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Title:
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Date:
2020

Citation:
Ghafoor, S. & Crawford, R. (2020). Comparative study of the life cycle embodied greenhouse gas emissions of panelised prefabricated residential walling systems in Australia. Ghaffarianhoseini, A (Ed.) Ghaffarianhoseini, A (Ed.) Nasmith, N (Ed.) 54th International Conference of the Architectural Science Association 2020, 2020-November, pp.256-265. The Architectural Science Association (ANZAScA).

Comparative study of the life cycle embodied greenhouse gas emissions of panelised prefabricated residential walling systems in Australia

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Abstract: Residential buildings account for 17% of global greenhouse gas (GHG) emissions. With detached housing accounting for over 70% of all of Australia's residential dwellings, and a projected doubling of population in the next 40 years, these houses represent a significant opportunity for GHG emissions reduction. Prefabrication can improve the environmental performance of buildings through lower resource input, reduction in waste and improved quality. However, little research exists on whether it reduces embodied GHG emissions, an increasingly significant proportion of a building's life cycle GHG emissions. The aim of this study was to compare the embodied GHG emissions associated with the construction of detached residential housing in Australia using panelised prefabricated external wall systems. This study used a Path Exchange hybrid life cycle inventory approach to quantify the construction-related embodied GHG emissions of a typical detached house with three external wall assembly variations: cross laminated timber (CLT), structural insulated panels (SIPs) and prefabricated timber framed panels. Compared to conventional brick veneer construction, the prefabricated timber framed panel was the only one that lowered embodied GHG emissions (by 7%). The SIPs resulted in the highest embodied GHG emissions for the house (6% higher than the brick veneer option). The use of prefabrication may not always reduce GHG emissions associated with house construction. In reducing the initial embodied GHG emissions, while the construction process accounts for around 30% of these emissions, the key focus should be on selecting materials with low GHG emissions intensity.

Keywords: Panelised prefabrication; life cycle assessment; embodied greenhouse gas emissions; residential buildings.

1. Introduction

Greenhouse gas (GHG) emissions have been, and contribute to be, one of the greatest contributors to the environmental effects associated with buildings, accounting for 39% of global energy-related GHG emissions (IEA and UNEP, 2018), while 17% of these emissions are associated with residential buildings (Nejat *et al.*, 2015). This significant contribution along with population growth and increased demand for better living standards make energy consumption and the associated GHG emissions of residential

Design Thinking, and the Scientific Method. 54th International Conference of the Architectural Science Association 2020, Ali Ghaffarianhoseini, et al (eds), pp. 256–265.

buildings a serious ongoing issue which needs to be addressed properly to avoid further environmental damage (Pérez-Lombarda *et al.*, 2008).

In Australia, several regulations such as the 6 Star Standard (BCA, 2019) for residential buildings attempt to address this issue. However, considering the population growth in Australia, which is predicted to increase to 48.3 million by 2061 (ABS, 2013) and an expanding housing industry focused on accommodating this target, strategies such as these that just focus on operational performance, although helpful, do not address the complete problem. The construction of buildings has been shown to contribute at least as much to building-related GHG emissions as their operation (Treloar *et al.*, 2001). For this reason, it is critical to not only decrease the operational GHG emissions of residential buildings, but also to ensure minimal GHG emissions associated with their construction.

To date, in an attempt to improve the environmental performance of buildings, several strategies, methods, and technologies have been adopted. Prefabrication is one of these novel building methods that in recent years has gained more attention. Prefabrication can be defined as manufacturing the whole building unit or its major components, typically as modules or panels, in a controlled factory environment to be erected on site (Gibb, 1999). This is in contrast to traditional construction, in which basic materials like steel, timber, concrete, etc. are cast or assembled in-situ. It has been demonstrated that prefabrication can improve the environmental performance of buildings through lower resource input, reduction in waste and improved quality of the final product (Monahan and Powell, 2011; Li *et al.*, 2014). However, little research exists on whether prefabrication reduces the construction-related GHG emissions of buildings. Several comparative analyses have been reported on the embodied emissions of different prefabricated building systems and their benefits compared to conventional methods (Mao *et al.*, 2013; Dodoo *et al.*, 2014; Hong *et al.*, 2016). The results of these studies vary depending on the studied prefabricated system. Systems applicable to detached housing and their benefits are rarely studied, especially in the Australian context. Besides, almost all rely on a process analysis approach which can exclude up to 87% of the energy requirements and its associated GHG emissions (Crawford, 2008). Therefore, there is a need to investigate the potential of innovative prefabricated systems applicable to detached housing to reduce construction-related GHG emissions compared to conventional construction.

The aim of this study was to compare the construction-related embodied GHG emissions of detached residential housing in Australia using conventional construction and panelised prefabricated external wall systems. It is hoped that this would provide insight into whether panelised prefabricated walling systems are capable of reducing the construction-related GHG emissions of detached residential housing. Section 2 describes the case study house, selected external wall system scenarios and the approach used to quantify the embodied GHG emissions. Section 3 presents the results, which are discussed in Section 4.

2. Research approach

This section describes the research approach used to quantify the construction-related GHG emissions of a case study house using a variety of panelised prefabricated walling systems. In order to evaluate the construction-related GHG emissions of prefabricated housing, this study focuses on the initial embodied GHG emissions, or module A1-A5 of EN 15978 (2011) (Figure 1). A typical detached dwelling was selected as a case study house (described in Section 2.1) and considered to be located in Melbourne, Australia, with three external wall assembly variations: cross-laminated timber (CLT), structural insulated panels (SIPs) and prefabricated timber framed panels (described in Section 2.2). The house's original brick veneer construction was selected as the base case (BC) scenario, representing the main building material for external walls of detached residential buildings in Australia, accounting for 70% share of the residential building stock (Beyond Zero Emissions, 2013). The alternative external wall systems were selected to be representative of emerging innovative timber-based panelised prefabricated wall systems suited to detached housing in Australia. The initial embodied GHG emissions of the alternative external wall systems were calculated and compared to that of the base case scenario as per Section 2.3.

	Initial embodied impacts					Recurrent embodied impacts					Operational impacts		End of life embodied impacts				
Modules	Row material supply	Transport	Manufacturing	Transport	Construction process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transportation	Waste processing	Disposal	Reuse, recovery or recycling potential
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Stage	Product stage			Construction process stage		Use stage							End of life stage				beyond system boundary

Included in this study

Figure 1: System boundary for the life cycle GHG emissions analysis of the case study house. (Source: based on EN 15978, 2011)

2.1. Case study house

A standard 3-bedroom brick veneer house design was chosen as the case study house (Figure 2).

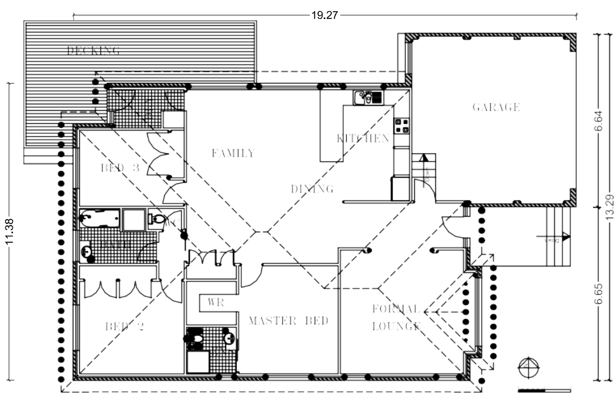


Figure 2: Floor plan of the case study house.

The house has a gross floor area of 202 m^2 and represents the broadest range of residential buildings in Australia, where detached houses account for 72.9% of the homes, and three or more bedrooms accounting for almost 90% of these homes (ABS, 2016). The characteristics of the case study house are presented in Table 1.

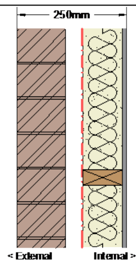
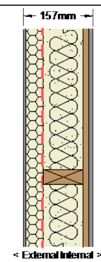
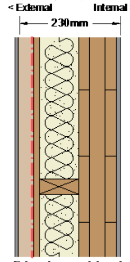
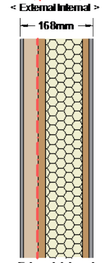
Table 1: Main characteristics of the case study house.

Characteristic	Value
Location	Melton, Australia
Floor area (m^2)	202
Number of bedrooms	3
Building floors	1
Floor to ceiling height (m)	2.4
Windows	Clear single glazed with timber frame
Superstructure	Brick veneer
Substructure	Reinforced concrete slab on ground
Roof	Concrete tile with timber truss

2.2. External wall scenarios

Table 2 illustrates the construction details of the brick veneer construction (BC) and the three panelised prefabricated external wall systems analysed as part of this study.

Table 2: Construction details of external wall system scenarios.

External wall system	Details (outer to inner)	Layout	External wall system	Details (outer to inner)	Layout
Brick veneer (BC)	110mm Brickwork 40mm Air gap Aluminium reflective foil 90mm Glasswool 90mm Timber stud 10mm Plasterboard		Timber framed panel	5mm Mesh reinforced acrylic render 40mm EPS Breathable membrane 90mm Glasswool 90mm Timber stud 12mm OSB 10mm Plasterboard	
Cross laminated timber (CLT)	7.5mm Fibre cement sheet 35x35mm Timber battens 12mm OSB Breathable membrane 90mm Glasswool 90mm Timber stud 85mm CLT panel 10mm Plasterboard		Structural insulated panels (SIPs)	7.5mm Fibre cement sheet 35x35mm Timber battens Breathable membrane 90mm SIPs 10mm Plasterboard	

Note: The R-value of all wall systems is 2.8-2.89 m^2.K/W, calculated by modelling the wall in Speckel (2020).

The design of the selected external wall systems is based on the common practices of companies designing and constructing these systems in Australia (Xlam, 2017; Impresa House, 2020; SIPS Industries, 2020) and to satisfy minimum regulatory requirements of a residential building in Melbourne, including a minimum external wall R-value of 2.8 m^2.K/W (BCA, 2019). Finishes were selected to allow for direct comparison between scenarios. While there is variation in external wall width, the architectural details and other parameters of the case study house are identical across the four scenarios.

2.3. Quantifying initial embodied greenhouse gas emissions

The initial embodied GHG emissions are associated with the production and supply of goods and services through product and construction process stages. It includes GHG emissions associated with extraction, transportation and manufacturing of raw materials (product stage, module A1-A3), transportation of materials, components and equipment to the construction site, and the construction/installation process (construction process stage, module A4-A5). The following sections outline the quantification method of each of these stages.

2.3.1. Product stage (A1-A3)

The product stage GHG emissions of the case study house were quantified using the Path Exchange hybrid analysis technique described by Crawford et al. (2019). This technique combines process and environmentally-extended input-output data to produce comprehensive embodied flow coefficients for building materials, ensuring the entire supply chain of the material is covered, while including relevant and detailed process data. Using these coefficients, the embodied GHG emissions of the product stage was quantified as per Equation 1. Physical material quantities are determined for the entire house and for each external wall scenario. To account for the material wastage during the construction process, a wastage factor (W_m) was applied to the physical quantity of materials contained within the house. These factors are extracted from Crawford (2004) and CSIRO (2016). For the prefabricated components, the wastage factor was assumed to be 0.

$$\mathrm{EGHG_{A1-A3}} = \sum_{m=1}^{m} \left(\mathrm{Q_m} \times \mathrm{GHGC_m} \times (1 + \mathrm{W_m}) \right) \quad (1)$$

Where:

$EGHG_{A1\text{-}A3}$ = Product stage (A1-A3) GHG emissions of the house materials (kgCO_2-e);

Q_m = Quantity of the material *m* in the house;

$GHGC_m$ = Hybrid GHG emission coefficient of material *m* (kgCO_2-e per functional unit);

W_m = Wastage factor for the material *m*.

2.3.2. Construction process stage (A4-A5)

The construction process stage GHG emissions of the case study house, excluding its external walls, was quantified as per Equation 2 by using environmentally extended input-output data (ABS, 2017) as more specific data on the GHG emissions associated with material transportation and on-site construction process was not readily available. Furthermore, as all elements of the study house are identical for every scenario, other than the external walls, the quality of data used for these elements was considered to not influence the comparison of scenarios.

$$EGHG_{A4-A5exW} = (TER_{rb} - \sum_{m=1}^{m} TER_m) \times (C_h - C_w) \quad (2)$$

Where:

$EGHG_{A4\text{-}A5exW}$ = Construction process stage (A4-A5) GHG emissions of the house materials, excluding external walls ($kgCO_2$-e);

TER_{rb} = Total GHG emissions associated with the Australian Residential Building Construction sector ($kgCO_2$-e/AUD);

TER_m = Total GHG emissions associated with the input-output pathway representing material *m* for which coefficients were used to calculate their embodied GHG emissions ($kgCO_2$-e/AUD);

C_h = Cost of the house (AUD);

C_w = Cost of the external walls (AUD).

As the study focuses on a comparison of external wall systems, it was considered critical to maximise the reliability and accuracy of the calculation of construction process GHG emissions for the wall systems. Thus, a detailed process analysis was used to quantify the construction process stage GHG emissions of each wall system; as per Equation 3. This approach breaks down the construction process stage into transportation, construction process and supporting services, which better facilitates a detailed comparison.

$$EGHG_{A4-A5W} = \sum_{m=1}^{m} \sum_{t=1}^{t} (Q_m \times L_m \times TEF_t) + \sum_{e=1}^{e} ((L_e \times TEF_e) + (D_e \times OEF_e)) + \sum_{p=1}^{p} (1.07 \times P_p \times D_p) + (TER_{rb} - \sum_{m=1}^{m} TER_m) \times C_w \quad (3)$$

Where:

$EGHG_{A4\text{-}A5W}$ = Construction process stage (A4-A5) GHG emissions of the external wall materials ($kgCO_2$-e);

Q_m = Quantity of the material *m* in the external wall system including wastage (t);

L_m = Distance between the production site of material *m* and the construction site (km);

TEF_t = GHG emission factor of the transportation method *t* ($kgCO_2$-e/tkm);

L_e = Distance between the equipment supplier and the construction site (km);

TEF_e = GHG emission factor of transporting the construction equipment *e* to the site ($kgCO_2$-e/km);

D_e = Duration of operation of the construction equipment *e* (hours);

OEF_e = GHG emission factor of operating the construction equipment *e* ($kgCO_2$-e/hour);

P_p = Power of the power tool *p* (kW);

D_p = Duration of operation of the power tool *p* (hours);

TER_m = Total GHG emissions associated with the input-output pathway representing material *m*, transport and on-site construction ($kgCO_2$-e/AUD).

In calculating the transportation GHG emissions, the travel distance for materials and equipment were measured based on the distance from the preferred supplier or manufacturer using Google Maps, and all were selected to be within Victoria. Diesel GHG emission factors were extracted from NGA (2018), with fuel consumption averaged between an outward trip (full load) and return trip (empty), and the average fuel use per tkm of each transportation method was based on the ABS (2018) survey of motor vehicle use.

In calculating the construction process GHG emissions two main types of equipment were identified to be used in the process of constructing the wall systems, namely, diesel powered equipment for lifting

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purposes and electricity powered equipment for fixing and applying finishes. The diesel and electricity GHG emission factors for Victoria for equipment and power tool use were extracted from NGA (2018), and the fuel use of construction equipment and power use of construction power tools were extracted from the manufacturers' datasheets. The operation duration of each item of equipment for constructing the wall systems was estimated using equipment properties and industry knowledge.

The initial embodied GHG emissions (EGHG) is the sum of GHG emissions associated with the product ($EGHG_{A1\text{-}A3}$) and construction process ($EGHG_{A4\text{-}A5exW}$+$EGHG_{A4\text{-}A5W}$) stages.

3. Results

The analysis of the initial embodied GHG emissions of the BC scenario shows that a total of 122 tCO_2-e or 605 $kgCO_2$-e per m^2 results from the construction of the house. The brick veneer external wall system was found to represent 15% of the total GHG emissions. This highlights the significance of exploring alternative walling systems for reducing housing-related GHG emissions. Figure 3 compares initial embodied GHG emission results of the three external wall system alternatives with the BC scenario. The timber framed panel is the only option that shows a significant reduction (by around 7.4 tCO_2-e or 7% compared to the BC) while SIPs increases the initial embodied GHG emissions by around 7.13 tCO_2-e or 6% compared to the BC. The CLT scenario results in an increase of 1 tCO_2-e or around 1% compared to the BC.

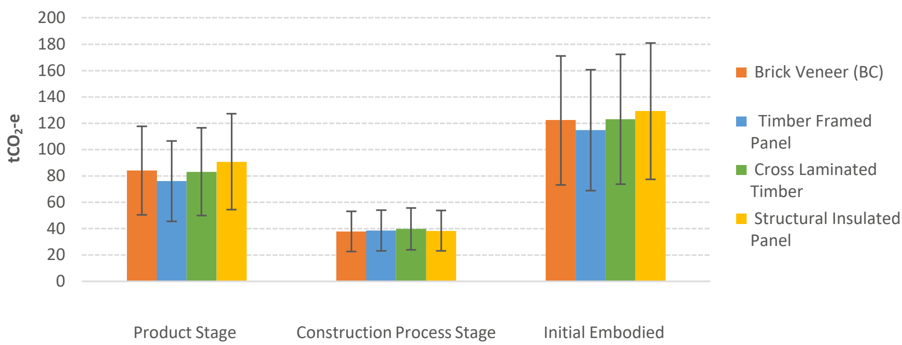

Figure 3: Initial embodied GHG emissions of four scenarios for the case study house showing a ±40% uncertainty.

The results emphasise the importance of product stage GHG emissions, which account for around 70% of the total initial embodied GHG emissions across the four scenarios. Among all, the prefabricated timber framed panel system presents the lowest product stage GHG emissions, with 7.97 tCO_2-e or a 9% reduction compared to the BC. The use of SIPs as the external wall system results in a 6.64 tCO_2-e or an 8% increase in the product stage GHG emissions compared to the BC. This is mainly because SIPs has one of the highest embodied GHG emission coefficients, which has resulted in higher product stage GHG emissions in the respective walling system.

Construction process stage results show all three alternatives lead to an increase compared to the BC results, with the highest increase for the CLT scenario (a 5% increase). This is mainly because of the necessity of heavy machinery and additional supporting services for the construction/installation process of prefabricated panels.

When comparing the initial embodied GHG emissions breakdown of the three external wall system alternatives with the BC results (Figure 4), it shows a reduction in GHG emissions associated with wall material transportation with the highest reduction for the timber framed panel system. However, the use of prefabrication in alternative external wall systems has increased the GHG emissions associated with diesel powered construction equipment, because of the necessity of mobile cranes in the installation process of prefabricated panels. The GHG emissions associated with diesel powered equipment has increased from 46 $kgCO_2$-e in the BC scenario up to 575 $kgCO_2$-e in the prefabricated scenarios. The difference in electricity use for power tools used in the installation process of all wall systems is insignificant.

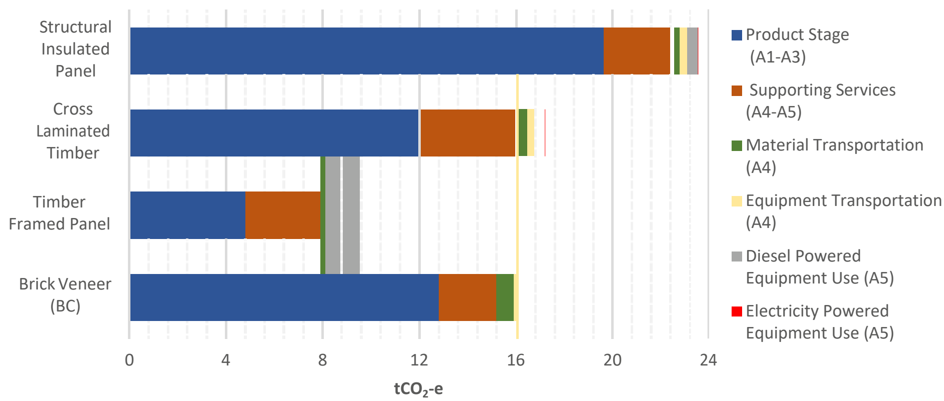

Figure 4: GHG emissions breakdown of the four external wall system scenarios for product and construction process stages (wall scale).

4. Discussion

This study has demonstrated the importance of embodied GHG emissions in reducing the effect of the built environment on climate change, which was also emphasised by Treloar *et al.* (2001). By keeping the operational performance consistent across four scenarios through equal R-value design of wall systems, it was shown that the use of prefabrication may not always reduce the GHG emissions of a building compared to the conventional construction. Among the three panelised prefabricated external wall systems considered, only the prefabricated timber framed panel provides a reduction in initial embodied GHG emissions compared to the BC. The SIPs scenario increases the initial embodied GHG emissions by 6% (35 $kgCO_2$-e/m^2), while the CLT scenario does not provide a significant difference (less than 1% increase) compared to the BC. Therefore, it is critical while complying with regulations like the 6 Star Standard to improve the operational performance of residential buildings, we ensure that the embodied GHG emissions do not negate any operational performance improvements.

The results also emphasise the importance of selecting materials with low GHG emission intensity, supporting the findings of Hong *et al.* (2015). This implies that even with heavy machinery requirements for the transportation and installation processes of panelised prefabricated alternatives, the choice of materials may be a critical factor in reducing the initial embodied GHG emissions of buildings. For example, the SIPs external wall system has resulted in the highest initial embodied GHG emissions mainly due to the high GHG emission intensity of SIPs (accounting for 11% of the initial embodied GHG emissions of the case study house). In contrast, for the CLT external wall system scenario, while it has lower product stage GHG emissions compared to the BC, the effect of the construction process stage has altered the equation to slightly higher initial embodied GHG emissions. Therefore, the effect of the construction process stage, although non-critical, should also not be ignored.

4.1. Limitations

This study is characterised by a series of limitations. Firstly, it does not consider the recurrent embodied GHG emissions associated with maintenance, refurbishment, replacement, and repair of building components during the life of the building. In addition, it does not consider the potential reuse, recycling, or incineration which can recover a significant amount of energy and resulting associated GHG emissions at the end of life stage for materials, considering the fact that panelised prefabricated systems may have a higher recycling rate compared to conventional construction methods (Aye *et al.*, 2012). While care has been taken to identify a typical case study house, the use of a single case study house in this study is subject to criticism for unwarranted generalisation (Zainal, 2007). The assumptions made in the process of quantifying the construction process stage GHG emissions such as the travel distance for supplying materials and equipment to the construction site is another limitation of this study. In addition, embodied energy figures can vary by up to at least 40% when using hybrid analysis for its quantification (Crawford, 2011). Despite these limitations, this study has developed a unique detailed embodied GHG emissions analysis of panelised prefabricated walling systems.

5. Conclusion

This study has quantified the initial embodied GHG emissions of three timber-based panelised prefabricated systems, namely, CLT, SIPs and timber framed panels, and compared them to the conventional use of brick veneer construction for the external wall system of a detached Australian house. The results show among the three panelised prefabricated external wall systems only the timber framed panel scenario provides a reduction (by 7%) to the initial embodied GHG emissions of the BC. The SIPs scenario has increased the initial embodied GHG emissions by 6%, while the CLT scenario does not provide a significant difference (less than 1% increase) compared to the BC. This study reinforces that embodied GHG emissions are significant contributors to the life cycle GHG emissions of a building and need to be integrated into the decision-making process for housing to ensure savings in operational GHG emissions are not offset by increased embodied GHG emissions. The study has shown that the on-site benefits of prefabrication, such as faster construction, may not be the critical factor for reducing housing-related embodied GHG emissions. Minimising GHG emissions associated with the process stage (i.e. production of materials) may have a much greater influence on reducing embodied GHG emissions, regardless of whether it is used in a prefabricated component or not. The consideration of other building elements such as roof and internal walls constructed of panelised prefabricated systems, and other modes of prefabricating such as modular prefabrication is recommended for future research.

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