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Achieving environmentally friendly building envelope for Western Australia's housing sector: A life cycle assessment approach

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Abstract

The rapid growth of Western Australia's population and economy will affect the sustainability of its building sector. The energy consumption of all processes during mining to material production, transportation, construction plant and tools, and operation (heating, cooling, lighting, hot water and home appliances) stages causes high greenhouse gas (GHG) emissions and embodied energy (EE) consumption. The literature review to date have confirmed that the building envelope consisting of exterior walls, windows, external doors, roof, and floor could significantly affect the energy consumption during operation stage. Australian construction industry could thus enhance the energy efficiency of the building envelope in order to achieve its GHG emissions reduction targets. This paper has assessed the GHG emissions and EE consumption associated with the construction and use of a typical house in Perth for sixty building envelope options using a life cycle assessment (LCA) approach. The results show that the building envelope consisting of cast in situ sandwich wall with polyethylene terephthalate (PET) foam core, double glazed windows, and concrete roof tiles has the lowest life cycle GHG emissions and embodied energy consumption.

Keywords: LCA; Building envelope; GHG emissions; Embodied energy

Abbreviations: ACC-XX, aerated concrete blocks; AusLCI, Australian Unit Process LCI; BV-XX, brick veneer; CB-XX, hollow concrete blocks; CO_2 e^-, carbon dioxide equivalent; CSIRO, Commonwealth Scientific and Industrial Research Organisation; CSW-PET, cast in situ sandwich with polyethylene terephthalate (PET) foam made of post consumed bottles; CSW-POL, cast in situ sandwich with polystyrene core; CT, concrete roof tiles; DB-INS, double clay brick with insulation; DB-XX, double clay brick without insulation; DG, double glazed windows with powder coated aluminium frames; EE, embodied energy (cumulative energy demand); EUP, Ecoinvent Unit Process; GHG, greenhouse gas; GJ, Giga Joule; HAp, home appliances; IPCC, Intergovernmental Panel on Climate Change; ISO, International Organization for Standardization; LCA, life cycle assessment; LCI, life cycle inventory; Lgt, lighting; MJ, Mega Joule; MS, metal profile roof sheet; NatHERS, Nationwide House Energy Rating Scheme; PCSW-XX, pre-cast light weight concrete sandwich panels; RBV-XX, reverse brick veneer; SG, single glazed windows with powder coated aluminium frames; SLCA, streamlined life cycle assessment; TJ, Terra Joule; tkm, tonne-kilometre; TMB-XX, timber frame; TT, terracotta roof tiles; W/m^2 K, watts per metre squared kelvin; WA, Western Australia; WH, water heater.

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1. Introduction

Australia's current per capita carbon footprint (23.1 tonnes of CO_2 e^-) and ecological footprint (6.3 global hectares) are approximately 5 and 3.5 times higher than the global average (DOE, 2015b; WWF, 2014) due to rapid population and economic growth (ABS, 2013). The building sector alone contributes to 20% and 23% of Australia's annual energy consumption and GHG emissions, respectively (ABCB, 2015; ASBEC, 2007). The reason for this carbon intensive building sector is that a majority of Australians are accustomed of living in detached houses with heavy reliance on artificial air-conditioning (Kelly et al., 2011; Miller and Buys, 2012). This is exacerbated by the fact that the recent estimate shows that more than 3.3 million additional houses will be needed by 2030 to maintain the pace with an economic growth (NHSC, 2011) and about 15% of these new houses alone will be built in Western Australia (WA).

In spite of various energy efficiency initiatives, the building sector's GHG emissions are growing at 1.3% annually (ASBEC, 2007). Other improvement opportunities are therefore needed for this sector to help Australia to meet its recent GHG emissions reduction target as committed in Paris (i.e. 26–28% on 2005 levels by 2030) (DOE, 2015a). It is crucial to investigate into the alternative building design that will not only consider the use of low energy and carbon intensive materials for the construction of houses, but also reduce operational energy consumption during the use stage. Aldawi et al. (2013a,b) suggested that unless the use of thermal mass and insulation materials in building envelopes is optimised, it is difficult to achieve relatively high energy efficiency through currently used building envelopes (Aldawi et al., 2013a,b).

The bulk of the operational energy required by the housing sector is utilised to compensate the thermal energy losses or gains through the building envelope, and so any improvements in thermal performance of envelope materials provide significant energy and GHG emissions reduction opportunities (Bambrook et al., 2011; Lai and Wang, 2011; Sadineni et al., 2011; Sozer, 2010; Xu and Dessel, 2008). The building envelope that separates the indoor environment of the house from the outdoor environment is influenced by various technological, functional, and socio-economic factors and must satisfy the functional as well as structural requirements (Horner et al., 2007; Oral et al., 2004; Zeng et al., 2011). Studies to date suggest that the increased amount of EE consumption due to use of some high thermal performance materials in the building envelope can be compensated through savings of operational energy during use stage (Verbeeck and Hens, 2010). The placement of thermal mass and its insulation are the most important elements for reducing operational energy demand and achieve the energy efficiency (Gregory et al., 2008).

The published literature shows that there are few studies to compare the operational energy consumption and environmental impacts of building envelopes such as clay brick, brick veneer, reverse brick veneer, timber frame, and reinforced concrete as wall elements and single/double/triple glazed windows (Aldawi et al., 2013a,b; Crawford and Fuller, 2011; Gregory et al., 2008; Islam et al., 2010; Lai and Wang, 2011) but there appears to be no comprehensive study, that has compared the building envelopes consisting of all elements (i.e. wall, window, and roof) for a semi-arid climate of Perth where houses are predominantly made of energy intensive clay bricks, single glazed windows, and concrete roof tiles.

This study has estimated the operational energy consumption, GHG emissions and EE consumption associated with the construction and use of a typical house in Perth for 60 envelope options (i.e. $10 \times 2 \times 3$ options) comprising 10 wall options, 2 window options, and 3 roof options using an LCA approach. Finally, this study recommends the best building envelope with reduced GHG emissions and EE consumption.

2. Methodology

The LCA framework for this study, integrates LCA tool with the widely used NatHERS accredited energy rating software (AccuRate, 2015; Aldawi et al., 2013a,b; Morrissey and Horne, 2011) to estimate the GHG emissions and EE consumption of the use of various building envelope options for the construction of a typical house in Perth. The information on materials and energy required during mining to material production, transportation of material to construction site, construction activities and operational energy during use stage has been considered to conduct this LCA analysis. Since the demolition and disposal of wastes to landfill or their recycling or reuse of the demolition wastes are not considered, it is best termed as a streamlined LCA (SLCA) (Bala et al., 2010; Biswas, 2014).

The life time of the house has been considered as 50 years (Biswas, 2014; Crawford and Fuller, 2011; Islam et al., 2010; Rouwette, 2010; Wan et al., 2011). The layout and design of a typical $4 \times 2 \times 2$ (4 bedroom, 2 bathroom and 2 car park) detached house of 243 m^2 footprint area in Perth (Clune et al., 2012; SOE, 2011) has been considered for this life cycle assessment analysis. The operational energy required for heating, cooling, lighting and hot water over the life of the house has been calculated using NatHERS accredited software tool (AccuRate V2.0.2.13SP2), which is based on Chenath engine developed by CSIRO. AccuRate software calculates the annual energy requirements to maintain thermal comfort of the house based on the building envelope, natural ventilation, thermostat settings and reference meteorological year weather data corresponding to the climate zone of the house (AccuRate, 2015). The inputs required for all stages of building life have been estimated to develop the life cycle inventory (LCI), which is a pre-requisite for carrying out a life cycle assessment. The data from LCI have been inputted into SimaPro 8.0.5.13 LCA software to calculate

GHG emissions and EE consumption associated with the use of different materials for building envelope for the construction of a house.

This SLCA has employed the four steps of ISO 14040-44 (Biswas, 2014; ISO14040, 2006; ISO14044, 2006): (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation (as presented in the 'Results' section of this report) in order to calculate the GHG emissions and EE consumption implications of the use of alternative materials for building envelope for the construction of house in Perth.

2.1. Goal and scope

The goal is to assess the life cycle GHG emissions and EE consumption implications of the use of different materials in a building envelope for the construction of a typical house in Perth, WA, in order to determine the most environmentally friendly envelope. The functional unit for this study is the construction and use of a typical 4 × 2 × 2 house over 50 years as shown in Fig. 1. The system boundary for this study is limited to use stage only.

This study has considered the following 60 (10 × 2 × 3) building envelope options for the construction of a typical house in Perth and as shown in Fig. 2:

(1) The walls are divided into total 10 wall groups including double clay brick without insulation (DB-XX), double clay brick with insulation (DB-INS), brick veneer (BV-XX), reverse brick veneer (RBV-XX), cast in situ sandwich with polystyrene core (CSW-POL), cast in situ sandwich with PET foam core (CSW-PET) where PET foam is made of post consumed polyethylene terephthalate bottles, hollow concrete blocks (CB-XX), aerated concrete blocks (ACC-XX), pre-cast light weight concrete sandwich panels (PCSW-XX), and timber frame (TMB-XX).
(2) The windows are divided into 2 groups including single glazed (SG) and double glazed (DG) with powder coated aluminium frames.
(3) The roof is divided into 3 groups including concrete tiles (CT), terracotta tiles (TT) and metal profile sheet (MS). The roof space is insulated for these 3 options.

Only GHG emissions and EE consumption have been considered for this study as these are two predominant and challenging impacts resulting from the building sector and these impacts have been considered by other studies (Biswas, 2014; Islam et al., 2015; Monahan and Powell, 2011; Ortiz et al., 2009; Ross Maher and Mary Stewart, 2011; Rossi et al., 2012; Zabalza Bribián et al., 2011). In addition, other associated environmental impacts i.e. acidification, eutrophication, human and eco-toxicity are very low as compared to aforementioned impacts (Khasreen et al., 2009; Rouwette, 2010). The internal walls and other fixtures, or support systems associated with walls, windows, and roof have been considered accordingly for 60 envelope options. The loose furniture, services, accessories and, external site development have been excluded from this study as they are not linked to the thermal performance of the building and also vary with occupant's choice.

2.2. Life cycle inventory

The LCI of a typical house in Perth consisting of detailed information on the quantities of construction materials, their transportation to construction site

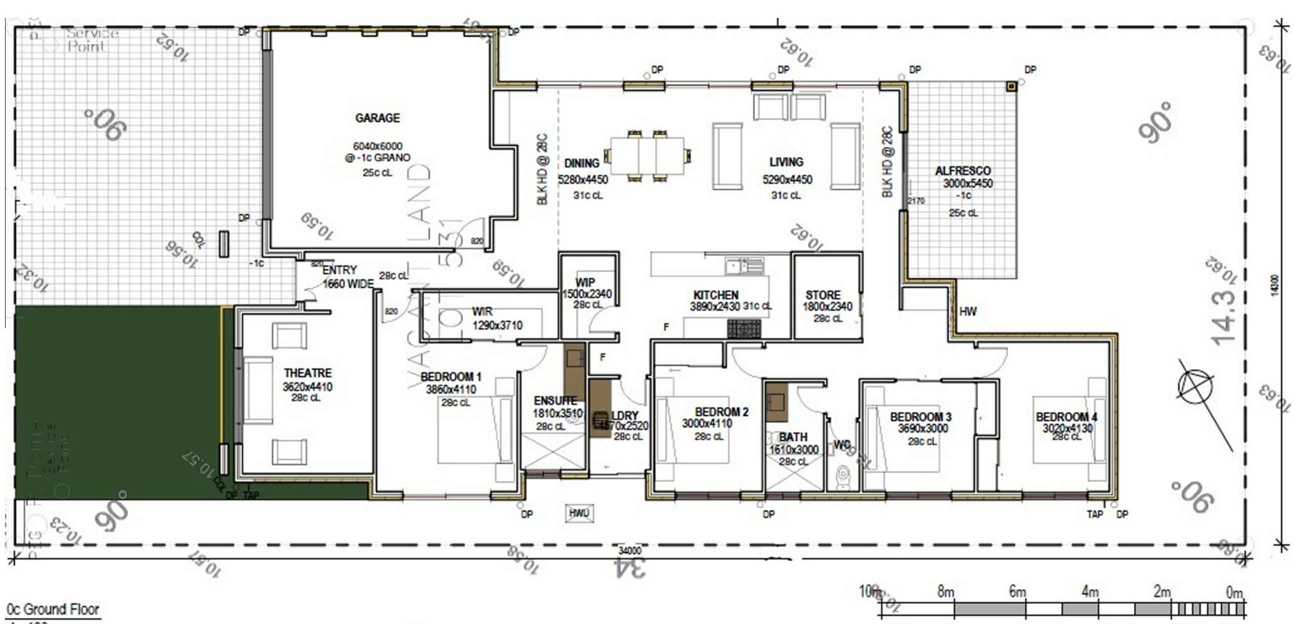

Figure 1. Floor plan of a typical 4 × 2 × 2 house in Perth.

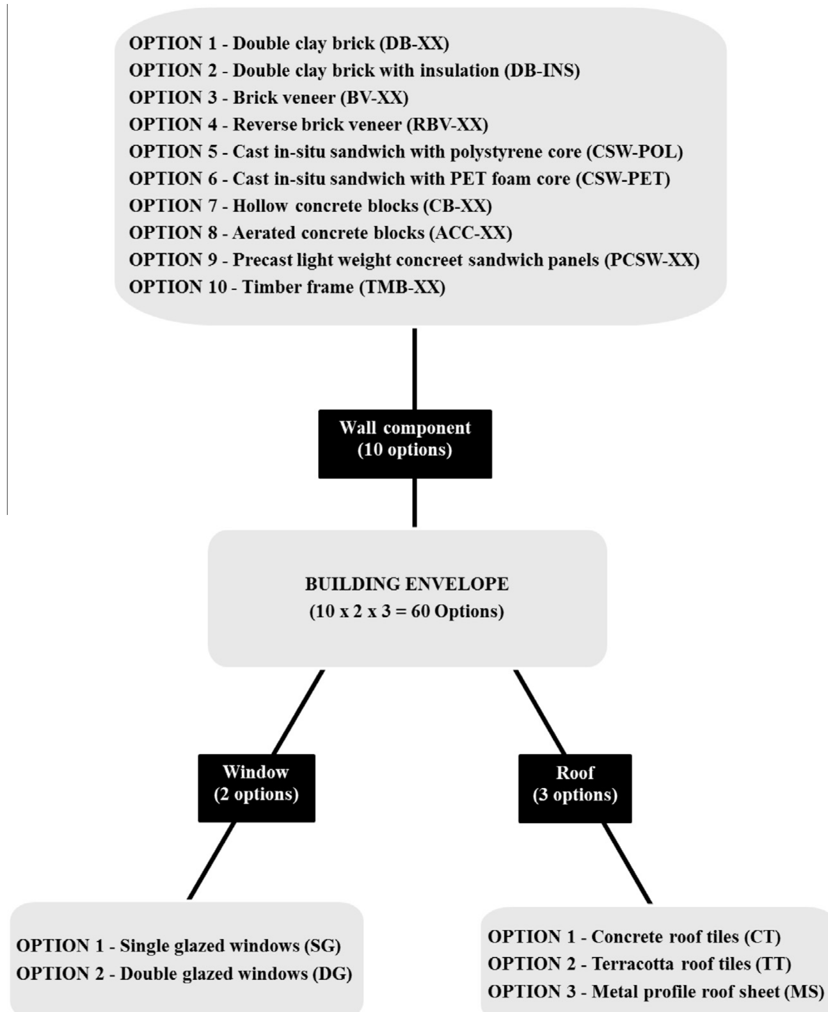

Figure 2. Building envelope options with varying materials.

(tkm = tonne × km travelled), and energy required for plants and tools on site during construction stage have been generated using detailed drawings, and material data sheets (BGC, 2014; Boral, 2014; Bunnings, 2014; Kennards, 2014; Masters, 2014; Staines, 2013). The operational energy consumption for heating (heat), cooling (cool), water heater (WH), and lighting (Lgt) during use stage has been calculated using AccuRate software for all envelope options. The calculation of operational energy consumption for home appliances (HAp) is based on the power rating and duration of usage of appliances. Table 1 shows the list of materials and energy inputs considered for preparation of LCI of each building envelope option, and Table 2 shows the Bill of materials of a typical 4 × 2 × 2 detached house in Perth for all envelope options.

2.3. Impact assessment

The GHG emissions and EE consumption assessment of the house consists of two steps. In the first step, the LCI data were entered into SimaPro 8.0.5.13 (PRé-Consultants 2015) LCA software. Each input was linked to relevant library in the SimaPro 8.0.5.13 software. The libraries in this software contain the emission factors of energy, materials and transportation inputs for estimating the environmental impacts. In the case of unavailability of local database in the software, new library databases have been created by obtaining the data on raw material and energy consumptions from local reports. In some cases, Ecoinvent (v2.2, 2010) Unit Process (EUP) libraries have been used for assessing GHG emissions (Hans-Jorg, 2010). The Australian Unit Process LCI (AusLCI) database library has been used to calculate the GHG emissions from the production of construction materials, such as aluminium, structural and sheet steel, concrete, cement, lime, sand, polystyrene, polyethylene, roof timber, ACC blocks, roof sheeting, weatherboard, and glass (Grant, 2011). New library databases have been created for mesh reinforcement, clay bricks, and PET foam by obtaining the information on raw material and energy consumptions from local reports (One Steel, 2014; Rouwette, 2010; Strezov and Herbertson, 2006). For some materials such as concrete roof tiles, ceramic tiles, timber doors, glass wool batts and gypsum board, Ecoinvent (v2.2, 2010) Unit Process

Table 1
Bills of material and energy inputs required for construction of a typical house in Perth for all building envelope options.

Material	DB-XX	DB-INS	CSW-POL	CSW-PET	BV-XX	RBV-XX	CB-XX	ACC-XX	PCSW-XX	TMB-XX
Non envelope elements										
Excavation for foundation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Excavation for levelling overall area	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Virgin sand to make up levels for pad	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Polythene sheet	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mesh reinforcement	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ready mix concrete	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Metal door frames	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Roof timber	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bat insulation for roof	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Gyprock boards & cornices	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Door shutters	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Floor tiles	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Wall tiles	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Envelope elements										
External walls										
Face bricks	✓	✓	–	–	✓	–	–	–	–	–
Utility bricks	✓	✓	–	–	–	✓	–	–	–	–
Cast in situ concrete	–	–	✓	✓	–	–	–	–	–	–
Concrete blocks	–	–	–	–	–	–	✓	–	–	–
Acc blocks	–	–	–	–	–	–	–	✓	–	–
Structural timber frame	–	–	–	–	✓	✓	–	–	–	✓
Gyprock board lining for internal face	–	–	–	–	✓	–	–	–	–	✓
Fibre cement board/weather board cladding	–	–	–	–	–	✓	–	–	–	✓
Pre-cast concrete sandwich panels	–	–	–	–	–	–	–	–	✓	–
Internal walls										
Utility bricks	✓	✓	–	–	–	✓	–	–	–	–
Cast in situ concrete	–	–	✓	✓	–	–	–	–	–	–
Structural timber frame	–	–	–	–	✓	–	–	–	–	✓
Concrete blocks	–	–	–	–	–	–	✓	–	–	–
Acc blocks	–	–	–	–	–	–	–	✓	–	–
Gyprock board lining	–	–	–	–	✓	–	–	–	–	✓
Pre-cast concrete sandwich panels	–	–	–	–	–	–	–	–	✓	–
Insulation										
Wall insulation	–	✓	–	–	✓	✓	–	–	–	✓
Moisture barrier	–	–	–	–	✓	✓	–	–	–	✓
Polystyrene insulation core for cast in situ walls	–	–	✓	–	–	–	–	–	–	–
Pet foam insulation for cast in situ walls	–	–	–	✓	–	–	–	–	–	–
Aluminium windows										
Single glazed (SG) or double glazed (DG)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Roof										
Concrete tiles (CT) or terracotta tiles (TT) or metal sheeting (MS)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Others										
Cement, brickie sand and lime for mortar	✓	✓	–	–	✓	✓	✓	–	–	–
Polymer modified mortar for acc blocks	–	–	–	–	–	–	–	✓	✓	–
Metal lintels and columns	✓	✓	–	–	✓	✓	✓	✓	–	✓
Wire mesh for cast in situ walls	–	–	✓	✓	–	–	–	–	✓	–
Metal tracks for pre-cast panels	–	–	–	–	–	–	–	–	✓	–
Cement, plaster sand and lime for rendering	✓	✓	–	–	–	✓	✓	–	–	–
Polymer modified render for acc blocks	–	–	–	–	–	–	–	✓	✓	–
Construction waste and disposal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Transportation – tkm	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy consumption for plants and tools during construction activities	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 2
Summary of bills of materials for construction of a typical house in Perth for all envelope options.

Envelope type			DB-XX	DB-INS	BV-XX	RBV-XX	CSW-POL	CSW-PET	CB-XX	ACC-XX	PCSW-XX	TMB-XX
CT	SG	Material – tonnes	261	262	202	248	214	215	233	189	181	167
		Transportation – tkm	12,342	12,348	9342	11,418	9423	9459	11,483	9573	8738	8232
		Construction Energy – GJ	16	17	28	23	9	9	23	16	36	37
	DG	Material – tonnes	262	262	202	248	214	216	233	190	182	167
		Transportation – tkm	12,255	12,261	9255	11,331	9335	9372	11,396	9486	8650	8145
		Construction Energy – GJ	16	17	28	23	9	9	23	16	36	37
TT	SG	Material – tonnes	259	259	199	245	211	212	230	186	178	164
		Transportation – tkm	11,865	11,871	8955	11,031	9036	9072	11,096	9187	8351	7845
		Construction Energy – GJ	16	17	28	23	9	9	23	16	36	37
	DG	Material – tonnes	259	259	199	245	212	213	230	187	179	164
		Transportation – tkm	12,356	12,362	9357	11,433	9437	9474	11,498	9588	8752	8247
		Construction Energy – GJ	16	17	28	23	9	9	23	16	36	37
MS	SG	Material – tonnes	249	249	189	235	201	202	220	176	168	154
		Transportation – tkm	12,269	12,275	9269	11,346	9350	9387	11,411	9501	8665	8159
		Construction Energy – GJ	15	16	26	22	8	8	22	15	35	33
	DG	Material – tonnes	249	249	189	235	202	203	220	177	169	154
		Transportation – tkm	11,879	11,886	8970	11,046	9050	9087	11,111	9201	8366	7860
		Construction Energy – GJ	15	16	26	22	8	8	22	15	35	33

Note: the shaded portion represents the most commonly used building envelope in Perth.

(EUP) libraries have been used for assessing GHG emissions (Hans-Jorg, 2010).

The AusLCI libraries have been used for transport. The library for WA electricity generation mix is used to calculate the GHG emissions associated with the electricity consumption (Grant, 2011). The emission factors associated with diesel combustion were also used to calculate the GHG emissions from construction machinery, including excavator, front end loader, fork lift, compactor, mortar mixer and hand tools.

In the second step, the GHG emissions and EE consumption of a typical house for all building envelope options in Perth are converted to CO_2 equivalent GHG emissions and TJ equivalent EE consumption. Finally, a flow network diagram has been generated by the SimaPro software to develop a detailed breakdown of these impacts in terms of inputs in order to identify the 'hotspots'.

As per IPCC (2007), different time scales are used to measure the cumulative chronic effects of GHGs on climate such as 20, 50, 100 and 500 year horizons (Forster et al., 2007). However, long horizons such as 500 years are subject to significant uncertainties in the decay rate of CO_2, and shorter horizons such as 20 and 50 years represent the maximum response to temperature. The IPCC found that the 100 year horizon provided the most balanced representation of the various time scales for the maximum rate of response of temperature, thus it is currently the most commonly used horizon (Forster et al., 2007).

3. Limitations

LCA is a data hungry tool and there are some limitations with this study. The impacts associated with the demolition and disposal activities at the end of life stage, and routine maintenance activities during the use stage have been excluded which may cause some minor impacts on the accuracy of the results (Islam et al., 2014; Monteiro and Freire, 2012). Some decision making factors of material selection such as economic feasibility and resource availability and the energy efficiency improvements of end-use appliances associated with technological change and energy mix change during the use stage are beyond the scope of this analysis. The use of Ecoinvent (v2.2, 2010) Unit Process (EUP) libraries for some of the material inputs in SimaPro may have some impacts on GHG emissions and EE consumption, as foreign databases do not exactly reflect the local situation (Biswas, 2014; Khasreen et al., 2009).

4. Results and discussion

4.1. Greenhouse gas emissions analysis

4.1.1. Variation of GHG emissions of 60 options

The results of SLCA show that the life cycle GHG emissions of a typical house of 243 m^2 area for 60 envelope options vary from a minimum of 403 tonnes CO_2 e^- for CSW-PET-DG-CT option (cast in situ sandwich wall with PET insulation core, double glazed windows and concrete roof tiles), which is 9% less than the GHG emissions of the conventional envelope option to a maximum of 498 tonnes CO_2 e^- for PCSW-XX-SG-MS option (pre-cast light weight concrete sandwich wall with single glazed windows and metal sheet roof), which is 12% more than the GHG emissions of a conventional envelope option (444 tonnes CO_2 e^- for DB-XX-SG-CT or clay brick wall without insulation, single glazed windows and concrete roof tiles) (Table 3). The main reason for this variation in GHG emissions across these envelope options is the variation in operational energy consumption during use, and mining to material production stages.

The results show that the use stage energy consumption of the house with an envelope of the highest carbon intensity (PCSW-XX-SG-MS) is 1.8% more than the conventional option (2689 GJ), while the house with an envelope of the lowest GHG emissions (CSW-PET-DG-CT)

Table 3
GHG emissions of a typical house in Perth for all envelope options.

Envelope Options		GHG Emissions - tonnes CO_2 e^-									
		DB-XX	DB-INS	BV-XX	RBV-XX	CSW-POL	CSW-PET	CB-XX	ACC-XX	PCSW-XX	TMB-XX
SG	CT	444	428	444	430	415	414	486	442	496	453
	TT	445	429	444	430	416	415	486	442	497	453
	MS	446	430	446	432	418	415	488	444	498	456
DG	CT	432	417	428	418	406	403	470	429	478	436
	TT	432	418	428	419	406	404	470	429	478	437
	MS	434	419	430	421	408	405	471	431	480	439

Legends: Conventional; Up to 5% lower; 5% - 10% lower; Higher consumes 10% less energy than the conventional envelope option. Thus CSW-PET-DG-CT option (cast in situ sandwich wall using PET foam as insulation, and double glazed windows with concrete tile roof) offers lowest carbon footprint (403 tonnes CO_2 e^-).

A structurally sound house with reduced material content does not necessarily have low carbon intensity. This research found that the material content of a house with the highest GHG emissions is 36% less than the conventional house (261 tonnes), and this situation is same for the house with the lowest GHG emissions (i.e. 15% lower than the conventional house). This can be explained by the fact that the house with a relatively low amount of material content has lower thermal mass resulting increased level of energy consumption for heating and cooling (Hacker et al., 2008).

The 59 envelope options have been classified in terms of GHG savings due to replacement of a conventional envelop (Table 3). The envelope options such as CSW-PET-(SG/DG/CT/TT/MS), CSW-POL-(SG/DG/CT/TT/MS), DB-INS-(DG/CT/TT/MS), and RBV-XX-(DG/CT/TT/MS) have between 5% and 10% less GHG emissions than the conventional one. The second group, which includes 22 envelope options such as DB-INS (SG/CT/TT/MS), RBV-XX (SG/CT/TT/MS), ACC-XX (DG/CT/TT/MS), DB-XX (DG/CT/TT/MS), BV-XX (DG/CT/TT/MS), TMB-XX (DG/CT/TT/MS), and BV-XX-SG-CT have up to 5% less GHG emissions than the conventional one. Interestingly, most of these 22 envelope options have double glazed windows to achieve GHG savings except for DB-INS, RBV-XX, and ACC-XX. The remaining 19 envelope options produces more GHG emissions than the conventional one mainly due to variation in operational energy consumption during use, and mining to material production stages.

4.1.2. Cause diagnosis

Further investigation has been carried out to identify the main causes of GHG emissions by breaking down the GHG emissions in terms of sub-stages. The GHG emissions from operational energy (HW/HAp/Lgt) application during use stage accounts for the highest portion (i.e. between 64% for PCSW-XX-SG-MS and 79% for CSW-PET-SG-CT) for all envelope options, because a large amount of energy (i.e. 2100 GJ, 70–90% of total energy) is consumed for hot water, home appliances and lighting during the life cycle of the house. This energy mainly comes from WA electricity mix which is currently dominated by fossil fuels such as coal and natural gas (DOF, 2015), resulting the highest GHG emissions during this stage.

The energy consumption for hot water, home appliances and lighting is consistent across the envelope options as these activities are not affected by the properties of the building envelope (Ross Maher and Mary Stewart, 2011; Swan and Ugursal, 2009). However, the choice of these appliances entirely depends on the lifestyle and behaviour of occupants (Karuppannan and Han, 2013), which is beyond the scope of this study. The prediction of technological change that may affect the operational energy consumption (e.g. connecting the home automation system with electricity and gas utility for energy saving) is also beyond the scope of this study (Paul Ryan, 2013).

Heating and cooling are the second largest source of GHG emissions, which vary between 41 tonnes CO_2 e^- for CSW-PET-DG-TT (cast in situ sandwich wall with double glazed windows and terracotta roof tiles) (i.e. 45% less than 75 tonnes CO_2 e^- for the conventional envelope option (DB-XX-SG-CT)) and 127 tonnes CO_2 e^- for CB-XX-SG-MS (concrete block walls with single glazed windows and metal sheet roof) (i.e. 69% more than the conventional envelope option) (Fig. 3). This is mainly because of the fact that the operational energy consumption for heating and cooling varies from 250 GJ (CSW-PET-DG-TT) (i.e. 52% less than the conventional envelope option (521 GJ for DB-XX-SG-CT)) to 866 GJ (CB-XX-SG-MS) (i.e. 66% more than the conventional envelope option) (Table 4). Similar finding were obtained by other studies (Aldawi et al., 2013a,b; Gregory et al., 2008; Iwaro and Mwasha, 2013; Lam et al., 2005; Ross Maher and Mary Stewart, 2011), where operational energy consumption for heating and cooling during use stage of the house is highly influenced by the thermal performance and characteristics (e.g. material density, insulation, windows, dimensions, and orientation) of the envelope materials and climatic conditions.

The envelopes consisting of key elements such as clay bricks, concrete, insulation, timber, aerated concrete, light weight concrete, fibre board, metal sheet, terracotta, aluminium, and glass demonstrate different levels of thermal performance under similar geometrical design and climatic conditions. This is due to the inherent thermal mass of the materials, which is the ability of material to absorb and store heat energy, and overall heat transfer coefficient of materials (i.e. U value) (Table 5). U value refers to the rate of heat transfer due to conduction, convection and radiation through a given thickness of the material (Al-Homoud, 2005). Also the thickness of material, and the degree of insulation controls the rate at which heat is absorbed and released through thermal mass. The best way to achieve the highest performance of thermal mass is to place it towards internal face of the envelope with an external insulation (Reardon et al., 2013).

The aforementioned facts have been reflected in the current study as CSW-PET-DG-TT envelope option comprising of cast in situ concrete sandwich walls (CSW-PET) of high thermal mass (i.e. with a very low U value of 0.27 W/m^2 K), double glazed windows (i.e. with a moderate U value of 4.8 W/m^2 K), and terracotta roof tiles (i.e. moderate thermal mass and medium U value of 5.47 W/m^2 K) has the lowest GHG emissions due to very low (250 GJ) operational energy consumption for heating and cooling. On the other hand, the envelope CB-XX-SG-MS comprising of hollow concrete block wall (CB-XX) of low thermal mass (i.e. with a high U value of

2.7 W/m^2 K), single glazed windows (i.e. very high *U* value of 6.7 W/m^2 K), and metal sheet roof of very low thermal mass (i.e. very high *U* value of 6.3 W/m^2 K) has the highest GHG emissions due to very high (866 GJ) operational energy consumption for heating and cooling.

This research confirms that the change in roof material does not appear to affect the thermal performance of the envelope significantly and so the GHG emissions ($\leqslant$1 tonnes CO_2 e^-) because the U values of these three types of roof vary slightly and in all cases, the roof space is insulated (Crawford et al., 2010; Reardon and Downton, 2013).

The replacement of single glazed (*U* value of 6.7 W/m^2 K) windows with double glazed (*U* value of 4.8 W/m^2 K) windows appear to offer a wide range of savings for these options. For example, the GHG saving varies from 10 to 18 tonnes CO_2 e^- (2.5–4% of total GHG emissions) for different wall elements of the envelope. This variation is because of the fact that the performance of the window as an element of a house envelope does not only depend on its own thermal properties but it also depends on other multiple factors, including architectural design (i.e. location of the windows), and climatic conditions which have direct impacts on the performance of windows (Aldawi et al., 2013a,b; Peter Lyons et al., 2013). For similar architectural design and climatic conditions for all envelope options, the performance of windows is controlled by its own *U* value and the thermal properties of wall elements. The replacement of SG with DG could reduce up to 10 tonnes CO_2 e^- (2.5% of total GHG emissions) for wall elements (CSW-POL, and CSW-PET) with high thermal mass, and insulation and then up to 18 tonnes CO_2 e^- (4% of total GHG emissions) for wall elements (BV-XX, CB-XX, PCSW-XX, and TMB-XX) with low thermal mass, and insulation mainly due to heating and cooling operational energy savings. Another similar study also found that the energy saving potential of the use of double glazed windows varies significantly with wall properties and the location of the window that depends on the type of wall (Singh and Garg, 2009).

The third largest GHG emission source is the mining to material production stage for envelope elements where GHG emissions varies from 12 tonnes CO_2 e^- for TMB-XX-SG-CT(timber frame wall with single glazed windows and metal sheet roof), which is 60% less than the conventional envelope option (30 tonnes CO_2 e^- for DB-XX-SG-CT) to 51 tonnes CO_2 e^- for PCSW-XX-DG-MS (pre-cast light weight concrete sandwich wall with double glazed windows and metal sheet roof), which is 70% more than the conventional envelope option (Fig. 3). The main reason for this variation is the differences in the quantity and type of material resources consumed for the construction of 59 envelope options and also due to the variation in their initial embodied energy consumption during mining to material production stage (Monahan and Powell, 2011; Ramesh et al., 2010).

The reduction in material consumption does not necessarily translate into the reduction of carbon footprints. The envelope PCSW-XX-DG-MS with the highest GHG emissions and envelope TMB-XX-SG-CT, having lowest GHG emissions, both consumes 70% less materials than the conventional envelope option (133 tonnes for DB-XX-SG-CT)). Even though the material consumption for envelope option PCSW-XX-DG-MS is 70% less than the conventional envelope option DB-XX-SG-CT, the GHG emissions are 70% more because the former uses highly energy intensive materials such as light weight concrete (6.7 MJ/kg), galvanised steel track (38 MJ/kg), fibre cement boards (13.7 MJ/kg), polymer modified thin bed mortar and skim coat (23.7 MJ/kg), and metal roof sheet (43.9 MJ/kg).

The GHG saving benefits between 10 and 18 tonnes CO_2 e^- during operational energy (heat/cool) application due to

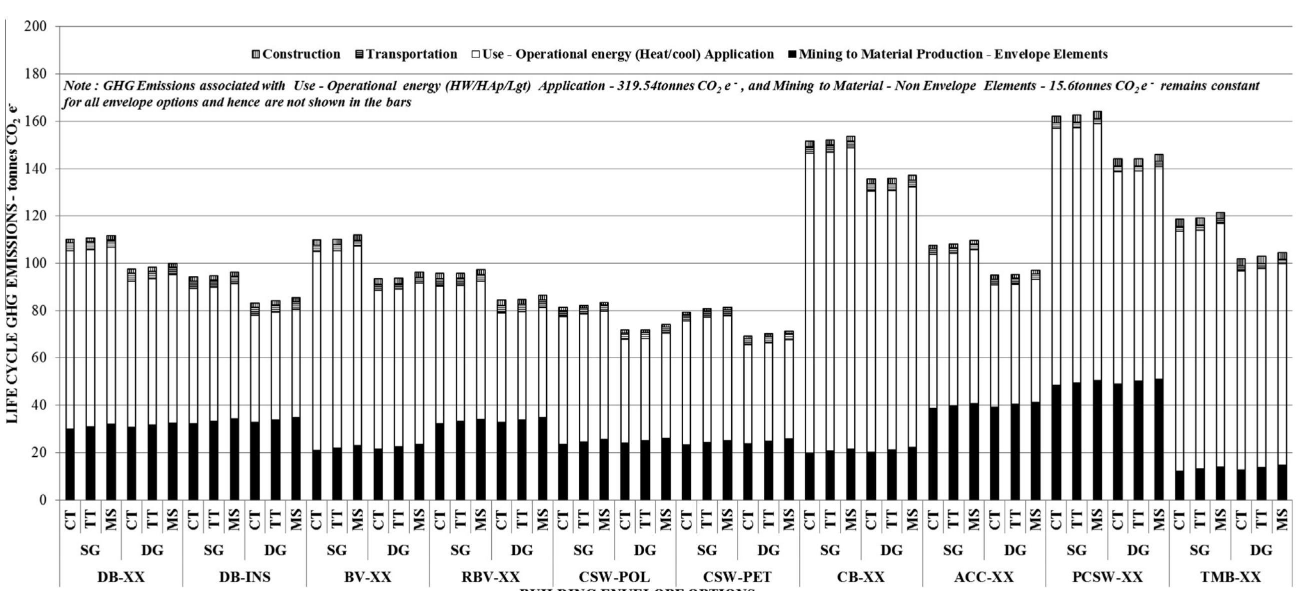

Figure 3. Stage wise GHG emissions for a typical house for all envelope options.

Table 4
Life Cycle heating and cooling energy consumption (GJ) for various envelope options.

Window	Roof ↓ Wall →	DB-XX	Diff (%)	DB-INS	Diff (%)	CSW-POL	Diff (%)	CSW-PET	Diff (%)	BV-XX	Diff (%)	RBV-XX	Diff (%)	PCSW-XX	Diff (%)	CB-XX	Diff (%)	ACC-XX	Diff (%)	TMB-XX	Diff (%)
SG	CT	521	–	364	−30.19	326	−37.41	312	−40.21	466	−10.60	369	−29.16	637	22.09	866	66.13	385	−26.22	569	9.13
	TT	520	−0.29	362	−30.49	326	−37.56	312	−40.21	463	−11.19	366	−29.90	634	21.65	865	65.83	382	−26.66	567	8.69
	MS	519	−0.44	364	−30.19	327	−37.26	313	−40.06	467	−10.46	369	−29.31	637	22.09	866	66.13	385	−26.22	574	10.16
DG	CT	451	−13.55	300	−42.56	267	−48.75	251	−51.84	377	−27.69	304	−41.68	540	3.53	781	49.78	313	−40.06	478	−8.39
	TT	450	−13.70	300	−42.42	263	−49.48	250	−51.99	374	−28.28	302	−42.12	536	2.80	778	49.19	310	−40.65	478	−8.39
	MS	452	−13.25	301	−42.27	269	−48.45	251	−51.84	381	−26.95	305	−41.53	539	3.39	779	49.34	313	−39.91	482	−7.51

Notes:
1. Diff. - % difference w.r.t. DB-XX envelope elements.
2. The life cycle energy demand for lighting (Lgt) (320.35 GJ), home appliances (HAp) (717.17 GJ), and hot water (HW) (1130.5 GJ) remains same for all envelope options.
3. Cooling thermostat setting for Perth (Zone 13) is 25 °C.
4. Heating thermostat setting for Perth (Zone 13).
  a. For living spaces (kitchen and other spaces used during waking hours) – 20 °C.
  b. For sleeping spaces (bedrooms and spaces closely associated with bedrooms).
    i. From 0700 to 0900, and 1600 to 2400 h – 18 °C.
    ii. From 2400 to 0700 h – 15 °C.

Table 5
Thermal mass and *U* values of various envelope elements.

Envelope Element	Thermal Mass	Insulation	U value W/m^2 K
CB-XX	Low	No	2.71
DB-XX	High	No	1.58
PCSW-XX	Very Low	No	1.07
TMB-XX	Very Low	Yes	0.71
DB-INS	High	Yes	0.67
RBV-XX	High	Yes	0.65
ACC-XX	Moderate	No	0.53
BV-XX	High	Yes	0.46
CSW-POL	Very High	Yes	0.36
CSW-PET	Very High	Yes	0.27
SG	Low	NA	6.7
DG	Low	NA	4.8
MS	Low	Yes	6.29
CT	High	Yes	5.81
TT	Moderate	Yes	5.47

replacement of single glazed windows with double glazed windows outweighs the additional emission of 0.6 tonnes CO_2 e^- associated with the mining to material production of additional glazing. The replacement of concrete roof tiles (CT) with TT and MS have been found to increase the GHG emissions of the mining to material production stage by only1 tonne CO_2 e^- and 2 tonne CO_2 e^- respectively mainly due to the fact that terracotta (3.7 MJ/kg) and metal roof sheet (43.9 MJ/kg) have higher embodied energy than concrete tiles (1.79 MJ/kg).

The GHG emissions for transportation and construction stages vary from 3.5 tonnes CO_2 e^- for CSW-POL and CSW-PET envelope options to 5 tonnes CO_2 e^- for DB-INS, RBV-XX, CB-XX, PCSW-XX, and TMB-XX envelope options. In the case of conventional envelope, the GHG emissions from transportation and construction are 4.9 tonnes CO_2 e^- (1.1% of total). The main reason for this variation is the gross weight of materials and distances between their sources and the construction site (e.g. concrete, bricks, timber, concrete roof tiles, and metal roof sheet) plus the energy consumed by the plant and equipment (i.e. fork lift, mortar mixer, and hand tools) for different envelope options.

The GHG emissions for non-envelope elements (15 tonnes CO_2 e^-) remain constant for all options as the amount of non-envelope materials such as ground slab, roof timber, floor and wall tiles, ceiling, and doors remains same for all envelope options.

The selection of an optimum envelope not only reduces GHG emissions associated with the mining to material production stage but GHG emissions associated with the operational energy for heating and cooling during use stage could also be potentially reduced.

4.2. Embodied energy analysis

The results of SLCA show that life cycle EE consumption for a typical house for 60 envelope options vary from 5.7 TJ for CSW-PET-DG-CT option (10% less than the EE consumption of a conventional envelope option (6.3 TJ for

Table 6
Embodied energy consumption for a typical 4 × 2 × 2 house in Perth for all envelope options.

Envelope Options		EE consumption - TJ									
		DB-XX	DB-INS	BV-XX	RBV-XX	CSW-POL	CSW-PET	CB-XX	ACC-XX	PCSW-XX	TMB-XX
SG	CT	6.3	6.1	6.2	6.1	5.8	5.8	6.8	6.3	6.9	6.3
	TT	6.3	6.1	6.2	6.1	5.9	5.8	6.8	6.3	6.9	6.3
	MS	6.3	6.1	6.3	6.1	5.9	5.8	6.8	6.3	7.0	6.4
DG	CT	6.1	5.9	6.0	5.9	5.7	5.7	6.6	6.1	6.7	6.1
	TT	6.1	5.9	6.0	5.9	5.7	5.7	6.6	6.1	6.7	6.1
	MS	6.2	6.0	6.1	5.9	5.8	5.7	6.6	6.2	6.7	6.2

DB-XX-SG-CT)) to 7 TJ for PCSW-XX-SG-MS option (11% more than the EE consumption of the conventional one) (Table 6). The main reason for this variation in EE consumption of these envelope options is the operational energy consumption during mining to material production and use stages.

Similar to GHG emissions trends, the EE consumption for operational energy (HW/HAp/Lgt) application during use stage and mining to material production for non-envelope elements remain same with a slight variation for transport and construction stages for all envelope options (Fig. 4).

Operational energy for heating and cooling is the second largest source of EE consumption, which varies between 0.6 TJ for CSW-PET-DG-TT (40% less than the conventional envelope option (1 TJ for DB-XX-SG-CT)) and 1.8 TJ for CB-XX-SG-MS (i.e. 80% more than the conventional envelope option (Fig. 4)). Like GHG emissions analysis, the main reason for this EE variation is the differences in the fossil fuel based energy consumption, which varies from 250 GJ for CSW-PET-DG-TT (52% less than the conventional envelope option (521 GJ for DB-XX-SG-CT)) to 866 GJ for CB-XX-SG-MS (66% more than the conventional one) (Table 4).

The third largest EE consumption source is the mining to material production stage for envelope elements where EE consumption varies from 0.14 TJ for TMB-XX-SG-CT (i.e. 68% less than the conventional envelope option (0.44 TJ for DB-XX-SG-CT)) to 0.69 TJ for PCSW-XX-DG-MS (i.e. 57% more than the conventional envelope option) to (Fig. 4). Similar to GHG emissions, the main reason for this variation in EE is due to the variation in the quantity of material resources consumed for the construction of the envelopes and their embodied energy consumption during mining to material production stage.

Both PCSW-XX-DG-MS with the highest EE consumption and TMB-XX-SG-CT with lowest EE consumption both consume 70% less material than the conventional envelope option (133 tonnes for DB-XX-SG-CT)). For the same level of material consumption, the EE consumption for PCSW-XX-DG-MS is higher than TMB-XX-SG-CT, due to the fact that the former uses more energy intensive materials than the latter. This is further supported by evidence that the galvanised steel, fibre cement board, double glazed windows, and metal roof sheet have high embodied energy consumption (Milne and Reardon, 2013). On the basis of comparison in terms of EE consumption between mining to material production (envelope elements) and operational energy (heat/cool) application, it is found that the concrete blocks (CB-XX) and timber frame (TMB-XX) walls with lowest EE consumptions during mining to material production stage have a significantly different EE consumption during operational energy (heat/cool) stage (Fig. 5). Aerated concrete blocks (ACC-XX) and pre-cast lightweight sandwich wall (PCSW-XX) have similar EE consumption during mining to material production but the

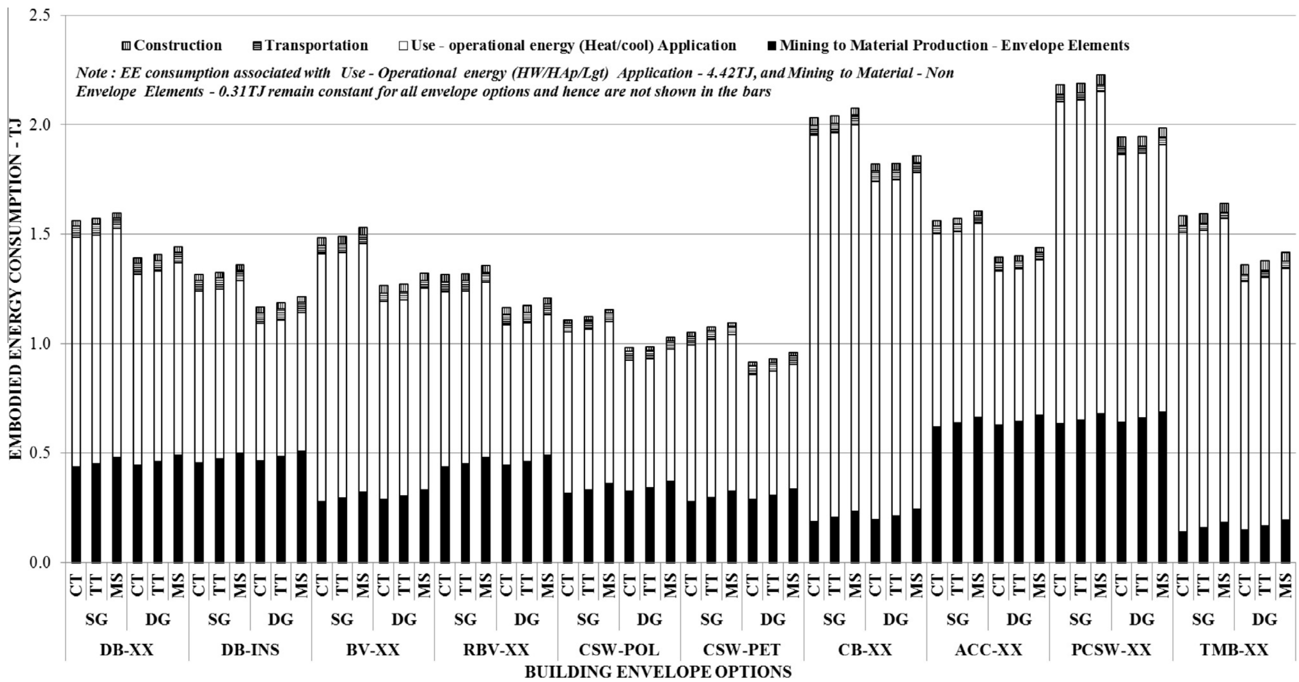

Figure 4. Stage wise embodied energy consumption for a typical house for all envelope options.

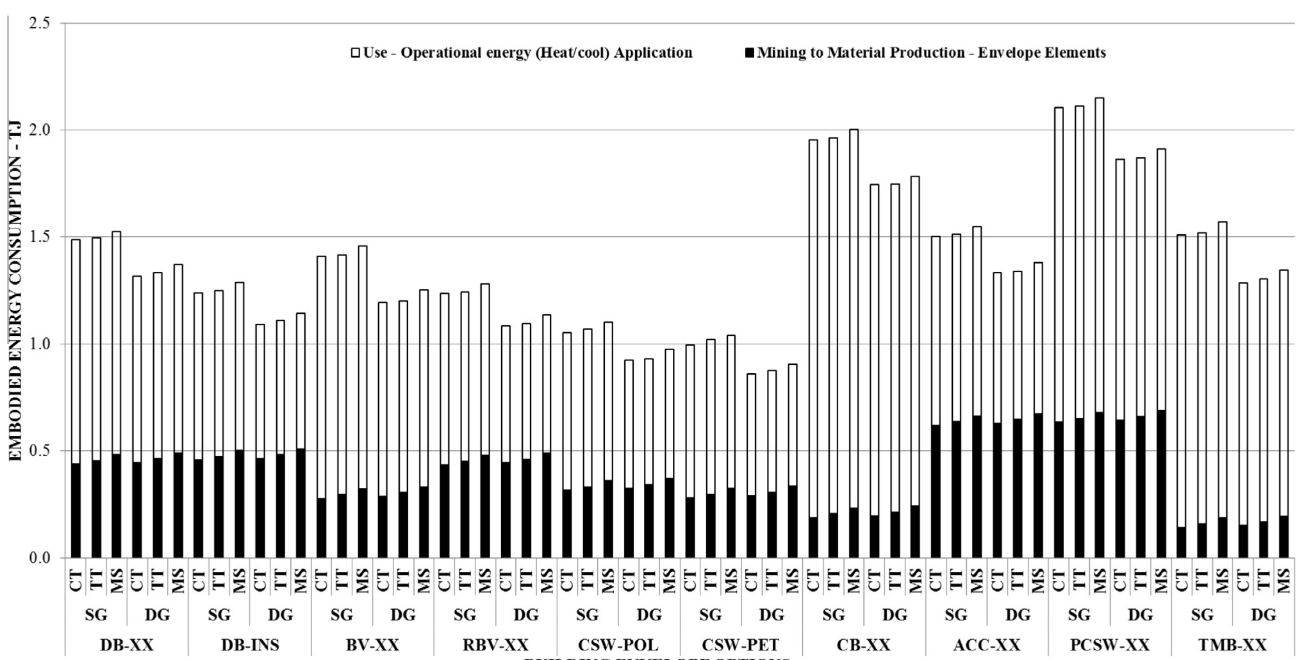

Figure 5. Embodied energy consumption for mining to material (envelope) and operational (heat/cool) application for all envelope options.

EE consumption of ACC-XX is significantly lower than the latter during operational energy (heat/cool) stage. Similarly, the reduction in EE consumption during operational energy (heat/cool) application of DB-INS is much higher than the reduction of EE during mining to material production stage due to incorporation of insulating material that in fact enhanced the thermal performance. The above results suggest that it is worth using materials of high thermal performance regardless of whether the materials are high energy intensive, as the operational savings (i.e. heating and cooling) are very high due to use of materials with high thermal performance. Similar conclusion was drawn by other studies as they found that 20–50% of operational energy savings were attained due to use of

Table 7
Summary of GHG emissions and EE consumption of a typical house in Perth for all envelope options.

	GHG Emissions tonnes CO_2 e⁻						Embodied Energy - TJ					
	SG-MS	SG-TT	SG-CT	DG-MS	DG-TT	DG-CT	SG-MS	SG-TT	SG-CT	DG-MS	DG-TT	DG-CT
PCSW-XX	498	497	496	480	478	478	7.0	6.9	6.9	6.7	6.7	6.7
CB-XX	488	486	486	471	470	470	6.8	6.8	6.8	6.6	6.6	6.6
TMB-XX	456	453	453	439	437	436	6.4	6.3	6.3	6.2	6.1	6.1
BV-XX	446	444	444	430	428	428	6.3	6.2	6.2	6.1	6.0	6.0
DB-XX	446	445	444	434	432	432	6.3	6.3	6.3	6.2	6.1	6.1
ACC-XX	444	442	442	431	429	429	6.3	6.3	6.3	6.2	6.1	6.1
RBV-XX	432	430	430	421	419	418	6.1	6.1	6.1	5.9	5.9	5.9
DB-INS	430	429	428	419	418	417	6.1	6.1	6.1	6.0	5.9	5.9
CSW-POL	418	416	415	408	406	406	5.9	5.9	5.8	5.8	5.7	5.7
CSW-PET	415	415	414	405	404	403	5.8	5.8	5.8	5.7	5.7	5.7

Legends: Conventional | Up to 5% lower | 5% - 10% lower | Higher

insulation, additional glazing, and high thermal mass materials (Crawford et al., 2010; Ramesh et al., 2010; Verbeeck and Hens, 2010).

The EE consumption of double glazed windows (DG) during mining to material production stage is 0.01 TJ higher than the single glazed windows (SG) because of the use of additional amount of glass and aluminium for double glazed windows. Similarly, the EE consumption due to use of terracotta tiles (TT) and metal roof sheet is 0.02 TJ and 0.04 TJ higher than the concrete roof tiles because clay and steel are energy intensive materials.

4.3. Summary of GHG emissions and embodied energy consumption results

The life cycle GHG emissions for all envelope options for construction and use of a typical house in Perth have been classified into 3 groups: envelopes having up to 5% less impacts than the conventional envelope option DB-XX-SG-CT, options with 5–10% less impacts and the options having more impacts than the conventional one (Table 7). Out of 59 envelope options, 40 envelope options have been found to have lower carbon footprint than the conventional envelope. The envelop option CSW-PET-DG-CT has been identified as the best option with the highest GHG mitigation potential.

The operational energy consumption results are consistent with some other studies as the use of double/triple glazed windows provide higher carbon reduction opportunities and the use of roof options alternative provide less energy-saving benefits (Crawford et al., 2010; Lai and Wang, 2011; Reardon and Downton, 2013). One local study on wall elements DB, BV, RBV, and TMB suggests that the use of RBV option could provide least amount of life cycle energy consumption (Gregory et al., 2008). Another local study found that the use of a reinforced concrete wall with polyurethane insulation core could reduce more life cycle energy consumption for heating and cooling compared to reinforced concrete wall with polystyrene insulation core, TMB, and BV wall elements (Aldawi et al., 2013a,b). DG windows offer superior thermal performance as compared to SG windows regardless of the use of any type of wall element (Aldawi et al., 2013a,b).

5. Conclusions

The detailed analysis suggests that a typical $4 \times 2 \times 2$ house in Perth having cast in situ sandwich wall with PET foam as core, double glazed windows and concrete roof tiles (CSW-PET-DG-CT) has the lowest life cycle GHG emissions and embodied energy consumption. The cast in situ concrete sandwich (CSW-PET) wall element provides an opportunity for resource reduction. As the PET foam which is used as insulating materials in cast in situ wall is made of post consumed polyethylene terephthalate bottles, the WA building industry in conjunction with Waste Authority and the Department of Environmental Regulation could develop guidelines to increase the recovery rate of solid waste by reducing the size of landfill. Considering the growing development of Perth houses, this CSW-PET-DG-CT envelope option could significantly reduce global warming impacts associated with the construction and use of clay brick house with single glazed windows and concrete roof tiles (conventional envelope option). Finally, this research will assist building industries and environmental regulators in the development of future GHG mitigation options.

The outcome of this study will provide useful information for Architects, designers, developers, and policy makers with a range of options for selection of a building envelope on the basis of the availability of the resources and cost-competitiveness.

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