The life cycle embodied energy and greenhouse gas emissions of an Australian housing development: comparing 1997 and 2019 hybrid life cycle inventory data

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Abstract: Data used to conduct a life cycle assessment, called a life cycle inventory (LCI), is rarely scrutinised and its effects on the results of an environmental assessment is understudied. Hybrid analysis is the most comprehensive technique to compile an LCI. It combines bottom-up industrial process data and top-down macroeconomic input-output data. This study compares two hybrid LCIs of construction materials, using the same technique, developed in 1997 and 2019. This paper evaluates the effect of LCI data on the life cycle embodied energy and greenhouse gas emissions of a recent housing development in Melbourne, Australia. The case study development consists of six different apartment buildings (~14,000m² gross floor area; 555 inhabitants) that have an improved environmental performance compared to business-as-usual. Results show that the 2019 LCI lead to a decrease in the life cycle embodied energy and greenhouse gas emissions over 50 years, from 39.1 GJ/m² to 32.2 GJ/m² (-17.6%) and from 2,338 kgCO_2e/m² to 2,218 kgCO_2e/m² (-5.1%), respectively. The embodied energy and greenhouse gas emissions ranking of some materials changed by up to five positions, while at the assembly level the top five assemblies did not change much. This analysis provides rare insights into the effects of hybrid LCI data on the life cycle assessment of built environment assets and implications for design.

Keywords: Embodied energy; embodied greenhouse gas emissions; hybrid life cycle inventory; housing; Australia.

1. Introduction

The current climate emergency, resulting from a significant increase in anthropogenic greenhouse gas emissions, needs to be addressed at once to avoid catastrophic disruptions to millions of lives and to global ecosystems (IPCC, 2018). The construction and operation of buildings are amongst the main drivers of energy use and greenhouse gas emissions, globally (IPCC, 2014). However, it is critical that energy use

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and greenhouse gas emissions associated with buildings are reduced across the entire life cycle of a building to avoid simply shifting burdens between life cycle stages (Crawford, 2011). The majority of existing studies on the life cycle assessment of buildings rely on process analysis which can significantly underestimate embodied energy and greenhouse gas emissions (Majeau-Bettez *et al.*, 2011). In order to ensure a more comprehensive coverage of embodied energy and greenhouse gas emissions, process data can be augmented with top-down macroeconomic data, known as input-output data. The resulting hybrid life cycle inventory provides embodied energy and greenhouse gas emissions figures that cover the entire supply chains of materials (Crawford *et al.*, 2018). Yet, there are very few databases of hybrid embodied energy and greenhouse gas emissions for construction materials, globally. This has impeded the uptake of hybrid analysis and is the reason behind the lack of comparison of hybrid life cycle inventories over time, compared to process or input-output life cycle inventories. Recently, Crawford *et al.* (2019) produced the EPiC Database of embodied environmental flow coefficients for construction materials in Australia. This comprehensive database uses the same method (Lenzen and Crawford, 2009) as the former database of Crawford and Treloar (2010) (which is based on 1997 input-output data and process data from the 1990s) to produce the hybrid coefficients. This offers a unique opportunity to compare the previous and new databases of hybrid coefficients, as applied to a case study development, in order to understand the changes in the data and their implications on decision-making. This comparison addresses the need for more applications and transparency in hybrid life cycle inventories, as called for by Pomponi and Lenzen (2018).

The aim of this paper is to compare the life cycle embodied energy and greenhouse gas emissions performance of a housing development, using 1997 and 2019 data, to determine the effect of data age on project decision-making.

The scope is limited to the initial and recurrent embodied energy and greenhouse gas emissions of a housing development in Melbourne, Australia. The system boundaries of this work account for life cycle embodied energy (LCEE) and life cycle embodied greenhouse gas emissions (LCEGHG). LCEE and LCEGHG are defined as the sum of primary energy and greenhouse gas emissions associated with the construction process, including construction materials and associated transportation, administration and other services including the recurrent embodied energy and greenhouse gas emissions related to the replacement of materials. These are equivalent to stages A1-A5 and B4 in the European Standard 15978 (2011). The period of analysis is 50 years.

2. Comparing embodied energy and greenhouse gas emissions data

2.1. Research design

Considering the lack of studies that analyse the influence of the age of different datasets when performing hybrid life cycle analysis on built environment assets, we decided to use a revelatory case study approach (Yin, 2018). This approach is characterised by the lack of application of the subject matter at hand and thus of the impossibility to rely on large samples of cases for the comparison.

We chose a new housing development located in Melbourne, Victoria, Australia as the case study to conduct the comparison. The development is characterised by its strong agenda on improved environmental performance, notably through a reduction in materiality to reduce embodied flows (Moore and Doyon, 2018). The case study is described in detail in Section 2.2.

We used Energy Metric (Beta 0.2), the advanced software tool developed by Stephan (2013), to quantify the embodied energy and greenhouse gas emissions of the development. This program enables specification of the dimensions of each building, estimating bills of material quantities and the initial and recurrent embodied environmental flows over a specified period of analysis. It is the only existing software that is able to conduct a hybrid life cycle assessment of buildings and neighbourhoods. We relied on the two versions (Crawford and Treloar, 2010; Crawford *et al.*, 2019) of the hybrid embodied energy and greenhouse emissions coefficients. The use of the same software and assumptions for the quantification of embodied energy and greenhouse gas emissions enables a more robust comparison. The life cycle embodied energy and greenhouse gas emissions are quantified in the software using Equation 1. The quantities of materials within each building within the development are multiplied by their relevant hybrid embodied flow coefficient and by a wastage coefficient that accounts for on-site waste. A so-called input-output remainder is added to the total to account for non-material inputs along the supply chain of the buildings. More details on the quantification approach at a coefficient and building level are available in Stephan *et al.* (2018) and Crawford *et al.* (2019), respectively.

Table 1: comparison of the hybrid life cycle inventory databases of 1997 and 2019, by indicator

Indicator	1997 data	2019 EPiC data
Number of processes in the process database	<200	4,531
Number of input-output sectors	106 (including capital)	114 + 4 sectors for capital expenditure
Number of materials	58	284
Environmental flows included	Energy, Water	Energy, Greenhouse gas emissions, Water

$$LCEF_d = \sum_{b=1}^{B}\sum_{a=1}^{A}\sum_{m=1}^{M}\left(Q_{m,a,b,d} \times FC_m\right) + \left(TFBS_{b,d} - \sum_{m=1}^{M} TFR_m\right) \times C_{b,d}$$

$$+\sum_{b=1}^{B}\sum_{a=1}^{A}\sum_{m=1}^{M}\left[\left\lceil\frac{POA}{SL_m} - 1\right\rceil \times \left[\left(Q_{m,a,b,d} \times FC_m\right) + \left(TFBS_{b,d} - TFR_m - NATFR_m\right) \times C_{m,a,b,d}\right]\right] \quad (1)$$

Where: $LCEF_d$ is the life cycle embodied flow of the development d in flow unit (e.g. $kgCO_2e$ for greenhouse gas emissions); B is the total number of buildings in the development d; A is the total number of assemblies in the building b; M is the total number of materials in assembly a; $Q_{m,a,b,d}$ is the quantity of material m in the assembly a in the building b in the development d (e.g. tonnes of steel); FC_m is the hybrid flow coefficient of material m in flow unit per functional unit of material (GJ/tonne); $TFBS_{b,d}$ is the total flow requirement of the input-output sector associated with the building type of building b (e.g. residential building), in flow unit/currency unit (e.g. $kgCO_2e$/AUD); TFR_m is the total flow requirement of the input-output pathway representing material m, in flow unit/currency unit (e.g. $kgCO_2e$/AUD); $C_{b,d}$ is the cost of building b in development d in currency unit (e.g. AUD); POA is the period of analysis in years (e.g. 50 years); SL_m is the service life of the material m, in years; $NATFR_m$ is the total flow requirement of all input-output pathways not associated with the installation or production process of material m being replaced, in flow unit/currency unit (e.g. $kgCO_2e$/AUD), e.g. pathways representing concrete production when replacing aluminium window frames; and $C_{m,a,b,d}$ is the cost of the material m used in assembly a, in building b, in development d in currency unit (e.g. AUD).

We subsequently compare the life cycle embodied energy and greenhouse gas emissions at a material and assembly level for each hybrid dataset. This enables us to compare both the initial (upfront) and recurrent embodied energy and greenhouse gas emissions across the 50-year life cycle of the development, for each database of hybrid embodied flow coefficients. Note that the service life of all materials remains constant across both cases to ensure consistency in the analysis. A flowchart diagram of the research design is presented in Figure 1.

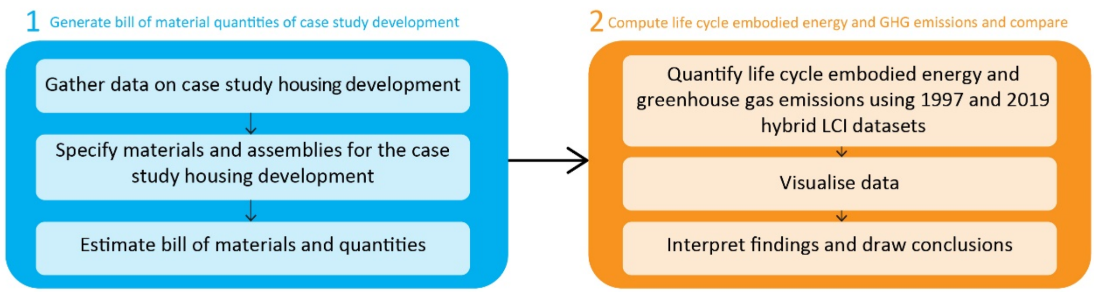

Figure 1: Flowchart of the overall research design. Note: LCI=life cycle inventory; GHG=greenhouse gas

2.2. Case study description

The Nightingale Village (Figure 2) is expected to be finalised in 2021 and will deliver 185 dwellings and integrated services within six mixed-use multi-storey buildings with approximately 14,000m² of gross floor area. Assuming an average of three users per dwelling, the development will host approximately 555 residents. ‘Green’ environmental credentials are claimed following a comprehensive sustainability strategy that touches on the embodied, operational and transport phases of the life cycle, a minimum 7.5 Nationwide House Energy Rating Scheme (NatHERS) rating and an average 80% Built Environment Sustainability Scorecard (BESS) rating across all buildings (Nightingale Housing, 2019).

The materials and construction assemblies of the case study are informed by the architectural plans and materiality schedules included in the planning application documentation advertised by Moreland City Council (2018) to ensure the broadest possible representativeness. Table 2 contains the characteristics of the six buildings of the development.

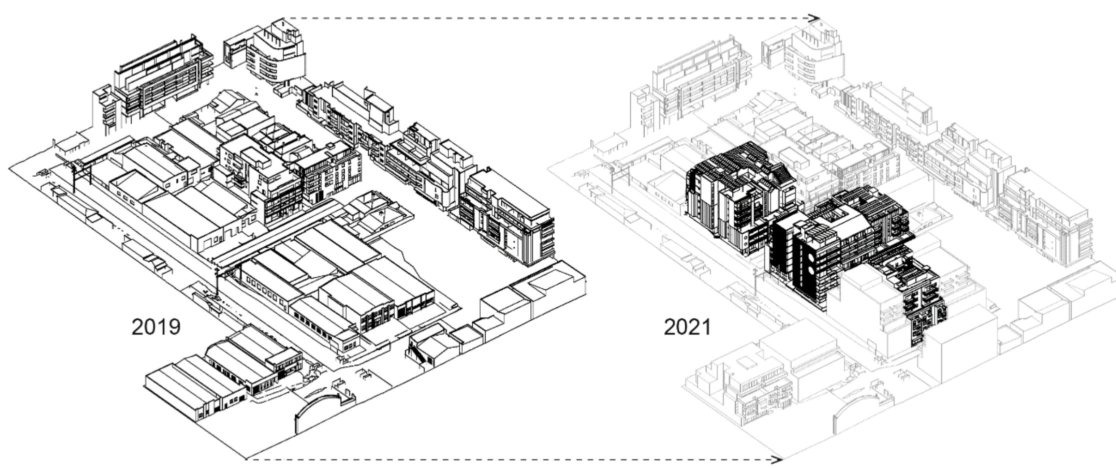

Figure 2: Perspective of the case study development.

Table 2. Characteristics of the case study development.

Characteristic	Value(s)
Average unit area	71.6 m^2 (including a 6 m^2 balcony)
Number of units	25, 27, 27, 35, 40, 41 (six buildings with different units in each)
Household size (number of occupants per unit)	3
Height between floors	3 m
Location	Brunswick, Victoria, Australia
Period of analysis (years)	50
Structure type	Concrete columns/beams; reinforced concrete slab on ground
Façade	R4 exposed precast concrete sandwich panel with no render (with 130 mm of EPS insulation); double glazed aluminium-framed windows (60% and 80% window-to-wall-ratios)
Roof	R8 reinforced concrete roof (with 275 mm of EPS insulation)
Flooring	Recycled hardwood timber flooring in bedrooms and living areas; precast terrazzo tiles for wet areas.
Internal walls	Timber-framed internal walls with plasterboard
PV solar panels	Monocrystalline (1.2 x 1.8 m), two panels per unit

3. Results

The life cycle embodied energy (LCEE) and greenhouse gas emissions (LCEGHG) of the case study development decreased by 17.6% and 5.1%, respectively when using the 2019 EPiC Database, compared to the older database of hybrid coefficients. Table 3 provides the breakdown of the embodied energy and greenhouse gas emissions for each data set. Note the significant initial embodied environmental flows due to the choice of more energy-intensive and emissions-intensive materials, with a longer life span.

Table 3: Life cycle embodied energy and greenhouse gas emissions of the case study development over 50 years, by life cycle stage.

Indicator	1997 data	2019 EPiC data	Relative difference
Initial embodied energy (GJ/m^2)	25.9	21.9	-15.5%
Recurrent embodied energy (GJ/m^2)	13.2	10.3	-21.8%
Life cycle embodied energy (GJ/m^2)	39.1	32.2	-17.6%
Initial embodied greenhouse gas emissions ($kgCO_2e/m^2$)	1,548	1,526	-1.4%
Recurrent embodied greenhouse gas emissions ($kgCO_2e/m^2$)	789	692	-12.4%
Life cycle embodied greenhouse gas emissions ($kgCO_2e/m^2$)	2,338	2,218	-5.1%

The extent of difference in the LCEE and LCEGHG intensities of individual materials between 1997 and 2019 data varies broadly (Figures 3-4). For instance, the LCEE and LCEGHG of *paint* did not change significantly (+3.8% and +5.1%, respectively), while the LCEE and LCEGHG of *sand* and *stone* rose dramatically, increasing by 5,622% and 7,280%, respectively. The LCEE and LCEGHG of *glass* dropped by ~80%. These changes are in part due to the much higher resolution in the process data of the 2019 database (~4,500 processes), compared to the few hundred processes available in the older version. When applied to the case study development, the ranking of materials changed. Using 1997 data, *steel*, *glass*, *other finishes*, *concrete* and *aluminium* where the top five contributors to both LCEE and LCEGHG.

With the 2019 data, this ranking shifts to *aluminium*, *steel*, *concrete*, *paint* and *insulation* for LCEE and to *concrete, aluminium, steel, paint* and *insulation* for LCEGHG. *Ceramics*, which are not widely used in the case study development due to their energy-intensive manufacturing process, witnessed a +356% and a +204% increase in their LCEE and LCEGHG. This further supports the design decision to reduce the amount of ceramics in the case study development.

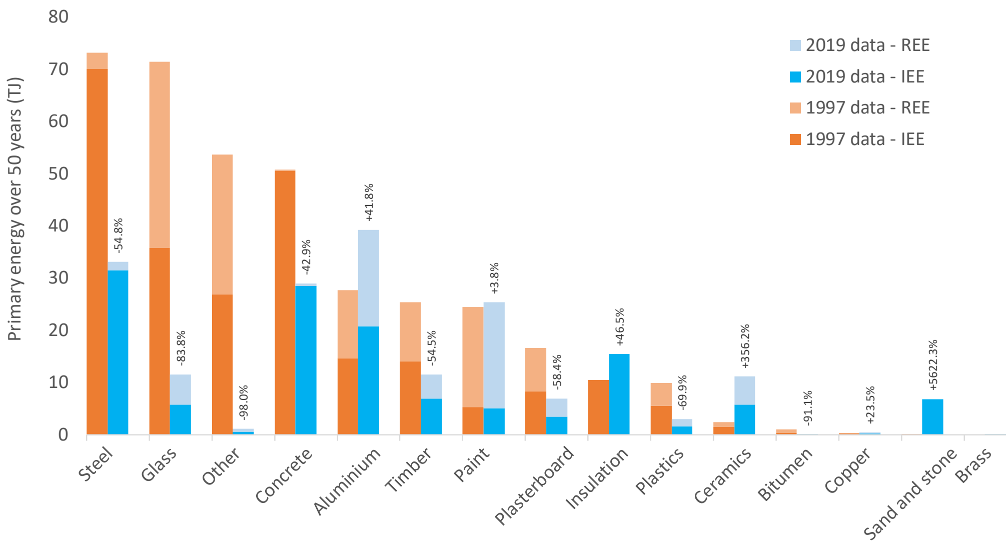

Figure 3: Initial and recurrent embodied energy, using 1997 and 2019 hybrid life cycle inventory data, by material. Note: IEE: initial embodied energy; REE: recurrent embodied energy.

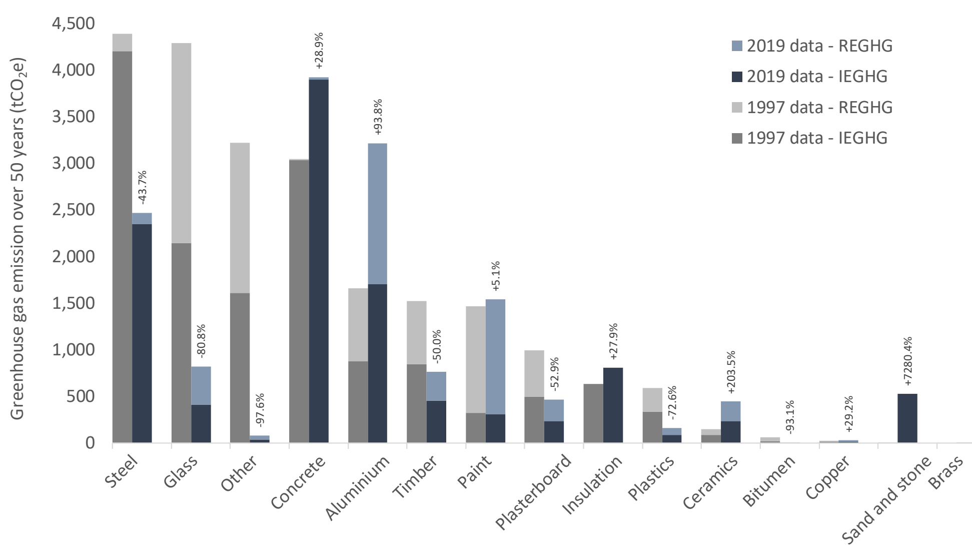

Figure 4: Initial and recurrent embodied greenhouse gas emissions, using 1997 and 2019 hybrid life cycle inventory data, by material. Note: IEGHG: initial embodied greenhouse gas emissions; REGHG: recurrent embodied greenhouse gas emissions.

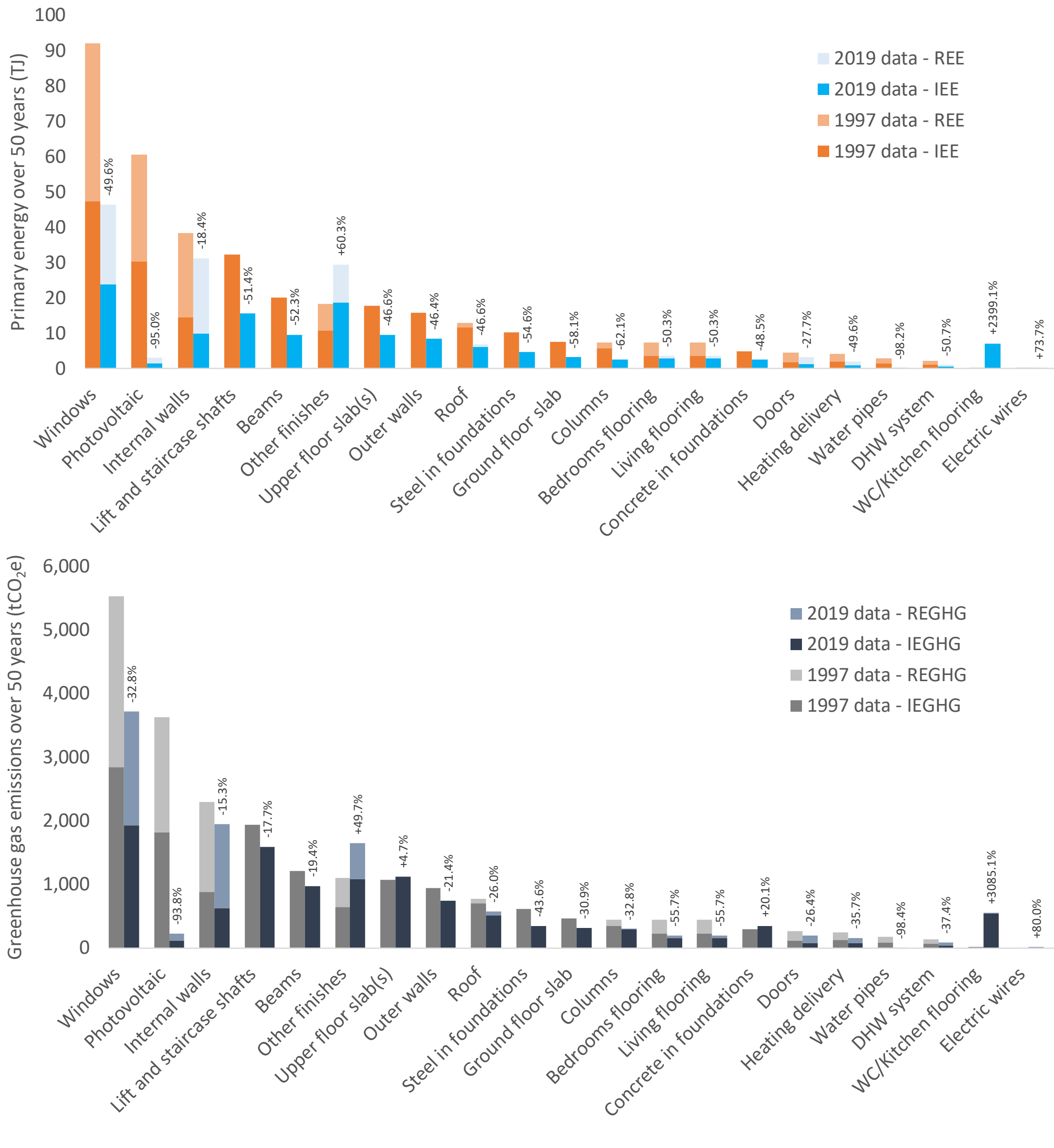

Figure 5: Initial and recurrent embodied energy (top) and greenhouse gas emissions (bottom), using 1997 and 2019 hybrid life cycle inventory data, by assembly.

Figure 5 depicts the life cycle embodied energy and greenhouse gas emissions of the case study development, by assembly type, using 1997 and 2019 data. It shows a significant reduction in both embodied energy and greenhouse gas emissions, across most assembly types. These reductions range from -18.4% to -98.2% and from -15.3% to -98.4% for embodied energy and greenhouse gas emissions, respectively. The most notable decrease is in the embodied energy and greenhouse gas emissions of photovoltaic panels, both in absolute and relative terms. Some assemblies such as finishes (+60.3% and +49.7%) and flooring (ceramic tiles) (+2,399% and +3,085%) witness an increase in their embodied energy and greenhouse gas emissions. The ranking of assembly types by life cycle embodied energy is not significantly affected, with the top five assembly types remaining the same, except for *other finishes* replacing *photovoltaic panels* due to their respective increase and drop. Note that the top five assembly categories by life cycle embodied greenhouse gas emissions using 2019 data is the same as for embodied energy, except for *upper floor slabs* replacing *beams* at the 5th position. Non-material inputs across the supply chain represent 179.3 TJ and 10,673 tCO_2e using 1997 data. These change to 255.7 TJ (+42.6%) and 15,791 tCO_2e (+48%) when using the new data. We did not plot these on the graphs since they are not associated with a particular material or assembly but they are extremely significant, representing more embodied energy and greenhouse gas emissions than any assembly category, when using either 1997 or 2019 data. The increase is non-material inputs is due to the fact that the overall energy and greenhouse gas emissions intensities of the Residential Building Construction sector have remained similar in GJ/AUD and $kgCO_2e$/AUD, while the price of construction per square metre has increased following the base inflation rate.

4. Discussion and conclusion

This study compared the initial and recurrent embodied energy and greenhouse gas emissions of a new housing development, based on LCI data from 1997 and 2019. Results show an overall decrease in life cycle embodied energy and greenhouse gas emissions when using more recent data. This is due to multiple factors. Firstly, there was an overall increase in the energy efficiency of industrial processes over the last two decades, which is translated into reduced embodied energy and greenhouse gas emissions. For example, state-of-the-art kilns used for cement production can significantly reduce greenhouse gas emissions during the firing process (Habert *et al.*, 2020). Secondly, the 2019 data integrates significantly more detailed process data compared to the 1997 data, which reflect far more accurately the relevant industrial processes of specific materials. Table 1 provides a more detailed comparison of the 1997 and 2019 data. Despite these significant changes in the embodied energy and greenhouse emissions of materials, the ranking of assembly types is not significantly affected. This means that the areas of focus to reduce embodied energy and greenhouse gas emissions remain fairly similar, i.e. reducing glazed surfaces, removing unnecessary partitions, reducing the amount of finishes where possible, and carefully choosing structural materials. However, when looking at particular materials, the new data shows significant changes to embodied energy and greenhouse gas emissions intensities.

The proportion of process data to input-output data for a specific material can have a considerable effect on its hybrid embodied energy and greenhouse gas emissions coefficient/intensity. 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 flow requirement of the input-output sector representing the material underestimates the embodied energy or greenhouse gas emissions of the material, then the resultant coefficient will likely end up being lower than reality. In this situation, as more process data is included, the coefficient increases, as has happened with the 2019 data for *ceramics* and *aluminium*, as seen in Figure 3 and 4. However, if the input-output data overestimates the embodied energy or greenhouse gas emissions for a material, adding more process data will likely reduce the coefficient. This is what has happened with the 2019 data for *steel* and *glass*, as can be seen in Figure 3 and 4. 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 or greenhouse gas emissions 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 or greenhouse gas emissions. However, research has shown that the use of input-output data in this way is much better than just excluding the embodied energy or greenhouse gas emissions 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 or greenhouse gas emissions 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 1997 and 2019, it is most likely that the 2019 values are more representative of reality given the much higher proportion of process data used.

At a whole development level, increases in the embodied energy or greenhouse gas emissions intensities of particular materials are compensated by decreases in others. This results in a slight decrease in the overall embodied energy and greenhouse gas emissions intensity of the entire case study development, over the 50-year period of analysis (-17.6% and -5.1%, respectively).

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. However, users should continue to be cautious when relying on this and similar data to make design decisions.

Authors contributions

AS and RC conceptualised the study. ALA collected the case study data, conducted the analysis and produced the results, under the supervision of AS. ALA, AS and RC wrote the manuscript. AS and RC revised the manuscript. ALA and AS created the figures.

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