manufacturing practices and efficiencies, fuel mix and intensity. Users should continue to be cautious when relying on LCI data to make design decisions, and should be particularly conscious of the age of data being used.

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