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Cost-effective GHG mitigation strategies for Western Australia's housing sector: a life cycle management approach

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Abstract The demand of natural resources for Western Australia's (WA) housing sector is increasing due to economic and population growth, which will be a challenging task for Australia to achieve its GHG reduction target. This paper has assessed possible GHG mitigation options for Western Australia's houses, where energy-intensive clay brick walls and single-glazed windows are currently being used. A life cycle management framework has been used to determine cost-effective GHG emissions mitigation strategies. This framework integrates life cycle assessment tool, energy rating tool (AccuRate), and life cycle cost (LCC) analysis in order to ascertain environmentally and economically viable alternative building envelop for constructing a house in WA. The results show that the house made of cast in situ sandwich walls, recycled core materials and double-glazed windows, and equipped with solar energy system for electricity and water heating is the best option. This option has life cycle GHG emissions and LCC saving potentials of 7 and 20 %, respectively.

Keywords Life cycle management · Life cycle assessment · GHG emissions · Life cycle cost

Introduction

The GHG mitigation is an urgent need for Australia as the nation has committed to reduce emissions to 26–28 % on 2005 levels by 2030 during Paris UN Climate Conference 2015 (DOE 2015). The Australian building sector alone contributes quite significant portions of annual energy consumption (20 %) and GHG emissions (23 %) (ABCB 2015). This situation will get worse as more than 3.3 million houses will be built by 2030 (NHSC 2011) due to rapid population growth.

The application of GHG mitigation strategies in the building sector could significantly reduce the overall GHG mitigation (Estokova and Porhincak 2014). A number of improved energy efficiency measures have already been introduced to new Australian houses to mitigate GHG emissions (ABCB 2015). However, the prediction shows that these emissions will still be increasing at the rate of 1.3 % per annum in the residential buildings (ASBEC 2007). Therefore, it requires technological innovation to meet the challenging target of GHG reduction.

The studies found that the improvement in thermal performance of an envelope (walls and windows) of the house could provide significant energy and GHG emissions reduction opportunities (Bambrook et al. 2011). The envelope of a house separates the interior environment of the house from the exterior environment without compromising the functionality and associated structural requirements (Zeng et al. 2011). Studies to date suggest that the use of additional resources (e.g. insulation material, double-glazed windows, concrete) for enhancing the performance of the envelope could significantly reduce the overall environmental impacts in a cost-effective manner (Islam et al. 2014). A recent study in Melbourne found that the study building made of lightweight timber frame, rendered phenolic foam panels, and cassette floor system produces 78 % of the total GHG emissions of a conventional building (Carre and Crossin 2015). These aforementioned studies have used life cycle

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assessment (LCA) approach to estimate GHG mitigation from buildings.

Similarly, Lawania et al. (2015) and Lawania and Biswas (2016) have used LCA to determine GHG emissions mitigation options for the building industries in Western Australia using alternative building envelops. However, it warrants investigations as to whether low carbon houses are always least cost-effective options (Hossaini et al. 2015). Thus, the aim of this research is to identify cost-effective low carbon building envelopes for Western Australia's (WA) residential sector, where houses are made of energy-intensive clay bricks and also only 14 and 20 % of these houses have roof top solar water heater and solar photovoltaic system, respectively (Kelly 2015).

This paper is different from all published studies in a way that it has endeavoured to assess the cost-effective GHG emissions mitigation strategies for a range of building envelopes (i.e. 20 options with different walls and glazing types) comprising wall and window elements and energy efficiency measures for a semi-arid climate of Perth using a life cycle management approach. This current research has incorporated the use of AccuRate energy rating tool to estimate location-specific operational energy by taking seasonal variation in energy consumption into account to conduct a realistic LCM analysis.

This paper has estimated both life cycle GHG emissions and costs associated with the construction and use of a typical house in Perth for 20 envelope options comprising 10 wall options, and 2 window options with and without solar systems. A LCM framework that is built on Lawania et al. (2015) has been used to carry out LCA and LCC analyses of 20 envelop options. Finally, this paper has come up with the least cost GHG mitigation option or envelop for a house in WA.

Methodology

The life cycle management framework of Lawania et al. (2015) has been modified by incorporating life cycle costing tool to calculate environmental and economic benefits of a range of building envelops in order to find out the best possible option (Fig. 1).

This modified framework is the integration of life cycle assessment (LCA) tool with energy rating software (AccuRate), and life cycle cost (LCC) in order to determine the cost-effective GHG emissions mitigation strategies for the construction and use of a typical house in Perth for an operational life of 50 years (Crawford and Fuller 2011). Similar tools have been used by Meyer and Upadhyayula (2013) for life cycle management research.

The methodology has been broadly divided into two steps. Firstly, an LCA approach has been used to calculate GHG emissions (Čuček et al. 2015) for all envelope options following ISO14,040- 44 (ISO 2006) guidelines. Secondly, LCC analysis has been carried out to ascertain the least cost GHG mitigation option (Ingwersen et al. 2013) for construction and use of a house in Perth, WA.

Life cycle assessment

Goal and scope

The goal is to determine the GHG emissions from a range of building envelops during the construction and use of a typical house in Perth, WA. The functional unit for this study is the construction and use of a typical 4 × 2 × 2 house over a period of 50 years. The system boundary for this study is limited to construction and use stage only. The envelope options which have been considered for the construction of a typical house in Perth have been described below (Fig. 2).

- Ten possible wall options have been considered, 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 lightweight concrete sandwich panels (PCSW-XX), and timber frame (TMB-XX).
- Two window options, including single-glazed (SG) and double-glazed (DG) windows, with powder-coated aluminium frames have been considered.

The internal walls, concrete roof tiles and other fixtures, and support systems have been considered same for all envelope options. The loose furniture, services, accessories, and external site development have been excluded from this study as they are not linked to the basic structural and thermal performance of the house and also they vary with occupant's choice.

Life cycle inventory

The detailed drawings and product data sheets have been used to develop a life cycle inventory (LCI) of a typical house for each envelope option following AS1181–1982, which is Australian standard method of measurement of civil engineering works and associated building works (Standard 1982). The LCI of mining to construction stage consists of construction material and energy inputs,

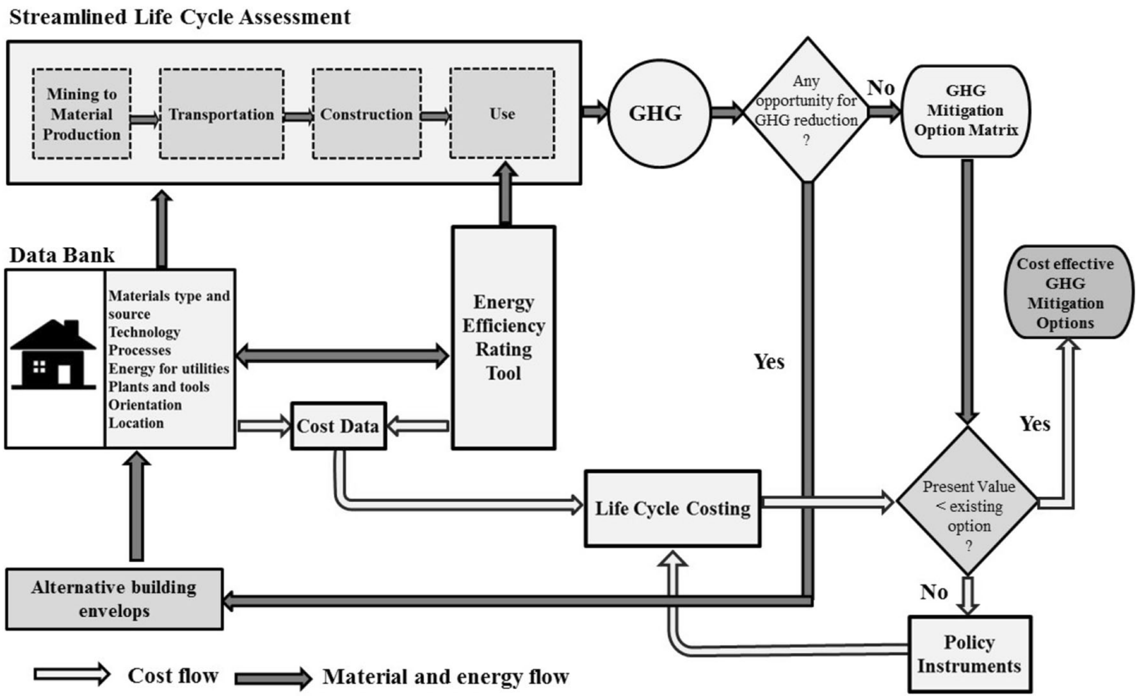

Fig. 1 Life cycle management framework

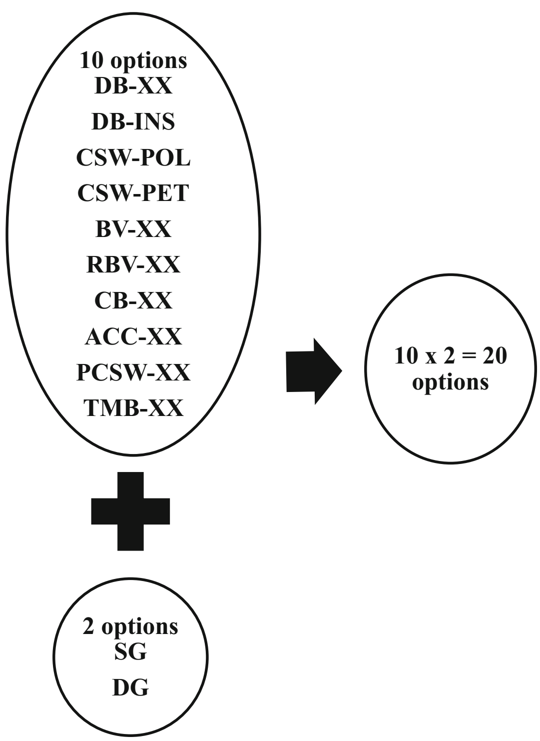

Fig. 2 House envelopes with different wall and window options

transportation of inputs to construction site, and then energy required for plants and tools on site during construction stage for estimating capital GHG emissions. In the case of last stage which is use stage, an AccuRate software has been used for estimating location-specific (i.e. local climate) operational energy consumption for heating, cooling, water heater, and lighting for all envelope options for estimating operational GHG emissions. The operational energy consumption for home appliances have been calculated on the basis of technical data sheets of appliances.

Impact assessment

In order to determine the GHG emissions associated with the construction and use of a typical house in Perth for each envelope option, the life cycle assessment has been carried out following ISO 14040-44 guidelines (ISO 2006). SimaPro 8.0.5.13 (PRé-Consultants 2015) LCA software that contains Australian emission databases of inputs for the building sector has been used to estimate GHG emissions. The demolition and disposal of wastes at the end of useful life of the house are not included for the LCA, hence the LCA is best termed as a streamlined LCA (SLCA) (Biswas 2014). In this paper, GHG emissions during mining to material production and construction stage have been termed as capital GHG emissions, and the GHG emissions due to energy consumption during the use stage have been termed as operational GHG emissions.

Interpretation

The interpretation that consists of the identification of hotspots, cause diagnosis, and the application of improvement measures, have been discussed in the "Results and discussions" section of this paper.

Life cycle costing

A detailed LCC analysis has been carried out following AS/NZS 4536:1999 (Standard 2014) in order to determine the cost effectiveness of less carbon-intensive envelope options in terms of life cycle cost (LCC_{xx-xx}) for a typical house in Perth using Eq. 1.

$$LCC_{xx-xx} = PV_{CapcostXX-XX} + PV_{RepcostRET} + PV_{Opncostxx-xx}, \quad (1)$$

where XX–XX represents various envelopes. The discounting converts the dollar value of costs and benefits of different periods to present value (PV) taking 2015 as a base year. The future costs have been estimated on the basis of current price using an inflation rate of 3 % per year (RBA 2015), and then the future costs were discounted at the rate of 7 % per year (DRDL 2012).

The PV of capital costs of labour, and building materials such as clay bricks, concrete, steel, timber, insulation material, cement, sand, moisture barrier, gypboard, fibre cement sheet, roof tiles, windows, door frames, timber doors, ACC blocks, concrete blocks, and their transportation to construction site have been considered in this LCC analysis.

The PV of operational costs for heating, cooling, hot water, home appliances, and lighting over 50 year of building have been determined using the information on electricity (DOF 2015) and gas (Alintaenergy 2015) utility prices in Eq. 2.

$$PV_{Opncostxx-xx} = \sum_{y=1}^{50} \frac{\text{Current price}_{(\text{electricity})} \times (1 + \text{inflation rate})^n}{(1 + \text{discount rate})^n} + \frac{\text{Current price}_{(\text{gas})} \times (1 + \text{inflation rate})^n}{(1 + \text{discount rate})^n} \quad (2)$$

The PV of replacement cost of renewable energy technologies (RET) have been considered as roof top solar photovoltaic system (SPS) (25 years) and SWH (13 years) have shorter life than the house (50 years).

Originally, the costs have been determined in Australian Dollar and then converted to American Dollar or USD (1AUD = 0.7229USD). The costs of both material and labour for the construction of a house for each envelope option were sourced from a widely accepted construction cost guide (Rawlinsons 2015).

The cost of painting, electrical works, sanitary, and plumbing works such as accessories, cabinets, soft furniture, garage door, home appliances, and external site development are excluded as they remain the same for all envelop options.

Limitations

There are few limitations due to the following considerations.

- The impacts associated with the end of life stage, and routine maintenance activities, which are not included in current study may have some minor impacts on overall GHG emissions and life cycle costing (Monteiro and Freire 2012).
- The resource availability of materials may change over time, which has not been factored into the analysis.
- In future, the construction technology and electricity generation mix may change. The consideration of these changes is beyond the scope of this paper.
- The exclusion of variation in inflation and discount rates may affect the accuracy of the life cycle cost outputs.
- The cost of demolition and disposal of wastes at the end of useful life of the house are excluded from the LCC analysis.

Results and discussion

Greenhouse gas emissions analysis for 20 envelop options

The findings of SLCA for 20 envelop options show that life cycle GHG emissions of a typical house vary from a minimum of 403 t CO_2 eq for CSW-PET-DG (cast in situ sandwich wall with PET insulation core, double-glazed windows) option [i.e. 9 % lower than the GHG emissions of a conventional envelope option (444 t CO_2 eq for DB-XX-SG or clay brick wall, single-glazed windows)] to a maximum of 498 t CO_2 eq for PCSW-XX-SG (pre-cast lightweight concrete sandwich wall with single-glazed windows) option (i.e. 12 % higher than the GHG emissions from the conventional one) (Table 1). The variation in operational energy consumption during use stage (2400

Table 1 Capital and operation GHG and costs of various envelopes

Options	Capital GHG t CO_2 eq	Operational GHG t CO_2 eq	Life cycle GHG t CO_2 eq	Capital cost USD$	Operational cost USD$	Life cycle cost USD$
DB-XX-SG	51	394	444	161,414	49,739	211,153
DB-XX-DG	51	381	432	166,923	48,376	215,299
DB-INS-SG	53	376	428	163,540	47,406	210,945
DB-INS-DG	53	364	417	169,048	46,190	215,238
CSW-POL-SG	43	373	415	149,711	46,938	196,649
CSW-POL-DG	43	363	406	155,219	45,862	201,081
CSW-PET-SG	42	371	414	146,268	46,730	192,998
CSW-PET-DG	43	360	403	151,777	45,610	197,387
BV-XX-SG	41	403	444	146,687	49,856	196,543
BV-XX-DG	42	386	428	152,195	48,128	200,324
RBV-XX-SG	53	377	430	162,010	47,528	209,538
RBV-XX-DG	53	365	418	167,519	46,295	213,813
PCSW-XX-SG	69	427	496	157,610	52,659	210,269
PCSW-XX-DG	70	408	478	163,118	50,766	213,884
CB-XX-SG	40	446	486	173,124	55,562	228,686
CB-XX-DG	41	429	470	178,633	53,895	232,528
ACC-XX-SG	58	383	442	176,588	48,049	224,638
ACC-XX-DG	59	370	429	182,097	46,678	228,775
TMB-XX-SG	33	420	453	147,603	51,714	199,317
TMB-XX-DG	33	403	436	153,112	49,943	203,054

Cost is based on 3 % inflation rate and 7 % discount factor. Cost data source: (Alintaenergy 2015; DOF 2015; Rawlinsons 2015)

GJ–3050 GJ) and resource consumption during mining to material production stages (167 t–262 t) could be the main reasons of this variation in GHG emissions across these envelope options.

Further investigation shows that the GHG emissions during use stage are the highest for all envelope options. The GHG emissions vary from 361 t CO_2 eq for CSW-PET-DG (8.5 % lower than conventional envelope DB-XX-SG) to 446 t CO_2 eq for CB-XX-SG (13 % higher than the conventional envelope) (Table 1). The operational energy consumption of an envelope option (PCSW-XX-SG) with the highest GHG emissions is 4.3 % more than the conventional option (2689 GJ), while the option (CSW-PET-DG) with the lowest GHG emissions consumes 10 % less energy than the conventional envelope option.

The WA electricity mix is currently dominated by coal and natural gas (DOF 2015), which is one of the main reasons for the highest GHG emissions during the use stage. These results show that double-glazed windows offer operational GHG savings between 10 and 18 t CO_2 eq (2.5–4 % of total GHG emissions) for different envelope options. This variation in energy saving is mainly due to various factors including thermal properties of the wall elements and the locations of the windows in the house (Peter Lyons et al. 2013). The double-glazed windows are usually found to be more effective wall elements (e.g. BV-XX, CB-XX, PCSW-XX, and TMB-XX), where up to 18 t CO_2 eq (2.5 % of total GHG emissions) can potentially be reduced and up to 10 t CO_2 eq (4 % of total GHG emissions) can be saved for CSW-POL and CSW-PET. Other studies have also confirmed that the thermal performance and characteristics of the envelope materials (e.g. material density, insulation, windows, dimensions, and orientation) and climatic conditions influence the operational energy consumption for heating and cooling significantly (Islam et al. 2015).

The capital GHG emissions during mining to material production and construction stages are the second largest source of GHG emissions for all envelope options. These GHG emissions vary from 33 t CO_2 eq for TMB-XX-SG (timber frame wall with single-glazed windows) [i.e. 35 % less than the conventional envelope option (51 t CO_2 eq for DB-XX-SG)] to 70 t CO_2 eq for PCSW-XX-DG (pre-cast lightweight concrete sandwich wall with double-glazed windows) (i.e. 38 % more than the conventional one) (Table 1). The variation in the amount of material and embodied energy consumption across 20 envelope options has been appeared to be the main reason for variation of this hotspot (Monahan and Powell 2011).

The results show that the material consumption reduction does not necessarily reduce the GHG emissions. The envelope (i.e. PCSW-XX-DG) with the highest capital

GHG emissions and the one (i.e. TMB-XX-SG) with the lowest capital GHG emissions consume 31 and 36 % less materials than the conventional envelope option (262 t for DB-XX-SG).

In the case of PCSW-XX-DG, it does not only consume 31 % less materials than the conventional envelope option (DB-XX-SG), but it also produces 38 % less capital GHG emissions due to use of less energy-intensive materials such as lightweight concrete, galvanized steel track, fibre cement boards, polymer-modified thin-bed mortar, and skim coat for this envelope option. The cost of these lightweight materials may be high, and therefore, it is important to determine as to whether the investment on capital-intensive materials would reduce the operational cost during the use stage to attain economic viability of this option.

The capital GHG emissions of double-glazed windows has been found to be 0.6 t CO_2 eq higher than single-glazed windows, which can be paid back quickly as the associated operational GHG savings is 10–18 t CO_2 eq. However, it warrants further investigation as to whether the energy saving benefits of the replacement of single glazing with double glazing would outweigh the incremental costs.

Integration of renewable energy technologies

Since the use stage accounts for significant portion of GHG emissions, the grid-connected solar photovoltaic system (SPS) and gas-boosted solar water heater (SWH) have been considered to further reduce the operational GHG emissions from electricity generation from fossil fuels in WA. Australia's annual average solar radiation is more than 14 MJ/m^2, which is more than required to run solar systems. The underlying principle is that the use of standalone renewable solar energy can offset a portion of the operational GHG emissions associated with the combustion of fossil fuels (Morrissey and Horne 2011).

The application of a 3 kW grid connected roof top SPS in residential areas is currently picking up in WA and has successfully been trialled on the roof top of a 4 × 2 × 2 detached house (IMO 2014). The average daily electricity generation by a 3 kW roof top SPS in Perth was based on the photovoltaic-grid connected (PV-GC) system designed by clean energy council (CEC 2011). This solar electricity data have been incorporated into SLCA of the LCM framework to calculate the GHG emissions from the reduced level of grid electricity consumption to meet the life-time energy demand.

The results show that the installation of a 3 kW grid-connected roof top SPS can alone mitigate the operational GHG emissions by 211 t CO_2 eq, which is between 47 and 58 % of operational GHG emissions of all envelope options (Table 2). The flat-plate type solar water heater with thermosiphon circulation reduces the demand of natural gas for storage-type gas hot water system. The hot water module in AccuRate software has been used to estimate the amount of natural gas that can be avoided due to use of solar water heater in Perth. Similar to SPS, the revised data on energy consumption for water heating was fed into SLCA to determine the reduced level of GHG emissions. The SLCA results show that the integration of SWH with gas-based water heater can mitigate the operational GHG emissions by 32 t CO_2 eq (Table 2). The economic analysis in the following section shows as to whether an additional investment on these renewable options could potentially reduce the overall life cycle cost for achieving cost-effective GHG mitigation options.

GHG mitigation options

Once renewable energy technologies have been integrated with 20 envelop options, the total GHG saving for each option has been estimated. Fourteen envelopes such as CSW-PET/POL-SG/DG, BV-XX-SG/DG, DB-INS-SG/DG, RBV-XX-SG/DG, ACC-XX-SG/DG, DB-XX-DG, and TMB-XX-DG are found to offer life cycle GHG emissions reduction of up to 20 % of the conventional envelope option (DB-XX-SG), only five envelope options emit 4–26 % more life cycle GHG emissions than the conventional one. The following section conducts an economic analysis for 20 envelops for finding out both economically and environmentally feasible options.

Life cycle cost analysis

The results of life cycle cost analysis show that life cycle cost (LCC) for a typical house for 20 envelope options vary from a minimum of USD$ 192,998 for CSW-PET-SG (8.6 % less than the conventional envelope option (USD$ 211,153 for DB-XX-SG) to a maximum of USD$ 232,528 for CB-XX-DG (10 % more than the conventional envelope option) (Table 1). The main reasons for this variation in LCC of these envelope options are due to the variation in costs of operational energy consumption and building materials (e.g. clay bricks, concrete, ACC blocks, timber, insulation, fibre cement board, windows).

The capital cost of the construction of a house varies between USD$ 146,268 for CSW-PET-SG (9.4 % less than the conventional envelope option (USD$ 161,414 for DB-XX-SG)) and USD$ 182,097 for ACC-XX-DG (i.e. 12.8 % more than the conventional envelope option) (Table 1). The possible reasons for this variation in LCCs are the differences in type, quantity of building materials, and manpower requirement for the construction of a house for 20 envelope options (Rawlinsons 2015).

Table 2 The implications of solar systems for GHG mitigation

Options	Original operational GHG t CO_2 eq	Operational GHG saving due to 3 kW SPS t CO_2 eq	Operational GHG saving due to SWH t CO_2 eq	Revised operational GHG t CO_2 eq
DB-XX-SG	394	211	32	151
DB-XX-DG	381	211	32	138
DB-INS-SG	376	211	32	133
DB-INS-DG	364	211	32	121
CSW-POL-SG	373	211	32	130
CSW-POL-DG	363	211	32	120
CSW-PET-SG	371	211	32	128
CSW-PET-DG	360	211	32	118
BV-XX-SG	403	211	32	160
BV-XX-DG	386	211	32	143
RBV-XX-SG	377	211	32	134
RBV-XX-DG	365	211	32	122
PCSW-XX-SG	427	211	32	184
PCSW-XX-DG	408	211	32	166
CB-XX-SG	446	211	32	203
CB-XX-DG	429	211	32	186
ACC-XX-SG	383	211	32	141
ACC-XX-DG	370	211	32	128
TMB-XX-SG	420	211	32	177
TMB-XX-DG	403	211	32	160

The operational cost varies between USD$ 45,610 for CSW-PET-DG (i.e. 8.3 % less than the conventional envelope option (USD$ 49,739 for DB-XX-SG) and USD$ 55,562 for CB-XX-SG (i.e. 11.7 % more than the conventional envelope option) (Table 1). Similar to GHG emissions, the main reason for this variation is the variation in operational energy consumption for heating and cooling and also due to the fact that the unit price of natural gas in WA varies with the level of consumption (Alintaenergy 2015).

The operational cost-saving benefit due to replacement of single-glazed windows with double-glazed windows has been found between 20 and 34 % of the additional capital cost incurred. This variation is due to the variation in thermal performance of the type of the materials of walls of 20 envelop options and the locations of windows (Aldawi et al. 2013).

Further analysis shows that the operational cost-saving benefit associated with the use of a 3 kW grid-connected SPS and SWH outweighs the incremental capital cost associated with the installation of the solar system. While the capital cost plus replacement costs (USD$ 9870) of grid-connected SPS and SWH remains constant during life time of house for all envelope options, the operational cost saving varies between USD$ 26,471 for DB-CC-SG and USD$ 26,669 for CSW-PET-DG due to variation in unit price of gas in WA for different level of consumption (Alintaenergy 2015) and the use of different building envelops cause the variation in thermal energy consumption. The use of above solar system provides a total operational energy saving of 1475 GJ during the life time of the house.

The payback period of solar water heater has been estimated to be 11 year, which is more than double the payback period of a 3 kW grid-connected SPS (around 5 year) as the latter saves more operation energy costs than former (Table 3). A 3 kW SPS offers a reduction of 17 GJ of energy consumption annually, while SWH saves only 12 GJ annual energy. Secondly, the gas prices [14.2 cents/unit till 12 units average per day and 12.8 cents/unit thereafter (1 unit = 1 kWh)] are almost half of the electricity prices [25.7 cents/unit (1 unit = 1 kWh)] (DOF 2015) in WA.

The LCCs of 11 envelopes such as CSW-PET/POL-SG/DG, BV-XX-SG/DG, TMB-XX-SG/DG, DB-INS-SG, RBV-XX-SG, and PCSW-XX-SG have been found to be up to 9.5 % less than the LCC of the conventional envelope option (DB-XX-SG). The remaining options are not economically viable as their LCCs are more than the conventional one (Table 3).

Economically viable GHG mitigation options

Nineteen envelop options excluding the conventional one have been classified into four categories on the basis of the

Table 3 Life cycle costs after the inclusion of solar systems

Options	Capital cost of house USD$	Original operational cost USD$	Capital cost of 3 kW SPS USD$	Operating cost saving due to SPS USD$	Capital cost of SWH USD$	Operating cost saving due to SWH USD$	Net life cycle cost USD$
CSW-PET-SG	146,268	46,730	3807	19,621	6063	7021	176,226
BV-XX-SG	146,687	49,856	3807	19,621	6063	6981	179,810
CSW-POL-SG	149,711	46,938	3807	19,621	6063	7008	179,890
CSW-PET-DG	151,777	45,610	3807	19,621	6063	7048	180,587
TMB-XX-SG	147,603	51,714	3807	19,621	6063	6931	182,635
BV-XX-DG	152,195	48,128	3807	19,621	6063	7012	183,560
CSW-POL-DG	155,219	45,862	3807	19,621	6063	7036	184,294
TMB-XX-DG	153,112	49,943	3807	19,621	6063	6962	186,340
RBV-XX-SG	162,010	47,528	3807	19,621	6063	6966	192,820
PCSW-XX-SG	157,610	52,659	3807	19,621	6063	6868	193,650
DB-INS-SG	163,540	47,406	3807	19,621	6063	6966	194,228
DB-XX-SG	161,414	49,739	3807	19,621	6063	6850	194,552
RBV-XX-DG	167,519	46,295	3807	19,621	6063	6993	197,069
PCSW-XX-DG	163,118	50,766	3807	19,621	6063	6900	197,233
DB-INS-DG	169,048	46,190	3807	19,621	6063	6993	198,494
DB-XX-DG	166,923	48,376	3807	19,621	6063	6859	198,688
ACC-XX-SG	176,588	48,049	3807	19,621	6063	6985	207,901
ACC-XX-DG	182,097	46,678	3807	19,621	6063	7013	212,010
CB-XX-SG	173,124	55,562	3807	19,621	6063	6850	212,085
CB-XX-DG	178,633	53,895	3807	19,621	6063	6850	215,926

Cost is based on 3 % inflation rate and 7 % discount factor. Three replacements for SWH and 1 replacement for SPS considered. Payback period for SWH—37 years and for SPS—5 years. Cost data source: (Alintaenergy 2015; DOF 2015; Rawlinsons 2015)

life cycle GHG emissions and life cycle costs of all envelope options for a typical house in Perth (Table 4). The conventional option has been considered as the basis of this classification. Of these 19 alternative envelope options, 9 envelope options are found to perform environmentally and economically better than the conventional option, 5 envelopes are environmentally viable but they are not economically viable (Fig. 3). Two envelope options are economically viable but they are not environmentally viable and the remaining 3 options are neither environmentally nor economically viable (Fig. 3).

Nine options such as CSW-PET-SG/DG, BV-XX-SG/DG, CSW-POL-SG/DG, TMB-XX-DG, RBV-XX-SG, and DB-INS-SG for construction of a house are found to be both economically and environmentally superior to conventional single-glazed window houses made of clay brick walls. This is mainly because of low heat transfer co-efficient characteristics of cast in situ sandwich wall (CSW), brick veneer wall (BV and RBV), and timber-framed wall (TMB) that not only has potentially reduced the operational demand of fossil generated electricity but it has also reduced the life-time energy cost significantly (Gregory et al. 2008; Lawania et al. 2015).

Implication of carbon tax

An analysis has been carried out as to what will happen to the cost effectiveness of these envelop options if carbon tax is introduced, because the number of countries such as Canada, Chile, Denmark, Finland, France, Iceland, Ireland, Japan, Mexico, Norway, South Africa, Sweden, Switzerland, and United Kingdom have carbon tax or emissions trading schemes in different forms (CTC 2015). If a carbon tax of USD$ 14.5 per tonne of CO_2 eq ($\approx$AUD 23) that was introduced by the previous government of Australia is considered, the additional carbon tax cost will vary from USD$ 2285 for CSW-PET-DG option [i.e. 8.6 % less than the C-tax of a conventional house (i.e. USD$ 2499)] to USD$ 2824 for CB-XX-SG which is 13 % more than the conventional one. The carbon tax-saving benefit associated with the use of roof top solar PV and SHS will vary from only USD$ 735 for a house with CSW-PET-DG (i.e. 22.6 % less than the conventional envelope option (USD$ 950 for CB-XX-SG)) to USD$ 1275 for CB-XX-SG (i.e. 34 % higher than the conventional envelope option).

The classifications of these 19 envelops appear to remain unchanged even the implications of the carbon tax

Table 4 Environmental and economic performance of house with various envelopes in comparison with DB-XX-SG

Options	Life cycle cost USD$	Life cycle GHG t CO_2 eq
Environmentally and economically viable		
CSW-PET-DG	180,587	161
CSW-POL-DG	184,294	163
CSW-PET-SG	176,226	171
CSW-POL-SG	179,890	173
BV-XX-DG	183,560	185
DB-INS-SG	194,228	186
RBV-XX-SG	192,820	187
TMB-XX-DG	186,340	193
BV-XX-SG	179,810	201
Environmentally unviable and economically viable		
TMB-XX-SG	182,635	210
PCSW-XX-SG	193,650	254
Environmentally viable and economically unviable		
ACC-XX-SG	207,901	199
DB-XX-DG	198,688	189
ACC-XX-DG	212,010	186
RBV-XX-DG	197,069	176
DB-INS-DG	198,494	175
Environmentally and economically unviable		
PCSW-XX-DG	197,233	236
CB-XX-SG	212,085	243
CB-XX-DG	215,926	227

Life cycle GHG emissions 202 t CO_2 eq, Life cycle cost $194,551 (conventional envelope option)

scenarios have been considered, which means that still only 9 options such as CSW-PET-SG/DG, BV-XX-SG/DG, CSW-POL-SG/DG, TMB-XX-DG, RBV-XX-SG, and DB-INS-SG have been found to be both economically and environmentally better than the clay brick walls.

Conclusions and recommendations

A thorough SLCA and LCC analysis suggest that a typical 4 × 2 × 2 house that uses cast in situ sandwich wall with PET foam as core, and double-glazed windows (CSW-PET-DG) is the most cost-effective GHG mitigation option. Further GHG emissions reduction (i.e. ≥50 %) during the operational stage is possible by replacing fossil fuel-derived electricity and thermal energy with solar photovoltaic system and solar water heater. Interestingly, the operational cost-saving benefit associated with the use of a 3 kW grid-connected SPS and SWH outweighs the incremental capital cost associated with the installation of the solar energy systems.

The incorporation of carbon tax (USD$14.5/tonne of CO_2) that was imposed by the former Australian government into the economic analysis does not appear to provide significant financial incentives to popularize the low carbon envelop options.

The outcome of this study provides a variety of envelop options for architects, designers, developers, and policy makers to choose from environmentally and economically viable envelope options for constructing a green building

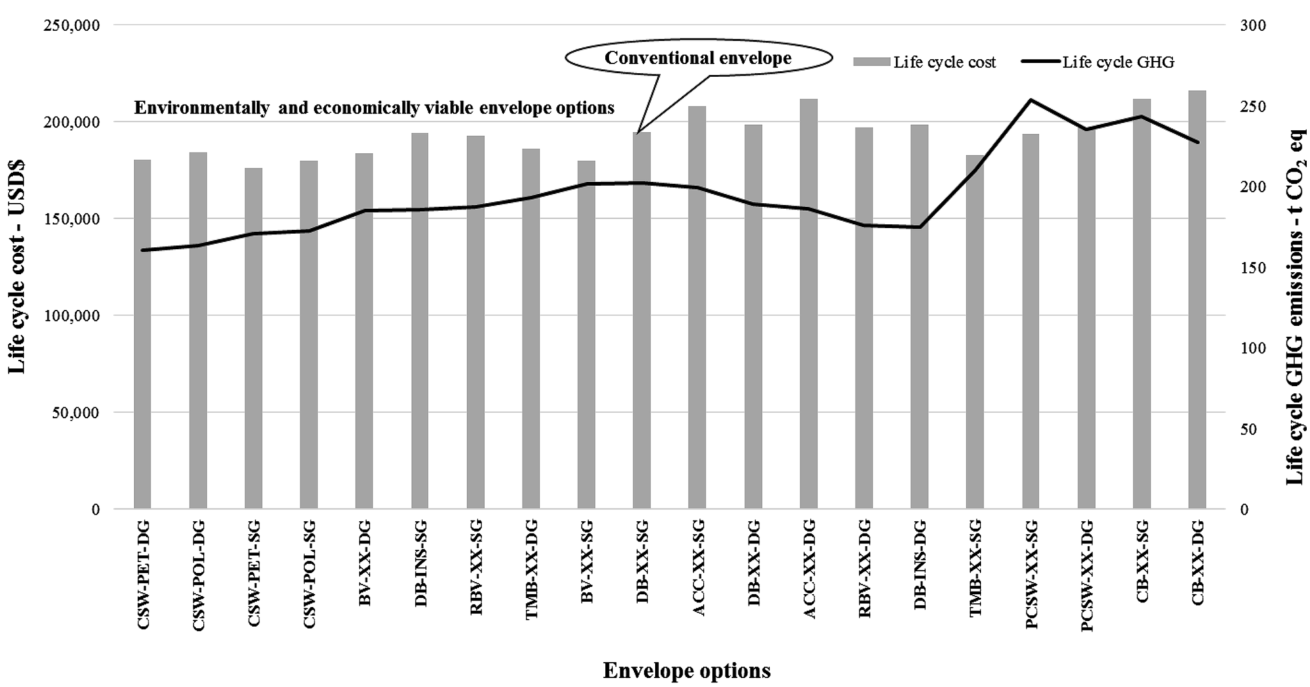

Fig. 3 Life cycle GHG emissions VS life cycle cost of a typical house for 20 envelope options

as resource availability and cost of materials fluctuate over time. The future study will consider the application of this LCM framework in other locations in Western Australia to find out the least cost low carbon building envelops by taking local specific climatic conditions and material availability into account.

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