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Application of life cycle assessment approach to deliver low carbon houses at regional level in Western Australia

Krishna Lawania[1] · **Wahidul K. Biswas**[1]

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Abstract

Purpose Australian building sector contributes 23% of the total greenhouse gas (GHG) emissions. This is particularly important for Western Australia (WA) as the houses here are made of energy- and carbon-intensive clay bricks. This research has utilized life cycle assessment (LCA) approach and cleaner production strategies (CPS) to design low-carbon houses in 18 locations in regional WA.

Methods An integrative LCA analysis of clay brick house has been conducted by incorporating energy efficiency rating tool (i.e., AccuRate) to capture the regional variation in thermal performance of houses in 18 locations in WA under five climatic zones. The data bank provided information on energy and materials for mining to material production, transportation of construction materials to the site of construction, and construction stages, while an energy rating tool has been utilized to generate location-specific information on energy consumption during use stage for developing a life cycle inventory for estimating life cycle GHG emissions and embodied energy consumption of a typical 4 × 2 × 2 detached house (i.e., 4 bed rooms, 2 bathrooms, and 2 cars/double garage). This approach has enabled us to determine the location-specific hotspot of a house in order to select suitable CPS for achieving reduced level of GHG emissions and embodied energy consumption.

Results and discussion Except for two hottest locations, the average life cycle GHG emissions and embodied energy consumption of houses at 16 locations in regional WA have been estimated to be 469 t of CO_2 equivalent (or CO_2 e-) and 6.9 TJ, respectively. Home appliances and water heating have been found to be the top two hotspots. The CPS options, including rooftop solar photovoltaic panels (PV), solar water heaters (SWH) integrated with gas based water heaters, cast in situ concrete sandwich wall, fly ash as a partial replacement of cement in concrete, and polyethylene terephthalate (PET) foam made of post-consumed polyethylene terephthalate bottles, have been considered to reduce GHG emissions and embodied energy consumption of a typical house in18 locations in regional WA. Excluding above two hottest locations, these CPS provide an opportunity to reduce GHG emissions and embodied energy consumption per house by an average value of 320 t CO_2 e- and 3.7 TJ, respectively.

Conclusions Considering the alarming growth rate of the housing industry in WA, the incorporation of optimum house orientation, rooftop solar PV, roof top SWH, cast in situ sandwich wall, partial replacement of cement in concrete with fly ash, and PET foam insulation core could reduce the overall GHG emissions and embodied energy consumption associated with the construction and use of clay brick wall house which in turn will assist in achieving Australia's GHG emission reduction target by 2050. The findings provide useful data for architects, designers, developers, and policy makers to choose from these CPS options based on existing resource availability and cost constraints.

Keywords Cleaner production strategies · Embodied energy · GHG emissions · Life cycle assessment

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✉ Krishna Lawania
krishna.lawania@curtin.edu.au

[1] Sustainable Engineering Group, Curtin University, Perth, Australia

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Abbreviations

AUP	Australian Unit Process
BCA	Building Council of Australia
C&D	Construction and demolition
CPS	Cleaner production strategies
EE	Embodied energy consumption
EPS	Expanded polystyrene
EUP	Ecoinvent Unit Process
GHG	Greenhouse gas
LCA	Life cycle assessment
LCI	Life cycle inventory
MCS	Monte Carlo simulation
PET	Polyethylene terephthalate
PV	Photovoltaic
PV-GC	Photovoltaic grid connected system
SWH	Solar water heater
WA	Western Australia

1 Introduction

Australia's current per capita carbon footprint (19 t CO_2 e-) and ecological footprint (6.3 global hectares) are significantly higher than the global average (Garnaut 2008; WWF 2014). In addition, the population is expected to increase to 48.3 million by 2061 and to 70.1 million by 2101 (ABS 2013). The rapid population increase coupled with an economic growth could increase Australia's overall energy demand to 7715 PJ in 2030 (ABARE 2010), and the GHG emissions could be increased by 70% of current level by 2050 (DOE 2014). The energy-intensive activities alone are making construction industries responsible for almost 23% (ASBEC 2007) of Australia's annual GHG emissions, and the energy used in buildings alone accounts for approximately 20% of the total energy consumption (ABCB 2015). On the other hand, this industry contributes significantly to the economy by creating employment opportunities for more than one million people per year and is worth more than $102 billion annually (or 8% of Australia's GDP) (ABS 2012).

Why construction industry accounts for major share of the national GHG emissions is that a majority of Australians are culturally accustomed to living in detached houses, of which 75% are made of conventional clay bricks (SOE 2011; Williams 2015). In addition, the number of houses in Australia is expected to increase from 8.7 million in 2010 to 12 million by 2030 which will result in the increase in carbon-intensive clay brick consumption. While these brick wall houses have a long life (NAHB 2007) and also require low maintenance, the veneer construction contributes little to the thermal performance of the building (Inglis 2013) that increases GHG emissions indirectly. The inclusion of a cement-based render on the internal face of brick walls of the house (Ravindrarajah and Mansour 2009) increases the material consumption. Also, there are considerable wastage of bricks due to design errors, poor operational planning, improper handling, and procurement during the construction of these clay brick houses (Crossin et al. 2014; Forsythe and Máté 2007; Gavilan and Bernold 1994). In Australia, about 20 million tons of construction and demolition (C&D) wastes are generated annually (DOE 2013) and the clay brick alone accounts for 16% of this C&D waste due to lack of reuse of end of life building materials (Reardon et al. 2013).

Australia is committed to achieve its 60% GHG reduction target by 2050 which makes housing industries as a potential avenue for reducing a considerable amount of this GHG emission (ASBEC 2007). This paper uses the life cycle assessment (LCA) method to discern life cycle GHG emissions and embodied energy consumption of construction industries (Asashish Sharma et al. 2011; Biswas 2014b; Monahan and Powell 2011; Ortiz et al. 2009) and to identify further environmental improvement opportunities to design low-carbon houses (i.e., the buildings which are specifically designed to achieve reduced level of life cycle GHG and embodied energy consumption). LCA is an environmental management tool that captures the overall environmental impacts of a product, process, or services from mining, production, assembly, operation, to end of life (ISO 2006a; Todd et al. 1999). Western Australia has been taken as a case study of this research as around 300 million clay bricks are annually produced for the construction of houses (Kelly 2015; Williams 2015) and about 460,000 new houses will be constructed in WA by 2030 (NHSC 2011). Also, carbon footprint of these houses could vary with locations in this largest state of Australia due to differences in thermal zones and the availability of materials for construction. No published LCA research to date has dealt specifically with low-carbon houses in various locations in Western Australia (WA). Therefore, this paper aims to discern strategies utilizing a life cycle assessment approach for constructing low-carbon houses in 18 different locations across Western Australia in order to reduce energy consumption as well as a waste of carbon-intensive materials. The current research considers the commonly used clay brick houses in WA as a case study. The innovative aspect of this research is that an energy rating tool has been integrated with the LCA analysis to capture the regional variation in GHG emissions and embodied energy consumption of clay brick houses in 18 locations in regional WA (Fig. 1) in order to develop location-specific decision-making strategies for delivering low-carbon houses in WA.

Firstly, this paper presents GHG emissions and embodied energy consumption of brick wall houses in 18 locations in WA. It also provides the breakdown of GHG emissions and embodied energy consumption in terms of inputs for identifying the "hotspot(s)" contributing to the significant amount of these impacts. Secondly, cleaner production strategies (CPS), including rooftop solar photovoltaic panels (PV), solar water heaters (SWH) integrated with gas-based water heaters, cast in situ concrete sandwich wall, fly ash as partial replacement of

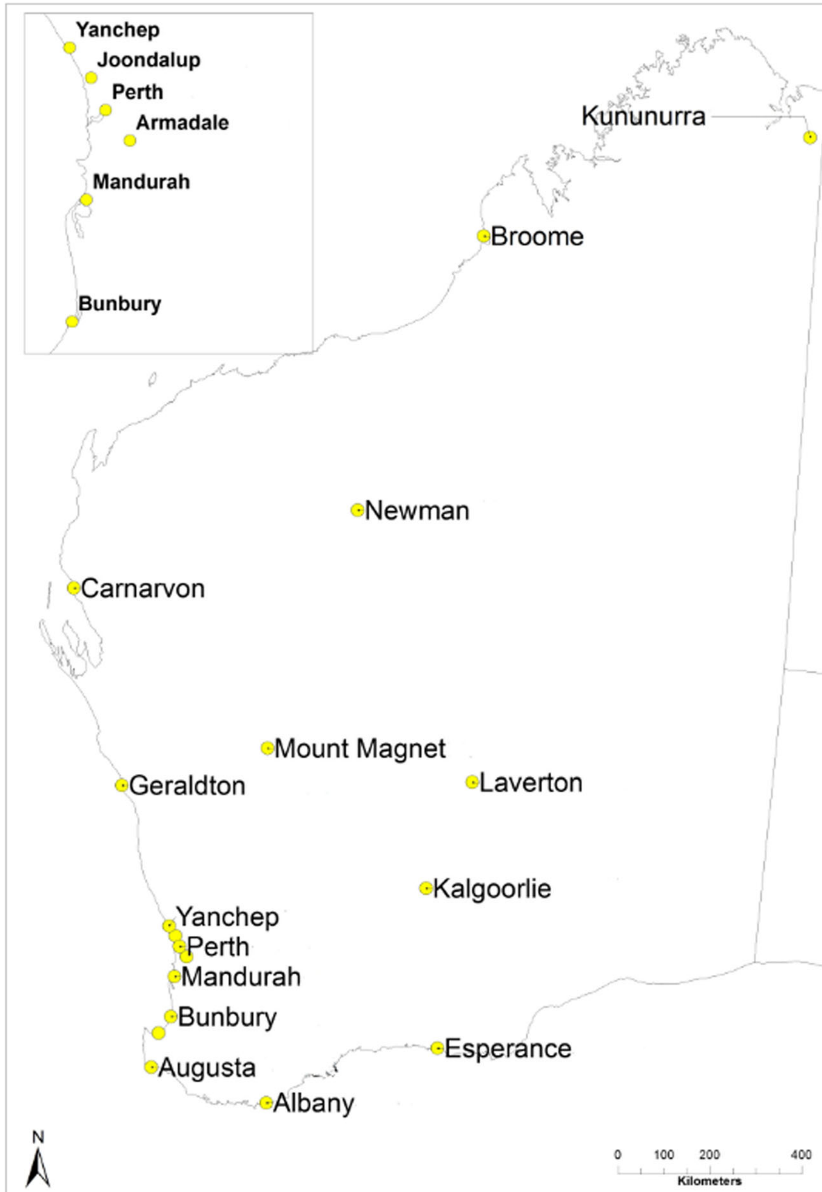

Fig. 1 WA map showing 18 locations in regional WA

cement in concrete, and polyethylene terephthalate (PET) foam made of post-consumed polyethylene terephthalate bottles, have been considered for reducing GHG emissions as well as embodied energy consumption of clay brick houses in 18 locations in WA under five climate zones. Finally, this paper presents as to how the application of LCA could assist in the delivery of low-carbon houses in 18 locations in WA.

2 Methods and materials

2.1 Building life cycle management framework

This framework integrates an LCA tool, a house energy rating tool, and cleaner production strategies to evaluate low-carbon houses in 18 locations in regional WA. This framework is the slightly revised version of a framework published by the lead author in Lawania et al. (2015).

The current analysis has taken into account the cleaner production strategies that could potentially improve the building envelope. Wong et al. suggested that the building envelopes (i.e., wall system, tiles, and glazing) have significant impacts on heating and cooling requirements and the trend of temperature rise due to climate change would require more energy for cooling leading to larger emissions (Wong et al. 2010; Guan 2009; Ren et al. 2011). Also, the cooling and heating load during the use stage would vary across 18 locations in regional WA mainly due to the variation in solar radiation, temperature, rainfall, humidity, and wind velocity (Aldawi et al. 2013a; Clune et al. 2012). As a result, the

Australian Building Code Board has divided the whole country into eight climate zones (ABCB 2014). This zone-wise thermal classification would facilitate realistic estimates of heating and cooling requirements in 18 locations in regional WA.

The heating, cooling, lighting, and hot water energy consumptions over the life of a house were calculated using the AccuRate house energy rating tool (V2.0.2.13SP1) software, which is Australia's nationally accredited energy rating assessment tool (Aldawi et al. 2013c; CSIRO 2013). These 18 locations fall into 5 of the 8 climate zones (1, 3, 4, 5, and 6).

- Zone 1—High humid summer and warm winter (Broome and Kununurra)
- Zone 3—Hot dry summer and warm winter (Carnarvon and Newman)
- Zone 4—Hot dry summer and cool winter (Kalgoorlie, Laverton, and Mount Magnet)
- Zone 5—Warm temperate (Armadale, Augusta, Bunbury, Busselton, Esperance, Geraldton, Joondalup, Mandurah, Perth, and Yanchep)
- Zone 6—Mild temperate (Albany)

Figure 2 shows how LCA has been integrated with the energy efficiency rating tool to capture the regional variation in thermal performance in these 18 locations to conduct a realistic LCA analysis of clay brick houses. This has enabled us to determine the location-specific hotspot(s) of the house or the process or inputs causing the most emissions in order to select location-specific CPS for reducing GHG emissions.

The databank consists of all data that were required to develop a life cycle inventory (LCI) for conducting a life cycle impact analysis. This provides data for developing inventories for both existing and environmentally friendly scenarios. Accordingly, the input data for developing a life cycle inventory for calculating environmental impacts of the house has been estimated. The design of a typical 4 × 2 × 2 (i.e., 4 bed rooms, 2 bathrooms, and 2 cars/double garage) detached house that followed the guideline of Building Council of Australia (BCA) has been utilized to calculate the amount of materials (e.g., steel, bricks) and energy (e.g., diesel, electricity) used in mining to material production, transportation of construction materials to the site of construction, and construction stages of the house. The information on dimensions of the rooms of the house, building materials, and orientation were incorporated into the energy rating tool software to determine the energy consumption of lighting, hot water, heating, and cooling during the use stage.

In this current research, this embodied energy includes the energy consumed by processes, including mining, manufacturing, transport, and the use of building and road (Biswas 2014a, 2014b). This is different to the approach being considered by Cellura et al. (2014) as this study had excluded the use stage from the calculation of embodied energy consumption.

The hotspot has been identified using LCA approach to determine relevant CPS to improve the inputs, processes, and technologies for attaining the reduced level of GHG emissions and embodied energy consumption of a house, known as

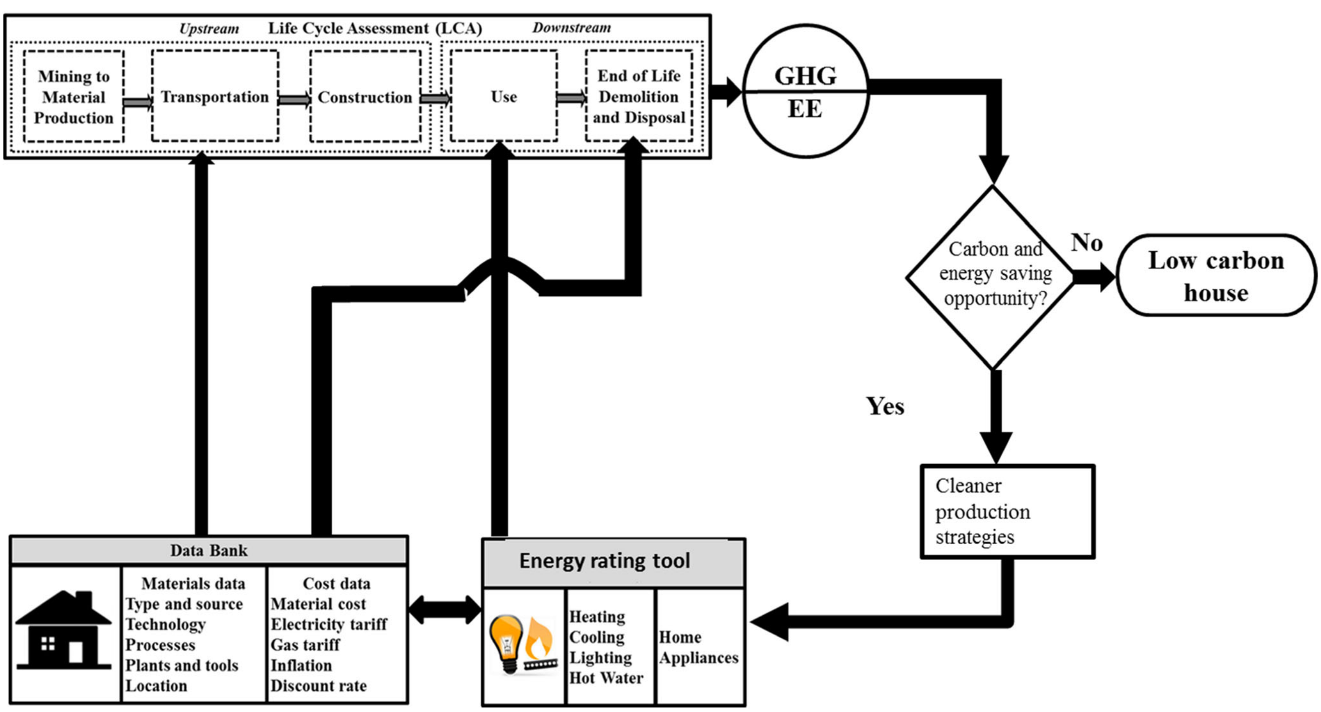

Fig. 2 House life cycle management framework

low-carbon house. Following this, an LCA has been carried out utilizing a revised life cycle inventory.

The entire process as discussed above has been continued for a number of times until a house with reduced levels of GHG emissions and embodied energy consumption was determined.

2.2 Life cycle assessment

This LCA has employed the four steps of ISO 14040-44 (ISO 2006a; ISO 2006b): (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation (as presented in the "Results and discussion" section of this report).

Goal and scope The goal is to determine the amount of life cycle GHG emissions and embodied energy consumption that can be reduced during the pre-construction, construction use/operational and disposal stages of a house using cleaner production strategies for with and without climate change scenarios. In order to conduct this LCA, a unit is selected to which all the GHG emissions and embodied energy consumption calculations relate, and this is known as the "functional unit." The functional unit of this current research is a typical 4 × 2 × 2 detached house equipped with standard features and amenities (Reardon et al. 2013) with a conditioned area of 153.6 m^2.

The current LCA considers a cradle to grave approach up to the end of life stage that mainly involves the disposal of construction and demolition waste of construction and demolition wastes.

The "mining to material production" stage includes inputs used during mining, processing, and production of construction materials (e.g., concrete, steel, glass).

The "transportation of construction materials" stage is the transportation of various construction materials from nearest producers, fabricators, retailers, and quarry to the construction sites. The mode of transportation and the distances between the suppliers and construction sites to supply inputs during the construction stage would vary with locations, which have been taken into account in this LCA analysis.

The "construction stage" includes energy consumption in construction processes, including site clearing, excavation and filling, concrete pouring, shuttering, mortar preparation for brick work and rendering, fork lift, loading construction materials, operating various hand tools, and the transportation of construction waste to landfill.

The "use stage" includes energy consumption of end-use appliances of each house, including lighting, home appliances, hot water, heating, and cooling. The duration of the use stage of the house has been considered the same as the lifetime of the house (i.e., 50 years) (Biswas 2014a; Islam et al. 2014).

The "end of life demolition and disposal stage" includes the energy consumption for crushing house and the transportation of demolition waste to landfill.

GHG emissions and embodied energy consumption have only been considered for this study as these are two predominant impacts (i.e., 23% of the total GHG and 20% of the energy consumption) that had resulted from the building industry in Australia (ASBEC 2007; ABCB 2015; Monahan and Powell 2011). Other associated environmental impacts, including acidification, eutrophication, human toxicity, and eco-toxicity, were excluded as discrepancies were found for these regional and local impact categories (Islam et al. 2015; Yoshida et al. 2013). According to Finkbeiner et al. (2011), this research considers a few impacts in terms of an LCA, with the limited focus on two impact categories only, i.e., climate change and embodied energy consumption.

The loose furniture, plumbing, drainage and electrical services, sanitary ware, tapware and lighting fixtures, external site development such as pavement, landscaping, garage door, and wall painting activities have been excluded from this LCA analysis, as the use of these materials depends on consumer's choice and does not affect the design and performance of the house. The current LCA analysis is an attributional LCA, and the consequences that will occur due to the use of CPS is beyond the scope of this study.

Life cycle inventory A LCI consisting of detailed Bill of Quantities was prepared using architectural and structural plans and specifications of the house. Figure A.1 in the Electronic Supplementary Material document presents a plan of a typical 4 × 2 × 2 house of 243 m^2 with a standard wall height of 2.4 m and a conditioned area of 153.6 m^2. Table 1 presents the amount of materials used during the construction of a typical brick wall house in Perth.

The available published commercial data (Austral-Bricks 2014; BGC 2014; Boral 2014; Bunnings 2014; Hanson 2014; Holcim 2014; Hotfrog 2014; Masters 2014; Midland-Brick 2014; Yellow-Pages 2014) have been reviewed to determine the sources of available materials for constructing houses in 18 locations to work out the distance travelled to bring inputs to these locations. For example, there is no brick manufacturing facility in Broome, Carnarvon, Kununurra, and Newman and also some places such as Kununurra and Newman do not have an adequate supply of ceramic tiles, roof tiles, insulation, roof timber, and doors. It was thus assumed that these materials have been transported from the suppliers in the nearest cities. Table 1 shows the information on transportation of materials to the construction site during construction of a typical house in Perth.

In the case of construction stage, the data on energy consumption of machineries (e.g., bobcat, compactor, loader, forklift) and the type of tools used for construction of a typical house in Australia was obtained from a local builder Fozdar

Table 1 Materials, transportation, and energy used during the construction, use, and disposal of a typical 4 × 2 × 2 house with various wall materials

Material	Unit	Clay brick wall	Insulated clay brick wall	Cast in situ sandwich wall	Brick veneer wall	Reverse brick veneer wall	Concrete block wall	Aerated concrete block wall	Pre-cast lightweight sandwich panels	Timber frame wall
Nonenvelope elements										
Sand to make up levels for footings and ground slab	t	35.96	35.96	35.96	35.96	35.96	35.96	35.96	35.96	35.96
Polythene sheet	t	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Mesh reinforcement	t	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Ready mix concrete	t	78.35	78.35	78.35	78.35	78.35	78.35	78.35	78.35	78.35
Metal door frames	t	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Roof timber	t	4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13
Bat insulation for roof	t	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Gyprock boards and cornices	t	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
Door shutters	t	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Floor tiles	t	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47
Wall tiles	t	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Envelope elements										
External walls										
Face bricks	t	33.29	33.29	–	33.29	–	–	–	–	–
Utility bricks	t	29.32	29.32	–	–	35.83	–	–	–	–
Cast in situ concrete	t	–	–	31.01	–	–	–	–	–	–
Concrete blocks	t	–	–	–	–	–	36.08	–	–	–
ACC blocks	t	–	–	–	–	–	–	16.92	–	–
Structural timber frame	t	–	–	–	14.54	13.82	–	–	–	13.82
Gyprock board lining for internal face	t	–	–	–	1.09	–	–	–	–	1.09
Fiber cement board/weather board cladding	t	–	–	–	–	2.64	–	–	–	2.64
Pre-cast concrete sandwich panels	t	–	–	–	–	–	–	–	19.33	–
Internal walls										
Utility bricks	t	32.01	32.01	–	–	32.01	–	–	–	–
Cast in situ concrete	t	–	–	35.9	–	–	–	–	–	–
Structural timber frame	t	–	–	–	2.09	–	–	–	–	2.09
Concrete blocks	t	–	–	–	–	–	27.54	–	–	–
ACC blocks	t	–	–	–	–	–	–	9.58	–	–
Gyprock board lining	t	–	–	–	2.37	–	–	–	–	2.37
Pre-cast concrete sandwich panels	t	–	–	–	–	–	–	–	10.94	–
Insulation										
Wall Insulation	t	–	0.2	–	0.27	0.12	–	–	–	0.26
Moisture barrier	t	–	–	–	0.14	0.13	–	–	–	0.13
Polystyrene insulation core for cast in situ walls	t	–	–	0.33	–	–	–	–	–	–
Aluminum windows	t	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Roof tiles	t	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52
Others										
Cement, brickie sand, and lime for mortar	t	11.48	11.48	–	3.66	7.82	10.33	–	–	–
Polymer modified mortar	t	–	–	–	–	–	–	1.26	0.5	–
Metal lintels, columns, bracings, wall ties, and structural fixtures	t	0.58	0.58	–	0.06	0.58	0.58	0.58	0.06	0.17
Wire mesh for cast in situ walls	t	–	–	2.52	–	–	–	–	–	–
Metal tracks for tilt-up panels	t	–	–	–	–	–	–	–	0.56	–

Table 1 (continued)

Material	Unit	Clay brick wall	Insulated clay brick wall	Cast in situ sandwich wall	Brick veneer wall	Reverse brick veneer wall	Concrete block wall	Aerated concrete block wall	Pre-cast lightweight sandwich panels	Timber frame wall
Cement, plaster sand, and lime for rendering	t	10.54	10.54	–	–	10.54	13.86	–	–	–
Polymer modified render	t	–	–	–	–	–	–	16.77	5.5	–
Cart away of excavated soil, and construction waste	tkm	3409.05	3409.05	2284.05	2509.1	2959.05	3409.05	2959.05	2509.05	2509.1
Material transportation to site	tkm	8932.62	8938.62	7138.49	6832.8	8458.83	8073.82	6614.3	6228.54	5722.7
Energy consumption for plants and tools during construction activities	GJ	16.12	17.47	9.38	27.65	22.93	22.94	16.12	36.45	36.52
Energy consumption for heating, cooling, lighting, home appliances, and hot water during use stage	GJ	2666.90	2509.46	2461.85	2611.60	2514.84	3011.73	2530.20	2782.10	2714.52
Energy consumption for plants and tools during end of life demolition activities	GJ	22.72	22.72	36.735	24.078	24.078	26.73	20.065	31.425	23.46
Transportation for disposal of demolition waste	tkm	7189.96	7195.47	5884.44	5547.58	6812.26	6396.89	5206.71	4980.69	4586.67

Technologies Pty Ltd. (Yousaf M, Fozdar Technologies Pty Ltd., Hay St., Perth, personal communication, November 30, 2014) and local equipment hire companies (Coates-Hire 2014; Kennards 2014). Table 1 shows the energy used during the construction stage of a typical house in Perth.

AccuRate software has been used to develop the inventory for the use stage as it calculates the heating, cooling, lighting, and hot water energy consumptions over the life of the house (Table A.1). This is the benchmark software for energy rating (NatHERS 2012; Alam et al. 2009) which consists of an improved multi-zone air flow model (Ren and Chen 2010) and is equipped with necessary information and formulae to calculate heating, cooling, lighting, and hot water energy consumptions in 18 locations under five climatic zones in WA.

This software simulates the heat flows in and out of a house during every hour of every day of the year and have four major components such as weather files, occupancy settings, heat loads, and star rating scale. For energy rating calculations, Australia is divided into 69 climate zones, which are coordinated with Australian postcodes. In a given climate zone, the weather impacts on a house design are calculated on an hourly basis for full 1 year to develop weather files using 25 years weather data from Bureau of Metrology. Occupancy settings consist of occupancy hours, thermal comfort, and heating and cooling thermostat settings. While the heat loads refer to humidity and the heat generated by occupants and home appliances, the star rating is determined based on the combined annual heating and cooling energy requirement (MJ/m^2) per unit area of a house.

With the help of this AccuRate energy housing rating tool, the total energy requirements for heating and cooling were calculated for eight orientations (north, south, east, west, north-east, north-west, south-east, and south-west) for each location. In the case of two coldest places in WA (i.e., Albany and Augusta), an optimum heating and cooling energy requirement can be attained by positioning the house towards a north-west direction. Similarly, the optimum orientation is west facing for the houses in Armadale, Bunbury, Busselton, Esperance, Kalgoorlie, Laverton, Mandurah, Mount Magnet, Newman, and Perth, and is east facing for the houses in Broome, Carnarvon, Geraldton, Joondalup, Kununurra, and Yanchep, for achieving minimum energy consumption for heating and cooling. These orientations were considered in the energy model to estimate optimum energy consumption in these locations.

The energy required for home appliances was calculated using published energy usage data for Australian home appliances (AER 2014; EcoHub-Perth 2014; Riedy et al. 2013a; Strategies et al. 2008). The commonly used items such as a ducted evaporative cooler unit for cooling and natural gas heaters for heating have been considered (AER 2014; Milne et al. 2013).

Most importantly, it was also considered that higher loads are likely to occur for cooling, and lower loads could happen for the winter season in the future due to temperature increase associated with climate change. However, Wang et al. (2010) found that in a cooling dominated hot or warm climate or a cooling and heating balanced temperate climate, the increase in the cooling energy requirement is much greater than the decrease in the heating energy consumption when responding to the global warming. Due to this reason, a local study of residential buildings in South East Queensland by Seo et al. (2013) considered the impact of global warming on cooling energy consumption only. Also, a review of studies on impact of climate change on energy use in the built environment in different climate zones by Li et al. (2012) showed that the most significant adverse impact on energy use in the built environment would occur in the hot summer and warm winter climate zone where building energy use is dominated by cooling requirement.

On this basis, this study had considered the implications of climate change (CC) on cooling energy consumption over the life of the house which generated following two scenarios:

- Scenario without CC impact, where the climate change impact for increasing the cooling load has not been considered.
- Potential scenario (with CC impact), where the cooling energy consumption is expected to increase by a minimum of 2 to 3% and a maximum of 9 to 14% during 2010–2030 and a minimum of 5 to 8% and a maximum of 27 to 47% during 2030–2065 due to climate change (Wang et al. 2010).

The information on increased levels of cooling energy consumption due to CC impacts was used to estimate the increased amount of overall energy consumption for each location (Table A.2). An Australian study on the assessment of climate change impacts on the residential building heating and cooling energy requirement found that in a cooling dominated hot or warm climate or a cooling and heating balanced temperate climate, the increase in the cooling energy requirement is much more than the decrease in the heating energy requirement when responding to the global warming (Wang et al. 2010). As most of the locations studied under this research falls within the above climatic categories, the impact of global warming on only cooling energy consumption has been considered.

The input data for energy consumption per house for different tools and machinery, including breaker, excavator, and front end loader and transportation data for different modes of transports for demolition waste material from the site to landfill area in terms of tkm have been linked with the Australian Life Cycle Inventory (AusLCI) database for electricity production, diesel combustion, and different modes of transport in order to estimate GHG emissions.

The consistency of the inventory data for the stage-wise energy consumption pattern for most of these 18 locations (Table A.2) has been checked by comparing with another local study. For example, this study shows that water heating, home appliances, heating and cooling, and lighting would account for 42, 27, 19, and 12% of the total household energy consumption, respectively, over the life of the house in Perth, WA. A study conducted by the Office of Energy, Government of WA, in 2009 found that 31, 39, 26, and 4% of the total energy are consumed for water heating, home appliances, heating and cooling, and lighting, respectively. These results slightly vary from this current study due to the changes in energy policy in the recent years. For example, the decision to phase out incandescent lamp was taken in 2009 and the Australian government developed a national strategy to accelerate energy efficiency measures during the same period (BREE 2014; DOEWHA 2009). In addition, a good number of new renewable energy technologies have been added to South West Interconnected System (SWIS) grid very recently for supplying Perth's electricity (e.g., renewable share increased from 4.5% in 2007 to 9% in 2013) (IMO 2014).

The LCI data were entered into SimaPro 8.02 (PRé-Consultants 2013) LCA software. Each input was linked to relevant libraries in the SimaPro 8.02 software. The libraries in this software contain the emission factors of energy, materials, and the transportation of inputs for estimating the environmental impact. Australian Unit Process (AUP) emission factor databases have been selected to represent local conditions.

AUP database library has been used to calculate the GHG emissions from the production of construction materials, such as aluminum, structural and sheet steel, concrete, cement, lime, sand, polystyrene, polyethylene, roof timber, and glass (Grant 2011). In the absence of local data in the software database, new library databases have been created for mesh reinforcement and clay bricks by obtaining the information on raw material and energy consumptions from local reports (OneSteel 2014; Strezov and Herbertson 2006; TBA 2010). For example, the local emission factors of some materials such as concrete roof tiles, ceramic tiles, timber doors, glass wool batts, and gypsum board were unavailable, and so the raw data have been sought from local industries and also relevant reports were reviewed for developing emission databases or libraries of these products/inputs. When local information was unavailable for developing libraries of these materials, Ecoinvent Unit Process (EUP) libraries have been used for assessing GHG emissions (Hans-Jorg 2010). The AUP library has been used for emission factors (i.e., kg CO_2 e- per tkm where "tkm" is ton-kilometer travelled) for different modes of transports.

Out of 18 locations in WA, the electricity in Broom, Carnarvon, Mount Magnet, and Newman is generated from gas, while diesel is used for electricity generation in Kununurra and Laverton (DOF 2015a), and the rest are connected to SWIS. The emission database for gas- and diesel-based electricity production was created by obtaining the information from AUP database (Grant 2011). The database that was used to calculate the GHG emissions associated with the electricity consumption was sourced from AUP database (Grant 2011). The emission factors associated with diesel combustion were also used to calculate the GHG emissions from the production of machinery, including excavator, front end loader, fork lift, and compactor.

ATCO is the sole supplier of gas in most of the locations in WA (ATCO 2012; Harrington et al. 2008), except for these locations, including Augusta, Broome, Carnarvon, Esperance, Kununurra, Laverton, Mount Magnet, and Newman. However, the local builders, whose contact addresses have been given in Table A.3, confirmed that gas is used in these locations. AUP database for emission factor of the combustion of natural gas for heating for all locations has been considered (Grant 2011).

Finally, inventory data for end of life stage that includes the energy consumption for plants and tools during end of life demolition activities and their transportation for disposal of demolition waste has been presented in Table 1.

Impact assessment The GHG emissions and embodied energy consumption assessment of the house consists of two steps. The first step was classification that involves the separation of all greenhouse gases that were emitted during the life cycle of a house, and the second step was to convert these gases to CO_2 equivalent (CO_2 e-).

Once the inputs in the inventories have been linked to the relevant emission databases in the software, Australian GHG method and the Cumulative Energy Demand method, which are available in SimaPro 8.02, were used to determine GHG emissions and the embodied energy consumption of brick wall houses in18 locations in WA, respectively. SimaPro 8.02 software has also been used to develop process networks for determining the breakdown of GHG emissions and embodied energy consumption in terms of inputs in order to identify the hotspot(s).

2.3 Uncertainty analysis

There are uncertainties associated with the use of inputs and emission factors for estimating environmental impacts. The use of Monte Carlo simulation (MCS) would estimate the uncertainty in each input variable and predict the impact of that variable on the environmental impacts (Hung and Ma 2009; McCleese and LaPuma 2002). MCS is essentially a reiterative process of analysis and uses repeated samples from probability distributions as the inputs for models and produces a distribution of possible outcome values for 1000 iterations (Guo and Murphy 2012; PRé-Consultants 2013). This method provides the decision maker with a range of potential outcomes along with the predicted chance of their occurrence. Therefore, an uncertainty analysis of LCA results of this research has been carried out using an MCS.

The mean, standard deviation, and standard error of the mean of GHG emissions and EE of the building in 18 locations were determined by MCS (1000 runs, 95% confidence interval) which is built in Simapro LCA software (Goedkoop et al. 2013). The ratio between the standard deviation and the mean is the coefficient of variability or CV. It is an important parameter for assessing the data quality by the relative magnitude of the uncertainty. The 95% confidence interval has been chosen as this is typically used in Applied Science practices (e.g., LCA analysis) (Zar 1984; Goedkoop et al. 2013).

2.4 Application of cleaner production strategies

Following the LCA analysis, the hotspot(s) have been identified and accordingly, potential CPS have been developed for the areas with greatest GHG emissions within the house life cycle measured. Resource efficiency and cleaner production initiatives involve the continuous application of preventative strategies to processes, products, and services to increase efficiency and reduce risk to humans and the environment by increasing the productive use of natural resources, minimizing waste and emissions and are necessary components for achieving sustainable development (UNEP 1994; UNIDO 2002). The five cleaner production strategies which are considered to reduce undesirable environmental impacts and to improve resource efficiency of building envelop have been discussed briefly as follows (Nilsson 2007; UNEP 2015; Van Berkel 2007).

- Good housekeeping—involves the improved management practices which aim to fetch low hanging fruits first such as energy management, proper maintenance, and product scheduling
- Technology modification—involves the implementation of new technologies and the change in or substitution of hazardous process
- Product modification—involves the change in product features to reduce its life cycle environmental impacts
- Input substitution—involves the use of environmentally preferred and "fit for purpose" process inputs
- Reuse and recycling—on-site recovery and reuse of materials, energy, and water

2.5 Limitations

The limitations of this study are listed in the following:

- The technological advancements that may take place during this life time are unpredictable and are beyond the scope of this research and so the same technologies have been considered throughout the life time. However, this framework has the flexibility to incorporate any changes in the data that may be associated with the technological change.
- The amenities including heating, cooling, household electrical appliances, and lighting have been considered same for all 18 locations while they will, of course, vary with

income, family size, etc. However, this information was not obtainable and therefore we have considered this as a limitation of the research.
- The use of EUP emission databases for some of the material inputs in SimaPro may have either overestimated or underestimated the GHG emissions and EE consumption results. Therefore, MCS has been carried out to assess the uncertainties of the LCA results of the current research (Cellura et al. 2011).

3 Results and discussions

3.1 Life cycle GHG emissions assessment

The life cycle GHG emissions from mining to material production, transportation, construction, and use stages for a typical clay brick house of 243-m^2 area in 15 locations except for Broome Kununurra and Laverton are more or less same. Broome and Kununurra are the hottest places in WA, where the total energy consumption is about three times higher than the remaining locations mainly due to the increased cooling energy consumption.

Figure 3 shows that the life cycle GHG emissions of clay brick houses in 16 locations would vary from 415 t of CO_2 e- in Joondalup to 757 t of CO_2 e- in Newman. The average GHG emissions in these locations are 469 t CO_2 e-. The variation in GHG emissions is mainly due to variation in energy consumption in heating and cooling. The temperature varies from extremely hot in the North of WA (e.g., between 21.3 and 34.9 °C in Kununurra) to extreme cold in the South of WA (e.g., between 11.7 and 19.5 °C in Albany). The GHG emissions from heating are nil in Broome and Kununurra, but are the highest from cooling (i.e., 612 and 1670 t CO_2 e-, respectively). The GHG emissions from heating are the highest in Albany and Augusta (i.e., 54 t CO_2 e-) and lowest from cooling (i.e., 9 t CO_2 e-). The GHG emissions from water heating and transportation also vary marginally across these locations mainly due to variation in solar radiation and the variation in sources of construction materials, respectively.

Further investigation has been conducted to identify the hotspot(s) for determining the appropriate mitigation strategies. In the case of Perth, the home appliances that accounted for the largest share (39%) of the total GHG emissions have been identified as the main hotspot (Fig. 4a). The end of life stage accounts for a very insignificant portion (0.2%) of the total emissions. While water heating consumes more energy than the electricity-operated home appliances, the later contributes more GHG emissions than the former due to the use of fossil fuels as primary sources for electricity generation in regional WA.

Since same design and materials have been considered for house construction in all cities, the GHG emissions from mining to material production have not been found to vary. The breakdown of GHG emissions in terms of constructions materials has been presented in Fig. 4b to select the use of alternative construction materials to further reduce life cycle GHG emissions. Lawania et al. (2015) have found that the choice of materials is also important as it could significantly influence the energy consumption for heating and cooling during the use stage. In the case of Perth in this current study, clay bricks (33%), windows (22%), and concrete (19%) have been identified as the top three carbon-intensive materials. All

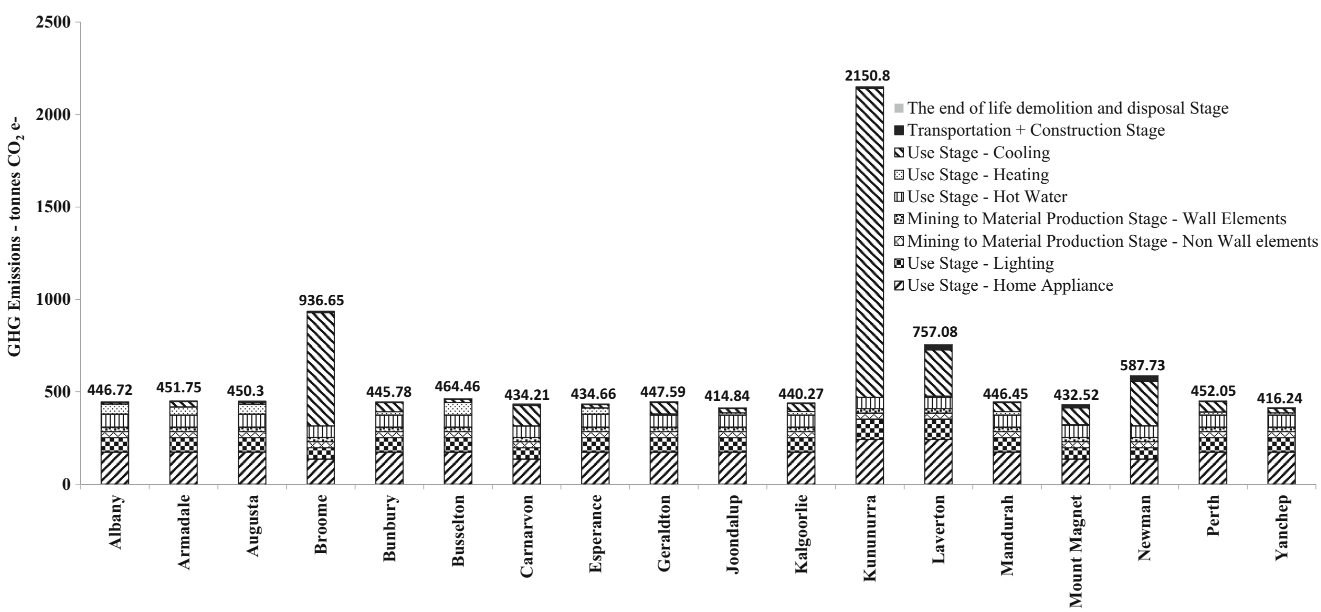

Fig. 3 GHG emissions (t CO_2 e-) of brick wall house in 18 locations in regional WA

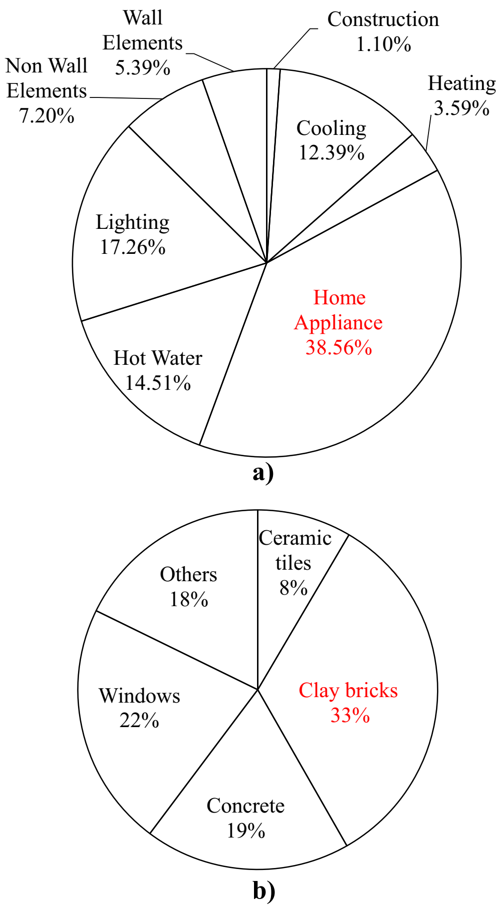

Fig. 4 Breakdown of GHG emissions in terms of inputs in Perth. **a** Mining to use. **b** Mining to material production stage only (end of life stage excluded as it accounts for very tiny portion of the total emissions)

other materials such as ceramic tiles, doors, windows, steel, timber, roof tiles, and mortar contributed to remaining GHG emissions (i.e., 25%).

3.2 Implication of climate change impact on building LCA

The climate change is expected to increase the cooling load during the life of the house, which could potentially increase the life cycle GHG emissions. Both low and high temperature rise scenarios were considered. In the case of low temperature rise scenario, it was found that the GHG emissions could be increased by a minimum of 0.1% in Albany and a maximum of 4.7% in Kununurra with an average incremental rate of 1.2%. In the case of high temperature rise scenario, the GHG emissions of a brick wall house in these locations can increase on an average by 4.7%. The GHG emissions of brick wall house in 18 locations for with and without climate change impacts (also known as a potential scenario) have been presented in Table 2.

3.3 Comparison with other similar studies

The results of the current research have been compared with similar type of contemporary research for validation purposes. The GHG emissions of WA's commercial building (i.e., 71 kg CO_2 e-/m^2/year) (Biswas 2014b) have been found to be 1.8 times more than the residential house (39.23 kg CO_2 e-/m^2/year) for the same system boundary (mining to construction, construction, and use stages). This is mainly because of the fact that the contribution of cooling load to life cycle GHG emissions of a commercial building is five times higher than the residential house (Biswas 2014b).

The total GHG emissions per square meter clay brick wall of this study (i.e., 47.4 kg CO_2 e-/m^2) has been found to be close to other values reported in Melbourne (40 kg CO_2 e-/m^2), which has the same system boundary (i.e., mining to construction stage) (TBA 2010).

3.4 Overall embodied energy consumption assessment

Embodied energy consumption appears to demonstrate similar trend as GHG emissions (Fig. 5). The embodied energy consumption for Broome and Kununurra are considerably higher than the remaining 16 locations as those two locations are the hottest places in Australia. The average embodied energy consumption of houses in the remaining 16 locations has been estimated to be 6.8 TJ and would vary from a minimum of 5.9 TJ in Joondalup to a maximum of 11.4 TJ in Newman. The main reason for this variation in embodied energy consumption is due to the variation in energy consumption for heating and cooling in these locations under five climatic zones. There is a significant variation in temperature in these locations as discussed in Sect. 3.1. The embodied energy consumption associated with heating energy is nil in Broome and Kununurra but is the highest for cooling (i.e., 9 TJ at Broome and 24.6 TJ at Kununurra). The embodied energy consumption of home appliances, lighting, and preconstruction stages is consistent across these locations, but the same varies marginally for hot water and construction stages mainly due to the variation in solar radiation and material resources availability.

Similar to GHG emissions, the home appliances (35.38%) and hot water (18%) have been identified as hotspots for embodied energy consumption (Fig. 6a). The end of life demolition and disposal stage here also accounts for a very negligible portion of EE consumption (i.e., <0.5%).

Clay bricks (35%) have been found to be the most energy-intensive construction material, followed by aluminium glazed windows (16%) and concrete (11%) in

Table 2 GHG emissions with and without climate change impacts considerations

Location	Emissions		
	GHG emissions (t CO2 e-) due to total energy consumption		
	Without CC impacts	With low CC impacts	With potential CC impacts[a]
Albany	445.95	446.50	448.19
Armadale	450.51	452.31	457.61
Augusta	449.53	450.11	451.91
Broome	935.88	973.27	1083.13
Bunbury	445.01	448.01	456.91
Busselton	463.69	464.69	467.89
Carnarvon	433.44	440.14	459.83
Esperance	433.89	434.99	438.29
Geraldton	446.82	450.62	461.82
Joondalup	414.07	415.57	419.87
Kalgoorlie	439.50	442.00	449.50
Kununurra	2150.00	2251.71	2550.52
Laverton	756.31	771.65	816.71
Mandurah	445.68	448.58	457.38
Mount Magnet	431.75	437.25	453.40
Newman	586.97	601.60	644.59
Perth	451.28	454.68	464.68
Yanchep	415.47	416.97	421.27

[a] For high-temperature rise scenario

the mining to material production stage (Fig. 6b). All other materials such as ceramic tiles, doors, windows, steel, timber, roof tiles, and mortar consume the remaining portion (i.e., 28%).

3.5 Uncertainty analysis

An uncertainty analysis of LCA results has been carried out using MCS for 95% confidence level. The standard deviation

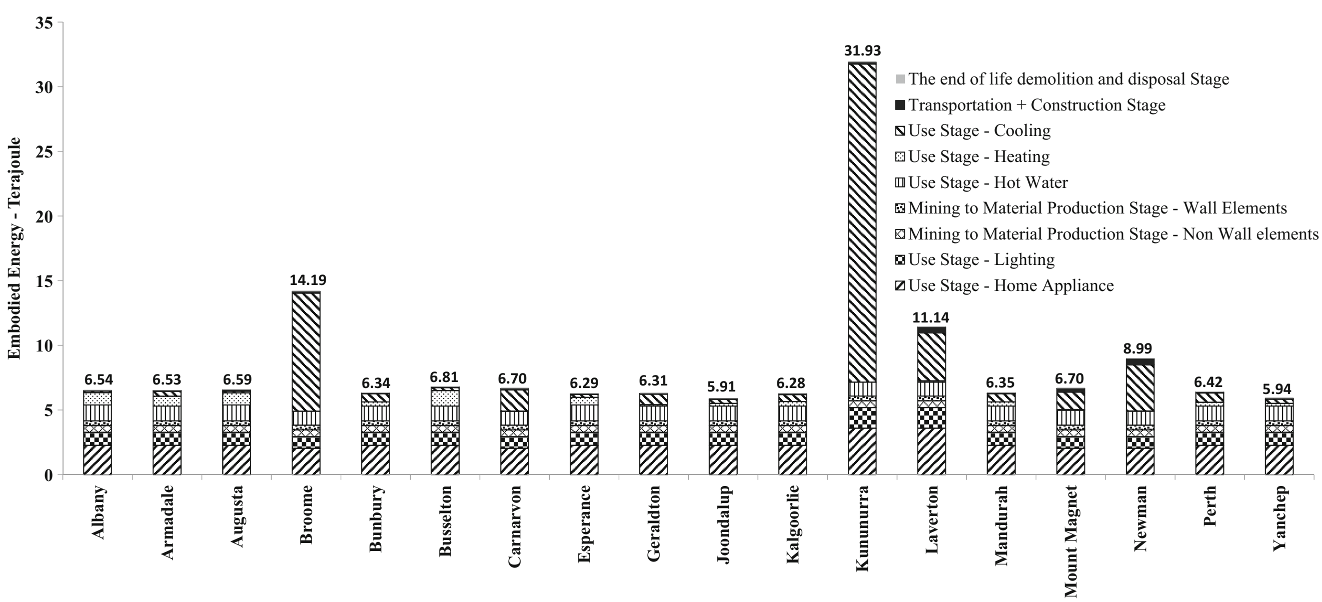

Fig. 5 Embodied energy consumption (TJ) of brick wall house in 18 locations in regional WA

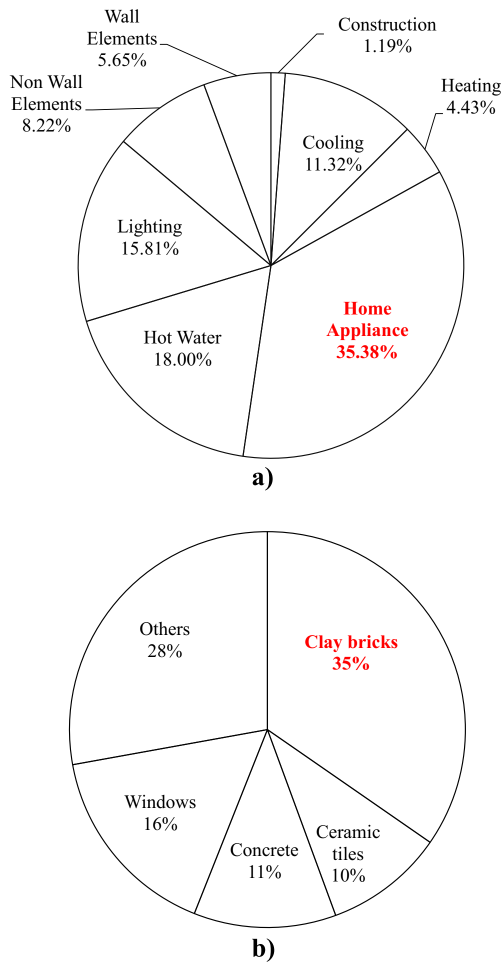

Fig. 6 Breakdown of embodied energy consumption in terms of inputs in Perth. **a** Mining to use. **b** Mining to material production stage

for GHG emissions is between 2 and 4% of the mean, and the embodied energy consumption varies between 0.3 and 3% of their respective mean values in 18 locations, thus statistically validating the LCA output of the current analysis (Table A.4 in the Electronic Supplementary Material).

4 Application of cleaner production strategy

The materials or energy inputs contributing to the significant portion of GHG emissions and embodied energy impacts during the life cycle stages of clay brick wall houses in 18 locations in WA have been identified as hotspots. Following the discussion in Sect. 2.4, five relevant CPS, which can potentially be implemented in the houses in 18 locations in WA to treat the hotspots have been selected on the basis of their availability and technical suitability (Table 3).

4.1 Technology modification strategy

Some portion of the conventional fossil energy has been considered to be substituted by renewable energy generated from PV system and solar water heaters.

Solar electricity for home appliances Grid-connected solar PV system has been considered as a substitute for grid electricity for not only to supply electricity to the house where it is installed but also to feed excess electricity into the grid. WA government has recently introduced a feed-in-tariff program for grid-connected solar PV system in 2008 (DOF 2015b). The most common roof top solar PV systems which are currently used by WA houses have capacities between 1.5 and 3 kW (CEC 2013; IMO 2014). Although the battery storage for this grid-connected solar PV system is peeking up recently, the inclusion of this storage system is outside the scope of this study. The area of the roof of a 4 × 2 × 2 double brick house is adequate to cover 22-m^2 solar panels of 3 kW (SEP 2015).

The average daily electricity production data of solar PV systems of three capacities (1, 1.5, and 3 kW) for 18 locations under 4 radiation zones was obtained from PV-GC spread sheet document produced by Clean Energy Council (CEC) (CEC 2011). The amount of life time electricity which can be generated using 1-, 1.5-, and 3-kW solar PV systems was calculated for all 18 locations, and this has also helped to work out the additional amount of grid electricity required to meet total

Table 3 CPSs for treating hotspots

Hotspots	CPS	Options recommended
Heating and cooling	Technology modification	Integrating solar PV with distribution grid
Concrete production	Input substitution	Partial replacement of cement in concrete with fly ash
Electricity consumption by home appliances	Technology modification	Integrating solar PV with distribution grid
Gas water heater	Technology modification	Integrating solar water heater with gas water heater
Clay bricks	Product modification	Replacing clay brick walls with cast in situ sandwich walls
Insulation core	Reuse and recycling	Replacing polystyrene insulation core with PET foam made of post-consumed PET bottles

household electricity demand. Accordingly, life cycle inventory has been revised using these energy values to run the LCA software to estimate the reduced level of GHG emissions and EE consumption. While performing this LCA study, the replacement of PV after its lifetime of 25 years was considered.

Table 4 shows that the life cycle GHG emissions saving associated with the substitution of 6.5 and 26% grid electricity (used for cooling, lighting, and home appliances) with solar PV electricity produced by a 1-kW PV system would be 55 and 111 t CO_2 e-, respectively. In the case of 1.5-kW solar PV, the GHG emissions saving associated with the substitution of 10% and 39% of the grid electricity would be 82 and 167 t CO_2 e-, respectively, whereas a 3-kW solar PV would reduce GHG emissions between 165 and 334 t CO_2 e- associated with the substitution of 20 and 78% grid electricity. The maximum GHG emissions saving will be for houses in Broome, Carnarvon, Kununurra, Laverton, and Newman due to maximum daily solar radiation in these locations.

In the case of embodied energy consumption, between 0.5 and 1.3 TJ can be saved due to the use of a 1-kW PV system and between 1.5 and 4 TJ can be saved due to the use of a 3-kW solar PV system.

Solar water heating The flat plate type solar water heater with thermosiphon circulation has been considered to reduce the demand for natural gas for the storage type gas hot water system. Australia's annual average solar radiation is more than 14 MJ/m^2, which shows that there is a potential for integrating solar water heater application with the gas water heater in WA (ABARE 2010).

The hot water module in AccuRate housing energy rating tool that consists of the information on solar radiation and reticulated water temperature for all 18 locations under 4 regions has been used to estimate the amount of natural gas that can be saved due to the use of solar water heater. The collector slope of 20° has been considered for simulation as this angle matches with the roof pitch of the house which means that these collectors can be placed directly on the roof and would avoid any additional requirements of supporting structure (Riedy et al. 2013b).

The simulation was carried out for all seven solar collector azimuths (0°, 30°, 60°, 90°, 270°, 300°, and 330°) for the same collector slope of 20°. From these simulation results, it was found that the maximum amount of energy saving can be obtained for positioning the collector at an azimuth angle of 330°. The amount of natural gas that can be conserved due to the use of solar water heater (azimuth angle 330°) for water heating in 18 locations has been presented in Table 5. Accordingly, life cycle inventory has been revised using these energy values to run the LCA software to estimate the reduced

Table 4 GHG emissions saving potential by using solar PV systems for houses in 18 locations in regional WA

Location	Original Life time grid electricity (MWh)	1.0-kW solar PV		1.5-kW solar PV		3.0-kW solar PV	
		% Reduction in electricity (MWh)	GHG saving potential (t CO_2 e-)	% Reduction in electricity (MWh)	GHG saving potential (t CO_2 e-)	% Reduction in electricity (MWh)	GHG saving potential (t CO_2 e-)
Albany	298.87	21.98%	57.56	32.97%	86.34	65.95%	172.69
Armadale	317.85	25.26%	70.35	37.89%	105.53	75.79%	211.06
Augusta	299.51	21.94%	57.56	32.90%	86.34	65.81%	172.69
Broome	1064.73	8.57%	62.34	12.86%	93.51	25.71%	187.01
Bunbury	336.41	23.87%	70.35	35.80%	105.53	71.61%	211.06
Busselton	307.83	26.09%	70.35	39.13%	105.53	78.26%	211.06
Carnarvon	426.44	21.40%	62.34	32.10%	93.51	64.19%	187.01
Esperance	306.33	21.45%	57.56	32.17%	86.34	64.34%	172.69
Geraldton	345.59	23.24%	70.35	34.85%	105.53	69.71%	211.06
Joondalup	311.24	25.80%	70.35	38.70%	105.53	77.40%	211.06
Kalgoorlie	322.76	24.88%	70.35	37.32%	105.53	74.64%	211.06
Kununurra	1399.67	6.52%	111.25	9.78%	166.87	19.56%	333.74
Laverton	433.48	21.05%	111.25	31.58%	166.87	63.15%	333.74
Mandurah	336.20	23.88%	70.35	35.83%	105.53	71.65%	211.06
Mount Magnet	379.08	21.18%	54.86	31.77%	82.29	63.55%	164.57
Newman	541.00	16.87%	62.34	25.30%	93.51	50.60%	187.01
Perth	340.04	23.61%	70.35	35.42%	105.53	70.84%	211.06
Yanchep	311.03	25.82%	70.35	38.73%	105.53	77.45%	211.06

Table 5 Net hot water energy demand without and with solar water heater with associated GHG emissions

Location	Energy consumption (GJ/year)		GHG emissions (t CO_2 e-)	
	Gas HWS	Solar HWS + gas	Gas HWS	Solar HWS + gas
Albany	24.14	13.34	70.40	42.30
Armadale	22.45	10.02	65.50	33.10
Augusta	24.14	13.34	70.40	42.30
Broome	21.18	5.72	61.80	21.50
Bunbury	22.45	10.02	65.50	33.10
Busselton	22.45	10.02	65.50	33.10
Carnarvon	21.18	5.72	61.80	21.50
Esperance	24.14	13.34	70.40	42.30
Geraldton	22.45	10.02	65.50	33.10
Joondalup	22.45	10.02	65.50	33.10
Kalgoorlie	22.45	10.02	65.50	33.10
Kununurra	21.18	6.65	61.80	23.90
Laverton	21.18	5.72	61.80	21.50
Mandurah	22.45	10.02	65.50	33.10
Mount Magnet	22.45	10.02	65.50	33.10
Newman	21.18	5.72	61.80	21.50
Perth	22.45	10.02	65.50	33.10
Yanchep	22.45	10.02	65.50	33.10

level of GHG emissions and EE consumption. This table also shows that the GHG emissions associated with the consumption of natural gas for with and without solar HWS.

The locations under solar radiation region 4 appear to have a minimum natural gas energy saving of 45%, while the locations under solar radiation region 2 have attained a maximum gas energy saving benefit of 73%. The average natural gas energy saving due to the use of solar water heater has been estimated to be about 58% of the natural gas energy required for water heating in four solar radiation regions.

Table 4 shows that the incorporation of the solar water heater on the rooftop that is integrated with gas-based storage-type water heater can mitigate GHG emissions between 40 and 65% with an average saving of 52% in 18 locations. The average GHG emission reduction is 34 t CO_2 e- per house. Similarly, the embodied energy consumption can be saved by a minimum of 41%, and a maximum of 66% with an average rate of saving of 53% of the embodied energy consumption associated with the use of gas-based storage-type water heater in 18 locations. The average embodied energy consumption saving has been estimated to be 0.6 TJ per house.

4.2 Product modification strategy

The use of alternative wall system has been considered to further reduce the life cycle environmental impacts (i.e., GHG emissions and embodied energy consumption) during mining to materials, construction, and use stages.

The major portion of heating and cooling energy consumed by the house is used for compensating the thermal energy losses or gains through walls, and so the improvements in thermal performance of the walls provide a 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 replacement of existing brick walls with less carbon-intensive alternative walls has been considered. The alternative material and methods of wall construction such as insulated clay brick, cast in situ sandwich, brick veneer, reverse brick veneer, concrete block, aerated concrete block, precast light weight concrete wall panel, and timber frame walls which have been recognized for use in Australian Built environment (Reardon et al. 2013) have been reviewed to replace the existing clay brick walls.

Accordingly, life cycle inventories consisting of materials, transportation, and energy use have been developed for seven alternative wall systems for a typical 4 × 2 × 2 house (Table 1). AccuRate energy rating tool was used for calculating the energy consumption of the use stage of this house for seven alternative wall systems (Table 1). The input data from the inventories have been inserted into the SimaPro software to calculate the embodied energy consumption and GHG emissions of the aforementioned house due to the use of seven alternative wall systems. As can be seen in Table A.5 in the Electronic Supplementary Material, the GHG emissions of a 4 × 2 × 2 house which is made of cast in situ sandwich wall has the lowest GHG emissions (6% less than the clay brick wall) as well as the lowest embodied energy consumption

(5.5% less than the clay brick wall) due to its better thermal performance and the reduced level of energy consumption during the construction stage (Aldawi et al. 2013b; Gregory et al. 2008; Reardon et al. 2013). Therefore, cast in situ sandwich wall has been considered as a potential replacement for clay brick wall in 18 locations in regional WA.

The cast in situ sandwich wall system consists of a welded wire space frame integrated with an expanded polystyrene (EPS) insulation core with thin layers of concrete sprayed on either side through shotcrete process after placing in position (QUESTECH 2013).

Other additional advantages of the use of this cast in situ wall are that it provides a combination of both lightweight and thermal mass, built-in insulation, resistance to earthquake and fire, low moisture absorption and constructability (Rezaifar and Gholhaki 2008). While cast in situ sandwich wall system is being used for building construction in Europe, the Middle East, and Asia, it is yet to gain popularity in Australia. There were some successful trials in the eastern states of Australia (QUESTECH 2013) where it was found that the cast in situ walls have complied with the BCA requirements; however, no initiative has yet been undertaken in WA to build houses using cast in situ sandwich walls.

In addition, the structural efficacy of these walls has been established through various studies. Structural, nonlinear dynamic, vertical in-plane forces and flexural behaviors of sandwich walls have been investigated to confirm that these walls can perform the same as the conventional pre-cast concrete walls (Carbonari et al. 2012; Gara et al. 2012; Kabir et al. 2004; Mashal and Filiatrault 2012; Mousa and Uddin 2012). Experimental and finite element analyses have confirmed the suitability of this system for slab application (Bajracharya et al. 2010), addressing fire safety issues (Cooke 2000; Lee et al. 2006) and demonstrating modularity capabilities (Sarcia 2004). Results of pseudo-static tests with horizontal loads and dynamic energy absorption and dissipations behaviors have been found to be promising for this sandwich wall system (Rezaifar and Gholhaki 2008; Ricci et al. 2013). Seismic performance testing for single and three-storey full-scaled buildings and four-storey scaled building model have revealed that a considerable resistance to earthquake vibrations could be attained by these sandwich walls (Rezaifar et al. 2009; Rezaifar et al. 2008; Ricci et al. 2012).

LCA was repeated for all 18 locations to estimate the life GHG emissions and embodied energy consumption of a cast in situ sandwich wall house for 18 locations. Tables A.6 and A.7 show the stage-wise detailed comparison between the brick wall and cast in situ sandwich wall houses in 18 locations in terms of GHG emissions and embodied energy consumption, respectively.

Table 6 shows the summary of GHG emissions reduction and embodied energy-saving benefits of the replacement of clay brick wall house with a cast in situ sandwich wall house in 18 locations in regional WA. The replacement could reduce GHG emissions by 4 and 16%, with an average saving of 8%. Similarly, this replacement could save embodied energy between 3.5 and 15%, with an average saving of 7%. From Table A.6, it is found that there is no reduction in GHG

Table 6 Summary of potential GHG emissions reduction and embodied energy saving due to wall replacement

Location	GHG emissions (t CO_2 e-)		Embodied energy (TJ)	
	Brick wall	Cast in situ sandwich wall	Brick wall	Cast in situ sandwich wall
Albany	445.95	415.92	6.51	6.04
Armadale	450.51	422.18	6.50	6.08
Augusta	449.53	418.07	6.56	6.07
Broome	935.88	843.85	14.16	12.82
Bunbury	445.01	421.66	6.31	6.00
Busselton	463.69	429.38	6.78	6.24
Carnarvon	433.44	410.17	6.67	6.36
Esperance	433.89	409.98	6.26	5.90
Geraldton	446.82	425.03	6.28	6.02
Joondalup	414.07	397.77	5.88	5.68
Kalgoorlie	439.50	410.88	6.25	5.86
Kununurra	2150.00	1830.09	31.90	27.19
Laverton	756.31	669.40	11.41	10.16
Mandurah	445.68	421.83	6.32	6.00
Mount Magnet	431.75	384.47	6.67	6.00
Newman	586.97	493.92	8.96	7.61
Perth	451.28	425.06	6.39	6.04
Yanchep	415.47	398.68	5.91	5.69

Table 7 Summary of GHG mitigation potential due to cleaner production strategies with and without climate change impacts

Location	Original GHG emissions (t CO_2 e-)		Mitigation potential using CPS (t CO_2 e-)						GHG emissions after implementation of CPS (t CO_2 e-)	
			Input substitution (IS)	Technology modification (TM)		Product modification (PM)		Reuse and recycling (RR)		
	Without CC impacts (O1)	With potential CC impacts (O2)		3.0-kW solar PV	SWH	Without CC impacts (PM1)	With CC impacts (PM2)		Without CC impacts (O1-IS-TM-PM1-RR)	With potential CC impacts (O2-IS-TM-PM2-RR)
Albany	445.95	448.19	2.66	172.69	28.10	30.03	30.02	1.86	210.61	212.86
Armadale	450.51	457.61	2.66	211.06	32.40	28.33	29.18	1.86	174.2	180.45
Augusta	449.53	451.91	2.66	172.69	28.10	31.46	31.46	1.86	212.76	215.14
Broome	935.88	1083.13	2.66	187.01	40.30	92.03	111.54	1.86	612.02	739.76
Bunbury	445.01	456.91	2.66	211.06	32.40	23.35	25.08	1.86	173.68	183.85
Busselton	463.69	467.89	2.66	211.06	32.40	34.31	34.37	1.86	181.4	185.54
Carnarvon	433.44	459.83	2.66	187.01	40.30	23.27	26.92	1.86	178.34	201.08
Esperance	433.89	438.29	2.66	172.69	28.10	23.91	24.49	1.86	204.67	208.49
Geraldton	446.82	461.82	2.66	211.06	32.40	21.79	24.69	1.86	177.05	189.15
Joondalup	414.07	419.87	2.66	211.06	32.40	16.30	17.24	1.86	149.79	154.65
Kalgoorlie	439.50	449.50	2.66	211.06	32.40	28.62	31.33	1.86	162.9	170.19
Kununurra	2150.00	2550.52	2.66	333.74	37.90	319.91	394.33	1.86	1453.93	1780.03
Laverton	756.31	816.71	2.66	333.74	40.30	86.91	104.69	1.86	290.84	333.46
Mandurah	445.68	457.38	2.66	211.06	32.40	23.85	25.43	1.86	173.85	183.97
Mount Magnet	431.75	453.40	2.66	164.57	32.40	47.28	53.99	1.86	182.98	197.92
Newman	586.97	644.59	2.66	187.01	40.30	93.05	109.09	1.86	262.09	303.67
Perth	451.28	464.68	2.66	211.06	32.40	26.22	28.69	1.86	177.08	188.01
Yanchep	415.47	421.27	2.66	211.06	32.40	16.79	17.78	1.86	150.7	155.51

emissions associated with energy used in home appliances, lighting and water heating and mining to material production of nonwall elements. The life cycle GHG emissions from mining to material of wall elements could be reduced by 21% in all 18 locations. The GHG emissions associated with heating could be reduced to a minimum of 41% and a maximum of 91% with an average reduction of 58%. The GHG emissions associated with cooling could be reduced up to 31% with an average reduction of 16%. The GHG emissions associated with the construction activities could be reduced to a minimum of 13% and a maximum of 72% with an average reduction of 35%. The embodied energy consumption would also follow similar reduction trends as shown in Table A.7. Clearly, the main reason for the overall reduction of energy demand for heating and cooling is mainly due to the improved thermal performance of cast in situ sandwich wall system and the avoidance of the use of energy-intensive clay bricks.

4.3 Input substitution strategy

The use of less carbon-intensive "fly ash" as a replacement of cement in concrete has been considered without affecting the structural integrity of the sandwich wall (known as "fit-for-purpose").

The partial replacement of cement with fly ash in concrete for house construction has been considered as a potential input substitution strategy. Studies in WA have demonstrated that up to 30 to 40% cement can be replaced with fly ash without compromising the physical and structural performance of the concrete (Lawania et al. 2015; Nath and Sarker 2011). About 25% GHG emissions saving in ready mix concrete production can be achieved by replacing 30% cement with flay ash (Ahmed 2014; Lawania et al. 2015; Nath and Sarker 2011). Although there are a considerable amount of GHG emissions associated with long-distance transportation of fly ash, a study in Australia found that there was still a net saving in GHG emissions due to partial replacement of cement by fly ash in concrete (O'Brien et al. 2009).

In order to use fly ash as a replacement for cement in concrete in the current LCA analysis, a separate emission factor database for concrete mix (i.e., 30% cement being replaced with fly ash) has been developed using the information (McLellan et al. 2011) has been created in the SimaPro 8.02 LCA software to estimate the life cycle GHG emissions and embodied saving benefits of the use of fly ash in concrete. It has been estimated that 2.66 t CO_2 e- of GHG emissions can be mitigated per house, and also, there is an embodied energy consumption saving potential of 20.37 GJ.

4.4 Recycling strategies

There is an opportunity to further improve the environmental performance of the cast in situ sandwich wall by using PET foam made of post-consumed PET bottles as a replacement of polystyrene core (Foti 2011; Intini and Kühtz 2011; Lawania et al. 2015; Saikia and de Brito 2014; Siddique et al. 2008). PET is a nondegradable material because the known microorganisms are unable to consume it due to its large molecules, and thus, the recycling of PET bottles into foam structure provides a durable insulation core for sandwich structures (Awaja and Pavel 2005; Japon et al. 2000). In Australia, the recovery and recycling rate of PET during 2013–2014 was 54.8% (APC 2014); therefore, the use of PET foam made of post-consumed PET bottles in WA building industries could potentially increase the recovery and recycling rate and reduce the generation of solid wastes.

The use of PET as core can not only reduce the use of virgin polystyrene but it also improves the thermal performance of the walls as compared to polystyrene insulation core (Intini and Kühtz 2011), and this replacement could reduce the energy consumption for heating and cooling of the house by 2 to 7% (Lawania et al. 2015).

The information on physical and thermal properties of PET were incorporated into AccuRate software to determine the thermal performance during the use stage which was used to modify the life cycle inventory to determine the environmental benefits of the replacement of polystyrene core with PET foam made of post-consumed PET bottles for use as core in cast in situ sandwich walls. The results of LCA show that the GHG emissions from mining to material production stage, cooling, and heating energy consumption could be reduced by 0.36, 0.9, and 0.62 t CO_2 e-, respectively, due to use of PET foam. The GHG emissions associated with transportation increases by 0.02 t CO_2 e- because PET foam is a denser material.

Similarly, the embodied energy consumption from mining to material production stage, cooling, and heating could be reduced by 0.04, 0.01, and 0.01 TJ, respectively, due to the use of PET foam.The implementation of this strategy alone could reduce GHG emissions by 1.86 t CO_2 e- per house and embodied energy consumption by 0.06 TJ per house.

Prior to the consideration of abovementioned packaging waste and by-products for CPS, their availabilities have been found out through literature review. According to Australian national plastics recycling survey held in 2013–2014, the recovery and recycling rate of PET bottles has been estimated to be 54.8% (APC 2014). On the other hand, only 42% of fly ash by-product is currently used in various infrastructure applications and the remainder is usually placed into onsite residue storage area or dumped into landfill sites, which are potentially causing serious environmental impacts (ADAA 2015). Therefore, there are still around 0.3 million tons of PET from packaging wastes and 8.1 million tons of FA from coal power plants available per year for utilization in the building industries as insulation and cementitious materials, respectively.

5 Summary of GHG and embodied energy savings due to use of CPS

Table 7 shows the GHG mitigation potential of five CPS comprising of partial replacement of cement in concrete with fly ash (input substitution), installation of a 3.0-kW roof top solar PV and roof top solar water heater (technology modification), incorporation of cast in situ sandwich walls (product modification), and the use of PET foam (reuse and recycling) for with and without climate change impacts (Table A.8).

It appears from Table 6 that the implementation of five CPS offers a total GHG saving of a minimum of 235 t CO_2 e- to a maximum of 696 t CO_2 e- per house with an average saving of 304 t CO_2 e- when the climate change impacts were not considered. When potential climate change scenario was considered, a minimum of 235 t CO_2 e- and a maximum of 770 t CO_2 e- per house with an average reduction of 312 t CO_2 e- were resulted due to the incorporation of aforementioned CPS.

Similarly, the implementation of above CPS offers embodied energy reduction saving between 2.7 and 12 TJ per house with an average value of 4.2 TJ for without climate change scenario and between 2.7 and 13 TJ per house with an average saving of 4.3 TJ could be obtained when considering potential climate change scenario for 18 locations in WA.

6 Conclusions

The integrated environmental assessment of houses in regional WA shows that there is a significant potential to reduce both life cycle GHG emissions and embodied energy consumption. The GHG emissions associated with the construction and use of a typical 4 × 2 × 2 brick wall house in 18 locations in regional WA could potentially be reduced by a minimum of 247 t CO_2 e- and a maximum of 938 t CO_2 e- by implementing CPSs, including solar PV system, solar water heater, fly ash in concrete, replacement of clay brick wall with cast in situ sandwich wall, and use of PET foam as insulation core. Apart from GHG emission mitigation, the application of CPSs can reduce the embodied energy consumption of a typical 4 × 2 × 2 brick wall house in 18 locations in WA to a minimum of 2.7 TJ and a maximum of 13 TJ.

Among five CPS, technology modification that involves the integration of rooftop solar PV and solar water heater has been found to have the highest GHG mitigation potential (i.e., 190–370 t CO_2 e-), followed by product modification involving the replacement of clay brick wall with cast in-situ sandwich wall (16–395 t CO_2 e-). Input substitution and on-site recovery and recycling, altogether have been found to have insignificant GHG mitigation potential (i.e., ≤4.5 t CO_2 e-).

This research will have a significant bearing on future housing planning as 460,000 houses will be constructed in regional WA by 2030. The application of aforementioned CPSs will thus assist in achieving Australia's commitment to meet GHG emissions mitigation target by 2050.

Sustainable and optimal use of infrastructure resources contributes to effective land use planning and development outcomes. This paper offers potential life cycle management tools for infrastructure planning to deliver low-carbon houses at the regional level. This research could potentially assist in the development of institutional framework by involving the Department of Planning, Western Australia, real estates, architects, developers and builders to adopt cleaner production strategies for planning for low-carbon houses. Similar analysis can be conducted for buildings in the commercial and industrial sectors.

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