School of Civil and Mechanical Engineering

Improving the Sustainability Performance of Western Australian House Construction: A Life Cycle Management Approach

Krishna Kumar Lawania

This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

July 2016

Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Date: 30 July 2016

Acknowledgements

I would like to express my gratitude to my supervisors Wahidul Biswas and Natalie Lloyd, for their continuous guidance and support in completing this research.

I am grateful to Associate Professor Michele Rosano, the Director of the Sustainable Engineering Group including other colleagues for the intellectual and administrative support in a number of ways. My fellow research scholars Yun, Felicity, Deborah, Faisal, Joni, Anja, and Danielle also deserve a special acknowledgement and thanks for their continuous encouragement, advice and valuable assistance extended during the research. It was a wonderful team.

It is a pleasure to thank the companies who assisted me with the acquisition of industry data and made this research possible.

This research work would not have been possible without the immense sacrifices and unconditional support of my wife Gauri and lovely daughters Mudhita and Harshita throughout the whole process. Gauri not only relieved me from all family responsibilities and allowed me to pursue my dream but she continuously acted as a driving force. The words and dedication of this work to them falls short to describe my appreciation and gratitude for all they have done for me.

I take this opportunity to acknowledge the inspiration and encouragement received from my mentor Dr. S. Basu, former Professor and Head, Earthquake Engineering Department, IIT Roorkee.

At last but not the least, I owe my deepest gratitude and regards to my late grandparents and parents for inculcating the thirst for academic excellence during childhood, which led to this journey.

Abstract

The residential building sector, which provides shelter, creates employment opportunities, and contributes to the economy of any nation has an adverse effect too as it has serious environmental implications. Globally, the construction and use of buildings alone are responsible for almost one third of the resource consumption, energy consumption, greenhouse gas (GHG) emissions, and solid waste generation which are rapidly growing due to population and economic growth. The residential building sector is now adopting innovative products and processes for the construction of houses in a resource constraint competitive market to comply or exceed environmental regulations. The concept of life cycle thinking hence steps in for addressing the sustainability challenge.

The building sector alone is responsible for Australia's 20% total energy consumption, and 23% GHG emissions, which are expected to grow rapidly as more than 3.3 million additional houses are expected to be built by 2030 to maintain the pace with an economic and population growth. A majority of Australians prefer the clay brick dominated detached houses with heavy reliance on artificial heating, cooling, and ventilation, which results in huge energy demand and GHG emissions. Under the National House Energy Rating Scheme (NatHERS), the Australian Building Codes Board (ABCB) has introduced the mandatory minimum energy efficiency standards for buildings through the National Construction Code (NCC). Primarily, these regulations focus on achieving thermal comfort for occupants through a reduction in the space heating and cooling energy requirements. However, the minimum energy efficiency standards alone are not adequate to address the sustainability aspects from a life cycle thinking perspective because the buildings are complex products of various materials, and technologies to meet unique requirements. Various studies to date suggest that the sustainability assessment, which integrates the energy, economic, social and environmental factors together from life cycle perspective has a potential in decision making for identification of optimum sustainable building options.

There is a gap in the current body of knowledge as the integration of all these aspects has not been considered to achieve sustainable houses in Western Australia (WA) where the building sector is unsustainable due to the use of energy intensive building materials, affordability, resource constraints, and varying climatic conditions. Whilst

the research on sustainable buildings for the Eastern States of Australia has been conducted to some extent, these studies are not representative of the whole of Australia for geographical, demographical, and climatic reasons. Considering the growing demand for housing and associated long-term environmental repercussions in WA, it is proposed that the life cycle thinking is applied to practice through a unique systematic, and dynamic life cycle management (LCM) approach. This would put the life cycle thinking tools, techniques, and frameworks into practice to improve the sustainability performance of houses. LCM approach has been found to be an effective tool for reducing the environmental, economic, and social impacts in order to apply the concept of life cycle thinking to construction industries.

The objective of this research was to develop a comprehensive life cycle management framework that integrates the NatHERS energy rating tool, life cycle assessment (LCA) approach, cleaner production strategies (CPS), life cycle costing (LCC) approach, and socio-political factors for improving the sustainability performance of a house construction in WA. The development of this framework has enabled the identification of a range of sustainable options of building materials and methods for construction of houses, which could be used to achieve WA's goals of the sustainable development.

In this research, a typical 4 bedroom, 2 bathroom, 2 car garage (4x2x2) detached single storey house made of double clay brick walls, single glazed windows, concrete floor, and concrete roof tiles hypothetically located in Perth, was considered as a reference house to represent the existing housing stock. The environmental impacts were assessed over a life cycle of 50 years. The operational energy requirements were modelled using AccuRate software. The material and energy inputs were used to build LCA model using SimaPro software to identify the hotspots causing the highest environmental impacts. Appropriate CPS were applied to mitigate the hotspots during various life cycle stages of a house to design an environmentally benign house. The life cycle inventory was revised by incorporating new material and energy inputs for each CPS to estimate life cycle energy and environmental impacts and to analyse the viability of these alternative options for the construction of a house. The LCC analysis has been conducted to assess the economic feasibility of the environmentally friendly options as compared to existing conventional house in terms of present value using appropriate inflation and discount rates. The environmentally and economically viable options were thus selected for assessing the social implications and to propose policies for application of these options.

WA is the largest state of Australia as it consists of 5 out of total 8 Australian climatic zones. In order to capture the variations in climatic conditions, resources, and utilities, seventeen additional locations were selected based on population, existing housing stock, and growth forecast data within WA for this research. The cost-effectiveness of the CPS may vary with geographical locations due to resource availability and climatic conditions. The environmental, economic, and social impacts of a typical house that has incorporated cleaner production options were assessed to identify the sustainable options in these additional 17 locations. Finally, the environmental and economic impact values of a typical house for all cleaner production options in 18 locations were normalized to identify the best-suited options for the construction of a sustainable house in Western Australia, The option CSW-POL-DG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core - double glazed windows - concrete roof tiles - 3kWp grid connected roof top solar PV - solar water heater - partial replacement of cement and aggregates in concrete mix by fly ash, and recycled aggregates) was found to be the optimum sustainable option for the construction houses in Western Australia due to the lowest environmental impacts, significant cost saving potential, and associated social benefits in terms of durability, affordability, and resource conservation.

Finally, as compared to the conventional house construction, the above cleaner production option has been found to offer significant sustainability benefits. The proposed life cycle management framework can help the Western Australian building sector to improve the sustainability of houses and minimize the resource consumption to contribute to Australia's commitment to emissions reduction.

List of publications

Journal publication

Lawania, Krishna Kumar, and Wahidul K. Biswas. 2016. "Achieving Environmentally Friendly Building Envelope for Western Australia's Housing Sector: A Life Cycle Assessment Approach" *International Journal of Sustainable Built Environment*. doi: http://dx.doi.org/10.1016/j.ijsbe.2016.04.005.

Lawania, Krishna Kumar, and Wahidul K Biswas. 2016. "Cost-Effective GHG Mitigation Strategies for Western Australia's Housing Sector: A Life Cycle Management Approach" *Clean Technologies and Environmental Policy: 1-10.* doi: 10.1007/s10098-016-1217-9.

Lawania, Krishna, Prabir Sarker, and Wahidul Biswas. 2015. "Global Warming Implications of the Use of by-Products and Recycled Materials in Western Australia's Housing Sector." *Materials* 8 (10): 5347. http://www.mdpi.com/1996-1944/8/10/5347.

Lawania, Krishna, and Wahidul Biswas. 2016. "Application of life cycle assessment to deliver low carbon houses at regional level in Western Australia", *The International Journal of Life Cycle Assessment* (Under review, the revised manuscript has been submitted).

Peer reviewed conference proceedings

Lawania, Krishna, Natalie Lloyd, and Wahidul Biswas. 2014. "Sustainability Assessment of the Replacement of Clay Brick Walls with in-Situ Composite Sandwich Walls" In *The Second Australasia and South-East Asia Structural Engineering and Construction Conference, Bangkok, Thailand*, November 3–7, 2014 edited by W. Suanpaga, Yazdani, S., Vimonsatit, V., Singh, A., and Chantawarangul, K.

Non-referred conference paper with platform presentation

Lawania, Krishna, and Wahidul Biswas 2015. "Carbon footprint and embodied energy consumption saving opportunities for Western Australia's housing industries – A Life Cycle Management approach" In *AusBuildLCA, The 1st Life Cycle Assessment Conference for Building and Construction, Melbourne, Australia,* November 26-27, 2015.

List of Abbreviations

ABARE	Australian Bureau of Agricultural and Resource Economics
ABBTF	Australian Brick and Blocklaying Training Foundation
ABCB	Australian Building Codes Board
AB-REIA	Real Estate Institute of Australia
ABS	Australian Bureau of Statistics
ACCC	Australian Competition and Consumer Commission
ACC-XX	Aerated concrete blocks
ADAA	Ash Development Association of Australia
AER	Australian Energy Regulator
ALCAS	Australian Life Cycle Assessment Society
APC	Australian Packaging Covenant
APVI	Australian Photovoltaic Institute
AS	Australian Standard
ASA	Australasian (Iron and Steel) Slag Association
ASBEC	Australian Sustainable Built Environment Council
ASBI	Australian Sustainable Building Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ASTM	American Society for Testing Materials
AUD	Australian Dollar
AusLCI	Australian Unit Process LCI

AWA	Australian Window Association
BCA	Building Code of Australia
BCEC	Bankwest Curtin Economics Centre, Western Australia
BOM	Bureau of Meteorology, Australia
BPIC	Building Products Innovation Council, Australia
BRANZ	Building Research Association of New Zealand
BREE	Bureau of Resources and Energy Economics, Australia
BV-XX	Brick veneer
C&D	Construction and Demolition
CBA	Commonwealth Bank of Australia
CB-XX	Hollow concrete blocks
CC	Climate change
CCA	Climate Change Authority, Australia
CCAA	Cement Concrete and Aggregates Australia
CEC	Clean Energy Council, Australia
CED	Cumulative energy demand
CFL	Compact fluorescent lamp
CH_4	Methane
CIF	Cement Industry Federation, Australia
CO_2 e-	Carbon Dioxide Equivalent
CO_2	Carbon Dioxide

COAG	Council of Australian Governments
CP	Cleaner production
CPS	Cleaner production strategies
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
CSW-POL	Cast in-situ sandwich with polystyrene core
CT	Concrete roof tiles
CTC	Carbon Tax Center
DB-INS	Double clay brick with insulation
DB-XX	Double clay brick without insulation
DEH	Department of Environment and Heritage, Australia
DER	Department of Environment Regulation, WA
DEWHA	Department of the Environment, Water, Heritage and the Arts, Australia
DG	Double glazed windows with powder coated aluminium frames
DIS	Department of Industry and Science, WA
DOE	Department of Environment, Australia
DOP	Department of Planning, Western Australia
DOSD	Department of State Development, Western Australia
DR	Discount rate
DRDL	Department of Regional Development and Lands
DRET	Department of Resources, Energy and Tourism, Australia

EE	Embodied energy (cumulative energy demand)
EUP	Ecoinvent Unit Process
FA	Fly ash
FHOG	First home owners grant
FWPA	Forest and Wood Products Australia
GC	Green concrete
GDP	Gross Domestic Product
GGBFS	Ground granulated blast furnace slag
GHG	Greenhouse gas
GJ	Giga Joule
GST	General sales tax
GWP	Global Warming Potential
HAp	Home appliances
HIA	Housing Industry Association
HWS	Hot water system
IA	Infrastructure Australia
IMO	Independent Market Operator, Australia
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kWh	Kilowatt Hours
LCA	Life cycle assessment

LCC	Life cycle costing
LCEA	Life cycle energy assessment
LCI	Life cycle inventory
LCIA	Life Cycle Impact Assessment
LCM	Life cycle management
LED	Light emitting diode
Lgt	Lighting
LPG	Liquefied petroleum gas
MCS	Monte Carlo simulation
MEPS	Minimum Energy Performance Standards
MFS	Manufactured sand
MJ	Mega Joule
MS	Metal profile roof sheet
MWh	Megawatt Hours
N_2O	Nitrous Oxide
NatHERS	Nationwide House Energy Rating Scheme
NHSC	National Housing Supply Council, Australia
NPV	Net present value
NWIS	North West interconnected system
OECD	Organisation for Economic Cooperation and Development
OPC	Ordinary Portland cement

OTTV	Overall thermal transfer value
PCB	Printed circuit board
PCSW-XX	Pre-cast light weight concrete sandwich panels
PET	Polyethylene terephthalate
PV	Photo Voltaic
RBA	Reserve Bank of Australia
RBV-XX	Reverse brick veneer
RCA	Recycled crushed aggregate
REIWA	Real Estate Institute of Western Australia
RTAA	Roofing Tile Association of Australia
SASA	Sustainable Aggregates South Australia
SCM	Supplementary cementitious materials
SEP	Solar Energy Products, Australia
SETAC	Society of Environmental Toxicology and Chemistry
SG	Single glazed windows with powder coated aluminium frames
SIA	Social impact assessment
SLCA	Streamlined life cycle assessment
SPV	Solar photovoltaic
SWH	Solar water heater
SWIS	South West interconnected system
TJ	Terra Joule

tkm	tonne-kilometer
TMB-XX	Timber frame
TT	Terracotta roof tiles
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
US	United States of America
W/m^2K	Watts per meter squared kelvin
WA	Western Australia
WAWA	Western Australian Waste Authority
WH	Water heater

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

The thesis assesses the sustainability of different building materials and methods for the construction of houses in Western Australia using a comprehensive life cycle management framework consisting of life cycle assessment (LCA) approach, Australian Nationwide House Energy Rating Scheme (NatHERS) energy rating tool, cleaner production strategies (CPS), life cycle costing (LCC) approach, and socio-political indicators.

1.2 Background

The term 'sustainability' is derived from the Latin verb *sustinere* meaning to support and has been used in relation to resources of the earth since late 18th century (Blair et al. 2004). The concept of sustainable development was popularized in 1987 by Brundtland Commission report "Our Common Future", published by the World Commission on Environment and Development (WCED 1987). The report defined the sustainable development as "*development which meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Blair et al. 2004). The Brundtland Commission report also suggested that sustainability is often cast as the triple bottom line (TBL) of environment, economy, and society (Hall and Purchase 2006). The concept of sustainable development gained real prominence when it was discussed and adopted by more than 178 Governments during the United Nation Conference on environment and development held at Rio de Janeiro, Brazil in 1992, referred as Rio Summit (UNCED 1992; Mebratu 1998). Whilst the concept of sustainability and sustainable development has received a wide spread recognition from policy makers to consumers in last 25 years, in reality, the unsustainable trends are still continuing because the concept of sustainable development has not yet found the political will and support, and thus it is progressing unevenly which has even been acknowledged during the United Nations Conference on Sustainable Development held again in Rio de Janeiro, Brazil in 2012 (UNCSD 2012).

The major industries such as agriculture, mining, construction, transportation, and livestock contribute to the development of any nation and thus hold the key to sustainable development (Sev 2009). The construction sector, which has a key role in providing the quality of life to society in the form of housing, transportation, workplace, and utility infrastructure including the employment opportunities contributes not only to the economy of any nation but also has serious environmental and social implications (Burgan and Sansom 2006).

Without the change of paradigm, the implementation of principles and guidelines of sustainable development into the building sector is difficult because of the complexity of the buildings, and due to the facts that the buildings are not just the assembly of raw materials, but they are complex products of various materials, and technologies assembled together to meet the unique requirements, and there is no unique solution for sustainable buildings (Ding 2008; Passer et al. 2015). Directly or indirectly, the buildings are responsible for greenhouse gas emissions due to energy consumed during various life cycle stages for raw material extraction, processing, transportation, manufacturing, fabrication, assembly, construction, operation, maintenance, and the end of life demolition and disposal (Sorrell 2003; Rwelamila, Talukhaba and Ngowi 2000).

As compared to other sectors, the buildings lasts much longer and thus have significant environmental repercussions over a long period of time, and hence it is important to implement the principles and guidelines of the sustainability from the project inception stage itself so that the goals of sustainable development are achieved by minimizing the resource consumption and environmental impacts during the entire life cycle stages (Sev 2009; Burinskienė and Rudzkienė 2007). To achieve the goals of sustainable building development, the major attempt should be made for improving the material and energy efficiencies, and which should not be limited to only production efficiency, but it should include the consumption efficiency as well (Iwaro and Mwasha 2013; Dincer and Rosen 2012).

Due to an increasing awareness of sustainability and sustainable development, the building sector is now forced to adopt the innovative products and processes to achieve sustainable buildings. This is because of the fact that globally, the construction and use of buildings alone is responsible for almost 30%-40% of resource consumption, energy consumption, GHG emissions, and solid waste generation which are still growing (Ristimäki et al. 2013; Nejat et al. 2015; Ibn-Mohammed et al. 2013; Xing, Hewitt and Griffiths 2011; Zeng et al. 2011; UNEP 2011a).

Various studies suggest that the integrated sustainability assessment framework, which considers the energy, ecological, economic, social and environmental factors have a key role in decision making to identify the sustainable building options (Ding 2008; Gibson 2006; Ortiz et al. 2009; Pope, Annandale and Morrison-Saunders 2004; GOWA 2003). There are various sustainability assessment approaches which exist worldwide, but their application growth is still slow (Berardi 2012). However, globally the sustainability assessment and certification of buildings is growing rapidly as around 650 million m^2 of constructed area obtained certification in 2010, which almost doubled in 2012, and this is expected to rise further to around 4600 million m^2 of constructed area by 2020 (Bloom and Wheelock 2010).

Though the Australian building sector is not the largest source of GHG emissions, it is the fastest growing sector. Annually, this sector alone is responsible for Australia's 20% of the total energy consumption, and 23% of the total GHG emissions (ABCB 2015b). Despite various energy efficiency improvement initiatives, the GHG emissions of building sector are growing annually at 1.3% (ASBEC 2007) and Australia's current per capita GHG emissions (23.1 tonnes of CO_2 e-) and ecological footprint (6.3global hectares) are about 5 and 3.5 times more than the global average (DOE 2015b; WWF 2014). The main reason for such a high contribution by building sector is because of the fact that a majority of Australians prefer to live in clay brick dominated detached houses with heavy reliance on artificial heating, cooling, and ventilation (Kelly, Breadon and Reichl 2011; Miller and Buys 2012).

In addition, the building sector in Australia generates annually about 20 million tonnes of construction and demolition (C&D) wastes (DOE 2013) of which the energy intensive clay brick accounts for 16% (Reardon and Downton 2013a). The Australian construction sector plays an important role in society and economy by providing more than 1 million job opportunities per year and contributes more than $102 billion annually to the economy (or 8% of Australia's GDP)(ABS 2012). Australia will require more than 3.3 million additional houses by 2030 to maintain the pace with economic growth (NHSC 2011), and about 15% of these new houses will be built in

Western Australia (WA). Such a rapid socio-economic growth could increase Australia's overall energy demand from 5,724 Peta joules (PJ) in 2008 to 7,715 PJ in 2030 (Geoscience-Australia and BREE 2010) and GHG emissions by 70% of current level by 2050 (DOE 2014a).

There is a growing consensus that the Australian building sector has to take initiatives to adopt the sustainable building materials and methods of construction. Considering the growing demand for housing and associated long-term environmental repercussions in Western Australia, this research has developed a comprehensive framework for improving the sustainability performance of house construction.

1.3 Research problem and rationale

To achieve sustainability, the Western Australia's building sector has to shift the paradigm of the traditional approach of use of non-renewable resources to use of renewable resources, and from the disposal of waste to landfill to reuse and recycling of waste (Kibert, Sendzimir and Guy 2000). The use of low impact, renewable and recyclable building construction materials including industrial by-products should be encouraged to achieve the sustainable buildings (Chwieduk 2003; Williams 2013). The building's operational heating, and cooling energy consumption is highly influenced by the thermal performance of the building envelope because the bulk of this energy is utilized to compensate for the energy losses or gains through the envelope, and thus the envelope holds the key to energy, and emissions reduction opportunities (Xu and Dessel 2008; Bambrook, Sproul and Jacob 2011; Sozer 2010; Sadineni, Madala and Boehm 2011; Lai and Wang 2011). However the building envelope's thermal performance acts as a double edge sword because of its dynamic nature, which is not only a function of the individual performance of materials used for different components of envelope (e.g. wall, roof, and floor), but is highly influenced by the climate conditions, and combination of materials used for different components of the envelope (e.g. double brick wall, brick veneer wall, autoclaved aerated concrete block wall, sandwich wall, concrete roof tiles, steel sheet roof, single glazed window, double glazed window, concrete floor, and elevated timber floor) (Pacheco, Ordóñez and Martínez 2012; Li, Yang and Lam 2013; Lawania and Biswas 2016).

In order to achieve sustainable building solutions, national and international studies have focused on the use of different tools and concepts for the assessment of energy, environment, and economic impacts associated with the buildings from the life cycle perspective, and to identify the energy efficiency measures to mitigate these impacts (Sadineni, Madala and Boehm 2011; Berry and Marker 2015b; Carre and Crossin 2015; Bahadori and Nwaoha 2013; Monteiro and Freire 2012; Lawania, Sarker and Biswas 2015; Moore 2014).

Life cycle thinking is converted into reality or practice through life cycle management (LCM). As per United Nations Environment Programme (UNEP), LCM is a unique systematic, and dynamic process, which puts the life cycle thinking tools, techniques, and frameworks into practice to achieve the sustainable products or services (UNEP 2007). Some studies suggest that the application of LCM approach could help in mitigating the economic and environmental impacts associated with even existing products or technologies (Ristimäki et al. 2013), and is an effective decision making tool to achieve sustainable outcomes (Ortiz et al. 2009; Memon, Rahman and Yacob 2014).

Most of the published studies lack the integration of the different tools and do not consider the economic, social, and environmental factors together to achieve sustainable buildings. Furthermore, the majority of the Australian research on sustainable buildings is limited to the Eastern States which is not representative of the Western Australia, which has geographically, demographically, and climatically unique landscape. WA is Australia's largest state and falls under five out of eight distinct climate zones (Figure A.1, Appendix A).

This research therefore explores a life cycle management framework integrating various tools from a life cycle thinking perspective to assess the life cycle impacts of a range of building materials and methods of construction of a typical house for 18 locations in Western Australia and to identify the appropriate location specific cleaner production strategies to achieve a sustainable house solution applicable to whole Western Australia.

The following primary research questions are addressed and presented in this thesis:

- What are the life cycle greenhouse gas (GHG) emissions and embodied energy (EE) consumption impacts associated with the cradle to grave stages of the conventional double clay brick wall house in Perth over a life cycle of 50 years?

- Which are the materials and processes causing the highest impacts (termed as hotspot(s))?

- What are the appropriate cleaner production strategies to treat the hotspot(s) for reducing GHG emissions and EE consumption from Western Australian houses?

- What is the cost effectiveness of environmentally viable technologies for different locations in WA?

- How does cost-effectiveness of cleaner production strategies (CPS) vary with economic factors (e.g. discount rate) and policy instruments (e.g. carbon tax)?

- How does cost-effectiveness of mitigation technologies vary across the regional WA?

1.4 Objectives and scope

The goal of this research is to develop a comprehensive framework that can assist with the improvement of the sustainability performance of house construction in Western Australia and to identify the areas of environmental, economic, and social concerns (hotspots). This approach will seek to integrate various life cycle assessment tools and concepts to identify the appropriate cleaner production strategies to construct sustainable houses. In order to attain this goal, the research will be focused on following five research objectives.

1.4.1 Objective 1: To develop a framework for improving the sustainability performance of houses in Western Australia

A number of methodologies and frameworks pertaining to sustainable building designs published by authentic bodies are reviewed to develop a comprehensive framework for sustainability assessment of a house specifically for Western Australia where there is a predominant use of clay bricks. The majority of these methodologies and frameworks have focused on a particular aspect of the buildings such as construction materials and methods, buildings' performance due to climatic variations, buildings' energy analysis, environmental impact assessment, the cost-effectiveness of buildings' energy efficiency improvement measures, and implications of renewable technologies. However, there is no comprehensive framework that has specifically been developed for sustainability assessment of houses after considering all the above mentioned aspects addressing Western Australia's housing sector. A range of sustainability assessment tools and cleaner production strategies are required to develop a comprehensive framework to improve the sustainability performance of Western Australia's housing sector as its geographical area is substantially large and most of the population centres are located in different climate zones. In addition, most of the Australian research on sustainable buildings is limited to the Eastern States, with a little representation only from Perth.

Therefore, this research proposes the development of a holistic life cycle management (LCM) framework comprising of NatHERS energy rating tool, life cycle energy assessment (LCEA), life cycle assessment (LCA), and life cycle costing (LCC) with a focus on different materials and methods of construction, climatic conditions, energy consumption (for heating, cooling, lighting, hot water, and home appliances), solar energy, environmental impacts, socio-economic implications, and resource availability for addressing WA's sustainability requirements in different locations under different climatic zones. The detailed methodology and framework for addressing this objective have been discussed in Chapter 3.

1.4.2 Objective 2: To estimate the life cycle environmental impacts of construction, use, and disposal of a typical house in Perth using LCA tool

The review of the contemporary literature indicated that the GHG emissions and embodied energy (EE) consumption are the most important impact categories of concern for building sector because of the substantial amount of material and energy consumption during the lifespan of the building. Although, the embodied energy is not an environmental impact itself, but it is a predecessor to most of the environmental impacts and hence is considered as an important impact category (Frischknecht et al. 2007; Carre 2011a; Dixit et al. 2012).

This research has thus considered the life cycle GHG emissions and EE consumption as important impact indicators associated with the construction, use, and the end of life demolition and disposal of a typical conventional double clay brick wall house in Perth using LCA approach. Australia is committed to reduce the GHG emissions to 26%-28% below 2005 levels by 2030 (DOE 2015a) and hence other impact categories such as acidification, eutrophication, ozone depletion, solid waste, and photochemical smog have not been considered for this research.

The LCA for this research has considered 'cradle to grave' approach and has followed the four steps of ISO 14040-44 (ISO14040 2006; ISO14044 2006): 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation to estimate the GHG emissions and EE consumption impacts in Chapter 4. The environmental impacts during all stages from mining to material production to the end of life demolition and disposal have been considered. The loose furniture, plumbing, drainage and electrical services, sanitary ware, tapware and lighting fixtures, pavement, landscaping, garage door, wall painting, and routine maintenance activities have been excluded from this LCA as they vary with the occupant's choices.

1.4.3 Objective 3: To identify hotspots and apply appropriate cleaner production strategies (CPS) to mitigate the life cycle environmental impacts associated with identified hotspots for a typical house in Perth

The NatHERS energy rating tool and life cycle assessment approach have been used to identify the areas of concern (hotspots) during various life cycle stages of a house in Perth and their causes are analysed to identify the appropriate resource efficiency and cleaner production strategies (CPS). According to UNEP (1994), and UNIDO (2002), the 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 human and the environment by increasing the productive use of natural resources, minimizing waste and emissions and are necessary components for achieving sustainable development. As recommended by UNEP (2015), the five cleaner production strategies such as good housekeeping, technology modification, product modification, input substitution, and recycling and reuse have been implemented to mitigate GHG emissions and EE consumption in Chapter 4. Once the appropriate CPS have been identified, the revised material and energy inputs have been estimated to modify the LCI and then revised LCI has been used to estimate GHG emissions and EE consumption to assess the viability of these CPS options for a typical house in Perth.

1.4.4 Objective 4: To estimate the socio-economic implications of environmentally viable cleaner production options for mitigation of life cycle impacts of a typical house in Perth

The life cycle costing (LCC) approach has been used to assess the cost-effectiveness of environmentally viable cleaner production options for the construction of houses. LCC is an effective technique for forecasting and evaluating the cost performance of buildings (ISO15686-5 2008(en)) and helps in the economic comparison between the capital cost and operating cost of competing building design options to find an optimum design option (Real and Pinheiro 2010). This research has used the Net Present Value (NPV) method for estimation of LCC, where the time value of money is expressed as a discount rate which is a function of capital cost, inflation, and social behaviour. The inflation rate of 3% per year (RBA 2015), and a discount rate of 7% per year (IA 2016) have been considered for estimation of LCC of all environmentally viable cleaner production options for the construction of a house in Chapter 5. The economic and environmental outcomes have helped in determining the appropriate policies and social implications. The social and policy barriers affecting the growth of sustainable buildings have also been identified and discussed. The LCC for this research has considered the same system boundary of LCA to maintain the consistency of the analysis.

1.4.5 Objective 5: To investigate the implication of environmentally, and economically viable options for 17 locations in regional Western Australia to capture the location specific climatic, economic, energy, and policy variations

The environmental and economic outcome of cleaner production strategies for Perth may not be the same for all the locations in Western Australia, because it is the largest state of Australia with a diverse climate, history, flora and fauna covering more than 2.5million square kilometres of area and is one of the most ancient lands on the planet. In order to represent the whole of Western Australia and to capture the variations in climatic conditions (WA falls under 5 out of 8 Australian climate zones), and the resource availability, the 17 locations have been identified based on population and existing housing stock census data of 2011 (ABS 2013), and growth forecast of regions (DOP 2015) within WA for this research. The variation in electricity generation mix and supply of natural gas across all 17 locations in regional Western Australia has also been considered for this research to capture the variation in fuel specific GHG emissions and EE consumption associated with household energy consumption.

The GHG emissions and EE consumption associated with the construction, use, and the end of life demolition and disposal of a typical house for all cleaner production options (identified as environmentally and economically viable in Perth) have been estimated for 17 locations in regional WA using LCA approach and the results are compared with the GHG emissions and EE consumption results of Perth in Chapter 6.

Similarly, the life cycle cost for construction, use, and the end of life demolition and disposal of a typical house for all cleaner production options have been estimated for 17 locations in regional WA using LCC approach to capture variations in cost-effectiveness of CPS and the results are compared with the LCC results of Perth in Chapter 6.

1.4.6 Summary

Through this comprehensive life cycle management approach, a number of important cleaner production strategies have been proposed that can help the Western Australian building sector to improve the sustainability of houses and minimize their resource consumption. The use of energy efficient construction materials and methods, and the integration of renewable energy technology were investigated to determine the technically, environmentally, economically, and socially viable solutions to contribute to Australia’s commitment for emissions reduction and address resource scarcity. Further research opportunities have also been identified so that the body of knowledge developed through this research could be utilized to address the inter-generational and intra-generational equity aspects of these cost-effective CPS for broader community benefits.

1.5 Research design and methodology

The development of LCM framework in this research was based on the comprehensive literature review, case studies, and statistical analysis. The extensive literature review not only helped in the development of an LCM framework to achieve sustainable houses in Western Australia but also enhanced the awareness of various national and international initiatives from sustainability and sustainable development perspectives. The national and international published literature that was reviewed included the peer reviewed journal articles, conference proceedings, books, government reports, Australian and New Zealand codes of practices, IPCC reports, ISO standards, government websites, reports from United Nations and its allied Institutions, product datasheets and catalogues, and websites of building material manufacturers, suppliers, and utility providers.

A 4x2x2 detached single storey house made of double clay brick walls in Perth, which is a common practice of a house construction in Australia (Ren et al. 2013; Karuppannan and Han 2013; DOH&DOP 2013) was considered as a case study of this research as it represents the existing housing stock condition.

The AccuRate 2.3.3.13SP2, which is an Australian Nationwide House Energy Rating Scheme (NatHERS) accredited software was used for the estimation of operational energy for heating, cooling, lighting and hot water and MS Excel 2013 software was used for estimation of building materials, and operational energy for home appliances.

The material and energy data were incorporated into the SimaPro 8.05.13 software to estimate GHG emissions and EE consumption. SimaPro LCA software is widely used by Australian industries as it supports the Australian National Life Cycle Inventory Database (AusLCI). The built in Monte Carlo simulation module in SimaPro was used to ascertain uncertainties of the inputs and outputs. The economic outcomes were validated for anticipated changes in policies.

The MS Excel 2013 software was used for estimation of life cycle cost following the Rawlinsons construction cost guide 2015, which has most up to date Australian cost data of various materials and methods of construction and is widely accepted by building sector (Islam, Jollands and Setunge 2015; Moore and Morrissey 2014; McLeod and Fay 2011).

Information has been gathered from a variety of published sources to use LCM framework. Some of the details regarding prevailing construction practices, costs, and the availability of the resources were obtained from local builders and building material suppliers across the Western Australia.

Based on census data from Australian Bureau of Statistics 2011, growth forecast of regions, and identified climatic zones of Australia, 17 additional locations in regional WA were selected to capture the location specific climatic, economic, energy, and resource variations. The GHG emissions and EE consumption of a typical house for cleaner production options, which were found to be economically and environmentally viable for Perth were estimated using SimaPro 8.05.13 software. Also, their cost-effectiveness was estimated using MS Excel 2013 software. Finally, the optimum sustainable solution for all locations in regional WA was identified.

1.6 Significance

This research has significance for a number of reasons. This research will help to define the life cycle environmental impacts, and life cycle cost associated with the existing housing in Western Australia. The inclusion of operational energy for lighting, hot water, and home appliances, in addition to operational energy for heating and cooling, makes the outcome distinctive from other studies. The research will help stakeholders in the building sector of WA to choose from a wide range of environmentally and economically viable cleaner production options consisting of building construction materials and methods, by-products and recyclates, and renewable energy technologies, depending upon the circumstances including the location of construction. The innovative alternative building construction materials and methods will enhance the adaptability of new houses to climate change and will minimize their vulnerability to climate change impacts.

Finally, this research will help establish the relevant strategies and policies that improve the Government and buildings sector's decision making process towards achieving the common goal of sustainable development in Western Australia. Whilst the research has focused on the Western Australian residential building sector, this life cycle management framework can be applied to other States of Australia, and other countries of similar socio-economic and climatic conditions.

1.7 Thesis outline

This research thesis consists of seven chapters as presented in Figure 1.1. Chapter 1 introduces the background, significance, goal, objectives, and scope of the research. In addition, it introduces the approach to achieve the research objectives including thesis layout, and introduces each chapter.

Chapter 2 presents the existing body of knowledge with respect to conventional houses, effects of a house on energy consumption and environment, sustainable houses, roles of tools and concepts in sustainability assessment of houses, renewable energy technologies, socio-economic impacts of houses, and current Australian situation with respect to construction of houses, in order to identify the research gaps which need to be addressed in this research.

Chapter 3 discusses the development of the life cycle management framework based on the extensive literature review in Chapter 2 that integrates the NatHERS energy rating tool with LCEA, LCA, and LCC to determine sustainable building options for Western Australia. The chapter further discusses the methodology for application of the life cycle management framework for sustainability assessment of houses.

Chapter 4 presents the design details of a typical reference house in Perth in order to develop a database and estimate the material and energy inputs including the assumptions for the development of the LCI, which is a prerequisite for conducting LCA. The chapter further presents the results of environmental impacts (i.e. GHG emissions and EE consumption); identify the hotspots, select and apply the relevant cleaner production strategies, and validates the outcome through sensitivity and uncertainty analysis.

Chapter 5 discusses the socio-economic implications of the environmentally viable cleaner production options for a sustainable house in Perth. The chapter further discusses the cost effectiveness of the energy efficiency improvement measures and validates the outcome through sensitivity analysis. The chapter further discusses the social implications of cost effective environmentally benign house options.

Chapter 6 discusses the regional implications of the cleaner production options for construction of a house, which were found to be environmentally and economically viable for Perth, for 17 locations in regional Western Australia. This captures the location specific climatic, economic, energy, resource availability, and policy variations. The chapter further presents and compares the location wise results of environmental and economic impacts with the reference house in Perth.

Chapter 7 summaries the significant research findings to ascertain a sustainable house in Western Australia and discusses the outcomes of the research objectives presented in the previous section of this chapter. The potential for future research opportunities has also been recommended at the end. Finally, it was made sure that the conclusions that are based on the research findings have addressed all objectives that are listed in this chapter.

Chapter 1 – Introduction to the thesis

Chapter 2 - The literature review shows that there is a need for integration of various life cycle tools and concepts for sustainability assessment of houses in Western Australia and identification of the sustainable options to contribute to Australia's commitment to emissions reduction

Chapter 3 – A life cycle management (LCM) framework is developed by integrating life cycle energy analysis, life cycle assessment, cleaner production strategies, life cycle costing, and policy instruments to achieve sustainable houses in Western Australia

Chapter 4 – Using LCM framework, the life cycle environmental impacts associated with the cradle to grave stages of a typical house in Perth are assessed and cleaner production strategies are applied for mitigation of impacts

Chapter 5 – Using LCM framework, the socio-economic implications of environmentally viable cleaner production strategies to mitigate the life cycle environmental impacts associated with all stages of a typical house in Perth are assessed

Chapter 6 – Regional implications of environmentally and economically viable cleaner production strategies for a typical house in Perth are assessed for 17 locations of regional Western Australia

Chapter 7 – Conclusion and recommendations

Figure 1.1 Thesis outline covered by seven chapters

Chapter 2

Literature review

2.1 Introduction

This chapter presents the critical review of the fundamental knowledge regarding sustainability assessment of residential buildings in order to identify the knowledge gap to be addressed in this research with a particular focus on the Western Australian housing sector. Firstly, a review has been conducted to determine the extent of environmental, economic and social implications of the housing sector. Secondly, the national and international literature which was published in the last 10 years have been reviewed to identify the historical and current methodological concepts and approaches of sustainability assessment and to determine what tools have been utilized for addressing the sustainability of Western Australian housing sector. Also, this chapter presents the review of literature on the integration of various tools such as life cycle energy analysis (LCEA), life cycle assessment (LCA), cleaner production strategies (CPS), life cycle costing (LCC), social implications, and policy instruments to achieve sustainability outcome and to identify the knowledge gap. The critical review of the literature has helped in developing a sound understanding of the potential of various tools and approaches for the development of LCM framework for this research and to meet the research objectives.

2.2 Sustainable development

According to Brundtland commission's report, the sustainable development is defined as "*development which meets the needs of the present without compromising the ability of future generations to meet their own needs"*(Blair et al. 2004). The sustainability is often referred as triple bottom line (TBL) of environment, economy, and society (Hall and Purchase 2006). During the United Nations Conference on Sustainable Development held in Rio de Janeiro, Brazil in 2012, it was acknowledged that the trends of unsustainable development are still continuing and a lot more efforts are needed to achieve the common goal of sustainable development (UNCSD 2012).

Burinskienė and Rudzkienė (2007), and Sev (2009) reported that as compared to other sectors, the buildings due to their long lifespan causes significant environmental impacts and in order to achieve the goal of sustainable development, the principles and guidelines of sustainable development must be implemented from the project initiation stage itself. Dincer and Rosen (2012), and Iwaro and Mwasha (2013) suggested that material and energy efficiency must be improved during the production as well as the consumption stages to attain the sustainable buildings.

2.3 Sustainability of construction sector: global perspective

Globally, the demand for housing, commercial buildings, and new infrastructure has been increasing substantially due to population growth, rapid urbanization, and economic development in emerging economies. The construction sector itself has been found to be a significant contributor to global and local economic growth, which is estimated to be worth more than US$7.5 trillion per year (Betts, Perspectives and Economics 2009). According to UNEP's *Global Environment Outlook (GEO-5) report*, about 60% of the total infrastructure which needs to be built by 2050 will increase the pressure on earth's resources exponentially (UNEP 2012). The construction sector is responsible for more than a third of global resource consumption including about 12% of all freshwater use and generates about 40% of the total volume of solid waste (UNEP 2011a). Joseph and Tretsiakova-McNally (2010) reported that globally, the resource intensive construction industry consumes 25% of the wood harvest, 40% of stone, sand and gravel, and 16% of water per year. Millions of tonnes of fired clay-brick waste is generated each year and a large portion of which goes to landfill as inert waste (Ray et al. 2009). Due to increasing concerns about climate change, resource scarcity, and waste generation, the construction sector is likely to come under tremendous pressure from consumers and policy makers to address the associated environmental impacts and to adopt the sustainable and affordable construction materials and methods of construction.

The construction materials such as aluminium, steel, cement, concrete, glass, plastics, and paint are energy and carbon intensive materials (Treloar et al. 2001; Joseph and Tretsiakova-McNally 2010; Praseeda, Reddy and Mani 2015; Zabalza Bribián, Valero Capilla and Aranda Usón 2011). As per PBL Netherlands Environmental Assessment Agency's 2014 report on trends in global CO_2 emissions, the fossil fuel combustion, and steel and cement industries released 35.3Gtonnes CO_2 e- in the year 2013 with China, United States and European Union contributing to more than 55% of these emissions (Olivier et al. 2014). Globally, the construction and use of buildings alone has been found to be responsible for almost 30%-40% of global energy use and GHG emissions which is still growing (Ristimäki et al. 2013; Nejat et al. 2015; Ibn-Mohammed et al. 2013; Xing, Hewitt and Griffiths 2011; Zeng et al. 2011).

2.4 Sustainability of construction sector: Australian perspective

The Australian construction sector comprises of mainly building construction, heavy and civil engineering construction, and construction services. Although the building sector is not the biggest contributor to GHG emissions, but this sector is found to be the fastest growing source of GHG emissions and contributes about 20% and 23% of Australia's annual energy consumption and GHG emissions, respectively (ASBEC 2007; ABCB 2015b). This is because of the fact that a majority of Australians are accustomed of living in material intensive detached houses with heavy reliance on artificial air-conditioning (e.g. heating, cooling, and ventilation) (Kelly, Breadon and Reichl 2011; Miller and Buys 2012) and in spite of various energy efficiency initiatives, the building sector's GHG emissions are growing at 1.3% annually (ASBEC 2007). In addition, the building sector in Australia generates about 20 million tonnes of C&D wastes annually (DOE 2013) of which the energy intensive clay brick itself accounts for 16% (Reardon and Downton 2013a). The Australian construction sector creates employment opportunities for more than 1 million people per year and is worth more than $102 billion annually (or 8% of Australia's GDP)(ABS 2012).

The recent estimate shows that in Australia more than 3.3 million additional houses will be needed by 2030 to maintain the pace with an economic growth (NHSC 2011), and about 15% of these new houses alone will be built in Western Australia (WA). Such a rapid socio-economic growth could increase Australia's overall energy demand from 5,724 Peta joules (PJ) in 2008 to 7,715 PJ in 2030 (Geoscience-Australia and BREE 2010) and GHG emissions by 70% of current level by 2050 (DOE 2014a).

Due to relatively long lifespan, buildings have the largest long-term GHG mitigation potential, which will have multiple benefits to economy and society both in terms of cost-saving and resource conservation. Therefore, there is a need for immediate action by building sector to meet Australia's GHG emissions reduction target committed at the climate change conference in Paris (i.e. 26% to 28% on 2005 levels by 2030) (DOE

2015a). In order to achieve this target, the overall approach has to shift from the use of non-renewable resources to renewable resources and from the minimization of waste to reuse and recycling of waste and estimation of GHG emissions should be realistic and representative (Kibert, Sendzimir and Guy 2000; Beattie et al. 2012). To achieve environmentally sustainable infrastructure, the use of renewable, low energy and carbon intensive, and recyclable building materials including use of industrial by-products should be prioritised (Chwieduk 2003; Williams 2013). The bulk of the operational energy required by the buildings is utilized to compensate the thermal energy losses or gains through the building envelope, and so any improvements in thermal performance of envelope materials provide significant energy and GHG emissions reduction opportunities (Xu and Dessel 2008; Bambrook, Sproul and Jacob 2011; Sozer 2010; Sadineni, Madala and Boehm 2011; Lai and Wang 2011).

As per State of Environment report, the impacts of global warming are already being witnessed at all levels as the Australian average surface temperature has risen by 1ºC between 1910 and 2009, the frequency of hot nights has increased, rainfall has largely decreased, length and intensity of droughts have increased, the population of many native species has declined, bush fire patterns have changed, soil acidification has increased, and biodiversity is in decline. These examples demonstrate that the impacts of global warming in Australia are no different to other parts of the world (SOE 2011). This report further says that the Australian population is expected to rise to 39.5 million by 2050 thus requiring additional infrastructure such as housing, transport, water supply, energy, communication, and associated services, which will exert pressure on the already stressed ecosystem (SOE 2011).

2.5 Sustainability assessment of buildings

Various studies have suggested that the integrated sustainability assessment framework with a focus on the energy, environmental, economic, and social factors, could be a powerful decision making tool for identification of sustainable building options (Ding 2008; Gibson 2006; Ortiz et al. 2009; Pope, Annandale and Morrison-Saunders 2004; GOWA 2003). A number of sustainability assessment approaches are available worldwide and their application for sustainability assessment of buildings is growing slowly (Berardi 2012; Bloom and Wheelock 2010).

The different tools and concepts have been utilized by the construction sector for the assessment of energy, environment, economic, and social impacts associated with the buildings to achieve the sustainable solutions and to identify the causes of the highest impacts (hotspots) so that appropriate mitigation strategies are implemented (Sadineni, Madala and Boehm 2011; Berry and Marker 2015b; Carre and Crossin 2015; Bahadori and Nwaoha 2013; Monteiro and Freire 2012; Lawania, Sarker and Biswas 2015; Moore 2014).

The roles of various tools and approaches such as life cycle energy analysis (LCEA), life cycle assessment (LCA), cleaner production strategies (CPS), life cycle costing (LCC), social impact assessment, and policy instruments including their integration for sustainability assessment of buildings are discussed in following sections.

2.5.1 Life cycle energy analysis (LCEA) approach

Life cycle energy analysis (LCEA) of a building is a simple most approach which concentrates on the determination of energy inputs during its various life cycle phases. In LCEA, the energy inputs required for mining to material production stage (embodied energy), construction stage (energy for tools and plants), use stage (operational energy for heating, cooling, lighting, hot water, and home appliances), and the end of life demolition and disposal stage (energy for tools and plants) are estimated and analysed (Atmaca 2016; Ramesh, Prakash and Shukla 2010; Karimpour et al. 2014). The operational energy demand for heating and cooling of a building is a complex function of the thermal performance of building envelope and occupant's behaviour. Anda and Temmen (2014) suggested that electricity consumption patterns are highly influenced by consumer behaviour. The building envelope that separates the indoor environment of the building from the outdoor environment is influenced by various technological, functional, and socio-economic factors while satisfying the functional as well as structural requirements (Oral, Yener and Bayazit 2004; Zeng et al. 2011; Horner, Hardcastle and Price 2007) and has a crucial role in reducing operational energy demand and improve the energy efficiency (Gregory et al. 2008).

The following section discusses the Australian initiative to improve the energy efficiency of the buildings with a particular focus on building envelope.

2.5.1.1 Australian initiatives for operational energy reduction of buildings

The Australian and New Zealand Minerals and Energy Council initiated a House Energy Rating Scheme (HERS) in the year 1993 to improve thermal energy efficiency through the design and construction of houses with the help of Commonwealth Scientific and Industrial Research Organization (CSIRO). After realizing the GHG emissions reduction potential of buildings, the Australian federation adopted a National Greenhouse Strategy and forged a partnership with Australian Building Codes Board (ABCB) through Australian Greenhouse Office (AGO) as a part of their commitment to the development of a minimum energy performance requirement for new houses in the year 1998. Considering the national role of HERS, the Building Code of Australia (now known as National Construction Code (NCC)) incorporated the minimum energy efficiency standards for residential buildings in the year 2003, which were further improved in the year 2006 and 2010 to NatHERS 5 star and 6 star ratings respectively (NatHERS 2015). NatHERS accredited software tools helps in designing the energy efficient houses for Australia’s diverse climatic regions and provide one of the methods to conform to the NCC’s minimum energy efficiency standards. However, the minimum energy efficiency standards of Building Sustainability Index (BASIX) system are applicable in NSW.

In 2007, the first generation NatHERS software tools, which were based on CSIRO’s CHEETAH thermal calculation engine were phased out and the second generation of software tools were introduced based on Chenath based thermal calculation engine developed by CSIRO (NatHERS 2015). In Australia, there are 3 NatHERS accredited software tools such as AccuRate, FirstRate5, and BERS Professional. Of these software, AccuRate 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). These software tools simulate 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 one 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.

AccuRate software has been widely used for estimation of operational energy demand by a number of studies for Australian residential building sector (Ren, Paevere and McNamara 2012; Aldawi, Alam, Date, et al. 2013; Gregory et al. 2008; Islam, Jollands and Setunge 2015; Clune, Morrissey and Moore 2012; Morrissey and Horne 2011a; McLeod and Fay 2011; Moore and Morrissey 2014; Seo, Wang and Grozev 2013) and also has been validated through various studies (Geard 2011; Delsante 2005; Dewsbury, Soriano and Fay 2011).

Various life cycle energy analysis studies have been conducted for operational energy management, which are discussed in the following section.

2.5.1.2 Review of contemporary LCEA studies of buildings and building sector

The review of Australian and international LCEA studies of buildings and building sector which have been conducted over the last 15 years have been summarised in Table 2.1. Most of these reviews consist of individual case studies and comprehensive review studies comprising of around 250 case studies undertaken in developed countries with a little focus on developing countries. In the case of Australia, most of the LCEA studies have been conducted in the Eastern states.

Majority of these LCEA case studies (Table 2.1) have estimated the embodied energy of materials used during construction and the operational energy that includes only heating and cooling with few exceptions where the total operational energy for heating, cooling, lighting, hot water, and home appliances has been estimated (Fay, Treloar and Iyer-Raniga 2000; Gustavsson and Joelsson 2010).

The lifespan of the building significantly influences its overall energy consumption performance and in most of the LCEA case studies, a 50 year lifespan has been considered for analysis. The comprehensive reviews of case studies have reported that lifespans vary from 25 to 100 years (Karimpour et al. 2014; Cabeza et al. 2014;

Ramesh, Prakash and Shukla 2010; Fay, Treloar and Iyer-Raniga 2000; Sartori and Hestnes 2007).

The system boundary of most of these LCEA case studies was limited to construction and operational stages. While Fay, Treloar, and Iyer-Raniga (2000) have considered the maintenance stage, Stephan, Crawford, and de Myttenaere (2013) have expanded the system boundary by considering the transportation energy for commuting due to the location of the building which is a consequential indirect impact. In a comprehensive review of LCEA studies, Cabeza et al. (2014) found that most of the studies included the energy consumption during demolition stage.

Most of the LCEA studies focused on impacts due to improvements of building envelope's thermal performance as compared to conventional building envelope systems. Pacheco, Ordóñez, and Martínez (2012) and Morrissey, Moore, and Horne (2011) considered the influence of orientations on the thermal performance of the building. Though the brick was found to be the most predominant wall material for buildings (e.g. double brick, insulated double brick, brick veneer, and reverse brick veneer), few case studies considered the buildings made of timber frame walls, autoclaved aerated concrete block walls, and structural insulated panels. Most of the case study buildings were residential (house) except for one case study where Ramesh, Prakash, and Shukla (2010) included office buildings.

Li, Yang, and Lam (2013) reviewed six case studies, where the renewable energy technology has been used in addition to the energy efficiency measures to reduce energy.

With reference to the life cycle energy consumption of buildings, the operational energy has been found to have the largest share (80%-90%), while the share of initial embodied energy of materials was quite low (10%-20%) in all case studies. The end of life demolition energy had a little or negligible share of life cycle energy of the building (Cabeza et al. 2014).

The share of initial embodied energy of replacement materials during maintenance stage was found to be significant and depends on the lifespan of the building (Crawford, Czerniakowski and Fuller 2010; Fay, Treloar and Iyer-Raniga 2000). However, in the case of highly energy efficient or zero energy building, the share of initial embodied energy of materials was found to be significant as compared to operational energy due to the inclusion of energy efficient materials or methods of construction (Sartori and Hestnes 2007; Gustavsson and Joelsson 2010). Fay, Treloar, and Iyer-Raniga (2000) reported that it is possible to achieve a net zero operational energy building but it is almost difficult to achieve energy natural building as upstream activities, materials, and construction activity consume energy.

Stephan, Crawford, and de Myttenaere (2013) reported that the transportation related energy demand due to the location of the building has an important role and should be considered for LCEA as consequential impact. This is because an energy efficient house located in a low density settlement will require high car usage for commuting as compared to high density settlement close to the workplace.

Most of the LCEA studies reported that the additional embodied energy incurred due to the inclusion of energy efficient materials and methods of construction could be recovered from the operational energy savings. Gregory et al. (2008), Sadineni, Madala, and Boehm (2011), Aldawi (2013), and Li, Yang, and Lam (2013) reported that the optimum insulation and thermal mass of the building envelope are the keys to the reduction of energy demand. Pacheco, Ordóñez, and Martínez (2012) and Li, Yang, and Lam (2013) reported that the over insulation and incorrect positioning of thermal mass may be counterproductive because they may be useful during a particular season or for a particular climate but may have adverse effects during other seasons or climatic condition. All these features have been considered for sustainable house design in the current study.

Sartori and Hestnes (2007), Bambrook, Sproul, and Jacob (2011), and Li, Yang, and Lam (2013) reported the use of roof top solar PV and solar water heater to achieve zero operational energy.

2.5.1.3 Summary and lessons learnt from review of contemporary LCEA studies

In summary, the system boundaries of these LCEA studies have been found to be different mainly due to the absence of any regulated framework, research objectives, and to meet the project specific requirements. However, the choice of different system boundaries does not appear to affect the outcome as the operational energy for conventional buildings has been found to be the biggest contributor to the life cycle energy and the energy efficiency improvement measures leads to significant reduction of operational energy. Though there is a variation in the assumption of building's lifespan, but there is a wide spread consensus on a 50 year lifespan for residential buildings in most parts of the world including Australia and has been considered for this research as well.

On the basis of the lessons learnt from the above studies, the operational energy of the residential building for different envelope materials under Western Australian climatic conditions have been analysed in Chapters 4, and 6. The renewable energy technologies and other energy efficiency improvement measures are also considered for this research.

These LCEA studies have focused only on consumption of energy which leads to various emissions and pollutions. The following section discusses the life cycle assessment approach to investigate the environmental impacts associated with the construction and use of buildings.

Table 2.1 Summary of contemporary LCEA studies reviewed

Life cycle energy analysis studies	Aim of the study and major assumptions	Results
Fay, Treloar, and Iyer-Raniga (2000)	• Investigation of the issues with LCEA to demonstrate its application in comparing the alternative design strategies. • Case study house - two storey energy efficient detached brick veneer house in Melbourne for the lifespan of 0, 25, 50, 75, and 100 years including maintenance stage. • Operational energy - heating, cooling, lighting, hot water, and home appliances.	• The process analysis, economic input-output analysis, and hybrid analysis are some of the methods used for estimation of embodied energy. The economic input-output analysis method is not considered as reliable for estimation of embodied energy of an individual product. • Additional embodied energy consumed due to a high level of insulation could be paid back from savings of operational energy within 12 years. • Embodied energy of materials was found to be significant as compared to operational energy. • A zero life cycle energy building is almost difficult even if the operational energy is zero.
Sartori and Hestnes (2007)	• Review of 60 LCEA case studies of residential and non-residential buildings from nine countries mainly in Europe, Australia, Japan, and the USA. • Lifespans of case study buildings - from 30 years to 100 years while the majority of the studies considered a 50 year lifespan.	• Operational energy represents the largest share of the life cycle energy of the buildings with a linear relationship irrespective of the climatic differences. • As compared to conventional buildings, both low energy and passive buildings were more energy efficient in spite of their high embodied energy. • Integration of solar system was more efficient than the use of green materials.
Gregory et al. (2008)	• To investigate the influence of thermal mass of cavity brick, brick veneer, reverse brick veneer, and light weight timber frame wall systems in NSW, Australia. • Operational energy – only heating and cooling.	• The thermal mass of the wall has a major role in minimizing the operational energy of a building. • Reverse brick veneer wall house consumes least amount of operational energy.

Life cycle energy analysis studies	Aim of the study and major assumptions	Results
Aste, Angelotti, and Buzzetti (2009)	• Investigation of energy saving potential of external wall systems with the same U values but with varying dynamic properties.	• Both dynamic thermal transmittance and admittance of the wall system should have optimum values to achieve the best thermal inertia performance. • Use of high thermal inertia walls in buildings would reduce the operational energy for heating, and cooling by 10%, and 20% respectively.
Zhu et al. (2009)	• Analyse the energy saving performance of the thermal mass walls using thermocouples and heat flux sensors in a zero energy house in Las Vegas, USA. • The low thermal mass wall house - conventional house with timber frame walls • High thermal mass wall house - zero energy house with pre-cast concrete sandwich walls.	• Internal wall surface temperature of high thermal mass wall changes slowly and thus maintain the stability of indoor comfort level. • High thermal mass walls help in reducing the operational energy for heating but cause a slight increase in the operational energy for cooling.
Crawford, Czerniakowski, and Fuller (2010)	• Development of a comprehensive framework for analysing the life cycle energy demand of a typical house for 2 floor, 2 roof, and 4 wall types in different climate zones of Australia. • Lifespan - 50 years with the end of life demolition and disposal stage excluded.	• The economic input-output analysis is carried out based on national average data on financial flows, hence its application to a particular product and reliability of results is limited. The economic input-output based hybrid approach was used for this study. • A particular construction type with high embodied energy at the construction stage may prove to be energy efficient during use stage due to the improved thermal performance. • The operational energy of the building during use stage was same for the steel sheet roof (high embodied energy) and concrete roof tiles (low embodied energy). • Wall systems with similar embodied energy could have different operational energy consumptions.

Life cycle energy analysis studies	Aim of the study and major assumptions	Results
Gustavsson and Joelsson (2010)	• Analyse 11 case studies of the primary energy use and GHG emissions for the conventional and low energy residential buildings in Sweden. • Functional unit – construction and use of $1m^2$ of floor area over a period of 50 years.	• Domestic hot water and home appliances consume a large part of the operational energy and the use of solar energy may offset the operational energy demand. • Low energy buildings have high embodied energy. • Ratios of energy saved to energy embodied for insulation and energy efficient windows were more than 10.
Ramesh, Prakash, and Shukla (2010)	• Review of 46 LCEA case studies on residential buildings, and 27 LCEA case studies on office buildings across Sweden, Norway, Indonesia, Thailand, India, Australia, Canada, Japan, New Zealand and the USA. • The case study buildings were made of timber, steel, concrete, and brick veneer with the lifespan varying from 30 years to 100 years while 46 of these case studies considered a 50 year lifespan.	• The economic input-output analysis involves a number of assumptions which underlines its reliability for estimation of embodied energy of construction materials and hence process analysis method was adopted for this study. • As compared to life cycle energy of the buildings, the share of operational energy was the highest (80%-90%) followed by embodied energy (10%-20%). • Life cycle energy of residential and office buildings were 150-400kWh/m^2, and 250-550kWh/m^2 respectively. • Excessive use of active and passive design methods for reducing the operational energy could be counterproductive.
Bambrook, Sproul, and Jacob (2011)	• Development of an optimization model for a detached house for brick veneer and structural insulated panel (SIP) walls in Sydney, Australia to achieve zero operational energy for heating and cooling by varying the wall and roof insulation thickness, window type, thickness of internal thermal mass wall, and night ventilation air change and using net present cost value approach.	• The inclusion of high insulation was identified as an economical way to reduce energy and the energy saving to cost ratio of internal thermal mass was relatively low. • Under varying wall and roof insulation performance, the low emissivity double glazed windows effectively reduces the operational energy. • Through the integration of roof top solar PV, practically an operationally zero energy house could be achieved.

Life cycle energy analysis studies	Aim of the study and major assumptions	Results
Morrissey, Moore, and Horne (2011)	• To assess the implications of orientation on the thermal energy efficiency of 81 detached house designs in Australia through a modelling experiment.	• Smaller and compact and highly energy efficient house designs were more adaptable to orientation change. • Passive solar features could effectively meet the goals of climate change impact mitigation.
Sadineni, Madala, and Boehm (2011)	• Review of various walls, windows, and roof types including insulation materials, phase change materials, thermal mass, infiltration and airtightness, and building envelope diagnostics from an energy efficiency point of view.	• Passive energy efficiency strategies were highly sensitive to climatic conditions. • Energy saving performance of thermal mass was maximum at the locations having a high temperature difference between day and night and energy efficient measures were economically viable. • Periodic energy audits and maintenance must be carried out to ensure the maximum benefits from the energy efficiency of the building envelope.
Pacheco, Ordóñez, and Martínez (2012)	• Investigation of the operational energy (heating and cooling) saving potential of residential buildings through orientation, shape, building envelope (wall, windows, and roof), passive heating and cooling methods, and shading.	• The operational energy of a building is highly influenced by its orientation, shape, and the ratio between the façade area, and the volume. • The performance of energy efficiency measures changes with different climatic zones and may not always be economically and or environmentally viable.
Li, Yang, and Lam (2013)	• Review of 15 case studies on energy efficient measures (EEM) for minimizing the energy demand of the buildings, and 6 case studies on adaptation of renewable energy or other technologies (RET) to meet the remaining energy demand of the buildings.	• Optimum thermal insulation and mass, window glazing, daylighting, reflective/green roofs, indoor design conditions, internal heat loads, HVAC, electrical services, and vertical transportation were an efficient EEM. • Solar energy, wind turbines, heat pumps, and district heating and cooling were highly efficient RET.

Life cycle energy analysis studies	Aim of the study and major assumptions	Results
Aldawi (2013)	• Investigation of the thermal performance and operational energy saving of a typical brick veneer wall, and 3 variants of concrete sandwich wall house in 10 Australian locations including Perth and Broome. • Operational energy - for heating and cooling only.	• All 3 concrete sandwich wall houses were energy efficient than the brick veneer wall houses in all locations. • While the externally insulated thermal mass walls were more energy efficient in cold climatic zones, internally insulated thermal mass walls were more energy efficient in humid and warmer climatic zones.
Seo, Wang, and Grozev (2013)	• Quantification of the regional cooling energy consumption in South East Queensland, Australia and to investigate its sensitivity to air temperature, number of households, cooling system penetration rate, energy efficiency of air conditioners, and ceiling insulation	• The increase of cooling energy demand would necessitate the expensive upgrading of the electricity grid and 1ºC temperature rise between 2010 and 2030 would cause an increase of cooling energy by 35% in 2030. • Ceiling insulation was most effective means to reduce the cooling energy demand.
Stephan, Crawford, and de Myttenaere (2013)	• Analysis of the total life cycle energy demand of a typical Belgian passive house over a period of 100 years and to investigate whether the net energy savings do occur as compared to a standard house. • The embodied, operational, and transport energy were considered.	• Because of the difficulty in obtaining data beyond a certain level in supply chain for process analysis and due to aggregation error for economic input-output analysis for the estimation of embodied energy, the hybrid analysis should be used. • As the passive house certification process does not consider the embodied energy, the life cycle energy demand of a passive house could be similar to of a standard house. • Use of an area-based functional unit could distort the findings as it does not take into account the impact due to a number of occupants. • Energy demand for occupant's commuting due to the location of a house should be included in the life cycle energy.

Life cycle energy analysis studies	Aim of the study and major assumptions	Results
Cabeza et al. (2014)	• Review of 25 LCEA, LCA, and LCC case studies on buildings and related fields from Australia, Sweden, Indonesia, Japan, Norway, India, USA, China, and the UK. • Functional units of the majority of these studies were energy per m^2 floor area over a lifespan of 30 to 100 years while the majority of the studies considered a 50 year lifespan. • The embodied energy, operational energy, and demolition energy were considered.	• With respect to life cycle energy, the share of operational energy was largest (80%-90%) followed by embodied energy (10%-20%). Demolition energy had a negligible share. • In spite of relatively small share, the opportunities of embodied energy reduction should be utilized. However, the energy efficiency measures to reduce operational energy results in an increased embodied energy. • Steel, cement, aluminium, and clay bricks were the largest contributors of embodied energy. • Optimally insulated building envelope, passive house standards, solar systems, waste recycling, and use of recycled products could significantly reduce the life cycle energy.
Karimpour et al. (2014)	• Review of 24 LCEA case studies on residential buildings from 10 locations in the world with varying lifespans of 40 to 100 years while the majority of the studies having 50 years of lifespan and to investigate the role of embodied energy in reducing the life cycle energy. • Operational energy - heating and cooling only.	• Embodied energy of a house in mild Australian climates could be up to 25% of the life cycle energy consumption. In order to reduce the life cycle energy, the embodied and operational energy both should be reduced. • If time value and reduction targets of GHG emissions are taken into consideration, the share of embodied energy from life cycle energy increases significantly.
Berry and Marker (2015b)	• Examination of the concept of net zero carbon and net zero energy homes in Australia and the technical and economic evidences that would support such a policy position.	• Australian housing industry has the tools, capacity, and technology to produce highly energy efficient houses. • Improving the energy efficiency of houses through performance based regulations could provide significant economic benefits to a wider community however due to varied vested interests and lack of political vision, the changes in the housing energy policy are slow and difficult.

Life cycle energy analysis studies	Aim of the study and major assumptions	Results
De Boeck et al. (2015)	• Review of 78 case studies on improving the energy performance of residential buildings during the year 2000 to 2013 from China, Sweden, Finland, Belgium and the USA with only one case study from Australia. • These case studies represented six domains such as the area of application and design variables, objectives and performance measures, type of analysis, solution methodology, software tools, case study locations and type of buildings.	• Development of new solution techniques should consider the building as a whole instead of individually analysing the building components. • Passive design measures should be developed for all climate zones. • The societal climate change effect of new buildings as well as retrofitting projects should also be included in the investigation.

2.5.2 Life cycle assessment approach

Rebitzer et al. (2004) described the life cycle assessment as a methodological framework which facilitates the estimation and assessment of the environmental impacts such as global warming, ozone depletion, eutrophication, acidification, ecological toxicity, and resource depletion caused by a product or service during its life cycle. In recent years, there is an increasing environmental awareness amongst all sectors and the life cycle assessment approach is being used in tandem with other management tools for the development of environmental policies.

The life cycle assessment (LCA) technique was developed in the late 1960's with a focus on environmental impacts of alternative packaging materials (Consoli et al. 1993) and this technique was applied to various products for next 20 years under different names, but it was limited to quantification of their life cycle material and energy consumptions and waste generation only (UNEP 2009). During mid 1990's, the Society of Environmental Toxicology and Chemistry (SETAC) developed standard guidelines for LCA (Consoli et al. 1993), which were later used by International Organization of Standardization (ISO) as a basis for development of systemized framework for conducting LCA in the form of a set of four standards (ISO 14040-14043 - 1997-2000) (Jensen 1996; UNEP 2011b). During this period, there were some other initiatives to develop LCA guidelines such as Environmental life cycle assessment of products: guide and backgrounds (Part 1) by Heijungs et al. (1992), Nordic Guidelines for Life Cycle Assessment by Lindfors et al. (1995), Life Cycle Assessment: What it is and How to do it by UNEP (1996), and European Environment Agency (EEA)'s Life Cycle Assessment (LCA) – A guide to approaches, experiences and information sources by Jensen et al. (1997).

After the release of ISO 14040 series of standards, the LCA practitioners raised various issues related to the efficiency of peer review process, interpretation of some of the terms, uncertainties, weighting process, allocation, and economic analysis and hence the discussions on revision process started in the year 2003 to address the concerns raised by practitioners. In the year 2006, after much deliberation, and surveys of practitioners, the original four standards (ISO 14040-14043) were replaced with following two standards, which are the basis for most of the LCA studies (Pryshlakivsky and Searcy 2013; Finnveden et al. 2009).

- ISO 14040:2006 – Environment management – Life cycle assessment – Principles and framework

- ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines

ISO 14040:2006 describes the LCA framework as four interconnected phases (Figure 2.1) and provide principles of reporting and critical review, limitations, and relationships between phases of LCA (ISO14040 2006). A number of software tools are available for performing life cycle assessment as described in Section 2.5.2.1.

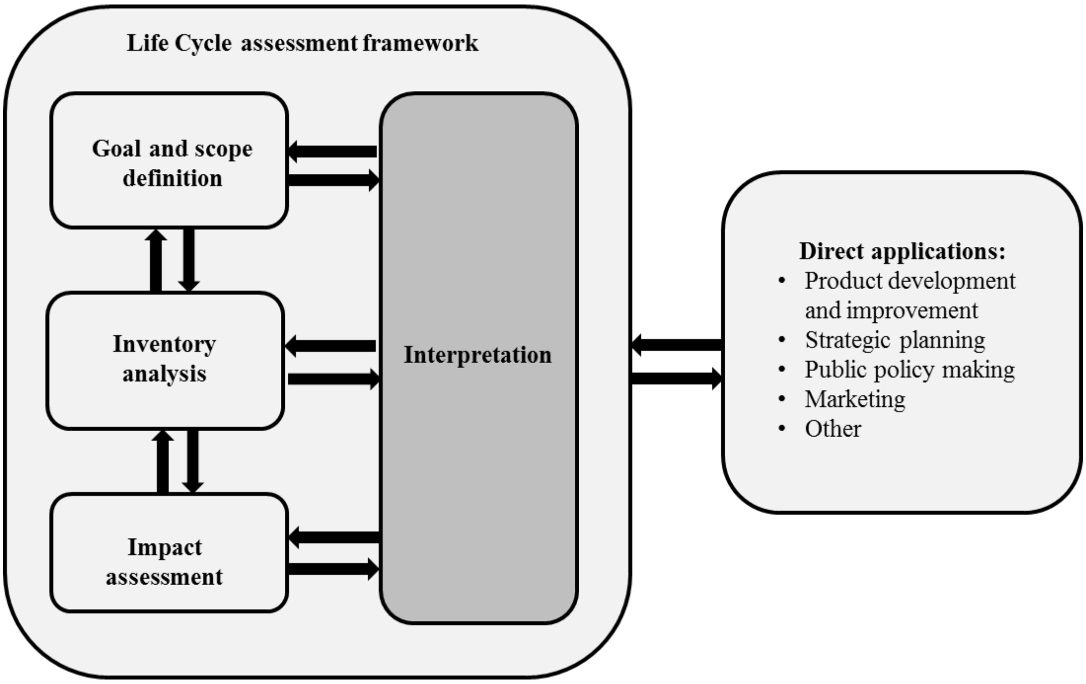


Figure 2.1 Life Cycle Assessment Framework (ISO14040 2006)

The building sector is a major energy and material consumer and buildings consume energy throughout their life. The application of LCA for environmental performance of building materials, and construction methods started in the 1990s and since then LCA has been widely used as a decision making tool for the selection of environmentally friendly materials and methods of construction (Aashish Sharma 2011; Cabeza et al. 2014; Ghattas et al. 2013; Ross Maher 2011; Rossi et al. 2012; Hedayati, Iyer-Raniga and Crossin 2014).

2.5.2.1 Life cycle assessment tools

A number of environmental modelling software, which can estimate the life cycle impacts of a product or service through a rigorous and complex analytical process in accordance with relevant ISO standards and guidelines such as GaBi (Germany), ATHENA (Canada), BREEAM (UK), LEED (USA), BEES (USA), SimaPro (Netherlands), EQUER (France), LCAid (Australia), Eco-Quantum, LISA (Australia), Envest (UK), LCAiT, PEMS, TEAM (France), Umberto (European), SBi (Denmark), and Boustead (UK) have been developed and being used by construction industries across the globe (Ortiz, Castells and Sonnemann 2009; Bayer et al. 2010). A majority of these software contain region specific database referred as life cycle inventories (LCI) of material and energy resources, waste, and emissions for various products (Islam, Jollands and Setunge 2010; Zabalza Bribián, Valero Capilla and Aranda Usón 2011; Khasreen, Banfill and Menzies 2009; Finnveden et al. 2009). The software takes material and energy requirements of a product or service as input and attaches them to LCI database/s. The software then calculates the outputs as emissions associated with the product or service followed by characterization which converts these outputs into impact categories such as global warming potential, acidification, eutrophication, ozone depletion, and solid waste. This software provides an option for normalization (changing the impacts indicators into a common unit less format) and weighting (changing the impact indicators to single score)(Bayer et al. 2010).

SimaPro software is widely used by various industries in Australia as it support the use of Australian National Life Cycle Inventory database (AusLCI) (Horne, Opray and Grant 2006; Clarkson and Bengtsson 2010; Iyer-Raniga and Wong 2012; Ximenes and Grant 2013; Engelbrecht, Biswas and Ahmad 2013; Campbell, Beer and Batten 2011; Rouwette 2010; Islam et al. 2015; Shahabi et al. 2015). SimaPro software has been developed by Pre Consultants of The Netherlands (PRé-Consultants 2015) and is a unique product design oriented software (Figure 2.2), which not only allows analysis and comparison of complex products with complex life cycles but user can trace the origin of any result as well as edit or expand the inventory databases and impact assessment methods (Bayer et al. 2010).

The Australian Life Cycle Assessment Society (ALCAS) has taken the initiatives to develop the AusLCI database, which has the comprehensive and transparent environmental information on a wide range of Australian products and services. In addition, the AusLCI database support and provide benchmarks for eco-labelling and environmental product declarations (EPDs) and helps in developing LCA based policies for building and infrastructure projects (Renouf 2015).

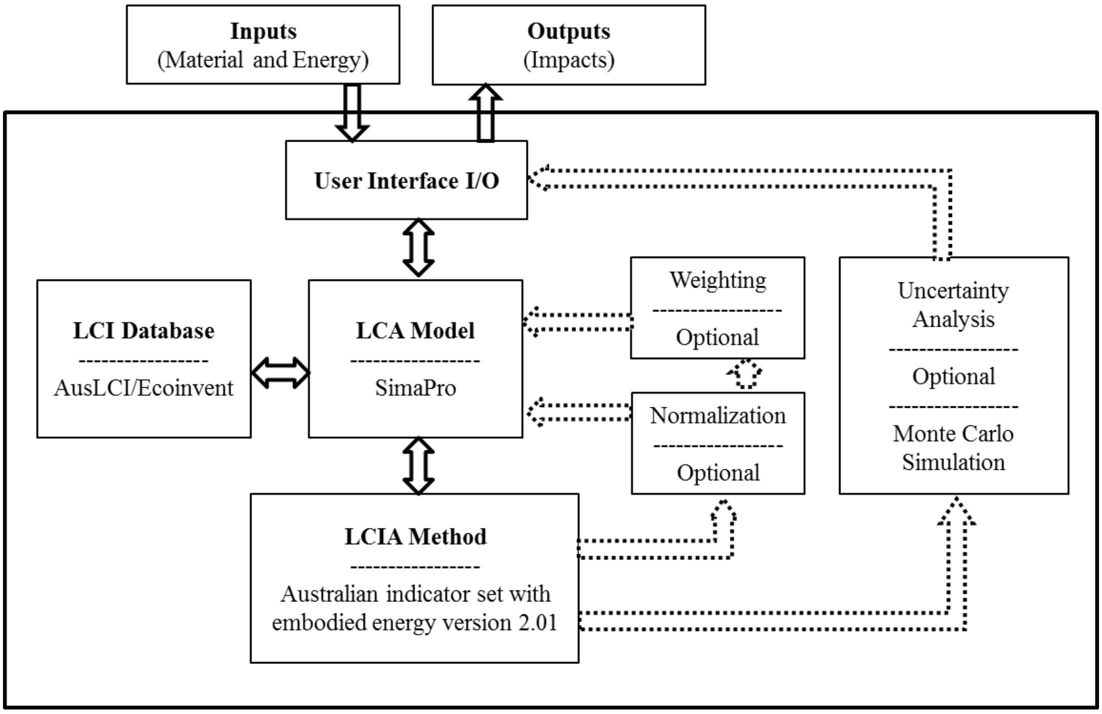


Figure 2.2 Modified configuration of SimaPro in Australia (Bayer et al. 2010)

In the case of non-availability of data of a particular product in AusLCI database, the European ecoinvent database, which is one of the largest and most comprehensive international database (managed by not-for-profit ecoinvent Association of Switzerland) has been used after replacing the European energy and transport input values in the ecoinvent database with Australian energy and transport values (Chen et al. 2010; Tharumarajah and Grant 2006).

SimaPro software has a number of region specific LCIA methods. There is no single LCIA method which can be considered as one-size-fits-all and is selected based on the specific goal and regional relevance (Monteiro and Freire 2012; Renouf 2015). The Australian indicator set with embodied energy version 2.01 is one of the LCIA methods embedded in SimaPro software. The 100 year time horizon is used for National Inventory Reporting in Australia (DOE 2014b) and is most commonly used time horizon for life cycle assessments of buildings (Renouf 2015; Carre and Crossin 2015; Zabalza Bribián, Valero Capilla and Aranda Usón 2011). The AusLCI database supports process based energy data for mining to material production stage of the building materials required for the construction (Crawford 2014). The Australian indicator set with embodied energy version 2.01 method provide total energy flows based on lower heating values (Burchart-Korol 2013; Farmery et al. 2015).

SimaPro software has the ability to estimate uncertainty propagation of life cycle impact assessment results using Monte Carlo analysis (Yu et al. 2012; Lloyd and Ries 2007; Guo and Murphy 2012; PRé-Consultants 2015).

2.5.2.2 Review of contemporary LCA studies of buildings and building sector

The review of Australian and international LCA studies of buildings and building sector which have been conducted over last 15 years have been summarised in Table 2.2. Most of this review consists of individual case studies and comprehensive review studies comprising of around 180 case studies undertaken in developed countries with few studies from developing countries. In the case of Australia, most of the LCA studies have been conducted in the Eastern states.

The majority of these LCA case studies (Table 2.2) have estimated the GHG emissions, and cumulative energy demand (CED) or embodied energy (EE) as important impact indicators. In addition to GHG emissions, and CED impact indicators, Islam et al. (2014) and Islam et al. (2015) included water use and solid waste generation indicators and Carre (2011a) included land use, water use, and solid waste generation indicators. The LCA study of thermal insulation materials by Pargana et al. (2014) included 8 indicators such as Primary energy use renewable (PE-Re), Primary energy use non-renewable (PE-NRe), Abiotic depletion (ADP), Acidification (AP), Eutrophication (EP), Global warming (GWP), Ozone depletion (ODP), and Photochemical ozone creation (POCP). In Australia, while LCA study of multi-level buildings by Carre and Crossin (2015) included GHG emissions, ozone depletion, abiotic depletion, photochemical oxidation, eutrophication, and acidification as an impact indicators, while the LCA study of heritage buildings by Iyer-Raniga and Wong (2012) included global warming, photochemical oxidation, eutrophication, land use, and water use as impact indicators. The comprehensive review studies by Ortiz, Castells, and Sonnemann (2009), Khasreen, Banfill, and Menzies (2009), and Aashish Sharma (2011) show that GHG emissions and embodied energy consumption or cumulative energy demand (CED) impact indicators followed by the acidification, and eutrophication are most commonly used impact indicators.

The lifespan of the building significantly influences its overall environmental repercussions associated with the operational energy consumption and in most of the LCA case studies, a 50 year lifespan is considered for analysis. Few individual and comprehensive reviews of case studies have reported that lifespans vary from 20 to 100 years (Cabeza et al. 2014; Rouwette 2010; Atmaca 2016). In Australia, the LCA study of multi-level buildings by Carre and Crossin (2015) considered the lifespan of the building as 60 years.

The system boundary of most of these LCA case studies was cradle to grave. For LCA study of a University building, Biswas (2014) excluded the end of life demolition and disposal stage and the LCA was termed as streamlined LCA. In the case of LCA study of building materials, the system boundary was limited to cradle to gate (Pargana et al. 2014). During use stage, most of the LCA studies included operational energy for heating and cooling only. Few LCA studies included operational energy for lighting, hot water and home appliances (Carre and Crossin 2015; Cuéllar-Franca and Azapagic 2012). The comprehensive reviews were conducted mainly to investigate the effectiveness of LCA as a decision making tool, and to determine whether the key milestones can be accomplished by LCA for building sector (Khasreen, Banfill and Menzies 2009; Ortiz, Castells and Sonnemann 2009; Singh et al. 2010; Atmaca 2016). These LCA studies show that the common functional units are impacts per m^2 dwellable area or per building. In the case of LCA studies for building materials, the functional units are found to be per m^2 material area or per tonnes of material weight. For a single LCA study, Rouwette (2010) used 4 different system boundaries and functional units such as cradle to gate manufacturing of one brick, cradle to grave life cycle of one brick, cradle to grave life cycle of $1m^2$ of a typical single layer brick wall, and cradle to grave life cycle of a house.

These LCA studies show that the use stage alone contributes to 50% to 90% of the life cycle GHG emissions and EE consumption of buildings due to the operational energy consumption (Rouwette 2010; Aashish Sharma 2011; Carre 2011a; Cuéllar-Franca and Azapagic 2012; Ortiz, Castells and Sonnemann 2009). With respect to the life cycle GHG emissions and EE consumption, the low value of share of use stage indicate that the energy for heating and cooling only is included for LCA, while the higher value of share of use stage indicate that the energy for lighting, hot water, and home appliances is also included for LCA (Rouwette 2010). While the construction stage of the building comprising of mining to material production, transportation of material to construction site, construction plants and machinery have been found to be the second largest contributor to life cycle GHG emissions and EE consumption (10%-90%), the end of life demolition and disposal stage contributes up to 1% of life cycle GHG emissions and EE consumption (Cuéllar-Franca and Azapagic 2012). An LCA study by Biswas (2014) reported that up to 7% of the life cycle GHG emissions of a building may be reduced by replacing the virgin materials with recycled materials and by-products. An Australian LCA study shows that the life cycle GHG emissions of a building may change by up to 8% due to change in orientation, while the change in climate zone may cause a change of up to 19% of life cycle GHG emissions (Rouwette 2010). In all LCA studies, the use stage is found to be the biggest contributor to the GHG emissions and EE consumption, thus use stage is the major hotspot during the life cycle of a house which is followed by mining to material production stage.

The comprehensive reviews of LCA case studies show that the LCA approach in building sector is less developed as compared to other sectors due to complex construction processes and longer operational life and the comparison of outcome of different studies is difficult due to the absence of a construction sector specific common international guideline on functional unit, system boundaries, methodologies, and set of impact indicators (Khasreen, Banfill and Menzies 2009; Singh et al. 2010; Cabeza et al. 2014). Nevertheless, the LCA approach has been found to be an efficient decision making tool and have the potential for achieving building sector's environmental performance objectives (Ortiz, Castells and Sonnemann 2009; Singh et al. 2010).

2.5.2.3 Summary and lessons learnt from review of contemporary LCA studies

In summary, the system boundaries have a major influence on the outcomes of LCA studies. For example, the functional unit, research objectives, and the project specific requirements directly affect the outcome. LCA software tools do not influence the outcome, but the region specific LCI database influences the outcome. Similar to LCEA studies, there is a variation in the assumption of building's lifespan, but there is wide spread consensus on a 50 year lifespan for residential buildings in most parts of the world including Australia and this lifespan has been considered for this research as well.

On the basis of lessons learnt from the above studies, the GHG emissions and EE consumption are found to be the predominant impacts associated with the construction, use, and the end of life demolition and disposal stages of a house. Similarly, the use stage of a house is found to be the hotspot causing largest impacts which is followed by mining to material production stage. Thus these two stages require mitigation strategies to minimize the life cycle environmental impacts.

The GHG emissions and EE consumption of a typical house for different building materials and methods under Western Australian climatic conditions have been estimated in Chapters 4, and 6. Impacts associated with operational energy consumption for heating, cooling, lighting, hot water, and home appliances as well as a change of orientations and climate zones have been considered in this research.

The following section discusses the cleaner production approach to mitigate the environmental impacts associated with the hotspots.

Table 2.2 Summary of contemporary LCA studies reviewed

Life cycle assessment studies	Aim of the study and major assumptions	Results
Khasreen, Banfill, and Menzies (2009)	• Review of 25 life cycle assessment (LCA) case studies on buildings and building materials from different parts of the world including Australia for different functional units, system boundaries, and lifespans.	• LCA studies in building sector are less advanced than the other sectors because of the complex construction processes and future phases based on assumptions due to long lifespans. • Due to the absence of common international dataset, no two studies could be compared directly because of different system boundaries, methodologies, and databases. • The single score approach was found to be subjective. • LCA tool has potential for helping to achieve the goals of sustainable development.
Ortiz, Castells, and Sonnemann (2009)	• Investigation of the key milestones accomplished in LCA for building industry from the year 2000-2007 using 25 case studies on building and building components from Europe.	• Use stage had the highest contribution to the life cycle environmental impacts. • LCA as an innovative tool could help improve the sustainability during all life cycle stages. • Small and medium scale enterprises (SMEs) of construction industry have a great potential to improve the environmental performance • LCA initiatives are not established in developing countries.
Rouwette (2010)	• Estimation of GHG emissions and EE consumption of a typical house in Newcastle, Melbourne, and Brisbane for a double brick with and without insulation, brick veneer, reverse brick veneer, and insulated timber walls using integrated LCA and thermal modelling approach over a lifespan of 50 years. Four different functional units such as	• Mining to material production stage of a house contributes between 45% and 59% of life cycle GHG emissions, if only heating and cooling energy is considered during use stage. This contribution reduces to 10% of life cycle GHG emissions if energy for lighting, hot water, and home appliances is also considered.

	○ Cradle to gate manufacturing of one brick ○ Cradle to grave life cycle of one brick ○ Cradle to grave life cycle of $1m^2$ of a typical single layer brick wall ○ One house • For sensitivity analysis, 2 different house layouts, 4 orientations, and 20, 40, 50, 60, 80, and 100 years of lifespan were considered.	• Timber wall house and insulated double brick wall house had the lowest GHG emissions during mining to material production stage and use stage respectively. • In terms of GHG emissions, the insulated double brick wall house performs better than brick veneer and reverse brick veneer wall house. • Changes in orientation and climate zones could increase building's GHG emissions up to 8%, and 19% respectively.
Singh et al. (2010)	• Review of 36 building construction related LCA studies.	• LCA approach is an effective decision making tool and a regulation on a common set of impact indicators specific to construction sector could improve the comparison of results of LCA studies. • LCA methods have not yet become the industry standard practices. The input-output and hybrid LCA methods could resolve some of the issues such as incorporating the interdependencies across the inputs, cut-off criteria associated with the process based LCA method. • LCA approach should be integrated with LCC and social aspects.
Aashish Sharma (2011)	• Reviewed 13 LCA case studies that consist of mainly residential buildings in different parts of the world. • The impacts that are assessed include energy use, GHG emissions, Acidification, and eutrophication impacts on per m^2 basis over a lifespan of 50 years.	• Use stage of the buildings contributes to more than 50% of the life cycle GHG emissions. • Environmental impacts associated with the conventional buildings could be minimized through alternative energy efficient methods of construction.
Carre (2011a)	• Comparison of a typical house design in Melbourne, Sydney and Brisbane for brick veneer with timber and steel frame, and timber weatherboard with timber frame walls in terms of environmental impacts on $1m^2$ area per year basis.	• For different construction types, the use stage contributes the highest (55%-86%) life cycle GHG emissions followed by mining to material production, and construction stages, which contributes 14%-45% of life cycle GHG emissions.

	• Operational energy - heating and cooling only. • Impact categories - GHG emissions, photochemical oxidation, eutrophication, land use, water use, solid waste, depletion of resources, and cumulative energy demand (CED).	• Variation of lifespan did not influence the outcome. • The concrete ground slab had higher impacts than the raised timber floor. • GHG emissions during mining to material production stage of the brick veneer construction were 43% higher than the weatherboard construction.
Cuéllar-Franca and Azapagic (2012)	• Conduct cradle to grave LCA including maintenance for most common type of detached, semi-detached, and terraced house in the UK over a lifespan of 50 years. • Operational energy - heating, lighting, hot water, and home appliances.	• Life cycle GHG emissions were 309 - 455tonnes CO_2 e- with up to 90%, 9%, and 1% contributions of the use, construction, and the end of life stages respectively. • Life cycle GHG emissions could reduce up to 3% if credited with the avoided burden from the recycling of construction waste at the end of life. • Insulation contributes to high Ozone depletion impacts due to the use of HCFCs as blowing agents during its manufacturing stage. • Small and compact house design could help in lowering the GHG emissions due to reduced heating energy demand.
Iyer-Raniga and Wong (2012)	• Environmental impact (global warming, photochemical oxidation, eutrophication, land use, and water use) assessment of retrofitting initiatives for heritage buildings in Victoria, Australia has been conducted using an integrated framework that combined LCA with building energy efficiency modelling. • Operational energy - heating and cooling only.	• Operational energy contributes significantly to the life cycle GHG emissions and the provision of insulation to external walls, roof, and the ceiling was the most effective way to reduce the impacts. • Aluminium framed windows had high embodied energy.
Biswas (2014)	• Estimation of the GHG emissions and embodied energy consumption of construction and use of Engineering Pavilion building at Curtin University, Western Australia	• As compared to conventional buildings, the use of energy efficient building management system (BMS) could help in reducing the GHG emissions, and EE consumption during use stage by 63%, and 20% respectively.

	using streamlined LCA approach over a lifespan of 50 years.	• Partial replacement of virgin materials with by-products (fly ash in concrete) and recycled materials (aluminium, and steel) could reduce the GHG emissions further by 7%.
Cabeza et al. (2014)	• Review of 36 LCA case studies on buildings and related fields from different parts of the world where one case study has been chosen from Australia. • Most of these case studies considered cradle to grave stages for a lifespan of 10 years for building materials to 100 years for buildings. The majority of the buildings had a 50 year lifespan. • Commonly chosen functional units are per m^2 material area or per house.	• Use of traditional process based LCA approach is most common as compared to advanced hybrid LCA approaches ▪ LCA outcome was sensitive to location, model, uncertainties caused due to assumptions and long lifespan, impacts of design choices on occupant's well-being, behaviour and performance during use stage, and non-availability of data on recycled materials in LCI database.
Islam et al. (2014)	• Environmental impacts of different cladding materials for timber frame walls such as clay bricks, ACC blocks, fibre cement sheet, pine saw log, and weatherboard including different levels of insulation for a typical timber frame wall house over a lifespan of 50 years in Brisbane, Australia using cradle to grave LCA approach and multi objective optimization method have been determined. • Operational energy - heating and cooling only.	• Normalized values of GHG emissions and CED of the best design options were found to be close to 1. • Wall assemblages influence the life cycle GHG emissions and solid waste. • Use stage had the highest GHG emissions and CED, while the end of life stage had the highest solid waste impacts. • Life cycle GHG emissions and CED could be reduced by 14%, and 10% respectively with each star rating improvement.
Pargana et al. (2014)	• Evaluation of environmental impacts and the production energy of various thermal insulation materials for buildings such as extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PUR), expanded cork agglomerate (ICB), and expanded clay lightweight aggregates (LWA) in Portugal using cradle to gate LCA approach for a thermal resistance value of $1m^2K/w$.	• EPS insulation had the lowest values for all impact categories. • ICB had the lowest PE-NRe, GWP, and ADP but high EP. • PUR had relatively low impacts in all categories. • XPS also had relatively low impacts in all categories except high GWP, and POCP. • LWA had the highest impacts in all categories.

	• Impact categories - Primary energy use renewable (PE-Re), Primary energy use non-renewable (PE-NRe), Abiotic depletion (ADP), Acidification (AP), Eutrophication (EP), Global warming (GWP), Ozone depletion (ODP), and Photochemical ozone creation (POCP).	
Carre and Crossin (2015)	• Comparison of the LCA results of the conventional building with pre-cast concrete tilt panels and concrete slabs and study building with light weight timber frame, rendered phenolic foam panels, and cassette floor system in Melbourne, Australia for $1m^2$ gross dwellable area for 60 years of lifespan. • Operational energy - heating, cooling, lighting, and hot water.	• Light weight timber framed building had lower GHG emissions, ozone depletion, and abiotic depletion impacts as compared to the conventional pre-cast concrete tilt panel building, while the conventional building had lower photochemical oxidation impact. • Main reason for lower environmental impacts of timber framed building was due to lighter weight and use of timber as compared to the conventional building.
Islam, Jollands, and Setunge (2015)	• Review of 12 LCA case studies of residential house designs including case studies from Eastern states of Australia. • A typical two storey brick veneer house with $101m^2$ usable floor area and a lifespan of 50 years was considered as the base case. • Operational energy - heating and cooling only.	• GHG emissions and CED were the most commonly used impact categories. • Use stage had the highest GHG emissions and CED impacts followed by the construction stage. The construction stage had the highest water use and the end of life stage had the highest solid waste impacts. • LCA studies had dissimilar functional units, assumptions, system boundaries, lifespans, designs, maintenance regimes, and impact categories hence the comparison of results becomes difficult. • Impacts were highly sensitive to the climatic location.
Islam et al. (2015)	• Investigation of the cradle to grave environmental impacts (GHG emissions, cumulative energy demand (CED), water use, and solid waste) of 8 roof options and 4 floor options for a typical timber frame wall townhouse	• Roofing type influences the life cycle GHG emissions and solid waste impacts. • Life cycle GHG emissions and CED of a house could be reduced by 16.3%, and 13% respectively for each star rating

	house in Brisbane, Australia using LCA over a lifespan of 50 years. • Operational energy - heating and cooling only. • Impact categories -.	improvement of roof design and 18.6%, and 17.2% respectively for each star rating improvement of floor design.
Atmaca (2016)	• Review of 32 LCA case studies of contemporary residential buildings from various parts of the world including Australia. • The lifespan of case study buildings varies from 30 to 100 years, while the majority of the studies had a 50 year lifespan.	• Life cycle GHG emissions were varying between 1 and 10tonnes CO_2 e-/m^2 floor area. • GHG emissions were sensitive to different climatic and socio-demographic variables, and various simplifications and assumptions made.

2.5.3 Cleaner production strategies

Cleaner production initiatives which 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 are necessary components for achieving sustainable development (UNEP 1994; UNIDO 2002). Giannetti et al. (2008), Khan (2008), Lopes Silva et al. (2013), and Yusup et al. (2014) suggested that there are many benefits associated with the implementation of cleaner production strategies such as improved operational efficiency, increased profitability, reduced consumption of raw material, energy, and water, increased recovery and recycling of waste, and reduced emissions. Brereton and van Berkel (2001) suggested that cleaner production practices can be implemented effectively for Western Australian building industry. Gheewala (2003) reinforced that the LCA is the most suited tool for achieving cleaner production. Nilsson (2007), Van Berkel (2007), and UNEP (2015) have recommended following five cleaner production strategies to reduce undesirable environmental impacts and improve resource efficiency:

- 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; and re-use and recycling, on-site recovery and reuse of materials, energy, and water.

From the literature review in previous sections, the use stage and mining to material production stage of a building were found to be hotspots. These five cleaner production strategies appear to have the potential to mitigate the impacts associated with these hotspots. The literature review on cleaner production strategies has been discussed categorically in following three sections.

2.5.3.1 Review of contemporary renewable energy technology studies

The review of Australian and international renewable energy technology studies related to buildings which have been conducted over last 15 years have been summarised in Table 2.3. Most of this review consists of individual case studies and comprehensive review studies comprising of around 140 case studies of roof top solar PV and solar water heater undertaken in various parts of the world. There are few more renewable technology studies, which have been reviewed for this research and are discussed in relevant sections.

The majority of these case studies (Table 2.3) have estimated the energy saving potential due to the integration of solar systems, energy payback time (EPBT), and GHG emissions mitigation potential as important indicators. In addition to these indicators, Koroneos and Nanaki (2012) included acidification, eutrophication, heavy metals, carcinogenic effects, winter and summer smog impact indicators, while Cucchiella and D'Adamo (2012) included energy return on investment (EROI), GHG payback time (GPBT), and GHG return on investment (GROI). In these studies, the lifespan of roof top solar PV was considered as 25 years (Kannan et al. 2006; Mitscher and Rüther 2012), while the lifespan of solar water heater vary from 10 to 20 years (Crawford and Treloar 2004b; Hernandez and Kenny 2012; Zambrana-Vasquez et al. 2015). This lifespan of renewable energy technologies was the deciding factor for considering the lifespan of solar PV and solar water heater in this current study.

The case studies by Cucchiella and D'Adamo (2012) and (Peng, Lu and Yang 2013) included all variants of solar PV such as Mono-crystalline (mono-Si), poly-crystalline (poly-Si), amorphous silicon (a-Si), and cadmium telluride thin film (CdTe). The case study by Zambrana-Vasquez et al. (2015) included 32 types of solar water heaters. While Macintosh and Wilkinson (2011), and Martin and Rice (2013) analysed the Australian policy instruments such as rebate programs and feed-in-tariff schemes as major force behind the performance of domestic solar PV, Kumar Sahu (2015) analysed the global solar PV developments and policy instruments of top 10 solar power producing countries such as Germany, Italy, Japan, Spain, China, France, Belgium, Czech Republic, and Australia. Some of these policy instruments have been considered while analysing the economic feasibility of renewable energy technologies in this study.

Bahadori and Nwaoha (2013) reported that Australian average solar radiation per m^2 area is the highest (Figure B.1, Appendix B) in the world and annually, Australia receives around 58 million peta-joules of solar radiation (i.e. approximately 10,000 times the annual Australian energy consumption). Kumar Sahu (2015) reported that on per capita basis, Germany' solar energy utilization was the biggest (0.39kW), while Australia's utilization was just 0.1kW in spite of being the sun blessed nation. All the studies univocally agreed that solar PV and solar water heater have a significant operational energy, and GHG emissions reduction potential during the use stage of the buildings and the performance is sensitive to location. Similarly, the short energy payback time (EPBT) of solar PV and solar water heater makes them highly sustainable solutions (Table 2.3). Macintosh and Wilkinson (2011) reported that the utilization of solar energy in Australia is significantly low and has failed to achieve the benefits for the community as a whole due to poor design and implementation of policy instruments.

As per individual LCA case study by Cucchiella and D'Adamo (2012), and comprehensive review of LCA cases studies of different solar PV cells by Peng, Lu, and Yang (2013), the cadmium telluride thin film (CdTe) solar PV cells have the lowest energy payback time (EPBT), the mono-crystalline (mono-Si), and poly-crystalline (poly-Si) solar PV cells have slightly higher EPBT. For each kWh of electricity generated, the GHG emissions of these solar PV cells were found to be similar.

Whilst these solar PV results show the environmental impacts like acidification, eutrophication only during the manufacturing stage, it reduces GHG emissions significantly which is the main concern of the building sector. An LCA study by Kannan et al. (2006) reported that use of electricity produced by a 2.7kWp roof top solar PV could reduce the life cycle GHG emissions by 75% of GHG emissions of equivalent oil based electricity and by 50% of GHG emissions of equivalent gas based electricity. The acidification was found to be the biggest impact associated with the manufacturing of solar water heater (Koroneos and Nanaki 2012). An LCA study by

Zambrana-Vasquez et al. (2015) reported that the GHG emissions of solar water heater system with biomass as an auxiliary fuel would be the lowest, even though it causes the highest eutrophication impacts.

2.5.3.2 Summary and lessons learnt from review of contemporary renewable energy technology studies

In summary, the location, auxiliary fuel, proper installation, and maintenance have a major bearing on the outcome of these EPBT, and GHG emissions, while the type of solar PV cells has low influence on the outcome.

On the basis of lessons learnt from the above studies, the GHG emissions reduction and EE consumption saving associated with the grid connected roof top solar PV and solar water heater for residential buildings for Western Australian climatic conditions have been estimated and discussed in Chapters 4, and 6. The overall emissions for the production and use of solar PV and solar water heater have been included into the building with an aim of making the buildings sustainable. The impacts of change of climate zones and solar collector orientations have been considered in this research.

These studies have focused on the energy, GHG emissions reduction, and other associated environmental impact potential of integration of solar PV and solar water heater to mitigate the impacts of hotspot during use stage of the buildings. The following sections discuss the cleaner production strategies that were used to mitigate the impacts of hotspot during the mining to material production stage.

Table 2.3 Summary of contemporary renewable energy technology (RET) studies reviewed

RET studies	Aim of the study	Results
Crawford and Treloar (2004a)	• Analyse energy payback time (EPBT) of gas and electricity boosted solar water heating (SWH) systems for a lifespan of 10 years as compared to conventional hot water systems in Melbourne, Australia.	• SWH has a significant potential of energy saving, which is influenced by location and auxiliary fuel. • EPBTs of electricity, and gas boosted SWH systems were found to be 0.5 years, and 2 years respectively.
Kannan et al. (2006)	• Conduct LCA of a grid connected 2.7kWp mono-crystalline solar PV system in Singapore over a lifespan of 25 years including manufacturing of solar PV, inverter, and support system.	• Manufacturing stage of solar PV modules consumes 81% of the life cycle energy. • EPBT of solar PV vary from 6 to 10 years for oil based and gas based electricity generation respectively. • Life cycle GHG emissions of solar PV vary from 25% to 50% of the GHG emissions of oil, and gas based electricity generation respectively.
Macintosh and Wilkinson (2011)	• Evaluation of the cost effectiveness and fairness of Australian photovoltaic rebate program (PVRP) and solar homes and communities plan (SHCP).	• PVRP and SHCP programs have failed to boost the share of solar PV in Australia, which is less than 1% of total energy. • GHG emissions abatement cost is \$238-282/tonnes CO_2 e-. • Due to poor design and implementation, these programs have failed to benefit the community as a whole.
Cucchiella and D'Adamo (2012)	• Investigation of EPBT, GHG emissions per kWh, energy return on investment (EROI), GHG payback time (GPBT), and GHG return on investment (GROI) for Mono-crystalline (mono-Si), poly-crystalline (poly-Si), amorphous silicon (a-Si), and cadmium telluride thin film (CdTe) solar PV systems in Milan, Rome and Palermo, Italy using LCA approach.	• EPBT is the lowest for CdTe but the highest for poly-Si. • GHG emissions/kWh of electricity is the lowest for mono-Si but the highest for CdTe. • EROI is the highest for CdTe but the lowest for poly-Si. • GBPT is the highest for CdTe but the lowest for mono-Si. • GROI is the highest for mono-Si but the lowest for CdTe. • EPBT and GPBT are decisive factors for sustainability of solar PV.

RET studies	Aim of the study	Results
Hernandez and Kenny (2012)	• Review of the actual performance of 6 flat plate and evacuated tube solar water heater installations in Ireland over a period of 1 year. • The lifespan of water heater – 20 years.	• EPBT was up to 3.5 years which depends on hot water demand, auxiliary fuel, and the control and maintenance of the system. • Measured performance net energy ratios (i.e. energy return of energy invested) could be as low as 1.3 to 7.9 as compared to expected values of 5.7 to 16 due to the improper installation.
Koroneos and Nanaki (2012)	• Estimation of GHG emissions, acidification, eutrophication, heavy metals, carcinogenic effects, winter and summer smog of the production and use of solar water heating system in Greece over a lifespan of 20 years.	• Acidification (54%) and winter smog (25%) were two biggest impacts followed by GHG emissions (12%). • Storage tank and solar collector had 58% and 25% of the total environmental impacts.
Mitscher and Rüther (2012)	• Economic implications of grid connected and distributed 2kWp crystalline rooftop solar PV for a lifespan of 25 years in 5 locations of Brazil to represent different solar irradiation, and electricity tariffs using discount rates of 3.5%, 10.5%, and 18.75% respectively.	• The capital cost of solar PV is a decisive factor and due to landing rates and in the absence of incentives, the solar PV in Brazil was an economically unviable solution. • Rooftop grid connected solar PV could be an economically competitive solution in developing countries.
Bahadori and Nwaoha (2013)	• Investigation of the need of improvement in utilization of solar energy in Australia including the challenges and advantages of this clean energy.	• Australia has the highest average solar radiation in the world. • Western Australia has the highest solar thermal consumption in Australia. • The relatively high capital cost of solar PV and lack of reliable electricity storage systems were major constraints hampering the adoption of solar PV on a large scale.
Martin and Rice (2013)	• Analysis of the feed-in-tariff scheme for small scale solar PV systems in NSW, Australian and highlighting the important lessons for future feed-in-tariff policy design.	• Feed-in-tariff scheme resulted in a better outcome than the originally anticipated. • For feed-in-tariff schemes to be sustainable, they must be aligned with the business plans of electricity distributors and retailers.

RET studies	Aim of the study	Results
Peng, Lu, and Yang (2013)	• Review of 86 LCA and EPBT case studies of mono-crystalline (mono-Si), multi-crystalline (multi-Si), amorphous silicon (a-Si), cadmium telluride thin film (CdTe), and copper indium gallium selenide thin film (CIS) including balance of system (BOS) (e.g. inverter, controller, cable, support, and battery).	• The highest life cycle energy input values (MJ/m^2) were for mono-Si (2860 to 5253) followed by multi-Si (2699 to 5150), and a-Si, CdTe, and CIS (710 to 1990). • The highest EPBT (years) was for mono-Si (1.7-2.7) followed by multi-Si (1.5-2.6), and a-Si, CdTe, and CIS (0.75-3.5). • The highest GHG emissions/kWh of electricity (gCO_2 e-) were for mono-Si (29-45) followed by multi-Si (23-44), and a-Si, CdTe, and CIS (10.5-50). • CIS and a-Si had the highest life cycle energy input, and EPBT respectively. The CdTe had the lowest EPBT and GHG emissions. • Solar PV systems are highly sustainable solutions.
Islam, Sumathy, and Ullah Khan (2013)	• Review of 55 case studies of solar water heaters with passive circulation (thermosyphonic) system and active circulation (pumped) system for energy efficiency and cost effectiveness including their market potential.	• Large solar water heating systems were found be highly viable as compared to domestic solar water heating systems. • By the year 2010, China had 70.5% of the global installed capacity of solar water heaters, while Australia's share was just 0.9%, which helped China to reduce GHG emissions by 26.36million tonnes CO_2 e-, while Australia and New Zealand could reduce only 0.73million tonnes CO_2 e-.
Kumar Sahu (2015)	• Investigation of the global solar PV developments, solar cell efficiencies, and government policies as their instruments.	• Germany, Italy, Japan, Spain, China, France, Belgium, Czech Republic, and Australia were found to be the top ten solar power producing countries. • On per capita basis, Germany' solar energy utilization was biggest (0.39kW), while Australia's utilization was just 0.1kW. • Policy instruments such as feed-in-tariff, net metering, investment tax credit, credits for green certifications, and

RET studies	Aim of the study	Results
		renewable portfolio standards were found to be effective incentives to promote solar PV. • Cell efficiency was a decisive factor towards the growth of solar PV.
Zambrana-Vasquez et al. (2015)	• Evaluation of the environmental implications of 32 types of SWH systems with biomass, electricity, natural gas and gasoil auxiliary fuels using LCA approach in Spain over a lifespan of 20 years including the credit for material recovery (steel, copper, and aluminium) at the end of life stage.	• SWH systems with biomass as an auxiliary fuel had the highest EPBT, while the SWH system with electricity as an auxiliary fuel had the lowest EPBT. • In all the cases, the EPBT was less than the lifespan of SWH system. • SWH system with biomass as an auxiliary fuel had the lowest GHG emissions, but the eutrophication impact was the highest. • Auxiliary fuel influences the overall environmental impacts of SWH system.

2.5.3.3 Review of contemporary alternative building envelope materials and system studies

The review of Australian and international studies of alternative building materials and systems which have been conducted over last 10 years have been summarised in Table 2.4. Most of this review consists of case studies undertaken to compare the energy or environmental performances of different building envelope (wall, roof, and window) elements or systems. The Australian case studies have mostly been conducted in the Eastern states. There are few more studies which have been reviewed for this research and have been discussed in relevant sections.

The majority of these case studies (Table 2.4) have considered walls made of double clay brick with and without insulation, brick veneer, reverse brick veneer, and timber frame, concrete and steel sheet roof, and single glazed windows as prevailing materials and systems of a house construction. The sandwich walls have been considered by some case studies (Bambrook, Sproul and Jacob 2011; Aldawi, Alam, Date, et al. 2013; Lawania, Lloyd and Biswas 2014), while few studies have considered autoclaved aerated concrete block walls for comparison (Monteiro and Freire 2012; Islam et al. 2014; Lawania and Biswas 2016). The majority of these case studies considered the most commonly used concrete slab on ground, but Crawford, Czerniakowski, and Fuller (2010), and Carre (2011a) considered the elevated timber floor also as an option for comparison. In addition to single glazed windows, the case studies by Bambrook, Sproul, and Jacob (2011) and Lawania and Biswas (2016) also considered double glazed windows also. Similarly, in addition to concrete tile and steel sheet roof, the terracotta tile roof has been considered for case studies by Aldawi, Alam, Date, et al. (2013), and Lawania and Biswas (2016). A case study by Pargana et al. (2014) compared different insulation materials.

The energy and environmental performances of these alternative materials and methods of construction were found to vary according to climatic conditions and material combinations, and generally, the options having optimum thermal properties have been found to have the best overall performance (Table 2.4).

These alternative materials and methods of construction have met the regulatory requirements laid down by Building Code of Australia (BCA) and are slowly gaining acceptance in Australian Built environment (DCCEE 2010).

While most of the wall elements have a long history of use in Australia, and are quite familiar to designers, developers, builders, and consumers and thus does not require any further introduction, the cast in-situ sandwich wall system is relatively new to Australian residential building sector. The cast in-situ sandwich wall system consists of a welded galvanized wire space frame integrated with an expanded polystyrene (EPS) insulation core with concrete layers sprayed on either side through shotcrete process and is extensively used in Europe, USA, Middle East and Asia. The cast in-situ sandwich wall system has been tested and has been found to comply with the regulatory requirements laid down by Building Code of Australia (BCA) (BRANZ 2011). This system offers a combination of properties such as lightweight and thermal mass, built-in insulation, low moisture absorption, and resistance to earthquake and fire (Rezaifar and Gholhaki 2008). The structural, non-linear dynamic, vertical in-plane forces and flexural behaviours of cast in-situ sandwich walls have been investigated to confirm that these walls can perform the same as the conventional pre-cast concrete walls (Mousa A.M. 2012; Kabir 2004; Carbonari 2012; Gara et al. 2012; Mashal 2012). Experimental and finite element analyses have confirmed the suitability of this system for slab application (Bajracharya et al. 2010). A case study by Sarcia (2004) has demonstrated the modularity capabilities of the cast in-situ sandwich wall system. Results of pseudo-static tests with horizontal loads and dynamic energy absorption and dissipations behaviours have been found to be promising for cast in-situ sandwich wall system (Ricci 2013; Rezaifar and Gholhaki 2008). 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 cast in-situ sandwich walls (Rezaifar 2008; Ricci 2012; Rezaifar and Gholhaki 2008).

2.5.3.4 Summary and lessons learnt from review of contemporary alternative building envelope materials and system studies

In summary, the climatic conditions and combination of various building envelope elements have a major influence on the outcome of these studies.

On the basis of lessons learnt from the above studies, the impacts associated with these alternative materials and methods of construction for residential buildings for Western Australian climatic conditions have been estimated and discussed in Chapters 4, and 6.

These studies have focused on the materials and methods of construction to mitigate the impacts of hotspot during mining to material production stage of the buildings. The following section discusses various cleaner production strategies to further mitigate the impacts of hotspots associated with the mining to material production.

Table 2.4 Summary of contemporary alternative building envelope materials and system studies reviewed

studies	Type of construction materials, and systems used	Environmental performance
Gregory et al. (2008)	• Cavity brick, brick veneer, reverse brick veneer, and light weight timber frame wall.	• Reverse brick veneer wall house performed better than a house with other wall options.
Zhu et al. (2009)	• Timber frame wall and pre-cast concrete sandwich wall.	• Pre-cast concrete sandwich wall house performed better than timber framed wall house.
(Rouwette 2010)	• Double brick with and without insulation, brick veneer, reverse brick veneer, and insulated timber walls.	• Insulated double brick wall house had a better performance than a house with other wall options.
Crawford, Czerniakowski, and Fuller (2010)	• Concrete tiles and steel sheet roofs. • Brick veneer with timber and steel frames, timber weatherboard, and polystyrene timber frame wall. • Elevated timber floor and concrete slab on ground	• Concrete roof tiles, concrete slab on ground, and polystyrene timber frame walls had better performance than the other alternatives.
Carre (2011a)	• Timber framed brick veneer with elevated timber floor and concrete slab on ground. • Steel framed brick veneer with elevated timber floor and concrete slab on ground. • Timber weatherboard with elevated timber floor.	• Timber weatherboard construction performed better than other options. • Elevated timber floor and timber frame for wall had better performance than other options.
Bambrook, Sproul, and Jacob (2011)	• Brick veneer wall and structural insulated panel (SIP) wall. • Single and double glazed windows.	• SIP wall house with double glazed windows performed better than the conventional house.
Monteiro and Freire (2012)	• Double hollow brick, double face and hollow brick, concrete block, thermal concrete block, autoclaved aerated concrete block, timber cladded hollow brick and timber frame walls.	• Timber framed wall had better performance as compared to the double wall with face brick, thermal concrete block all, and autoclaved aerated concrete block wall.
Aldawi (2013)	• Brick veneer wall, and 3 variants of the concrete sandwich wall. • Single glazed windows. • Terracotta/concrete roof tiles.	• Concrete sandwich wall house performed better than brick veneer wall house.

studies	Type of construction materials, and systems used	Environmental performance
Islam et al. (2014)	• Timber framed walls with clay brick, autoclaved aerated concrete (ACC) block, fibre cement sheet, pine saw log and weatherboard cladding.	• Pine saw log wall house had better performance followed by weatherboard cladding wall house.
Lawania, Lloyd, and Biswas (2014)	• Double brick wall, double brick wall with insulation, and in-situ composite sandwich wall	• In-situ composite sandwich wall had better performance than the other alternatives.
Pargana et al. (2014)	• Extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PUR), expanded cork agglomerate (ICB), and expanded clay lightweight aggregates (LWA) insulation.	• EPS had better performance followed by PUR.
Islam et al. (2015)	• Gable concrete roof tiles, gable steel sheet roof, skillion flat steel sheet roof, and skillion pitch steel sheet roof options. • Carpet, timber, and ceramic, floor options.	• Gable concrete roof tiles and mixed floor (ceramic tiles and timber) had better performance than other options.
(Lawania and Biswas 2016)	• Double clay brick, double clay brick with insulation, brick veneer, reverse brick veneer, cast in-situ sandwich with polystyrene core, cast in-situ sandwich with polyethylene terephthalate core, hollow concrete block, aerated concrete block, pre-cast light weight concrete sandwich panels, and timber frame walls. • Single and double glazed windows. • Concrete tiles, terracotta tiles, and steel sheet roofs.	• Cast in-situ sandwich with polyethylene terephthalate core, concrete tile roof, and double glazed windows were found to have better performance than other alternatives.

2.5.3.5 Review of contemporary use of by-products and recyclates studies

The review of Australian and international studies of the use of by-products and recyclates which have been conducted over last 10 years have been summarised in Table 2.5. Most of this review consists of individual case studies and comprehensive review studies comprising of around 129 case studies undertaken to analyse the impacts of by-products and recyclates on the mechanical and environmental performance of concrete. There are few more studies on the use of by-products and recyclates which have been reviewed for this research and have been discussed in relevant sections.

Majority of these case studies (Table 2.5) have considered the partial replacement of cement, and aggregates in conventional concrete mixes of varying grades with different proportions of fly ash (FA), ground granulated blast furnace slag (GGBFS), recycle concrete aggregate (RCA), and manufactured sand (MFS) to investigate their impacts on mechanical and environmental performance of concrete mixes. The comprehensive review studies by Fate (2014) and Silva, de Brito, and Dhir (2014) assessed the environmental implications of partial replacement of natural sand (NS) with manufactured sand (MFS), and natural aggregates (NA) with recycled concrete aggregate (RCA), recycled masonry aggregates, and mixed aggregates in concrete mixes. Cavalline and Weggel (2013) investigated the impacts of aggregates made of clay bricks from construction and demolition (C&D) waste on the mechanical performance of the concrete. A case study by Collins (2013) investigated the carbon sequestration ability of concrete having recycled aggregates. In addition to partial replacement of NS with MFS in the concrete mix, Jadhav and Kulkarni (2012) included water cement ratio also as a variable for impact assessment.

Flower and Sanjayan (2007) reported that the partial replacement of cement in a typical concrete mix with GGBFS and FA could reduce GHG emissions of concrete by 22%, and 13%-15% respectively. About 30%–40% cement in the high strength concrete mix could be replaced with FA and a further adjustment in the concrete mix proportions could increase strength, reduce shrinkage and improve permeability properties (Nath and Sarker 2013). A case study by Turk et al. (2015) reported that even where the source of FA had a longer distance than the distance of source of cement, the use of FA in concrete mix was found to be environmentally sustainable i.e. the emissions savings benefit of the replacement outweighs the emissions from long distance transport of FA. Up to 50% cement in high strength concrete mixes could be replaced by GGBFS without having any adverse impacts on the performance of concrete (Berndt 2009; Arivalagan 2014), and this partial replacement of cement with GGBFS could reduce up to 47.5% of the GHG emissions of concrete (Crossin 2015).

If RCA is used then about 5% of additional cement would be required as compared to NA to achieve similar performance (Marinković et al. 2010). The replacement of NA with RCA causes a decrease of compressive strength of concrete during the short period but the strength increases over a long period of time (Silva, de Brito and Dhir 2014). The loss of strength and workability of concrete due to the use of RCA could improve by including FA, and water reducing admixtures which even improves the environmental performance of the concrete (Turk et al. 2015; Silva, de Brito and Dhir 2014; Cavalline and Weggel 2013; Kou, Poon and Agrela 2011). If the contribution of carbonation of RCA is included for the impact assessment than the GHG emissions of concrete could be offset up to 55%-65% (Collins 2013).

The strength of concrete has been found to increase till 65% replacement of NS by MFS (Jadhav and Kulkarni 2012; Mogre, Parbat and Dhobe 2015) and optimum replacement ratio was found to be 50% (HE, WANG and LI 2015). The use of MFS in concrete mix affects the workability due to its angular particle distribution (Fate 2014) and the use of microfines enhances the workability of concrete (Ji et al. 2013). The blending of MFS with NS improves the workability of concrete and could reduce the requirement of microfines (CCAA 2008).

The LCA case study of a typical 25MPa concrete mix by Lawania, Sarker, and Biswas (2015) reported that the concrete mix where 30% cement was replaced by FA, 40% NA was replaced by RCA, and no replacement of NS with MFS had the lowest GHG emissions. Even though the partial replacement of NS with MFS was found to be technically feasible but this replacement caused a slight increase in GHG emissions due to the additional energy needed to process MFS to make it suitable for concrete applications, however this replacement could reduce the landfill demand and resource depletion (Ahmed 2012; O'Flynn 2000). Therefore, LCA is important to compare all environmental impacts associated with the change in the use of any materials.

According to Australian Cement Industry Federation report, the GHG emission intensity of Australian cement production in 2012–2013 was 700 kg CO_2 e- per tonne (CIF 2014). In the year 2013, Australia produced 12.3 million tonnes of fly ash and only about 52% was utilized and every year new fly ash is being produced while there is an unutilized stock of more than 400 million tonnes (ADAA 2014). According to Australasian (Iron & Steel) Slag Association report, about 1.3 million tonnes of slag was produced in the year 2009 and availability of the substantial quantity of slag is assured as long as iron production continues in Australia (ASA 2011). In the year 2010, Australia produced around 1.3 million tonnes of recycled aggregate (SASA 2010). As per Cement Concrete and Aggregates Australia, about 30% of quarry production is crushed fine, which can further be processed into manufactured sand (MFS) which is suitable for concrete (CCAA 2008).

2.5.3.6 Summary and lessons learnt from review of contemporary use of by-products and recyclates studies

In summary, the use of by-products and recyclates have been found to improve the mechanical performance of the concrete mix, however, the proportions and combinations of by-products and recyclates have a major influence on the outcome of these studies.

On the basis of lessons learnt from the above studies, the environmental impacts associated with these by-products and recyclates for residential buildings for Western Australia have been estimated and discussed in Chapter 4.

The studies in above Sections 2.5.1.2, 2.5.2.2, and 2.5.3.1 to 2.5.3.5 have focused on the energy and environmental performances of materials and methods of construction including cleaner production strategies to mitigate the associated impacts termed as hotspots. The following section discusses the life cycle costing approach to investigate the cost effectiveness of various cleaner production options to mitigate the impacts of hotspots.

Table 2.5 Summary of contemporary use of by-products and recyclates studies reviewed

Studies	Aim of the study and major assumptions	Results
(Flower and Sanjayan 2007)	• Investigation of GHG emissions reduction potential of the use of FA and GGBFS in Australia.	• Portland cement contributes to 74%-81% of the total GHG emissions of concrete production. • Use of GGBFS and FA could reduce the GHG emissions of a typical concrete mix by 22%, and 13%-15% respectively.
(Berndt 2009)	• Investigation of mechanical properties of 40MPa concrete mixes having no cement substitution, 50% cement replaced with FA, 50% and 70% cement replaced with GGBFS, and 50% cement replaced equally with FA and GGBFS for natural aggregates (NA) and recycled aggregates (RCA).	• Concrete with 50% GGBFS for both NA and RCA provides best mechanical properties. • Coefficients of permeability and chloride diffusion of concrete with RCA were slightly higher than the conventional mix but within the acceptable limits.
(Marinković et al. 2010)	• Evaluate the environmental impacts of the production of concrete with NA and RCA using LCA approach.	• About 5% additional cement would be required for RCA concrete to achieve the performance similar to NA concrete. • Use of RCA in concrete minimizes the landfill and natural mineral resources depletion.
(Safiuddin et al. 2010)	• Analyse the environmental implications of solid wastes including their recycling potentials and possible use as construction materials.	• FA and GGBFS could be used for high performance concrete. • Bottom ash, quarry waste, and C&D waste could be utilized as aggregates.
(Kou, Poon and Agrela 2011)	• Investigation of the effect of mineral admixtures (silica fumes, metakaolin, FA, and GGBFS) on mechanical properties of concrete mixes with 50%, and 100% NA replaced with RCA respectively.	• Contributions of the mineral admixtures to performance improvement of the recycled aggregate concrete were found to be higher than that of the natural aggregate concrete
(Jadhav and Kulkarni 2012)	• Investigation of the effect of water cement ratio (0.4, 0.45, and 0.55) and replacement of natural sand (NS) with manufactured sand (MFS) (0%, 20%, 40%, 60%, 80% and 100% respectively) on the mechanical properties of M20 concrete.	• Mechanical properties increased with 60% replacement of NS with MFS and the overall strength increased linearly due to 0% to 60% replacement of NS with MFS. • MFS is an environmentally and economically viable alternative to NS.

Studies	Aim of the study and major assumptions	Results
(Cavalline and Weggel 2013)	• Investigate the feasibility of the potential sustainable reuse of crushed and graded recycled aggregate from clay bricks.	• Water reducing admixture could improve the workability of concrete due to high absorption and angularity of particles of aggregates from clay bricks.
(Collins 2013)	• Investigation of the ability of recycled concrete to chemically react with airborne CO_2 and thereby significantly reducing GHG emissions.	• CO_2 capture capacity of RCA from the demolition of the first generation built elements was significantly high. • Up to 55%-65%, GHG emissions of concrete could be offset if the contribution of carbonation of RCA is included.
(Ji et al. 2013)	• Investigation of the effect of microfines content (0%, 6%, 12%, 18%, 24%, and 30% replacement of cement with microfines) on the workability and mechanical properties of 45MPa MFS concrete	• Mechanical properties of MFS concrete increased gradually with increased percentage of microfines. • Mixing of microfines could reduce the GHG emissions due to the reduction of cement.
(Nath and Sarker 2013)	• Investigation of the effect of mixture proportions on the performance of high strength concrete containing a large volume of local class F fly ash.	• Up to 30%–40% cement could be replaced with FA. • FA along with adjustments in the water cement ratio could significantly increase the performance of concrete.
(Arivalagan 2014)	• Evaluation of the strength and strength efficiency factors of hardened concrete by partial replacement of cement by various percentages of GGBFS for M35 grade of concrete at different ages.	• The strength of concrete increases, if 20% of the cement replaced with GGBFS. • Workability of concrete was found to be normal till 40% replacement of cement with GGBFS.
(Fate 2014)	• Review of 10 case studies of the replacement of NS in concrete with MFS.	• The strength of concrete increases due to the use of MFS but the workability reduces due to angular particle shape. • Concrete with MFS is found to be economical.
(Silva, de Brito and Dhir 2014)	• Review of 119 case studies on the influence of the use of recycled aggregates on the compressive strength of concrete.	• Though the replacement of NA with RCA causes a decrease of compressive strength of concrete during the short period but the strength increases over a long period of time. • RCA recycled masonry aggregates and mixed recycled aggregates were found to be most suitable for concrete.

Studies	Aim of the study and major assumptions	Results
		• Water reducing admixtures could compensate the water absorbed by RCA. • Loss of strength of concrete due to the use of RCA could be effectively improved with the use of FA.
(Crossin 2015)	• Investigation of the GHG emissions implications associated with the use of GGBFS for application of 1m^3 of grade 32MPa concrete over a lifespan of 50 years for different market conditions in Australia using LCA approach.	• Replacement of GP cement in concrete with GGBFS could reduce up to 47.5% of GHG emissions. • The total cementitious content of concrete mix with GGBFS has to be higher than the conventional concrete mix to achieve similar strength performance.
(HE, WANG and LI 2015)	• Evaluation of the compressive strength of grade C50 concrete for replacement of NS by MFS.	• Optimum replacement ratio of MFS to NS by mass was 50%.
(Mogre, Parbat and Dhobe 2015)	• Development of a mathematical model based on experimental results to estimate the compressive and flexural strength of concrete mixes for replacement of NS with MFS.	• The strength of concrete was found to increase till 65% replacement of NS with MFS and while the percentage increase in strength for concrete of grade M20 was found to be maximum, the strength gain in the concrete of grade M40 was the lowest.
(Turk et al. 2015)	• Evaluation of the environmental impacts of green concrete consisting of various combinations of foundry sand, GGBFS, FA, RCA and conventional concrete using LCA approach.	• FA option was sustainable even where the source of FA had a longer distance than the distance of the source of cement. • Foundry sand could replace a certain portion of natural aggregate and cement in concrete. • The landfilling requirement for C&D waste as well as by-products could be reduced if the by-products and recycled aggregates are utilized for concrete.
Lawania, Sarker, and Biswas (2015)	• GWP implications of the use of by-products and recycled materials in Western Australia's housing sector.	• 25MPa concrete with a composition of 70% OPC + 30% FA + 60% NA + 40% RCA + 100% NS was found to have the lowest GHG emissions

2.5.4 Life cycle costing approach

The economic factors are important for the decision making strategy (Gluch and Baumann 2004; Kulczycka and Smol 2015; Swarr et al. 2011). Blanchard (2014) suggested that life cycle costing (LCC) allows a better resource management due to long term cost visibility and identification of high cost functional stages and provides improvement opportunities. Rebitzer, Hunkeler, and Jolliet (2003) termed the LCC as an economic cousin of LCA and suggested that LCA based LCC is a powerful method to achieve sustainable solutions.

Kayrbekova, Markeset, and Ghodrati (2011) suggested that LCC is typically a cash flow oriented cost accounting system without cause and effect relationships. Kulczycka and Smol (2015) reported that LCC is widely used for capital investment projects and if combined with LCA, it can help in achieving the optimal or cost-effective environmental solutions.

Pelzeter (2007) described the life cycle costing as a form of synopsis of the capital and consequential costs of building related decisions and a useful tool for achieving economic sustainability. The LCC tool is an effective technique for forecasting and evaluating the cost performance of building (ISO15686-5 2008(en)). The life cycle cost approach helps compare the capital cost with operating cost for competing building design options and to find an optimized option (Gurung and Mahendran 2002; Real and Pinheiro 2010).

2.5.4.1 Review of contemporary life cycle costing studies of the building

The review of Australian and international LCC studies of buildings and building sector which have been conducted over the last 15 years have been summarised in Table 2.6. Most of this review consists of individual case studies except for the one that made a comprehensive review of 8 case studies undertaken in Australia, Europe, and North America. In the case of Australia, all the LCC studies have been conducted in the Eastern states.

The majority of these LCC case studies (Table 2.6) have estimated the cost effectiveness of the energy efficiency measures to achieve low or zero energy residential buildings. A few studies included the analysis of the relevance of LCC tool in a sustainability assessment (Klöpffer and Ciroth 2011; Moore and Morrissey 2014; Islam, Jollands and Setunge 2015). While Leckner and Zmeureanu (2011), and Moore (2014) included the payback periods in LCC, the case study by Moore, Morrissey, and Horne (2014) included a through life cost/benefit approach also. The time horizon or lifespan of the building significantly influences its life cycle cost mainly due to the operational energy consumption. Most of the LCC case studies have considered the time horizon of 50 years for analysis. Only a few case studies have considered multiple time horizons varying from 1 to 100 years (Klöpffer and Ciroth 2011; Morrissey and Horne 2011b; Moore 2014; Moore and Morrissey 2014). While the case studies by Morrissey and Horne (2011b) and (McLeod and Fay 2011) considered time horizon of 25 years, a time horizon of 40 years was considered by Leckner and Zmeureanu (2011) and Moore, Morrissey, and Horne (2014).

The system boundary of most of these LCC case studies included construction, and operational stage, which was limited to energy for heating and cooling only. While the case study by Islam et al. (2014) included maintenance and the end of life stages, Gurung and Mahendran (2002) included maintenance stage within the system boundary of LCC analysis. The LCC is highly influenced by the discount rate and rate of inflation, and some of these case studies considered multiple discount rates between 1.65% and 15% (Gurung and Mahendran 2002; Bostancioğlu 2010; Morrissey et al. 2013; Moore and Morrissey 2014; Moore 2014), few case studies considered single discount rate between 3% and 6% (Kneifel 2010; Leckner and Zmeureanu 2011; Islam et al. 2014). Most of the case studies have considered the inflation rate in LCC analysis, which has been found between 2% and 3.32% (Leckner and Zmeureanu 2011; Morrissey and Horne 2011b; Islam et al. 2015).

These LCC studies show that the capital cost of the highly energy efficient buildings is higher than the conventional buildings, but the life cycle cost of the energy efficient buildings is lower than the conventional buildings. This is because the additional capital cost was compensated by operational cost savings on energy (Gurung and Mahendran 2002; Klöpffer and Ciroth 2011). The review of case studies shows that the construction, operational, maintenance, and the end of life demolition and disposal costs of the building contributes to 58%-88%, 11%-34%, 2%-20%, and 0%-2% of the life cycle cost respectively (Islam, Jollands and Setunge 2015). The additional capital cost of a typical zero energy building due to use of active solar system, optimum insulation, and double or triple glazed windows was substantially higher than that of a conventional building, but the payback period was found to be less than one third of the lifespan of the building (Leckner and Zmeureanu 2011; Moore 2014). The lowest to highest life cycle cost of the building in Brisbane with different wall assemblages was found to vary up to 17% (Islam et al. 2014). The cost of renewable energy technologies (RET) such as roof top Solar PV and SWH were found to be a significant factor in reducing capital and operational costs for zero energy building (Moore and Morrissey 2014).

The case studies show that the LCC approach in building sector is not only an effective decision making tool to compare and promote the environmentally viable solutions, it could offer much more than its current realised potential (Moore and Morrissey 2014; Klöpffer and Ciroth 2011; Islam, Jollands and Setunge 2015). The case studies confirmed that LCC is sensitive to the discount rate and while a low discount rate results in an increased value of discounted cash flow, the value of discounted cash flow reduces with high discount rate (Morrissey et al. 2013; Islam et al. 2014). The cost effectiveness of the energy efficiency improvement measures for buildings was found to be sensitive to time horizon (Kneifel 2010; Morrissey and Horne 2011b). For different energy efficient materials and methods of building construction, the correlations between capital costs and net operational cost savings have been found to be inconsistent (McLeod and Fay 2011).

2.5.4.2 Summary and lessons learnt from review of contemporary life cycle costing studies

In summary, the system boundaries, and the country specific discount, and inflation rates have a major bearing on the outcome of LCC studies but in the absence of universally accepted regulations and guidelines, they have been found varying with individual research objectives, and the project specific requirements. Similar to LCEA, and LCA studies, there is a variation in the assumption of building's lifespan, but there is wide spread consensus on a 50 year lifespan or time horizon for LCC studies of residential buildings in most parts of the world including Australia and has been considered for this research as well.

On the basis of lessons learnt from the above studies, the life cycle costs associated with construction, use, and the end of life demolition and disposal stages of the residential building including cleaner production strategies for Western Australia have been estimated and discussed in Chapter 5, and 6.

The following section reviews the social impact assessment and policy barriers to achieve the sustainable residential buildings.

Table 2.6 Summary of contemporary life cycle cost (LCC) studies reviewed

LCC studies	Aim of the study and major assumptions	Results
(Gurung and Mahendran 2002)	• Conduct LCC of construction, use, and maintenance of a building for conventional and alternative energy efficient material and method in Brisbane, over a lifespan of 50 years for a discount rate of 7%. • Discount rates of 5%, 9%, and 11% were considered for sensitivity analysis. • Operational energy - heating and cooling only.	• Energy efficient building of high capital cost had a low life cycle cost as compared to the conventional building. • Absolute values of LCC changed with discount rates but without affecting the outcome.
(Bostancioğlu 2010)	• Conduct LCC to investigate the impact of 4 building shapes, 8 orientations, and brick and autoclaved aerated concrete (AAC) block walls having varying thickness and location of extruded and expanded polystyrene, and rockwool wall insulation on construction, energy costs, in Istanbul, Turkey over a lifespan of 50 years for discount rates of 15%, 10%, and 5%.	• LCC increased up to 26.92% when the ratio between external wall area and floor area of the building increased. • Change of orientation had a minor impact on LCC. • The construction cost of the conventional building was the lowest in all cases but it was found to be the highest during use stage. • LCC of the conventional building was the highest under all shapes, orientations, and materials.
(Kneifel 2010)	• Conduct LCA and LCC of energy efficiency measures in 12 new commercial buildings in the United States for 4 time horizons such as 1, 10, 25, and 40 years for a discount rate of 3% including effectiveness due to the probable carbon tax.	• Cost effectiveness of the energy efficient building design was sensitive to time horizon. • The introduction of a carbon tax could increase the rate of return on energy efficiency investments.
(Klöpffer and Ciroth 2011)	• Analyse the relevance of LCC in a sustainability assessment.	• LCC results show that the environmentally friendly products of high initial costs are found to be economical. • LCC is an effective decision tool to promote the environmentally viable products.
(Leckner and Zmeureanu 2011)	• Conduct LCC and energy analysis of a net zero energy house (NEZH) in Montreal, Canada having active solar	• The Very high additional capital cost of the active solar system, optimum insulation, and triple glazed windows for a

LCC studies	Aim of the study and major assumptions	Results
	systems for heating, hot water, and electricity over a lifespan of 40 years for a discount rate of 4% and an inflation rate of 2%.	NZEH could be recovered within 8-11 years from energy cost savings. • At least the less expensive energy efficient measures must be incorporated as a first step towards NEZH.
(McLeod and Fay 2011)	• Investigation of the cost effectiveness of thermal performance enhancement measures to reduce GHG emissions from a typical brick veneer house in Hobart Australia over a lifespan of 25 years. • Operational energy - heating and cooling only.	• GHG reduction due to energy efficiency measures was found to be limited because of the electricity mix, which is dominated by hydro-electricity. • Different energy efficient materials and methods were found to have inconsistent correlations between initial costs and net savings during use stage.
(Morrissey and Horne 2011a)	• Investigation of LCC of energy efficiency measures in 100 different detached brick veneer wall buildings in Melbourne, Australia over 4 time horizons such as 5, 10, 25 and 40 years for a discount rate of 3.5% for the first 30 years, and then 3% for remaining period and an inflation rate of 3.32%. • Operational energy - heating and cooling only.	• Significant cost savings due to higher efficiency standards could be achieved over 25 years and 40 years' time horizons. • Higher thermal performance scenarios were more cost effective with longer time horizon. • Energy cost savings of more thermally efficient building designs were found to outweigh the higher build cost beyond first few years of occupation.
(Morrissey et al. 2013)	• Investigate the impact of the discount rate on LCC of thermal efficiency improvement measures for residential buildings in Victoria, Australia over a time horizon of 25 years for discount rates of 1.65%, 3.5%, and 8% and an inflation rate of 3.32%.	• The present value of cost savings due to higher thermal performance is highly influenced by the discount rate. • The value of discounted cash flow increases when the discount rate is low but high discount rate reduces the value of discounted cash flow. • Based on sustainability principals, the low discount rate has potential to prioritise the environmentally viable projects.
(Islam et al. 2014)	• Analyse LCC for construction, use, maintenance and disposal of the building for alternative wall assemblages of a typical house in Brisbane, Australia over a lifespan	• On average, the construction, operational, maintenance, and the end of life demolition and disposal costs contributes to 63%, 9%, 26%, and 3% of the LCC respectively.

LCC studies	Aim of the study and major assumptions	Results
	of 50 years for a discount rate of 6% and an inflation rate of 3% using multi objective optimization method. • Operational energy - heating and cooling only.	• For an increase of each star rating, the LCC increased by 14%, but the capital cost increased by 21%. • LCC of a house due to different wall assemblage designs was found to vary up to 17% (from the highest to lowest). • LCC was found to be sensitive to change in discount rate.
(Moore 2014)	• Conduct a cost-benefit analysis of a typical zero energy brick veneer detached house in Melbourne, Australia having 4.3kWp roof top solar PV and solar water heater over a lifespan of 60 years for discount rates of 1.65%, 3.5%, and 7% for first 30 years with a reduction of 0.5% for next 30 years and an inflation rate of 3%. • Lifespans of 10, 20, and 40 years were considered for sensitivity analysis.	• The capital cost of zero energy house was substantially higher than the conventional and energy efficient house design. • Zero energy house had the lowest operational energy cost with a payback period of 12-14 years. • Current minimum energy performance standards which are based on capital cost should be modified to incorporate the renewable energy technologies and through-life approach to achieve low carbon future.
(Moore and Morrissey 2014)	• LCC sensitivities for 80 zero energy buildings in Melbourne, Australia having detached brick veneer walls, roof top solar PV and solar water heater over a time horizon of 40, 60, 80, and 100 years for discount rates of 1.65%, 3.5%, and 7% for first 30 years with a reduction of 0.5% for next 30 years and an inflation rate of 3%.	• An additional 20% of the capital cost would be required to achieve zero energy building. • The cost of Solar PV and the solar water heater was a significant factor in reducing costs of zero energy building. • The discount rate has a significant impact on the net present value. • LCC analysis could offer a much more potent policy tool than its current realised potential.
(Moore, Morrissey and Horne 2014)	• Investigation of the life cycle economic and environmental costs and benefits of a typical detached sustainable house design having improved insulations, window glazing, infiltration control and shading in Melbourne over a time horizon of 40 years for a discount	• Capital costs of the energy efficiency improvement measures were found to be high especially for roof top solar PV, and solar water heater. • Additional mortgage repayment, which the home owner has to make due to the inclusion of energy efficient measures was higher than the cost of energy saving benefits.

LCC studies	Aim of the study and major assumptions	Results
	rate of 3.5% for first 30 years with a reduction of 0.5% for remaining 10 years and an inflation rate of 3.32%.	
(Islam, Jollands and Setunge 2015)	• Review of the LCA and 8 LCC studies of residential house designs and compare the LCC results of a typical two storey brick veneer base case house design for a discount rate of 6% and an inflation rate - 3%. • Operational energy - heating and cooling only.	LCC is an effective tool for comparing different investment scenarios and to assess the cost effectiveness of energy efficiency measures. • LCC could play an important role in the optimization process. • The construction, operational, maintenance, and the end of life demolition and disposal costs contributes to 58%-88%, 11%-34%, 2%-20%, and 0%-2% of the LCC respectively. • LCC was found to be sensitive to the discount rate.
(Islam et al. 2015)	• Conduct LCC for construction, maintenance, and disposal of building for different floor and roof designs of a typical timber frame wall townhouse house in Brisbane, Australia over a lifespan of 50 years for a discount rate of 6% and an inflation rate of 3%. • Operational energy - heating and cooling only.	• Construction and maintenance contribute to 86%-91% of the LCC. • Additional capital costs due to improved energy efficient roofing and flooring materials could be recovered from operational energy cost savings. • Skillion pitch or flat roof house design was cost effective with moderate GHG emissions reduction potential. • The ceramic tile flooring house design was cost-effective with the highest GHG emissions reduction potential as compared to carpet floor house.

2.5.5 Social implications and policy barriers to sustainable buildings

The slow progress in achieving the sustainable buildings is not only attributed to the lack of technology, materials, regulations, and design and assessment methods, but there is a resistance from the society for adopting the new technology, materials, and regulations due to a perceived fear of risk and unforeseen costs of change (Häkkinen and Belloni 2011). There is a continuous need for policy and regulations to keep pace with the building sector's best practices so that they are clear and enforceable (Williams and Dair 2007). The lack of use of renewable energy technologies, unwillingness to use sustainable materials due to the traditional attitude of workers and high capital costs of energy efficiency measures are few major barriers to the growth of sustainable buildings (Osmani and O'Reilly 2009; Nelson, Peterhansl and Sampat 2004; Williams and Dair 2007).

In Australia, the policy responses such as Nationwide house energy rating scheme (NatHERS) and mandatory energy rating of appliances under equipment energy efficiency (E3) program have shown positive outcome but due to lack of motivation and stringent implementation of policies, there is still disconnection between various stakeholders and also due to absence of any mechanism, it is difficult to verify the actual implementation during construction and post construction stages (Moore, Horne and Morrissey 2014; Horne and Hayles 2008; Blismas and Wakefield 2009; Strengers and Maller 2011). A recent Australian study suggests that before implementing the energy efficiency programs, policy makers should take a holistic view with a full understanding of complexities within remote communities and their behavioural preferences (Stewart, Anda and Harper 2016). Quite often, the actual amount of energy savings obtained through various energy saving strategies have been found to be less than anticipated because of socio-behavioural impacts (de Meester et al. 2013). Energy consumption in Australia is influenced by spatial and socio-economic inequalities (Wiedenhofer, Lenzen and Steinberger 2013).

Due to political reasons, the current electricity tariffs for households in Western Australia are heavily subsidised and are about 33.5% below the production, and delivery cost and have gradually started increasing since 2009 (REMCo 2014; DOF 2015b). In future, the increased electricity tariff coupled with increased household energy consumption may have adverse economic and social impacts; however, it may force the occupants to use more efficient appliances to reduce the cost.

Various countries such as Canada, Chile, Denmark, Finland, France, Iceland, Ireland, Japan, Mexico, Norway, South Africa, Sweden, Switzerland, and the United Kingdom have implemented a carbon tax or emissions trading schemes in different forms (CTC 2015). Carbon tax mechanism is a better alternative to emissions trading schemes for carbon abatement (Andrew, Kaidonis and Andrew 2010). Due to political compulsions, the carbon tax in Australia has been repealed in 2014 but the re-enactment of a carbon tax may happen in near future which will have adverse social impacts (Hunt 2015). A review study on the effectiveness of carbon taxes in various countries reported an overall GHG emissions reduction up to 15% in the countries where carbon taxes were implemented in the early 1990s (Sumner, Bird and Dobos 2011). Though, the carbon tax has some disadvantages but it is effective means that not only helps in reducing GHG emissions but it helps improve energy efficiency and implementation of renewable energy (Lin and Li 2011). A study by Avi-Yonah and Uhlmann (2009) found that carbon tax with periodical rate adjustment option along with renewable energy sources and other management strategies is an effective method to combat climate change impacts.

Australia's solar energy assets are substantial and underutilized (Bahadori and Nwaoha 2013). The grid connected roof top solar photovoltaic (PV) electricity system, and roof top solar water heater are an integral part of Australia's energy supply mix to improve energy security and to meet the challenges of climate change. The Australian federal and state governments introduced feed-in tariffs in different forms as one of the instruments to encourage the residential sector to install solar system (Martin and Rice 2013; Zahedi 2010). A feed-in tariff scheme provides a guaranteed return for a long period to encourage investment in renewable energy source (Poullikkas 2013). The energy produced by roof top solar PV is first consumed by the household and then the excess electricity is fed into the electricity network. Different states and territories in Australia have different feed-in tariffs based on either gross metering or net metering. The Western Australian Government has closed the feed-in tariff scheme for new applicants since July 2011 (DOF 2015d), which has affected the growth of installation of solar system even though the cost of technology has significantly reduced. Byrnes et al. (2013) also suggested that the effective policy with the regulatory framework is the backbone of the renewable energy deployment initiatives and due to policy barriers, desired results are not achieved.

Despite the implications of the high cost of energy in future, building owners continue to accept the energy inefficient products due to lack of understanding (e.g. conventional building materials, lighting fixtures, and appliances) (Bond 2011; Crabtree and Hes 2009). An Australian study on the influence of socio-behavioural characteristics of households on energy consumption found a significant gap between their desire to save energy and actual efforts to do so and a lack of their understanding towards the amount of energy consumption and associated costs (Randolph and Troy 2007). The high density mixed use urban development form has potential to promote social equity (Burton 2003). Availability of affordable housing has been found to be the most accurate indicator to evaluate social equity (Crawford 2003; Gurran 2008).

2.5.6 Summary and lessons learnt from social implications and policy barriers studies

In summary, the capital costs of energy efficiency improvement measures, tendency to maintain traditional practices, energy prices, and carbon tax have a major bearing on the sustainability of building sector. The overall progress is slow in the absence of integrated policies and monitoring mechanisms.

On the basis of lessons learnt from the above studies, the impacts of these factors on sustainability assessment, for Western Australia have been analysed and discussed in Chapter 5.

The following section discusses the integration of all the tools and approaches utilized for achieving the sustainable buildings.

2.5.7 Life cycle management (LCM) approach

Unites Nations Environment Programme defined the life cycle management (LCM) as a dynamic process, which collects, structures and disseminate product related information from various programs, concepts and tools with an aim to minimize the environmental and socio-economic burdens associated with a product throughout its entire life cycle in order to improve life cycle thinking (UNEP 2007). Islam et al. (2015) had endeavoured to follow a similar approach by integrating LCA and LCC tools to support sustainable decision making while assessing roof and floor materials for the construction of a house.

2.5.7.1 Review of contemporary life cycle management studies

The review of LCM studies which have been conducted over last 15 years has been summarised in Table 2.7. Most of this review consists of individual studies. The majority of these LCM studies (Table 2.7) have integrated LCA and LCC tools. Sonnemann and Leeuw (2006) and Westkämper, Alting, and Arndt (2000) analysed the potential of LCM approach including future developments, while Memon, Rahman, and Yacob (2014) assessed the level of implementation of LCM approach for the construction industry of Malaysia. Ortiz et al. (2009) and Ristimäki et al. (2013) utilized the LCM approach to analyse the environmental and economic implications of energy efficiency measures for residential buildings.

The studies univocally agree that the LCM approach is an effective decision making tool and is applicable to all industries who desire to implement a preventive and sustainable management concept using a system oriented platform. The study by Memon, Rahman, and Yacob (2014) reported that LCM approach is gaining popularity amongst the building practitioners because it allows the integration of various concepts and programs related to risk assessment, environmental management, and social accounting and corporate social responsibility and makes it a versatile tool to achieve sustainability goals. The LCM initiatives to change consumer’s behaviour could promote the sustainable construction practices (Ortiz et al. 2009; Westkämper, Alting and Arndt 2000). The application of LCM approach by combining LCA and LCC tools was found to help in mitigating the economic and environmental impacts even with the existing technologies (Ristimäki et al. 2013), thus offering a sound environmental management framework. LCM approach has potential to solve the socio-ecological and economic problems from a full systems perspective in order to identify most suitable strategies towards sustainability (Ny et al. 2006). LCM is not just a collection of tools and approaches, but it is an integrated framework to improve products, services and operations from life cycle perspective and to improve decision making (Hunkeler et al. 2003).

2.5.7.2 Summary and lessons learnt from review of contemporary life cycle management studies

In summary, the LCM approach provides flexibility and platform to integrate various tools and concepts to achieve the goals of sustainable building design. The integration of various assessment tools and concepts in LCM approach have been found to complement each other thus making it an efficient decision making tool.

On the basis of lessons learnt from the above studies, the LCM approach has been utilized to estimate and minimize the impacts associated with the residential buildings in Western Australia and discussed in Chapter 3, 4, 5 and 6.

Table 2.7 Summary of contemporary life cycle management (LCM) studies reviewed

LCM studies	Aim of the study	Results
(Ortiz et al. 2009)	• Evaluation of the environmental and economic impacts of construction and use stage of a typical Mediterranean case study house based on LCM approach in Barcelona over a lifespan of 50 years. • Operational energy - heating, cooling, hot water, lighting, and home appliances.	• LCM approach was found to be a very effective decision making a tool for optimizing the sustainability indicators of a house construction in Spain. • LCM initiatives on occupant's behaviour could reduce the energy, cost, and environmental impacts thus promoting the sustainable construction practices.
(Sonnemann and Leeuw 2006)	• Review of the potential of LCM approach.	• LCM approach applies the life cycle thinking into practice by using LCA, and LCC tools. • LCM approach could be applied to any commercial, industrial, and other organizations who desire to implement a preventive and sustainable management concept. • A strong focus on LCM approach could initiate the changes in unsustainable patterns of resource consumption and production.
(Westkämper, Alting and Arndt 2000)	• Investigation of the existing LCM approach and future developments.	• LCM approach could protect the resources by maximizing the effectiveness during operational stage with the help of LCA, product data management, technical support, and LCC. • LCM must be an integral part of any engineering, operation, and the end of life recycling and disposal processes as a precondition for a sustainable development.
(Ristimäki et al. 2013)	• Investigate whether a residential development could practically deliver the targeted sustainable viability (i.e. environmental and economic benefits both together) using LCM approach by combining LCA and LCC tools in Finland.	• Alignment of economic and environmental interests through LCM approach was found to be complementary to each other and could help in mitigating the economic and environmental impacts even with existing technologies. • In real estate development projects, the LCM approach could improve the economic incentives to reduce the costs.

LCM studies	Aim of the study	Results
(Memon, Rahman and Yacob 2014)	• Assess the level of implementation of LCM approach including different tools for the construction industry in Malaysia based on the completed responses from 125 construction practitioners with diverse academic, skill, and experience backgrounds.	• 80% of the respondents were using LCM approach in their projects but the degree of the application was low. • Under LCM approach, the LCA, environmental risk assessment, substance flow analysis, material flow analysis, Cumulative energy demand, LCC, and environmental monitoring are the most common tools. • The degree of implementation of environmental concepts and programs such as environmental management system, environmental accounting, design for environment, environmental labelling, environmental reporting, and product stewardship is increasing. • The degree of application of social concepts and programs such as cost benefit analysis, corporate social responsibility, social accounting, and stakeholder expectation analysis is relatively low.
(Lawania and Biswas 2016)	• Application of LCM framework by integrating LCA, energy rating tool, LCC to ascertain environmentally and economically viable alternative options for construction of a typical house in Perth over a lifespan of 50 years for a discount rate of 7%, and an inflation rate of 3%. • In addition to conventional option, 19 alternative options for construction of a house including roof top solar PV and solar water heater were considered.	• Cast in-situ sandwich walls with polystyrene or PET foam cores were the most cost effective environmentally viable options for the construction of a house, while the concrete block walls, and precast light weight concrete sandwich wall options had the highest impacts. • Use of roof top solar PV and the solar water heater was cost-effective environmental impact reduction measure.

2.6 Research gaps

This chapter has presented the existing body of knowledge on various aspects of sustainable building construction, which has been found to be a major issue in Western Australia. Therefore, it was important to investigate the tools or frameworks for addressing building sustainability issues in WA. As a result, this chapter reviewed various tools and approaches utilized for estimation and minimization of the impacts associated with various stages of the buildings to achieve the goals of sustainability.

The use of energy during the lifespan of a house has been found to be the major source of the environmental impacts. Though the LCEA approach helps in analysing the energy hotspots and develops energy efficiency strategies but it can't determine the environmental impacts associated with the use of energy and energy efficiency measures and hence LCA approach is needed. The LCA approach can help in estimation of not only the environmental impacts associated with the use of energy but the environmental impacts associated with the mining to material production, construction and other activities also can be estimated. LCA helps in identification of environmental hotspots and accordingly develop the cleaner production strategies to mitigate the impacts. However, both these approaches fail to highlight whether the energy and environmental impact mitigation strategies are cost-effective or not and to overcome this issue, LCC has been found to be an efficient approach. Through LCC all future costs can be converted into present values and thus a fair comparison of various environmentally competitive products can be made. To achieve the goal of sustainable building, it is important to assess the social impacts of environmentally and economically feasible decisions and to analyse the impacts of policy barriers. The LCM approach provides an opportunity to integrate these tools and concepts and helps to achieve the sustainable buildings. The published literature to date suggests that no LCM framework has been developed exclusively for Western Australia to capture all regional climatic, environmental, socio-economic variations, which could assist the policy makers, developers, and consumers in the housing supply chain to identify the sustainable solutions applicable for Western Australia.

The LCM framework which integrates all the above tools and concepts for sustainability assessment of residential buildings is discussed in Chapter 3.

Chapter 3

Research Methodology

3.1 Introduction

This chapter discusses the development of life cycle management (LCM) framework that consists of life cycle assessment (LCA), life cycle energy analysis (LCEA), cleaner production strategies (CPS), life cycle costing (LCC), and social impact assessment (SIA). Then it describes the methods for implementing this framework for achieving the following research objectives for attaining the sustainable house construction option in Western Australia.

Objective 1: To develop a framework for improving the sustainability performance of houses in Western Australia (Chapter 3)

Objective 2: To estimate the life cycle environmental impacts of construction, use, and disposal of a typical house in Perth using LCA tool (Chapter 4)

Objective 3: To identify hotspots and apply appropriate cleaner production strategies (CPS) to mitigate the life cycle environmental impacts associated with identified hotspots for a typical house in Perth (Chapter 4)

Objective 4: To estimate the socio-economic implications of environmentally viable cleaner production options for mitigation of life cycle impacts of a typical house in Perth (Chapter 5)

Objective 5: To investigate the implication of environmentally, and economically viable options for 17 locations in regional Western Australia to capture the location specific climatic, economic, energy, and policy variations (Chapter 6)

The chapter discusses the premise of LCM framework which was based on the detailed literature review in Chapter 2. Explanations of LCA and LCEA tools for identifying the environmental impact mitigation opportunities through CPS are provided. The use of LCC for assessing the cost-effectiveness of feasible CPS options is presented. Finally, the methods for assessing social impacts of the cost-effective CPS have been discussed using relevant social indicators.

In summary, this chapter explains the flexibility of the LCM framework as to how various tools, concepts, and techniques have been utilized for this research to achieve sustainable building envelope specifically for Western Australian houses at a regional level by taking climate and resource availability into account.

3.2 Life Cycle Management Framework

3.2.1 Premise of the LCM framework

This framework is based on the following premise:

- This framework for WA's building sector complies with the definition of United Nations Environment Programme (UNEP), as this organization defines LCM as a dynamic process, which collects, structures and disseminates product related information from various programs, concepts and tools with an aim to minimize the environmental and socio-economic burdens associated with a product throughout its entire life cycle and improves the life cycle thinking (UNEP 2007).

- LCM is an integrated decision oriented approach that helps apply the concept of life cycle thinking to practice while maximizing the functionality of the product with minimum environmental impacts and costs, thus, LCM is an essential component of sustainable development (Westkämper, Alting and Arndt 2000; Rebitzer and Hunkeler 2003; Ortiz et al. 2009). Accordingly, this current LCM framework considers the components for delivering socially equitable but cost-effective CPS strategies for WA's building sector.

- There is a dire need for LCM framework for Australian building sector as the building sector alone contributes to 20% and 23% of Australia's annual energy consumption and GHG emissions, respectively (ABCB 2015b; ASBEC 2007). This LCM framework considers WA, as 15% of the total houses (3.3 million) in Australia, will be built in this state by 2030 (NHSC 2011). In addition, the houses in WA are made of energy intensive clay bricks. Consequently, the material and energy consumption during the life cycle of a house could potentially result in high greenhouse gas (GHG) emissions and embodied energy (EE) consumption.

The building sector's GHG emissions are growing at 1.3% annually (ASBEC 2007) despite the fact that various energy efficiency measures have already been implemented. Therefore, there is an urgent need for further improvement opportunities of this sector to help Australia to meet its GHG emissions reduction target committed at the climate change conference in Paris (i.e. 26% to 28% on 2005 levels by 2030) (DOE 2015a).

- This situation compels to investigate the alternative house designs that will not only consider the use of low energy and low carbon intensive construction materials but also reduces operational energy consumption while achieving social and economic objectives of sustainability.

- As explained in Chapter 2, the literature published to date for building construction materials and methods (Lawania, Sarker and Biswas 2015; Islam, Jollands and Setunge 2015; Cabeza et al. 2014; Todd et al. 1999; Fay, Treloar and Iyer-Raniga 2000; Rouwette 2010; Del Borghi 2013; Aldawi 2013; Van Berkel 2007) have not considered a comprehensive framework for addressing aforementioned triple bottom line objectives for sustainable houses in WA.

The proposed LCM framework with the help of environmental management tools and approaches will endeavour to achieve sustainable houses at the regional level in Western Australia.

3.2.2 Description of Life Cycle Management Framework

A life cycle management framework has been developed to meet the objectives of this research (Figure 3.1). This LCM framework is a modified version of the LCM framework developed by Lawania and Biswas (2016) and integrates the life cycle assessment (LCA) tool, Australian Nationwide House Energy Rating Scheme (NatHERS) accredited tool for LCEA, Data Bank, cleaner production strategies (CPS), life cycle costing (LCC) tool, social impact assessment, and lastly the policy instruments to identify the environmentally benign, economically viable, and socially equitable option for the construction of houses.

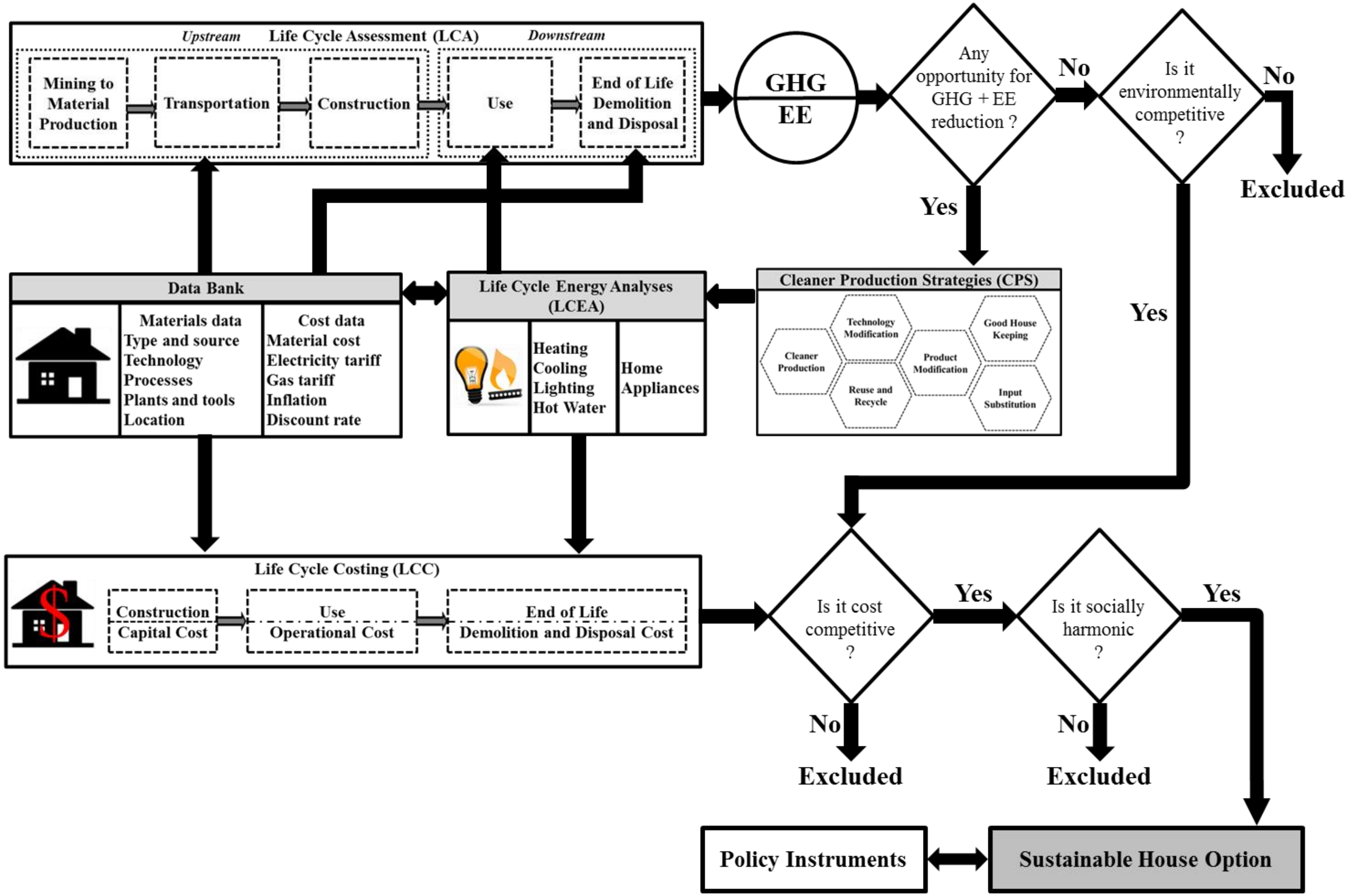


Figure 3.1 Life cycle management (LCM) framework

The key components of LCM framework are described as follows:

i. Application of life cycle assessment (LCA)

The first step of LCM framework is to estimate the GHG emissions and embodied energy consumption associated with the construction, use and the end of life demolition and disposal of a typical 4x2x2 detached single storey double clay brick wall house in WA following the ISO14040-44 guidelines of LCA. The life cycle inventory (LCI) consisting of material and energy input data of all stages of the building's life cycle is a prerequisite for the estimation of GHG emissions and EE consumption. The Data Bank provides information for the development of LCI by utilizing the architectural and structural drawings for quantifying the materials required for construction of a house, the transportation distances between their sources and the construction site and the electricity and diesel consumed during the construction stage. The information on energy rating of various tools, plants and equipment and duration of their use helps in the estimation of energy consumption during construction or assembling of various components.

The energy consumption during use stage of a house is consumed mainly for maintaining thermal comfort (i.e. heating and cooling), lighting, hot water, and home appliances. The Data Bank provides all the information such as dimensions, locations and details of materials used for the construction of a house to AccuRate software to estimate the annual heating and cooling energy demand, which is a function of thermal performance of the building envelope (e.g. walls, windows, floor, roof), orientation of the house, and climatic conditions. AccuRate software also assists in the estimation of annual energy demand for lighting and hot water. The energy rating of home appliances and their duration of use by occupants helps to estimate annual energy demand for home appliances. Once the operational energy demand is estimated, the life cycle energy analysis (LCEA) is performed.

The information on energy rating of various plants and equipment required for demolition of a house including duration of their use and distance between site and landfill helps in the estimation of energy consumption during demolition and disposal of demolition waste during the end of life stage.

All material and energy data is incorporated into SimaPro as inputs to estimate the GHG emissions and EE consumption. The net flow chart produced by SimaPro software has been used for stage wise breakdown of GHG emissions and EE consumption associated with each input. The inputs, which causes the maximum impacts are termed as 'hotspots' and are ranked from the highest to lowest as per GHG emissions and EE consumption. Accordingly, priority is given to apply the mitigation or cleaner production strategies to treat these hotspots.

ii. Application of cleaner production strategies (CPS)

Once the appropriate CPS has been implemented to mitigate the impacts, the LCI has been revised for incorporation of revised material and energy inputs into SimaPro software for estimation of revised GHG emissions and EE consumption. The process of CPS application continues until the maximum level of GHG emissions reduction and EE consumption savings are achieved.

iii. Application of life cycle costing (LCC)

The data bank also provides the capital and operational cost inputs of material and utilities associated with a house including inflation and discount rates required for discounted cash flow (DCF) analysis. The DCF analysis technique is used to derive economic performance criteria such as net present value (NPV) for investment projects. All future costs are converted into present values and life cycle costs are estimated for all CPS options. Also during this process, the payback periods of energy efficiency measures are determined which helps in decision making for product selection. The framework guides the decision making process as to whether any LCC of an alternative building or CPS options is lower than the LCC of reference option. The options having higher LCC than the reference option are not considered for further analysis.

iv. Social impact assessment

The social indicators allow the comparison between social implications of reference option and environmentally and economically viable alternative options. The policy instruments are investigated to identify the barriers and to determine the further improvement opportunities to achieve the sustainable development.

Following sections describe the implementation of framework including the background and reasons for selection of these tools and concepts to achieve all research objectives:

3.3 Method for GHG and Embodied Energy Estimation for LCM framework

The global warming potential (GWP) and cumulative energy demand (CED) or embodied energy (EE) are the two most relevant and critical impact categories for Australian built environment (Biswas 2014; Lawania, Sarker and Biswas 2015; Islam, Jollands and Setunge 2015; Dowdell 2014) and hence have been considered for this research. Globally, the life cycle assessment methodology is the most popular method to estimate these impacts associated with products or services of built environment (Khasreen, Banfill and Menzies 2009; Rossi et al. 2012; Cabeza et al. 2013) and hence is the decision making tool for identifying the mitigation strategies as a first step of the LCM framework (Figure 3.2).

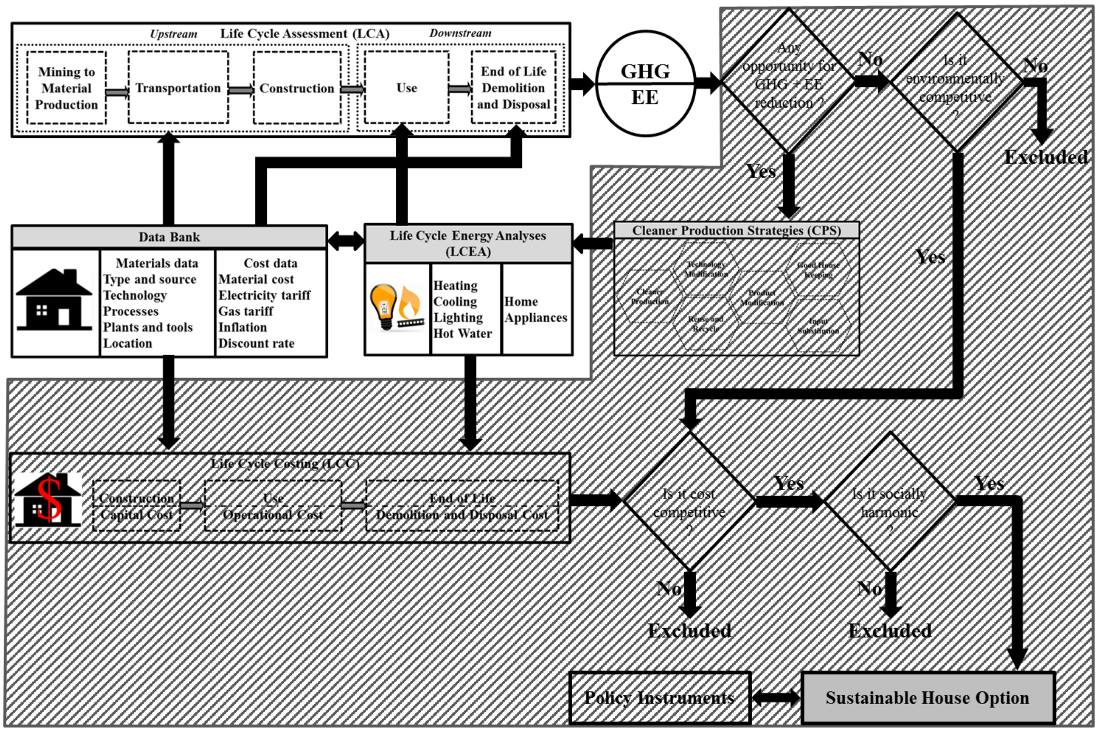


Figure 3.2 LCM framework: Part 1 - Life Cycle Assessment Methodology

GHG emissions and embodied energy consumption of life cycle stages of a house have been estimated by employing the four steps of ISO14040-44: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation as described in sections 3.3.1 to 3.3.4.

3.3.1 Goal and scope definition

The goal is the basis for LCA analysis and offers decision making strategies to the stakeholders in the environmental supply chain of a product or service. The goal of this LCA is to find out a building envelope with reduced GHG emissions and EE consumption. A cradle to grave LCA has been carried out to achieve this goal within the technical and environmental constraints, assumptions, and limitations.

As per ISO14040 (2006), the scope defines the depth and breadth including details of the study to address the goal as this LCA includes mining to material production, transport, construction, use, and end of life demolition and disposal stages. The scope also defines the quality and representativeness of data as to how it will be sourced and analysed, and what impacts it might have on the outcome of the study. The function i.e. the technical or social purpose of the product or service for stakeholders is also defined within the scope. The functional unit is needed to carry out a mass balance that involves the estimation of inputs and outputs of all stages of product life cycle and thus it quantifies the utility of the service or a product system and provide a reference to which input and output data can be related and facilitate the comparison with the results of similar products on equal basis.

The functional unit of this research, is the construction, use, and end of life of a typical 4x2x2 (4-bedroom, 2-bath and 2-garage) detached house of 243m^2 footprint area in Perth (Figure 3.3) and equipped with standard features and amenities. Based on the actual life of the Australian houses and various life cycle assessment studies for Australian housing, the life cycle of a house has been considered as 50 years (Rouwette 2010; Carre 2011b; Ross Maher 2011; Islam, Jollands and Setunge 2015). For detailed analysis and identification purpose, double clay brick walls, single glazed windows, and concrete roof tiles which form the house envelope have been represented as DB-XX, SG, and CT respectively and hereinafter the envelope of reference house has been termed as a conventional envelope.

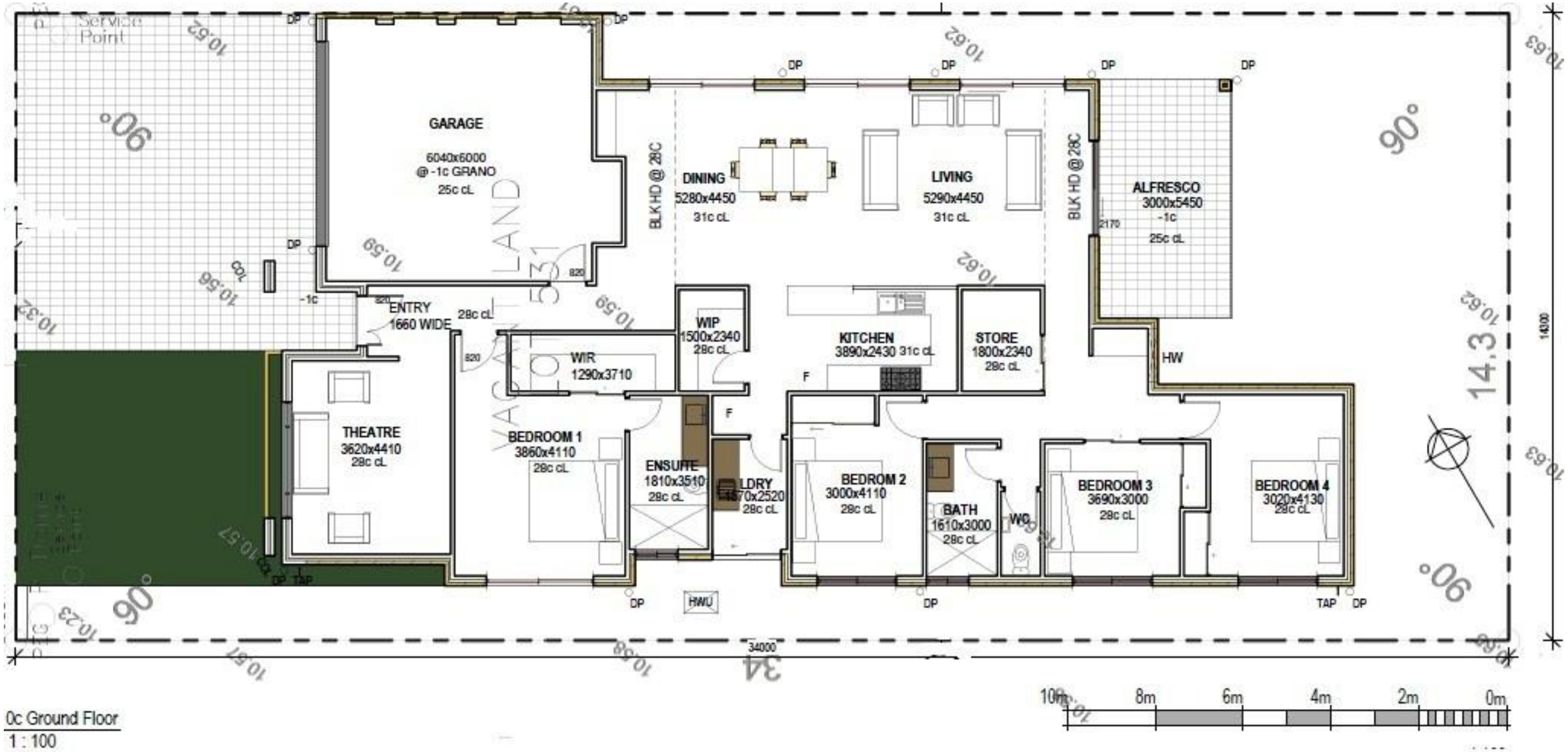


Figure 3.3 Plan of a typical 4x2x2 detached house in Perth (Source: Fozdar Technologies Pty Ltd.)

Due to complex life cycle process flow or sequence of activities of a product or service, it is not possible to collect the complete data for life cycle assessment and hence it is critical to set up limits or boundaries for data collection and process flow (Li et al. 2014). The loose furniture, plumbing, drainage and electrical services, sanitary ware, tapware and lighting fixtures, external site development such as pavement, landscaping, garage door, wall painting, and routine maintenance 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 environmental performance of a house (Horne, Opray and Grant 2006; Carre 2011b; Monahan and Powell 2011).

The system boundary is described as an interface between a product and environment and defines that what phases of life cycle of a product or service (such as extraction, processing, manufacturing, transport, use, maintenance, and end of life) (Figure 3.4) and associated environmental impact categories, and limitations and assumptions are considered for LCA analysis.

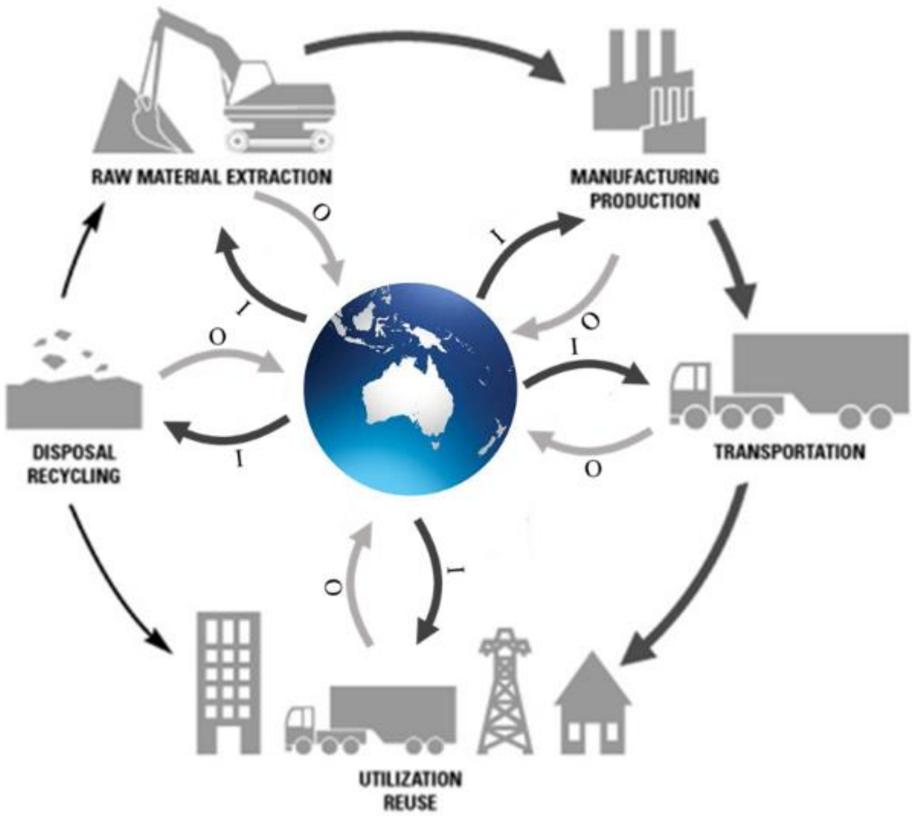


Figure 3.4 Typical product life cycle stages with inputs (I), and outputs (O) (Modified from Product's lifecycle.jpg – National Institute of Standards and Technology's Manufacturing Engineering Laboratory Programs, 2008)

The combination of different life cycle phases of a product or service are referred as "Cradle to Grave", "Cradle to Gate", "Cradle to Cradle", and "Gate to Gate" (Bayer et al. 2010). This LCA considers cradle to grave approach including all emissions and energy consumption for estimation of GHG emissions and EE consumption.

3.3.2 Life Cycle Inventory Analysis

LCI is a pre-requisite to carry out an LCA analysis and consists of input and output data of all stages including mining to material production, transportation, construction, use, end of life demolition and disposal of solid waste. Inventory development thus requires the information on material and energy consumptions and outputs (e.g. atmospheric and waterborne emissions including solid wastes) during each of the life cycle stage of a product which is a house in this current study and to relate them to chosen functional unit through mass balancing (Biswas 2014; Westkämper, Alting and Arndt 2000). The measured, modelled, adapted, and or sampled data for development of life cycle inventory have been obtained from various accountable sources such as laboratory tests, field tests, government databases, and reports, journals, trade associations, other similar life cycle inventories, public surveys, and or equipment specifications. Accordingly, the LCM framework has a Data Bank as an important component to capture all regional variations in data in order to carry out LCAs of a number of building envelope options to find the best option with the highest mitigation potential for different locations in WA.

3.3.2.1 Data Bank

Based on Australian Bureau of Statistics 2011 Census report (ABS 2013), growth forecast of regions (DOP 2015) (Table C.1, Appendix C), and variations in climatic conditions within WA, at least one location from each region and 18 locations in total have been selected for this study (Figure 3.5) to represent all regions of WA. In order to carry out LCAs of a wide range of house options for 18 locations in WA, all material and energy details and their sources and transportation infrastructure related to construction and use of houses in Western Australia have been collected to develop a comprehensive data bank.

The main purpose of the data bank is to provide information for developing the LCI for houses for a particular design type. Data bank consists of material specification, codes of practice, meteorology of WA, bill of materials including supply sources and their respective distances from the construction sites, modes and methods of transportation, locations of landfill areas, plants and tools required during construction, and labour. In order to provide information to develop the LCI, the details of energy demand during various life cycle stages of a house including energy generation and distribution in Western Australia as well as details of climate zones are included in the data bank.

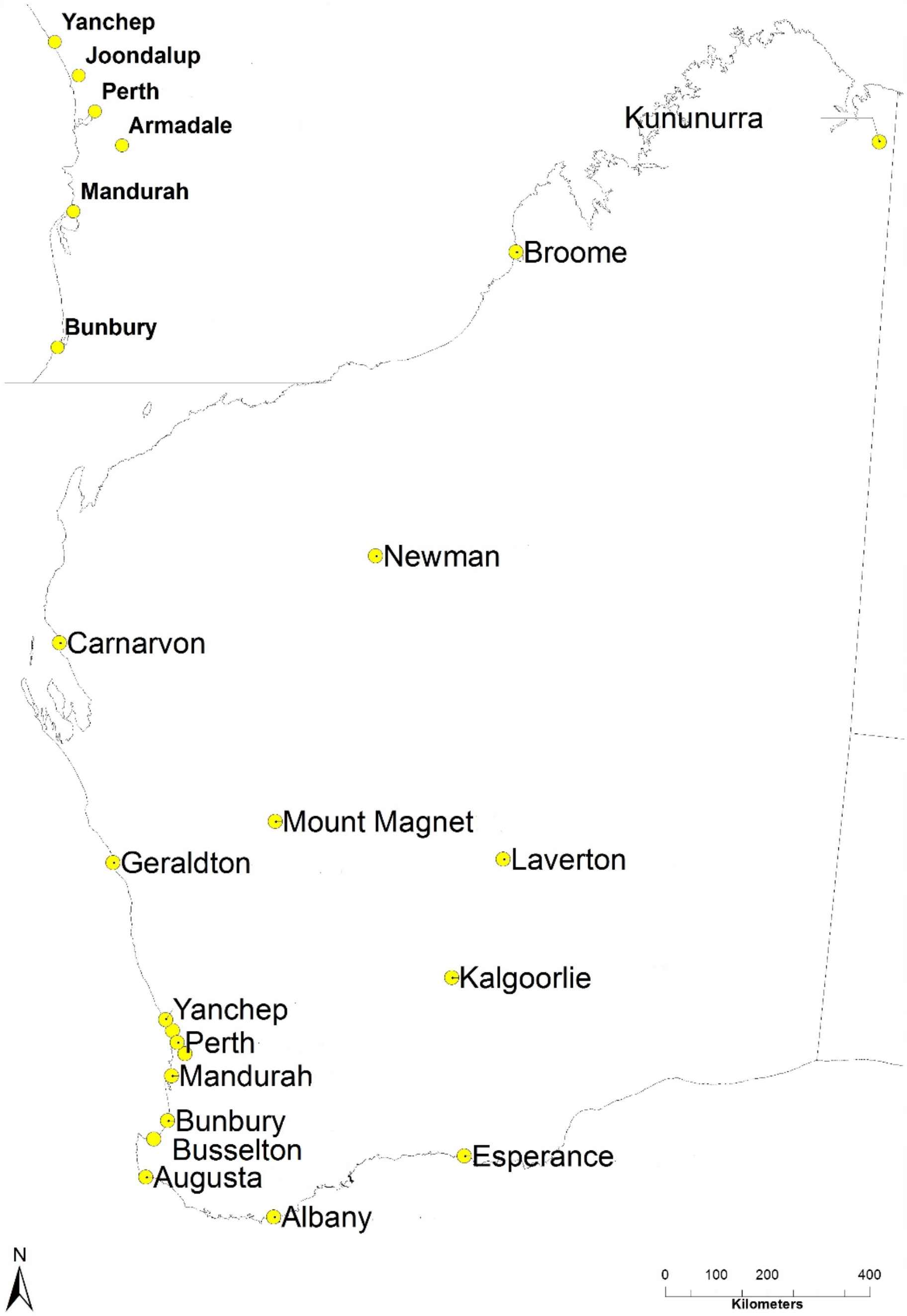


Figure 3.5 Locations representing all regions of WA

In addition, the data bank provides details of alternative materials and technologies for developing inventories for cleaner production strategies and life cycle cost analyses. The data bank providing information for different stages of LCA have been discussed as follows:

3.3.2.1.1 Mining to material production stage

To develop an inventory of materials, a detailed Bill of Quantities has been prepared using architectural and structural plans and specification of a typical house in Perth in accordance with AS1181-1982, which is an Australian standard method of measurement of civil engineering works and associated building works (Standard 1982). Based on most common practices and application in WA, the reference house in Perth has been considered where the house has a concrete slab on ground (Dick Clarke 2013; CCAA 2007), double clay brick walls (Williams 2015), single glazed sliding aluminium frame windows (AWA 2014), and concrete roof tiles (RTAA 2013) laid over timber roof frame (Belusko, Bruno and Saman 2011).

The face bricks for the outer skin of external walls, utility bricks for the internal skin of wall as well as for internal walls with galvanized iron lintels and columns have been considered. The internal walls are considered as rendered (float and white set). The gyprock ceiling with rock wool batt insulation and gypsum cornices are considered throughout the house. The fibre cement sheet eaves, metal door frames with timber door shutter, ceramic wall and floor tiles for wet areas, and porcelain tiles for flooring of the house have been considered. All necessary fixtures, and or support systems associated with walls, windows, and roof have been considered accordingly.

The quantities of aforementioned materials for the development of LCI for mining to material production stage have been estimated using Equation (3.1).

$$\boldsymbol{BM_a} = \Big(\sum_{\boldsymbol{i=1}}^{\boldsymbol{i=n}} \boldsymbol{L_{a(i)} x B_{a(i)} x H_{a(i)}}\Big)\, \boldsymbol{x \rho_{a(i)}} \qquad \textbf{(3.1)}$$

Where,

BM_a : Building material - mining to material production (tonnes/house)

a : Type of material (e.g. concrete, brick, steel, glass, cement) i : 1,2,…..n; location in the house (e.g. room, garage, bath, passage)

L : Length (m)

B : Width (m)

H : Height or thickness (m)

ρ : Density of material in (tonnes/m^3)

The numerator in the inventory input will ultimately become the denominator of the emission factor. Therefore care has been taken in a way that the numerators of inputs match the denominators of their respective emissions factors.

3.3.2.1.2 Transportation stage

One of the useful features of the data bank is to record the material sources and their distances, modes and capacities of material transport for Perth and 17 regional locations in WA as they vary according to the location. The available published commercial data from various manufacturers and distributors (Austral-Bricks 2014; BGC 2014; Boral 2014; Bunnings 2014; Hanson 2014; Holcim 2014; Masters 2014; Midland-Brick 2014) has been used to determine the sources of materials to estimate the tonnes-km travelled to bring materials to the construction site using Equation (3.2), where each mode of transport such as road, sea, air, rail, and truck and their capacity is considered.

$$\boldsymbol{tkm_{transport(a)}} = \sum_{i=1}^{i=n} \boldsymbol{BM_{a(i)} x D_{a(i)}} \qquad \textbf{(3.2)}$$

Where,

$tkm_{transport}$: Tonnes-km travelled (tkm/house)

a : Mode and type of transport (e.g. road, sea, air, rail, truck and capacity)

BM_a : Building materials (e.g. concrete, sand, cement, glass, and steel) transported using a particular mode and type of transport (tonnes)

D_a : Distance from material source to construction site (km) for a particular mode and type of transport

i : 1,2,…..n; type of materials transported from source to the construction site by a particular mode of transport ‘a’

3.3.2.1.3 Construction stage

In the case of construction stage, the data on power rating of machineries (e.g. bobcat, compactor, loader, forklift) and type of tools used for construction of typical house in Australia including their duration of usage was obtained from a local builder Fozdar Technologies Pty Ltd and local equipment hire companies (Coates-Hire 2014; Kennards 2014). The energy consumption during construction stage has been calculated using Equation (3.3).

$$\boldsymbol{Energy_{construction}} = \sum_{i=1}^{i=n}\sum_{j=1}^{j=m} \boldsymbol{Plant/tool_{i(j)} x duration_{i(j)}} \qquad \textbf{(3.3)}$$

Where,

$Energy_{construction}$: Energy consumption (MJ/house)

i : 1,2,…..n; type of energy (e.g. electricity, diesel, gas)

j : 1,2,….m; type of plant and tool (e.g. excavator, loader, mortar mixer, and hand tools)

Plant/tool : Hourly electricity consumption of plant/tool (MJ/hour/house)

Duration : Hourly diesel consumption of plant/tool (MJ/hour/house)

The transportation required for disposal of excavated soil and construction waste during the construction stage has been calculated using Equation (3.2).

3.3.2.1.4 Use stage

During use stage of a house, the energy is consumed by households mainly for heating, cooling, lighting, home appliances, and hot water. This component of data bank has been designed to provide information required by AccuRate software for estimation of energy demand for heating, cooling, hot water, and lighting. The key details required by AccuRate software are the project location and postal code, physical dimensions and respective locations of rooms and other living areas, construction details of each component (e.g. foundation, external walls, internal walls, windows, external doors, flooring, ceiling, roof, thermal bridging between two layers of construction, shadings including external screens), no. of lamps and their ratings, water entities including taps, sanitary ware, and occupancy pattern.

The information for calculating the energy demand for home appliances such as the type of home appliances, energy rating, and their duration of use has also been included in the data bank. Based on the tools used for estimation of energy consumption (termed as operational energy) during use stage, the operational energy is divided into following two groups:

- Operational energy for heating, cooling, hot water and lighting, which are estimated using AccuRate software.

- Operational energy for home appliances, which is estimated using MS Excel software.

The building envelope has no influence on the operational energy consumption for lighting, home appliances, and hot water, but energy demand for heating and cooling is influenced by the design and location of a house and thermal performance of the building materials.

Australia has a varied climate, which affects the design and construction requirements of the houses including their thermal performances (Aldawi, Alam, Khan, et al. 2013) and hence the details of regional climatic variations have been included in the data bank. In order to address the regional climatic variations, the National Construction Code has combined the locations with similar climates into following eight climate zones and have aligned the zone boundaries with local government areas (ABCB 2014; Reardon and Downton 2013b) to comply with deemed-to-satisfy energy efficiency provisions.

Climate zone 1 – High humidity summer and warm winter (Houses in this zone requires high cooling energy but no energy for heating)

Climate zone 2 – Warm humid summer and mild winter (Houses in this zone requires high cooling energy but little heating energy)

Climate zone 3 – Hot dry summer and warm winter (House in this zone requires high heating and cooling energy)

Climate zone 4 – Hot dry summer and cool winter (Houses in this zone requires moderate heating and cooling energy)

Climate zone 5 – Warm temperate (Houses in this zone requires low heating and cooling energy)

Climate zone 6 – Mild temperate (Houses in this zone requires very low heating and cooling energy)

Climate zone 7 – Cool temperate (Houses in this zone requires high heating energy but no energy for cooling)

Climate zone 8 – Alpine (Houses in this zone requires the highest heating and cooling energy)

Similarly, for water heating, Australia is divided into 4 climatic regions (Figure 3.6) based on solar insolation and ground temperatures, which affect the temperature of reticulated water (Standard 2008).

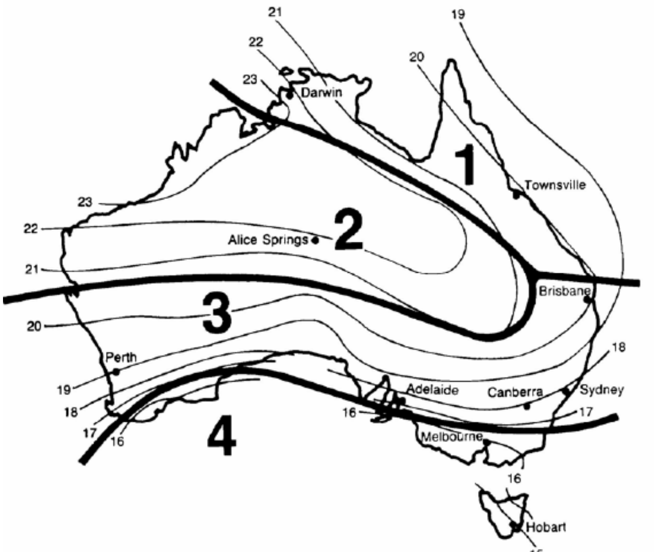


Figure 3.6 Australian climate regions for hot water (AccuRate 2015)

Due to vast landmass, and demographic conditions, Western Australia's electricity infrastructure is complex and consists of South West Interconnected System (SWIS) serving major population centres in the south-west of WA, North West Interconnected System (NWIS) serving north-west of WA, and a number of regional and non-interconnected systems (DOF 2015a). The regional locations in Western Australia such as Albany, Armadale, Augusta, Bunbury, Busselton, Esperance, Geraldton, Joondalup, Kalgoorlie, Mandurah, Yanchep, and metropolitan Perth are connected to SWIS network. The locations of non-interconnected networks in Western Australia are Broome, Carnarvon, Mount Magnet, and Newman where electricity generation is gas based and Kununurra and Laverton where diesel is used for electricity generation (Horizon 2015b; DOF 2015a; Horizon 2015a). ATCO Gas Australia maintains the gas distribution network in WA to serve Perth metropolitan area and regional centres through retailers such as Alinta Energy, Kleenheat Gas, Synergy, and Gas trading Australia (ATCO 2012; DOF 2015c).

Operational energy for a typical house for heating, cooling, hot water, and lighting

The AccuRate software works in regulatory rating mode (thermal envelope energy rating) and non-regulatory non-rating (voluntary assessment) mode. In the non-rating mode, the software has 5 modules such as lighting, hot water, water use, space heating, and space cooling and allows estimation of thermal bridging effect for non-glazing constructions. The software allows development of building model through databook, which consists of various sections such as Project, Constructions, Zone, Shading, Elements, Ventilation, Lighting, Hot water, and water including project defaults for simulation as discussed in following sections:

Project Section

The project module helps in creating project particulars, details of assessors, building class, design options, and most importantly, the postal code and NatHERS zones, which links the project to AccuRate's database.

Construction Section

The construction module helps in developing a master table consisting of construction details of the external wall, windows, external door, floor/ceiling, internal wall, roof, skylight, and roof window. AccuRate's library database contains the list of all basic construction materials along with their thermal resistance (m^2K/W) and thermal capacitance (kJ/m^3K) properties including the properties of air gaps and bulk insulation. Each building component, which is essentially a group of layers of construction materials and air gaps can be defined by specifying the thickness of each construction material layer and the bridging or connection with other material layers. AccuRate simultaneously calculates the overall thermal properties of these constructions expressed as total R (heat flow up), total R (heat flow down), total U (heat flow up), and total U (heat flow down).

Zone Section

The Zone section helps in creating the details of the building spaces as zones including floor and ceiling heights, the option of heating and cooling including infiltrations and ceiling penetrations. AccuRate allows maximum 150 user-defined zones in a house and each space is designated by a pre-defined type such as living, bedroom, living/kitchen, day time, night time, unconditioned, garage, garage conditioned, roof space, and sub-floor. The roof space zone allows selection of different roof types such as Hip, Gable, and Single including pitch and roof infiltration.

Shading Section

Shading section helps in creating details on horizontal and vertical shadings such as eaves, balcony projection, fencing, pergola, and neighbouring property including their respective dimensions and locations.

Elements Section

Element section helps in creating the details of actual dimensions and geometry of all zones in a house on the basis of the external wall, Internal wall, floor, ceiling, and roof including the type of construction, locations of doors and windows, shading, and openings.

Ventilation Section

The ventilation section helps in developing the footprint of the building and orientation azimuth of the building. Accurate allows 0º to 360º azimuth angles and to represent all azimuth angles, 8 orientations including North (0º), North-West (315º), West (270º), South-West (225º), South (180º), South-East (135º), East (90º), and North-East (45º) have been selected for this study following Andersson et al. (1985), and Morrissey, Moore, and Horne (2011). The accurate software uses this data to calculate the natural ventilation available for the house in a particular orientation.

After completing the data entry for all sections, the simulation of the model is carried out and the details of a simulation of each module such as heating, cooling, hot water, and lighting are discussed in the following section.

Heating and cooling module

AccuRate calculates the annual energy requirements to maintain the thermal comfort of the house based on the building envelope, natural ventilation, thermostat settings and one year of weather data corresponding to the climate zone of the house. Lam et al. (2005) and Yik and Wan (2005) described the heat transfer through building envelope as conduction through wall, roof, and window glazing and solar radiation through window glazing and used the concept of overall thermal transfer value (OTTV, W/m^2) developed by ASHRAE (Codes and Standards 1980) for determination of energy consumption for heating and cooling. The OTTV of a wall is the weighted average of heat conducted through the wall, and window glazing and solar radiation through window glazing. OTTV has been expressed as shown in Equations (3.4), which has been developed following the equations provided by Yik and Wan (2005), Lam et al. (2005), and Vijayalaxmi (2010).

$$\boldsymbol{OTTV_{wall}} = \frac{\sum_{i=1}^{i=n}\left(A_{w(i)} x U_{w(i)} x TD_{eq} + A_{g(i)} x U_{g(i)} x \Delta T + A_{g(i)} x SC x SF_i\right)}{\sum_{i=1}^{i=n}\left(A_{w(i)} + A_{g(i)}\right)} \quad \textbf{(3.4)}$$

Where,

OTTV : OTTV of all external walls (W/m^2)

i : 1,2,……360; wall orientations of the house (0º to 360º)

A_w : Area of wall with same orientation (m^2)

U_w : U value of wall elements (W/m^{2}K)

A_g : Area of window glazing with same orientation (m^2)

U_g : U value of window glazing (W/m^2K)

ΔT : Difference between exterior and interior temperatures (K)

SC : Shading coefficient of windows

SF : Solar factor for that orientation (W/m^2)

TD_{eq} : Equivalent temperature difference (K), which is dependent on weather conditions and the duration for which temperature and solar radiation data are averaged including surface finishes and has been expressed as:

$$\boldsymbol{TD_{eq}} = \Delta \boldsymbol{T} + [\boldsymbol{\alpha}\ \boldsymbol{x}\ \boldsymbol{R_{wsr}}\ \boldsymbol{x}\ \boldsymbol{avg}(\boldsymbol{I_t})] \quad \textbf{(3.5)}$$

Where,

ΔT : Difference between exterior and interior temperatures (K)

ά : Absorption coefficient of the wall surface

R_{wsr} : Wall surface resistance (m^2K/W)

Avg(I_t) : Average solar intensity falling on the wall surface (W/m^2)

The same equations are applicable for calculation of OTTV of the roof after excluding window glazing (Lam et al. 2005). The annual energy demand for the heating and cooling of the house (MJ) can be calculated as a total heat gain or loss through an envelope (Lam et al. 2005; Yang, Lam and Tsang 2008; Chow and Yu 2000) using Equation (3.6).

$$\boldsymbol{Total\ heat\ gain\ or\ loss} = \boldsymbol{3.6x}\frac{(\boldsymbol{OTTV_{wall}} + \boldsymbol{OTTV_{roof}})\boldsymbol{xA_{tgewa}xT}}{\boldsymbol{1000}} \quad \textbf{(3.6)}$$

Where,

$OTTV_{wall}$: OTTV of all external walls of the house (W/m^2)

$OTTV_{roof}$: OTTV of roof of the house (W/m^2)

At_{gewa} : Total gross external wall area of the house (m^2)

T : Duration of hot or cold season in a year (hours)

AccuRate software converts this annual energy requirement for heating and cooling to an area adjusted energy requirement on the basis of per m^2 of the floor area of the house by employing an area correction factor to eliminate the errors due to the variation in wall surface to floor areas of different house sizes (NatHERS 2012). The heat transfer through the building envelope is proportionate to total building surface area, and an area correction factor is applied to ensure that the smaller house with less building surface area but having high wall surface area to floor area ratio can be fairly compared with the large house (NatHERS 2012). In AccuRate software, the area correction factor is set to 0 for house area of $196m^2$. If the house area is bigger than $196m^2$, then the area correction factor is simply added to the annual energy requirement obtained by AccuRate simulation but if house area is smaller than $196m^2$, then the area correction factor is subtracted from the annual energy requirement obtained by AccuRate simulation (CSIRO 2012).

Lighting module

The lighting module of AccuRate software calculates the lumens which can be achieved through specified lamps in each house zone as per AS/NZS1680.1:2006 and then it compares these values with actual lumens needed to provide adequate light in each zone and top up the short fall to avoid any underlighting. AccuRate software estimates the annual energy requirement for lighting for the house by using a series of Equations from (3.7) to (3.10) (AccuRate 2015).

$$\boldsymbol{Lumen_{maint} = LExW_{lamp}xN_{lamp}xN_{luminaire}xUFxMF} \quad \textbf{(3.7)}$$

$$\boldsymbol{Lumen_{topup} = IL_{recom}xA - Lumen_{maint}} \quad \textbf{(3.8)}$$

$$\boldsymbol{W_{ezw} = (W_{lamp} + W_{cgear})xN_{luminaire}xN_{lamp}xDFxSF + \frac{Lumen_{topup}}{5.005}} \quad \textbf{(3.9)}$$

$$\boldsymbol{E_{lighting} = \sum_{i=1}^{i=n} W_{ezw(i)}\, x\, T_{avg(i)} x\, \frac{365}{1000}} \quad \textbf{(3.10)}$$

Where,

$Lumen_{maint}$: Maintained lumens provided by the lighting system in a zone (lumen)

LE : Maintained luminous efficacy (lumens/W) (e.g. for 25W, 60W, 100W incandescent lamps – 8.5, 13.3, and 14.9 respectively and for 5-8W, 15-24W CFL – 32, and 44 respectively)

W_{lamp} : Lamp (e.g. incandescent, compact fluorescent, LED) wattage (W)

$N_{luminaire}$: Number of luminaires in the zone

N_{lamp} : Number of lamps in each luminaire

UF : Utilization factor (the fraction of light provided by a lamp source that reaches the plane of measurement and ranges between 0.25 – 0.8)

MF : Maintenance factor which is 80% of the room surface maintenance factor (e.g. 0.95 for downlights, 0.85 for surface mounted or suspended fittings, and 0.77 for uplights)

$Lumen_{topup}$: The difference between the recommended maintained lumens required and maintained lumens provided (lumen)

IL_{recom} : Recommended maintained average illuminance (lux) (160lux for kitchen, 80 lux for rooms and bath, and 40 lux for entry and passage

A : Floor area of the Zone (m^2)

W_{ezw} : Effective zone wattage (W)

W_{cgear} : Control gear (e.g. ballast, transformer, PCB) wattage (W)

DF : Dimming factor (1 for no dimming and 0.95 for manual dimming)

SF : Switching factor (1 for manual, 0.55 for motion sensor based, and 0.85 for automatic timed switch)

$E_{lighting}$: Annual energy requirement for all the zones of the house (kWh/year) i : 1,2,…n; zones in the house (e.g. kitchen, bed room, garage, bath)

T_{avg} : Average daily operating hours (hours)

Based on the input data, AccuRate software provides the result of total annual lighting energy consumption in kWh along with average illumination power density of the house in W/m^2.

Hot water module

The hot water module of AccuRate software calculates the total annual energy demand for water heating in GJ using '*WHAT HO!*' Evaluation model which is developed by Burgess and Cogan (as cited by Ren et al. (2013) and AccuRate (2015)). To determine the energy demand for water heating, the model first estimates the hot water demand of the house including the standing and delivery losses from hot water and then calculates the energy demand based on the energy intensity of the type of fuel (e.g. gas, electricity, and solid fuel) used for water heating. The model allows the evaluation of energy saving potential, if the conventional water heating system is integrated with the solar water heater or if heat recovery system is used within the water network of the house. AccuRate software estimates the hot water demand for the house by using a series of Equations from (3.11) to (3.14), which have been developed following the equations provided by AccuRate (2015).

$$\boldsymbol{Occupants = max\left(1 + 0.66xN_{bed}\ \frac{A}{50}\right)} \quad \textbf{(3.11)}$$

$$\boldsymbol{HW_{shower} = \left(\frac{OccupantsxT_{shower}}{N_{shower}}\right)xFlow_{shower}} \quad \textbf{(3.12)}$$

$$\boldsymbol{HW_{bath} = \frac{135xOccupants}{N_{bath}}} \quad \textbf{(3.13)}$$

$$\boldsymbol{HW_{other} = \frac{(20 + 2.5xOccupants)}{N_{other}}} \quad \textbf{(3.14)}$$

Where,

Occupants : Number of house occupants (without rounding off, e.g. 3.32person)

HW_{shower} : Daily hot water demand for the shower in the house (litres/day)

N_{bed} : Number of bed rooms in the house

A : Floor area of the house (m^2)

T_{shower} : Daily duration of shower operation for each occupant (minutes/per person/day)

N_{shower} : No of shower units in the house

$Flow_{shower}$: Water flow rate of shower (litres/minute)

HW_{bath} : Daily hot water demand for the bath in the house (litres/day)

N_{bath} : No of bath units in the house

HW_{other} : Daily hot water demand for other amenities (e.g. kitchen, laundry) in the house (litres/day)

N_{other} : No of other amenities in the house

AccuRate software is able to estimate the heat losses from various activities or components of hot water system such as pipe work, and water storage vessels using Equations (3.15), and (3.16), which have been developed following the equations provided by AccuRate (2015). The control losses ($HL_{control}$) are assumed to be constant at 0.16GJ/year.

$$\boldsymbol{HL_{pipes} = \frac{K_{pipes} x C_{water} x T_{diff} x max\left(1, 3 + Occupants^{0.75} - N\right)}{N}} \qquad \textbf{(3.15)}$$

$$\boldsymbol{HL_{vessel} = 3.6x\frac{(T_{store} - T_{ambient})}{(T_{store} - T_{indoor})} x(axV_{vessel} + b)} \qquad \textbf{(3.16)}$$

Where,

HL_{pipes} : Heat loss from pipe work (MJ/day)

K_{pipes} : Coefficient of pipe heat loss (e.g. 2 for storage type heater and insulated pipe work. In case of uninsulated pipe work, the value is 4)

C_{water} : Specific heat of water (0.0042 MJ/litre/K)

T_{diff} : Difference between hot water temperature and ambient temperature of the house (ºC)

N : Number of hot water amenities (e.g. bath, shower, and kitchen)

HL_{vessel} : Heat loss from water storage vessel (MJ/day)

T_{store} : Temperature of water in storage vessel (ºC)

$T_{ambient}$: Ambient air temperature (ºC)

T_{indoor} : Indoor ambient temperature (ºC)

V_{vessel} : Storage capacity of vessel (litres)

a : Constant (a=0.0048, if V_{vessel} > 90litres, otherwise a=0.0084)

b : Constant (b=0.72, if V_{vessel} > 90litres, otherwise b=0.4)

In addition, AccuRate software is able to estimate the energy saving potential due to various energy saving measures such as integration of solar water heater with conventional water heater using Equation (3.17) (AccuRate 2015).

$$\boldsymbol{SWHE_{saving} = K_{inclin} x K_s x ASR x A_c} \quad \textbf{(3.17)}$$

Where,

$SWHE_{saving}$: Energy saving due to integration of solar water heater (MJ/day)

K_{inclin} : Collector non-ideal orientation factor (0.46 to 1 based on collector's orientation and inclination from the horizontal)

K_s : Solar factor of the water heater (0.45 to 0.57 based on collector type (e.g. plate, vacuum tube) and circulation type (e.g. thermosiphon, pump))

ASR : Solar radiation absorbed by the collector (5.9 to 28 based on hot water region and month of the year) (MJ/m^2/day)

A_c : Area of collector of solar water heater (m^2)

AccuRate software calculates the difference between the sum of all heat losses and sum of all energy savings opportunities as total energy savings (MJ/day) from water heater using Equation (3.18), which has been developed following the equation provided by AccuRate (2015).

$$\boldsymbol{E_{saving} = (SWHE_{saving} - HL_{pipes} - HL_{vessel} - HL_{control})} \quad \textbf{(3.18)}$$

Where,

E_{saving} : Total energy saving from water heater (MJ/day)

$SWHE_{saving}$: Energy saving due to integration of solar water heater (MJ/day)

HL_{pipes} : Heat loss from pipe work (MJ/day)

HL_{vessel} : Heat loss from water storage vessel (MJ/day)

$HL_{control}$: Heat loss through control (MJ/day)

Once the daily hot water demand, heat losses through various activities and components of hot water system, and energy saving opportunities have been calculated, the AccuRate software calculates the energy demand for water heating on daily, and annual basis, the energy demand to compensate the heat loss from hot water storage vessel, and the net total energy demand for hot water system using a series of Equations from (3.19) to (3.22), which have been developed following the equations provided by AccuRate (2015).

$$\boldsymbol{E_{con-daily} = C_{water} x\big((HW_{shower} + HW_{bath}) x (T_{bath} - T_{coldwater}) + HW_{other} x (T_{hot} - T_{coldwater})\big)} \quad \textbf{(3.19)}$$

$$\boldsymbol{E_{con-annual} = \sum_{i=1}^{i=12} \frac{(E_{con-daily(i)} - E_{saving(i)}) x DIM_i}{1000 x COP_c}} \quad \textbf{(3.20)}$$

$$\boldsymbol{E_{maint-annual} = \sum_{i=1}^{i=12} \frac{(MR_i x DIM_i}{1000}} \quad \textbf{(3.21)}$$

$$E = E_{con-annual} + E_{maint-annual} \quad \textbf{(3.22)}$$

Where,

$E_{con\text{-}daily}$	: Daily energy demand for conversion of cold water to hot water (MJ/day)
C_{water}	: Specific heat of water (0.0042 MJ/litre/K)
HW_{shower}	: Daily hot water demand for the shower in the house (litres/day)
HW_{bath}	: Daily hot water demand for the bath in the house (litres/day)
T_{bath}	: Temperature of water used for bathing (ºC)
$T_{coldwater}$	: Cold water temperature (8 to 29 based on solar hot water region and month of the year) (ºC)
HW_{other}	: Daily hot water demand for other amenities (e.g. kitchen, laundry) in the house (litres/day)
T_{hot}	: Temperature of hot water (ºC)
$E_{con\text{-}annual}$	: Annual energy demand for conversion of cold water to hot water (GJ/year)
E_{saving}	: Total energy saving from water heater (MJ/day)
DIM	: Days in a particular month
COP_c	: Conversion efficiency of water heater (0.5 to 0.75 based on type of water heater)
$E_{maint\text{-}annual}$	: Annual energy demand to compensate the heat loss from water heater storage vessel (GJ/year)
MR	: Maintenance rate (provided by the manufacturer of the water heater) (MJ/day)
E	: Total annual energy demand for water heating of the house (GJ/year)

Water module

The water module of AccuRate software calculates the average water usage in litres/day for a house using the relevant information (e.g. capacity, flow rate, and quantity) of the indoor and outdoor water entities (e.g. kitchen sink, dishwasher, cloth washer, laundry tub, bath, toilet, shower, spa, swimming pool, and garden tap) including water consumption practices by individual occupants. The module has an option for inclusion of variable sources of water (e.g. potable water, rainwater tank, on-site treatment, greywater, and bore water).

Operational energy for a typical house for home appliances

The operational energy consumption for home appliances such as television, refrigerator, washing machine, cloth dryer, dish washer, cook top, oven, microwave, computer, toaster, kettle, mixer/grinder, coffee maker, iron, vacuum cleaner, range hood, and set top box is influenced by the occupant's unique personal behaviour and environmental awareness, socio-economic status, lifestyle, and energy efficiency of appliances (Ren et al. 2013). The operational energy consumption for home appliances for every individual house may vary, however the published data on energy ratings of Australian home appliances and patterns of usage (DEWHA 2008b; Riedy, Milne and Foster 2013; AER 2014; EcoHub-Perth 2014; ABS 2006; DEWHA 2008a) have been utilized to estimate the operational energy consumption of a typical household in Western Australia. The home appliances operate in active, standby, and off modes with different energy consumptions for each mode. The total annual energy consumption for home appliances of a typical house has been estimated using Equation (3.23) (Ren, Paevere and McNamara 2012):

$$\boldsymbol{E_{happliance}} = \sum_{i=1}^{i=n} \frac{(\boldsymbol{W_{a(i)} x T_{a(i)} + W_{sby(i)} x T_{sby(i)} + W_{off(i)} x T_{off(i)}})}{\mathbf{1000}} \qquad \textbf{(3.23)}$$

$E_{happliance}$: Total annual energy consumption for home appliances (kWh/year)

i : 1,2,…..n; type of home appliances (e.g. TV, refrigerator, oven, computer)

W_a : Power rating of home appliance in active mode (W)

T_a : Duration of active mode of the home appliance (hours/year)

W_{sby} : Power consumption of home appliance in standby mode (W)

T_{sby} : Duration of standby mode of the home appliance (hours/year)

W_{off} : Power consumption of home appliance in off mode (W)

T_a : Duration of off mode of the home appliance (hours/year)

Due to behavioural changes of occupants, technological advancements and implementation of mandatory energy rating of home appliances under cross jurisdictional equipment energy efficiency (E3) program of Australian Government, states and territories and the New Zealand (ABS 2014), the majority of the operational energy for home appliances in Australia is consumed in active mode. Around 8% of the total energy is consumed in standby mode for battery chargers, security alarm, networking devices, media players, and microwaves (DIS 2015).

3.3.2.1.5 End of life demolition and disposal stage

In the case of the end of life stage, the data on the type of tools and equipment used for demolition of a typical house in Australia including their duration of usage was obtained from a local builder Budget Developments Australia Pty Ltd. The end of life stage consists of two major activities such as the use of tools and equipment used for demolition and use of transport for disposal of the demolition waste to landfill area. The energy consumption during demolition has been calculated using Equation (3.3) and transportation required for disposal of the demolition waste from site to landfill area has been calculated using Equation (3.2).

3.3.3 Impact assessment

Once the LCI of material and energy has been developed following aforementioned equations and using relevant data from the data bank, these LCI inputs have been entered into SimaPro 8.05.13 LCA software and each material and energy inputs are linked to relevant emission databases in the SimaPro software (PRé-Consultants 2015). The databases in this software contain the emission factors of different energy, materials and transportation inputs for estimation of environmental impacts. Locally available databases have been utilized to represent the WA's situation and as a result, the AusLCI emission factor databases have been used to calculate the emissions. The Australian indicator set with embodied energy version 2.01 method, which is embedded in SimaPro 8.05.13 software, has been used to convert emission outputs to assign impact categories using characterisation factors of GHGs. The 100 year time horizon, which has also been used for National Inventory Reporting is most commonly used time horizon for life cycle assessments of buildings (Renouf 2015; Carre and Crossin 2015; Zabalza Bribián, Valero Capilla and Aranda Usón 2011; DOE 2014b).

The greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydro fluorocarbons (HFCs), and chlorofluorocarbons (CFCs) are converted to CO_2 equivalent and SimaPro 8.05.13 uses the most recent global warming potential (GWP) factors for a 100 year time horizon as reported in the Intergovernmental Panel on Climate Change's (IPCC) fifth Assessment Synthesis Report (Hauschild et al. 2013; IPCC 2014; Renouf 2015). The Equation (3.24) shows the conversion of masses of different greenhouse gases associated with the material and energy inputs into global warming potential (GWP), which is a single carbon dioxide-equivalent metric (CO_2 e-).

$$\boldsymbol{GWP(CO_2e-)} = \sum_{i=1}^{i=n}\sum_{j=1}^{j=m} \boldsymbol{GHG}_{\mathrm{i(j)}} \mathbf{x}\, \boldsymbol{CF}_{\mathrm{i(j)}} \qquad \textbf{(3.24)}$$

i : 1,2,…..n; inputs (e.g. bricks, concrete, glass, electricity, natural gas)

j : 1,2,…..m; characterization factors of GHGs (e.g. 1 for CO_2, 28 for CH_4, 265 for N_2O)

The SimaPro software has estimated the GWP in terms of GHG emissions and embodied energy (EE) consumption associated with the life cycle stages of the house as discussed in following sections.

3.3.3.1 GHG emissions

The GHG emissions during life cycle stages of the house have been estimated as following:

Mining to material production stage

AusLCI database is utilized to estimate the GHG emissions from mining to material production stage associated with quarrying, refining, processing, and production of construction materials (e.g. aluminium, structural and sheet steel, concrete, cement, lime, sand, polystyrene, polyethylene, roof timber, concrete roof tiles, ceramic tiles, insulation, gypsum board, and glass) required for the construction of a typical house. In the absence of local data in the AusLCI database, the new databases have been created (e.g. mesh reinforcement, clay bricks) by obtaining the information on raw material and energy consumptions from local industry reports (OneSteel 2014; Strezov and Herbertson 2006; Rouwette 2010). The GHG emissions during mining to material production stage have been estimated using Equation (3.25).

$$\boldsymbol{GHG_{material} = \sum_{i=1}^{i=n} BM_i x EF_i} \quad \textbf{(3.25)}$$

Where,

$GHG_{material}$: GHG emissions (tonnes of CO_2 e-) during mining to material production stage of building materials per house

BM : Building material (tonnes)

EF : Emission factor for material (tonnes of CO_2 e-/tonnes)

i : 1,2,…..n; materials (e.g. cement, brick, concrete, glass)

Transportation stage

The estimated transportation data for different modes of transports for building material from their production source to constriction site in terms of tkm have been linked to AusLCI database for different modes of transport and GHG emissions during transport have been estimated using Equation (3.26).

$$\boldsymbol{GHG_{transport} = \sum_{i=1}^{i=n} tkm_i x EF_i} \quad \textbf{(3.26)}$$

Where,

$GHG_{transport}$: GHG emissions (tonnes of CO_2 e-) during transportation stage per house

tkm : tonnes-km travelled by each mode of transport (tkm)

EF : Emission factor for transport (tonnes of CO_2 e-/tkm)

i : 1,2,…..n; mode of transport (e.g. road/sea/air, truck capacity/type)

Construction stage

The amount of construction energy required by different hand tools and construction equipment and machinery, including excavator, front end loader, fork lift, and compactor used during construction stage and transportation data for disposal of excavated soil and construction waste have been linked to AusLCI database for electricity production, diesel combustion, and transport to estimate GHG emissions during construction stage have been estimated using Equation (3.27).

$$\boldsymbol{GHG_{construction}} = \left(\sum_{i=1}^{i=n} \boldsymbol{Energy_i x EF_{energy(i)}}\right) + \boldsymbol{tkm x EF_{trans}} \qquad \textbf{(3.27)}$$

Where,

$GHG_{construction}$: GHG emissions (tonnes CO_2 e-) during construction stage per house

Energy : Energy consumption by tools and plants (e.g. excavator, mortar mixer) (MJ)

EF_{energy} : Emission factor for energy (tonnes of CO_2 e-/MJ)

i : 1,2,…..n; energy types (e.g. electricity, gas, diesel)

tkm : tonnes-km travelled for disposal of excavated soil and construction waste (tkm)

EF_{trans} : Emission factor for transport (tonnes of CO_2 e-/tkm)

Use stage

The annual operational energy per house for heating, cooling, lighting, hot water, and home appliances has been linked to the AusLCI database for electricity production and gas distribution. The GHG emissions during use stage have been estimated using Equation (3.28).

$$\boldsymbol{GHG_{use} = \sum_{i=1}^{i=n} Energy_i x EF_{energy(i)}\, x L} \quad \textbf{(3.28)}$$

Where,

GHG_{use} : GHG emissions (tonnes of CO_2 e-) during use stage of the whole life of the house

Energy : Annual energy demand (e.g. heating, cooling, lighting, hot water) (GJ)

EF_{energy} : Emission factor for energy (tonnes of CO_2 e-/GJ)

i : 1,2,……n; type of energy (e.g. electricity, gas, bottled gas, diesel)

L : Lifespan of the house (year)

End of life demolition and disposal stage

The energy consumption for a house for different tools and machinery, including breaker, excavator, and front end loader for demolition activities and transportation data (in terms of tkm) for different modes of transports for disposal of demolition waste material from site to landfill area have been linked with AusLCI database for electricity production, diesel combustion, and different modes of transport and GHG emissions have been estimated using Equation (3.29).

$$\boldsymbol{GHG_{endoflife} = \sum_{i=1}^{i=n} Energy_i x EF_{energy(i)} + \sum_{j=1}^{j=m} tkm_j x EF_{trans(j)}} \quad \textbf{(3.29)}$$

Where,

$GHG_{endoflife}$: GHG emissions (tonnes CO_2e-) during end of life stage of the house

Energy : Energy consumption by plants and tools (e.g. excavator, loader) (MJ)

EF_{energy} : Emission factor for energy (tonnes CO_2 e-/MJ)

i : 1,2,…..n; type of energy (e.g. electricity, gas, diesel)

tkm : tonnes-km travelled for disposal of excavated soil and construction waste (tkm)

EF_{trans} : Emission factor for transport (tonnes CO_2 e-/tkm)

j : 1,2,…m; mode of transport (e.g. truck capacity/type)

Total life cycle GHG emissions

The GHG emissions for all stages are added to determine the life cycle GHG emissions using Equations (3.30).

$$\boldsymbol{GHG_{house} = GHG_{material} + GHG_{transport} + GHG_{construction} + GHG_{use} + GHG_{endoflife}} \quad \textbf{(3.30)}$$

3.3.3.2 EE consumption

The embodied energy is a predecessor to most of the environmental impacts and hence used as a screening indicator for environmental impacts (Frischknecht et al. 2007; Carre 2011a; Dixit et al. 2012). The AusLCI database supports process based energy data for mining to material production stage of building materials (Crawford 2014). The SimaPro 8.05.13 software which applies the Australian indicator set with embodied energy version 2.01 method provides total energy flows based on lower heating values (Burchart-Korol 2013; Farmery et al. 2015) after converting all the direct and indirect energy used for mining to material production, transportation, construction, use and demolition stage into cumulative energy demand (CED) or total embodied energy (EE) (Zabalza Bribián, Valero Capilla and Aranda Usón 2011). The EE of a house comprises of the initial embodied energy contained in building materials during mining to material production, transportation, construction, operational energy for maintaining the comfort level to occupants (heating, cooling, lighting, hot water, and home appliances), and the end of life demolition and disposal stages (Cabeza et al. 2014; Ramesh, Prakash and Shukla 2010; Fay, Treloar and Iyer-Raniga 2000) and has been estimated using a series of Equations from (3.31) to (3.35).

$$\boldsymbol{EE_{material}} = \sum_{i=1}^{i=n} \boldsymbol{BM_i\, xEEBM_i} \qquad \textbf{(3.31)}$$

Where,

$EE_{material}$	: Initial embodied energy contained in building materials (MJ)
BM	: Mass of the building material (tonnes)
EEBM	: Embodied energy content of building material (MJ/tonnes)
i	: 1,2,….n; type of building material (e.g. concrete, brick, steel, glass)

$$\boldsymbol{EE_{transport}} = \sum_{j=1}^{j=m} \sum_{i=1}^{i=n} \boldsymbol{BM_{i(j)}\, xD_{i(j)} xEEMOTR_{i(j)}} \qquad \textbf{(3.32)}$$

Where,

$EE_{transport}$	: Embodied energy consumed for transportation of building materials to construction site (MJ)
BM	: Mass of the building material (tonnes)
D	: Transport distance between source and the construction site (km)
EEMOTR	: Embodied energy consumed by mode of transport (e.g. truck, ship) (MJ/tkm)
j	: 1,2,…m; mode of transport (e.g. truck, tanker, ship)
i	: 1,2,….n; type of building material (e.g. concrete, brick, steel, glass)

$$\boldsymbol{EE_{const}} = \sum_{j=1}^{j=m} \sum_{i=1}^{i=n} \boldsymbol{ED_{i(j)}\, xEN_{ed(i(j))} xEE_{en(i(j))}} + \boldsymbol{EECW_{transport}} \qquad \textbf{(3.33)}$$

Where,

EE_{const}	: Embodied energy consumed for construction activities and transportation of excavated soil and construction waste to landfill (MJ)

ED : Equipment days (e.g. number of days equipment required at site) (days)

EN_{ed} : Fuel consumption of equipment per day (Unit/day)

EE_{en} : Embodied energy of fuel (e.g. electricity, diesel, gas) (MJ/Unit)

j : 1,2,…m; type of fuel (e.g. electricity, diesel, gas)

i : 1,2,….n; type of equipment and tools (e.g. excavator, forklift, mortar mixer, drill machine, grinder)

$EECW_{transport}$: Embodied energy for transportation of construction waste to landfill (MJ) is expressed in Equation (3.32)

$$\boldsymbol{EE_{use}} = \sum_{j=1}^{j=m}\sum_{i=1}^{i=n} \boldsymbol{EN_{activity(i(j))} x Life x EE_{en(i(j))}} \qquad \textbf{(3.34)}$$

Where,

EE_{use} : Embodied energy consumed during use stage during lifespan of the house (MJ)

$EN_{activity}$: Annual energy demand for activity (e.g. heating, cooling, lighting, hot water, home appliances) (MJ/year)

Life : Lifespan of the house (year)

EE_{en} : Embodied energy of fuel (e.g. electricity, diesel, gas) (MJ/Unit)

j : 1,2,…m; source of energy (e.g. electricity, diesel, gas)

i : 1,2,….n; activities (e.g. electricity for cooling, lighting, home appliances and gas for heating, hot water) Type of equipment and tools (e.g. excavator, forklift, mortar mixer, drill machine, grinder)

$$\boldsymbol{EE_{eolife}} = \sum_{j=1}^{j=m}\sum_{i=1}^{i=n} \boldsymbol{ED_{i(j)}\, x EN_{ed(i(j))} x EE_{en(i(j))} + EEDW_{transport}} \qquad \textbf{(3.35)}$$

Where,

EE_{eolife} : Embodied energy consumed for end of life demolition and disposal of demolition waste to landfill (MJ)

ED : Equipment days (e.g. number of days equipment required at site) (days)

EN_{ed} : Fuel consumption of equipment per day (Unit/day)

EE_{en} : Embodied energy of fuel (e.g. electricity, diesel, gas) (MJ/Unit)

j : 1,2,…..m; type of fuel (e.g. electricity, diesel, gas)

i : 1,2,….n; type of equipment and tools (e.g. excavator, loader)

$EEDW_{transport}$: Embodied energy consumed for transportation of demolition waste to landfill (MJ) is expressed in Equation (3.32)

Total life cycle EE consumption

The embodied energy consumption for all stages is added to determine the life cycle EE consumption using Equation (3.36).

$$EE_{house} = EE_{material} + EE_{transport} + EE_{const} + EE_{use} + EE_{eolife} \quad \textbf{(3.36)}$$

3.3.3.3 Uncertainty Analysis

Finnveden et al. (2009) described uncertainty as the discrepancy between a calculated quantity and its true value. In life cycle assessment, there can be random or biased reasons for uncertainty such as erroneous and inadequate data, improper system boundary, differing time horizons, inconsistency in goal and scope, and incorrect relationships between different processes.

The uncertainty analysis improves the reliability of the LCA outcome for decision makers. Monte Carlo Simulation (MCS) is a widely used tool for estimation of the uncertainty in each input variable and predict the impact of that variable on the output (Lo, Ma and Lo 2005; Hung and Ma 2009; McCleese and LaPuma 2002; Ciroth, Fleischer and Steinbach 2004). 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. (Maurice et al. 2000; Guo and Murphy 2012; Huijbregts et al. 2003; PRé-Consultants 2015).

The AusLCI database is an exclusive database for Australian energy and material production, and therefore its use for estimation of impacts can significantly reduce the uncertainty associated with the data gaps and errors (Iyer-Raniga and Wong 2012). The ecoinvent database includes uncertainty data for most of the flow data and allows four different statistical distributions such as uniform, triangular, normal, and lognormal to be included with data points. The uncertainty factors in ecoinvent database have been provided based on expert judgement. The Centre for Design at RMIT University has introduced uncertainty information into AusLCI database using the approach similar to the one adopted by ecoinvent and carries out the updates on an annual basis.

The MCS, which is essentially a numerical method to process uncertainty data and establish an uncertainty range in the calculated results (PRé-Consultants 2015) has been applied. The statistical variation, errors, and technological or geographical gaps in life cycle inventory data are the main reasons of uncertainties in the life cycle impact assessment results as shown in Equation (3.37), and also the uncertainties propagate through various stages of the process. Guo and Murphy (2012) suggested that the statistical or expert judgement based approaches are most common methods of quantification of uncertainty and variability of life cycle inventory data and in the case of industrial or literature data which is represented by single values, the expert judgement based approach is an effective method. Ciroth, Fleischer, and Steinbach (2004) suggested that it is not possible to exclude uncertainty in any measured values including material and energy data inputs in life cycle assessment for identification of uncertainties. The average or mean error that is likely to occur is more important than single random error. The standard mean error of a variable is calculated as the standard deviation of the random error and unknown true value and is expressed as mean (Equations (3.38) and (3.39)).

$$\Delta X = X_{measured} - X_{true} \text{ or } X_{measured} = X_{true} + \Delta X \quad \textbf{(3.37)}$$

Where,

ΔX : Error in variable X

$X_{measured}$: Measured /simulated value of variable X

X_{true} : True value of variable X

$$S = \sqrt{\frac{1}{m-1}\sum_{i=1}^{i=m}(X_{measured(i)} - X_{true})^2} \quad (3.38)$$

$$X_{true} \cong \bar{X} = \frac{1}{m}\sum_{i-1}^{i=m} X_{meaured(i)} \quad (3.39)$$

Where,

S : Standard deviation of the random errors ΔX

$X_{measured}$: Measured / simulated value of variable X

X_{true} : True value of variable X

i : 1,2,….n; number of calculations performed

$\bar{X}$: Mean

The Monte Carlo function, which is embedded within SimaPro 8.05.13 software randomly varies the material and energy inputs values based on defined probability distribution, and recalculate the results. The calculation is repeated after taking different values within uncertainty range, and results are stored. The calculations are repeated often enough in order to achieve the results that satisfactorily represent the defined probability distribution or till the criteria to stop the calculations are met. MCS for this study has been run for 1000 iterations at the 95% confidence level to determine the uncertainty ranges (Guo and Murphy 2012; PRé-Consultants 2015; Minne and Crittenden 2014) in the life cycle impact assessment results.

3.3.4 Life Cycle Interpretation

Life cycle interpretation is the last stage of the LCA of a product or service, which helps to analyse and interpret the outcomes of LCA so as to draw a conclusion in accordance with the goal and scope of the study (ISO14040 2006; Cabeza et al. 2013) and to identify the aspects of environmental significance. The interpretation involves not only the problematic areas requiring environmental improvements but involves cause diagnosis, thus refereeing back to LCI (Bienge et al. 2010). SimaPro 8.05.13 software helps in developing the process networks (as shown in sample Figure 3.7) for determining the breakdown of GHG emissions in terms of inputs to help identify the 'hotspot(s)', which are the inputs or processes causing the most impacts.

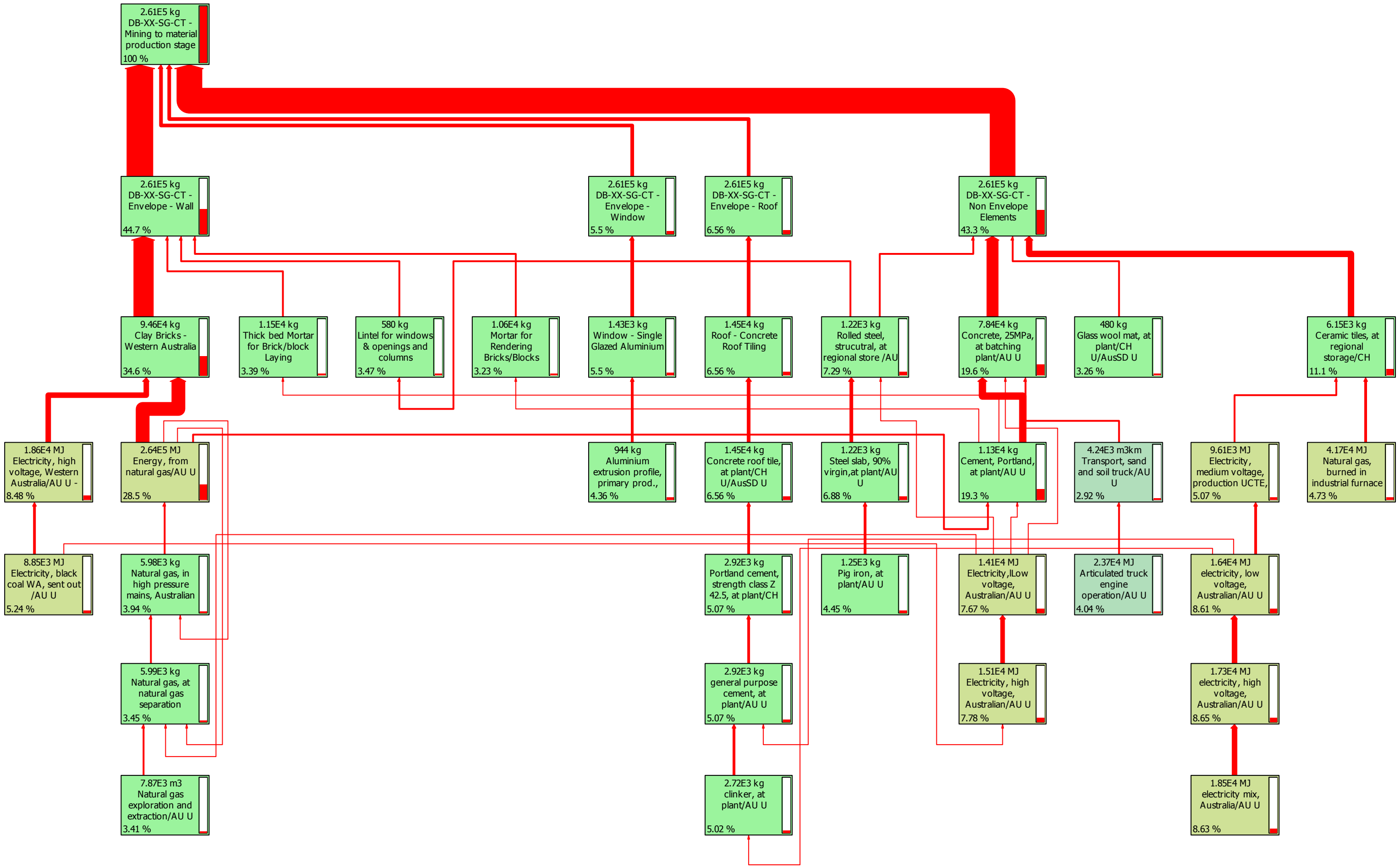


Figure 3.7 Sample process network - GWP

The high priority areas termed as “hotspot(s)” (as shown in sample Figure 3.8) across all the stages of a product or service life cycle identified for improvements have been analysed and compared with other published literature to identify the material and energy inputs and process during various stages of product life cycle responsible for these ‘hotspots’. These values have been considered as reference values for comparative analysis to achieve the research objectives in Chapter 4.

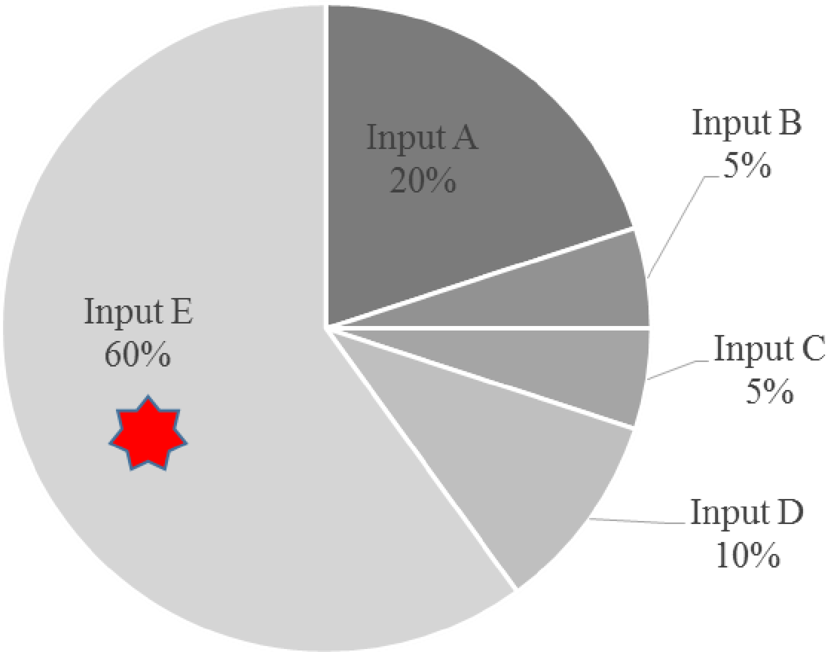


Figure 3.8 Sample pie chart showing "hotspot"

Cause diagnosis

Further investigation has been carried out to identify the main causes of GHG emissions and EE consumption impacts by breaking them down in terms of sub-stages and material and energy inputs so as to develop suitable cleaner production strategies for mitigation of these impacts without compromising the life cycle performance of a house.

3.4 Implementation of Life Cycle Management Framework: Part 2 – Cleaner Production Strategies

In order to treat the environmental hotspots identified during the life cycle impact assessment, cleaner production strategies have been included in the current LCM frame work as suggested by Khan (2008) and Jørgensen (2008) (Figure 3.9). 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). There are many environmental and economic benefits associated with the implementation of cleaner production strategies such as improved operational efficiency, increased profitability, reduced consumption of raw material, energy, and water, increased recovery and recycling of waste, and reduced emissions (Yusup et al. 2014; Lopes Silva et al. 2013; Giannetti et al. 2008; Khan 2008).

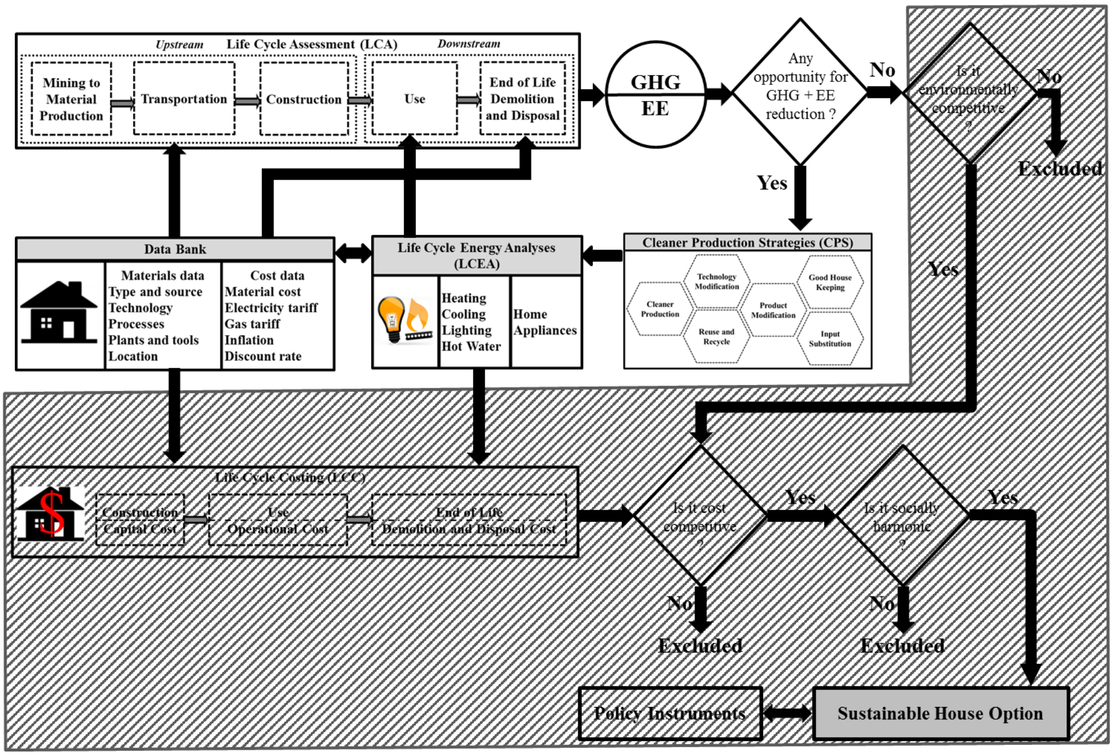


Figure 3.9 LCM framework: Part 2 - Cleaner Production Strategies

Since the case study of this current LCA work is a typical clay brick house, the CPS have been selected accordingly to treat the hotspots. Table 3.1 presents relevant alternatives materials, technologies, and methods of construction for developing CPS specifically for building sector. Once the LCA has been conducted in Chapter 4, relevant CPS will be applied and their environmental implications will be assessed to identify their suitability for achieving sustainable houses.

Table 3.1 Proposed cleaner production strategies to treat hotspots

Input Substitution	Product Modification	Technology Modification	Re-use and Recycling	Good Housekeeping
• Replacing the cement in concrete mix with supplementary cementitious materials (e.g. by-products such as fly ash and or blast furnace slag) • Replacing the metal columns and lintels with light weight pultruded fibre glass sections	• Replacing single glazed windows to double glazed windows • Replacing concrete roof tiles to terracotta tiles or metal roof sheeting • Replacing the material of wall construction from double clay brick to brick veneer, reverse brick veneer, cast in-situ concrete sandwich with polystyrene insulation core, concrete block, light weight aerated concrete block, pre-cast light weight concrete sandwich panel, or timber frame	• Providing grid connected roof top solar PV • Integrating the gas based water heater with roof top solar water heater • Use of building management system	• Replacing the natural aggregate in concrete mix with recycled aggregate and natural sand with manufactured sand (e.g. processed construction and demolition waste) • Replacing polystyrene insulation core with polyethylene terephthalate (PET) foam manufactured from post consumed PET bottles	• Changing the house orientation to gain from natural ventilation • Providing wall insulation to conventional double clay brick wall • Minimizing the duration of construction to reduce logistics • Minimizing the waste generation • Minimizing the use of water at site

Similar to the reference clay brick house, the double clay brick walls with insulation are termed as DB-INS, brick veneer walls as BV-XX, reverse brick veneer walls as RBV-XX, cast in-situ concrete sandwich walls with polystyrene core as CSW-POL, concrete block walls as CB-XX, autoclaved aerated concrete block walls as ACC-XX, pre-cast light weight concrete sandwich panel walls as PCSW-XX, timber frame walls as TMB-XX, and cast in-situ green concrete sandwich walls with PET foam core as GCSW-PET. While the double glazed windows have been termed as DG, the terracotta roof tiles and metal roof sheets are termed as TT and MS respectively.

A number of envelope combinations have been developed using above wall, window, and roof options while maintaining the same architectural features for all alternative envelope options (Figure 3.10). The details of wall, window and roof elements of these envelopes are presented in Table C.2 (Appendix C).

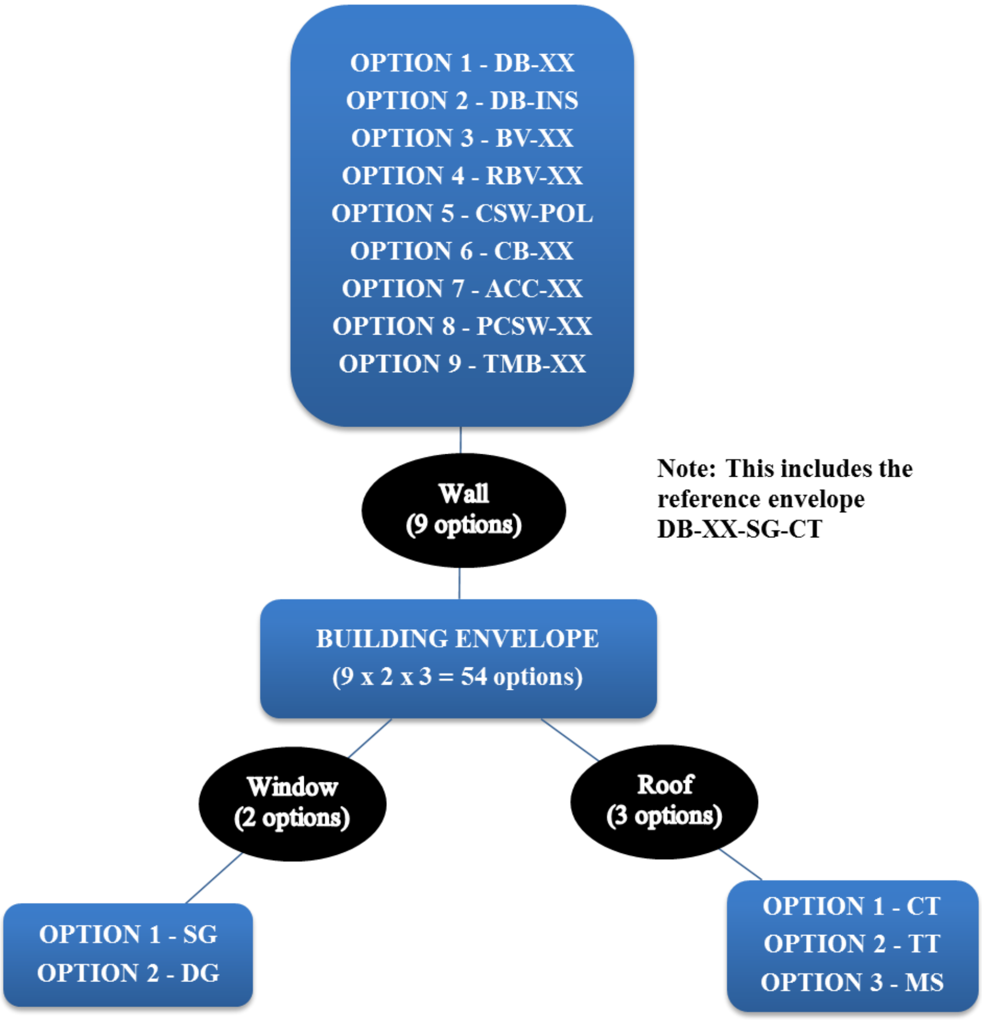


Figure 3.10 Envelope options using different wall, window and roof elements

Non envelope elements such as foundation, roof timber frame, timber doors, metal frames, gyprock ceiling with insulation and cornices, ceramic tiles for wet areas, and porcelain tiles have been considered same for all envelope options.

The introduction of CPS changes the material and energy inputs during different life cycle stages of a house. Accordingly, the material and energy inputs have been revised for different CPS options and revised LCIs have been used to estimate the revised greenhouse gas (GHG) emissions and Embodied Energy (EE) consumption of a typical house using AccuRate and SimaPro software. The detailed material and energy inventories have been prepared for each envelope option including the estimation of operational energy demand for heating, cooling, lighting, hot water, and home appliances for a typical house (Figure 3.10).

The GHG emissions and EE consumption results of a typical house for each alternative envelope option have been compared with those for a reference house to identify the environmental viability of the options and to determine the effectiveness of cleaner production strategies. Based on the outcome of the comparative analysis, the environmentally viable options have been shortlisted for life cycle costing as analysed in Chapter 4.

The impact of climate change (CC) on cooling energy consumption over the life cycle of a house for these alternative envelopes has also been considered to evaluate the additional cooling energy demand.

3.5 Implementation of Life Cycle Management Framework: Part 3 – Life Cycle Costing

The economic factors are important for decision making strategy (Gluch and Baumann 2004; Kulczycka and Smol 2015; Swarr et al. 2011) and the life cycle costing (LCC) tool is an effective technique for forecasting and evaluating the cost performance of building (ISO15686-5 2008(en)). The life cycle costing is the second most important tool of the LCM framework (Rebitzer and Hunkeler 2003) used for evaluation of the economic effectiveness of the environmentally viable alternative building envelope options (Figure 3.11).

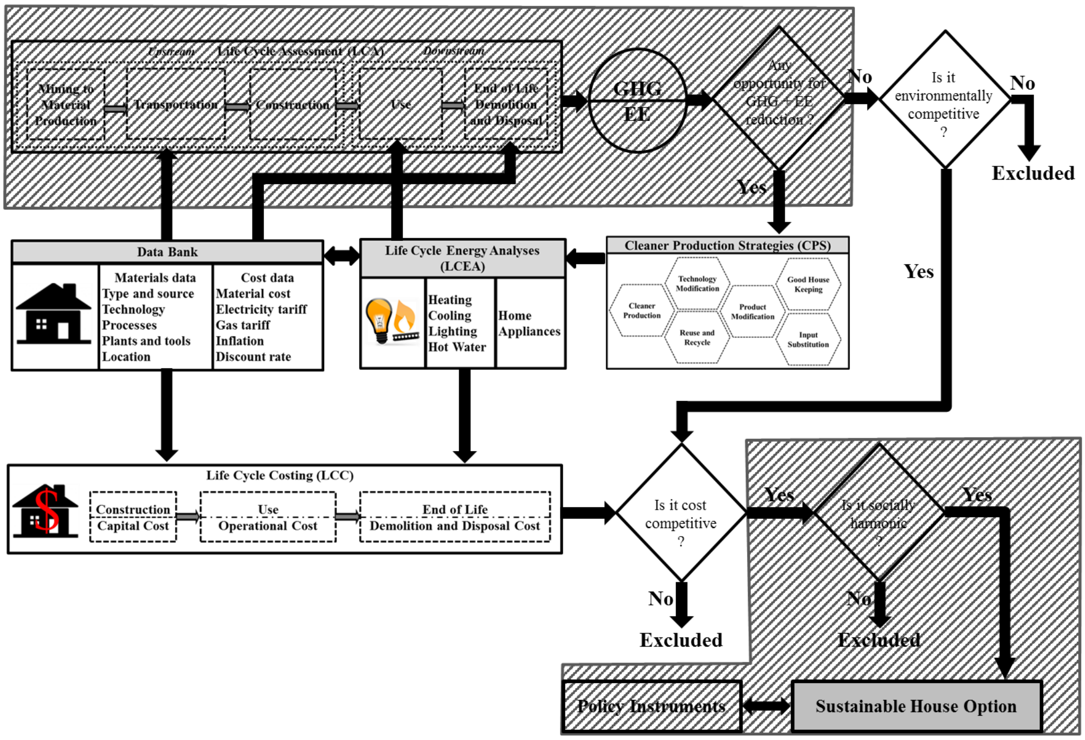


Figure 3.11 LCM framework: Part 3 - Life Cycle Costing

Pelzeter (2007) described life cycle costing as a form of synopsis of the capital and consequential costs of building related decisions and useful tool for achieving economic sustainability. The life cycle cost approach helps in economic comparison of capital cost with life cycle operating cost for competing building design options and find an optimization point (Gurung and Mahendran 2002; Real and Pinheiro 2010). This phenomenon has been tested while assessing the cost competitiveness of mitigation options in Chapter 5. For example, the increase in investment on efficient options could reduce the operational cost and so LCC.

A detailed LCC analysis has been carried out following AS/NZS 4536:1999 (Standard 2014), AS1181-1982 (Standard 1982), and using a widely accepted construction cost guide (Rawlinsons 2015), which has most up to date cost data of various materials and methods of construction in Australia.

Along with the physical data for conducting an LCA of houses, the Data Bank provides the $ value of corresponding input values of constructing a house for use over a period of 50 years. The detailed life cycle cost inventory has been developed to estimate the capital cost for construction of a house for all environmentally viable envelope options using “estimation by engineering procedures” method. Originally, the costs have been determined in Australian Dollar and then converted to US$ (1AUD = 0.7229US$).

The capital cost includes material, labour, and other costs until the construction of a house and the operational costs over 50 years of service life include the costs of annual energy consumption for heating, cooling, hot water, home appliances, and lighting as per current utility prices. The cost associated with the end of life demolition and disposal has been considered. In this LCC, all inputs that are used for LCA analysis have been used to maintain the consistency in the analysis.

All future costs have been determined by escalating the current price by 3% per year (RBA 2015) and then the escalated price has been discounted at a rate of 7% per year (DRDL 2012). The discounting converts the dollar value of costs and benefits of different time periods to present value after considering 2015 as a base year. The replacement costs for the components with a lifespan lower than building’s life have been considered. For example, the lifespans of roof top solar PV (25 years) and SWH (13 years) are found to be lower than the lifespan of a house (50 years), hence replacement costs have been included after converting them to escalated price and discounting to present value.

The Net Present Value (NPV) is the most common method of estimation of the life cycle cost of a building in practice for the construction sector (Islam, Jollands and Setunge 2015; Morrissey and Horne 2011a; Kneifel 2010; Schade 2007; Kshirsagar, El-Gafy and Abdelhamid 2010).

The time value of money is expressed as a discount rate which depends on capital cost, inflation, and social behaviour (Harrison 2010; Gluch and Baumann 2004; Korpi and Ala-Risku 2008). After considering the inflation rate and discount factor, the present value of any future cost of product or service can be expressed using Equation (3.40).

$$\boldsymbol{Present\ Value} = \sum_{i=1}^{i=n} \frac{\boldsymbol{PCx(1+IR)^i}}{\boldsymbol{(1+DR)^i}} \qquad \textbf{(3.40)}$$

Where,

i : 1,2,…..n; year value till the end of life of the product or service, which is 50 years in this study

PC : Present cost (US$)

IR : Inflation rate (%)

DR : Discount rate (%)

The life cycle cost of a house is expressed as the summation of all costs occurred during the life cycle of a house as shown in Equation (3.41).

$$\boldsymbol{LCC_{house} = PV_{material} + PV_{transport} + PV_{construction} + PV_{operation} xY + PV_{maint/rep} + PV_{endoflife}} \quad \textbf{(3.41)}$$

Where,

LCC_{house} : Life cycle cost for construction and use of a house (US$)

$PV_{material}$: Present value of materials for construction of a house (US$)

$PV_{transport}$: Present value of transport for all materials to construction site (US$)

$PV_{construction}$: Cost of construction (labour and supervision) (US$)

$PV_{operation}$: Present value of annual cost of energy consumed for heating, cooling, lighting, hot water, and home appliances (US$)

Y : Service lifespan of the house (year)

$PV_{maint/rep}$: Present value of maintenance/replacement during service life (US$)

$PV_{endoflife}$: Present value of end of life demolition and disposal (US$)

As mentioned above, the same material and energy inputs have been considered for both LCA and LCC analyses in order to maintain the consistency of the assessment. As a result, the cost of painting, electrical works, drainage and plumbing works including accessories, cabinets, soft furniture, garage door, home appliances, and external site development are excluded as they were not considered for impact assessment.

The results of life cycle costing of a house for all environmentally viable envelope options have been compared with the results of a reference house to assess the cost competitiveness of the options and to determine the cost effective cleaner production options. Based on the outcome of the comparative analysis, environmentally and economically viable options have finally been selected for analysing the social impacts as discussed below.

3.6 Implementation of Life Cycle Management Framework: Part 4 – Social impacts of the environmental and economic outcome

UNEP (2009) describes the social impacts as a complex function of politics, economy, ethics, psychology, law, culture, and personal behaviour. The house must provide not only a safe, healthy and comfortable indoor environment for its occupants while meeting their psychological, behavioural, and aesthetic requirements, it should be able to enhance the intergenerational and intra-generational equity due to long service life (Leung et al. 2005; Horner, Hardcastle and Price 2007; Kverndokk, Nævdal and Nøstbakken 2014). Therefore the care has been taken to select an economic and environmentally feasible option, offering similar or better performance in terms of durability, comfort, safety, and functionality as the replacement of conventional brick wall house. It does also mean that the economic and environmental objectives are affected while compromising with the comfort, and associated cultural issues of social wellbeing.

The ongoing material and energy consumption patterns are causing huge challenges for society as fossil fuels and mineral resources are being exhausted at an alarming rate, thus causing social inequalities by not leaving enough resources for future generations (UNEP 2011a). In Australia, there is a strong notion amongst house owners that traditional houses provide status, cultural identity, and economic security and are wary of changes in design and construction materials (Buys et al. 2005) from the intra-generational equity perspective.

The Australian housing sector is worth $40billion and provides employment to approximately 300,000 skilled and unskilled workers (Kelly 2015). Generally, the housing in Australia has been unaffordable due to gap in supply and demand of houses and Government’s housing policies which is causing housing stress for building sector

(Berry and Dalton 2004; Beer, Kearins and Pieters 2007; Kelly 2015; QBE 2015; Nepal, Tanton and Harding 2010; BCEC 2014). Thus this study will assume that the employment opportunities are not affected due to sustainable house design option.

In order to achieve sustainable building envelope option, it is important to evaluate the social impacts of the environmentally and economically feasible options which have been considered as the third part of the LCM framework (Figure 3.12).

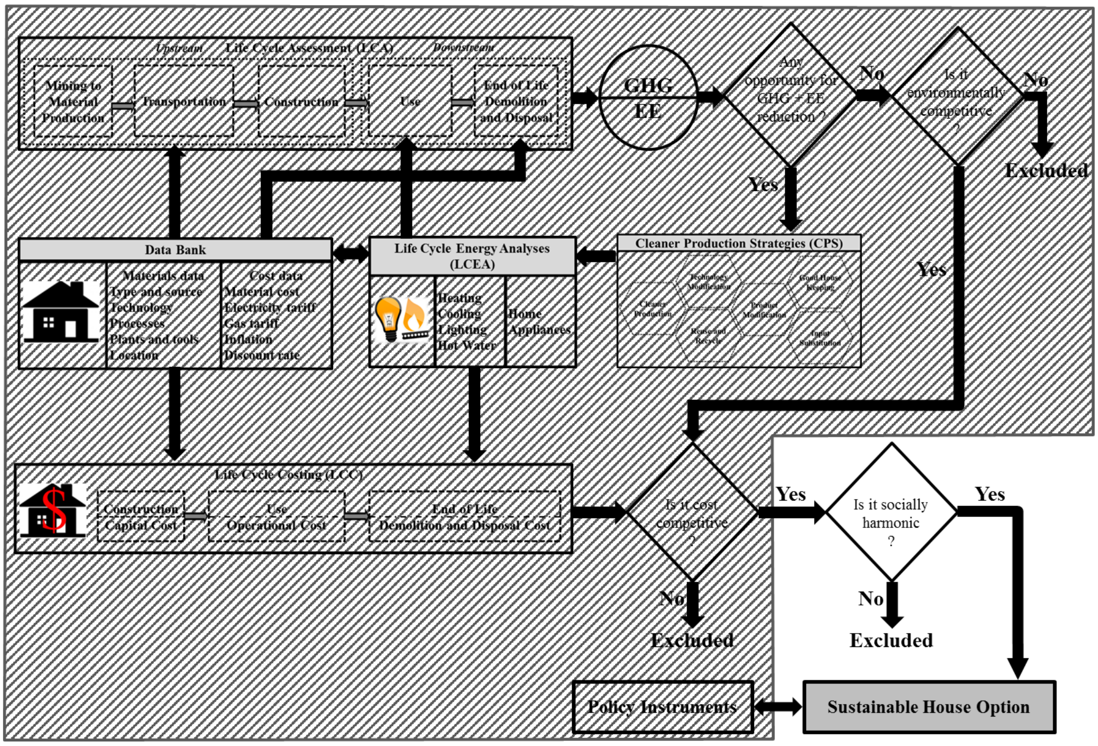


Figure 3.12 LCM framework: Part 4 - Social impacts

The most relevant social issues of the housing sector in Western Australia have been identified using the following social indicators which have been developed to analyse the positive and negative impacts due to different methods and materials of construction of houses in Western Australia. The following tangible (objective and quantitative) and intangible (subjective and qualitative) social indicators have been used to achieve the research objectives:

Tangible social indicators

- *Affordability:* The 30/40 rule is most commonly accepted rule of housing affordability in Australia (Nepal, Tanton and Harding 2010) and various industry groups such as HIA-CBA, AB-REIA, BIS Shrapnel, and REIWA have developed scales to measure affordability based on house price, household incomes, mortgage repayment, maintenance costs, and operational costs. This indicator is classified as intra-generational social equity as it improves the wellbeing of the current generation (BCEC 2014; QBE 2015; Beer, Kearins and Pieters 2007).

- *Employment opportunities*: In spite of best efforts provided by Australian Competition and Consumer Commission (ACCC) and Australian Brick and Blocklaying Training Foundation (ABBTF), there is still a shortage of skilled masons which is a major constraint of the housing sector. The brick laying activity is a specialized trade requiring hard labour, attention, and onsite precision, and so the shortage of brick layers is causing delays (ABBTF 2016; ACCC 2014). The current research will take into account if there are adequate skilled labour and trained supervisors for implementing new designs offering both economic and environmental benefits.

- *Project duration*: The method and process of construction coupled with a shortage of skilled labour have a great influence on the project duration. The delay may unnecessarily increase the mortgage cost as a consumer is forced to pay the interest on the loan while incurring the rental cost elsewhere (Alwi and Hampson 2003; Chidambaram, Narayanan and Idrus 2012).

- *Resource conservation*: An efficient and innovative method of design and construction of the house can not only reduce consumption of raw material and energy but can reduce the onsite waste, and so the landfill size (Blismas and Wakefield 2009).

Intangible social indicators

- *Acceptability:* The adaptation to a new and non-traditional design by developers, builders, suppliers, trades, professionals, and owners is a challenging task where acceptability is an issue for an Australian housing sector. The new design requires the market availability of materials, technical skill and supporting policy structure (Häkkinen and Belloni 2011; Bond 2011).

- *Human comfort*: One of the most critical roles of the house is to provide thermal comfort to the occupants with minimum auxiliary heating or cooling. The climate responsive design of a house has a crucial role in minimizing the adverse effects of the anticipated occurrences of intensive heat waves on human comfort. (Bluyssen 2010; Manioğlu and Yılmaz 2006)

These indicators have helped in analysing the intergenerational and intra-generational equity issues of environmental and economic assessment outcome in Chapter 5.

3.7 Implementation of Life Cycle Management Framework: Part 5 – Development of Policy Instruments

Various studies have confirmed that the buildings are the largest material and energy consumers in the world and so they have a substantial material and energy saving potential through the use of cleaner production strategies, but the implementation of cleaner production strategies is difficult due to lack of policies, institutional framework, and harmonized approaches (Weisz and Steinberger 2010; Li, Yang and Lam 2013; Shen et al. 2010; Kibert, Sendzimir and Guy 2000; Passer et al. 2015). The lack of technology or assessment tools are not the cause of slow implementation of new building approaches, in fact, it is the organizational resistance and procedural difficulties which slow down the implementation of new methods or materials (Häkkinen and Belloni 2011). The new technologies require changes in existing process, which may cause fear of risk and unforeseen costs. The LCM framework has considered the review of existing policies that will enable to develop new policies to overcome the barriers of sustainable development (Figure 3.13).

The aforementioned environmental, economic, and social factors will formulate strategies (e.g. skill development, by-product supply, carbon tax, landfill levy, utility tariffs, rebate and incentives on renewable energy, feed-in tariff, first home owners grant (FHOG), passive solar design, implementation strategies for energy efficiency measures, and supply and demand gap) that require policies to be implemented. So the next step is to examine existing policies to find out the gap. Once the gaps are identified, appropriate policies pertaining to sustainable house development will be formulated. The strategies that will be developed on the basis of the outcomes of LCA, LCC and social impact assessment will be compared with the existing strategies that involve direct (Department of Housing, Waste Authority, Building Commission, Western Australian Planning Commissions, and Department of Environment Regulations) and indirect stakeholders (Builders, Suppliers, House Owners).

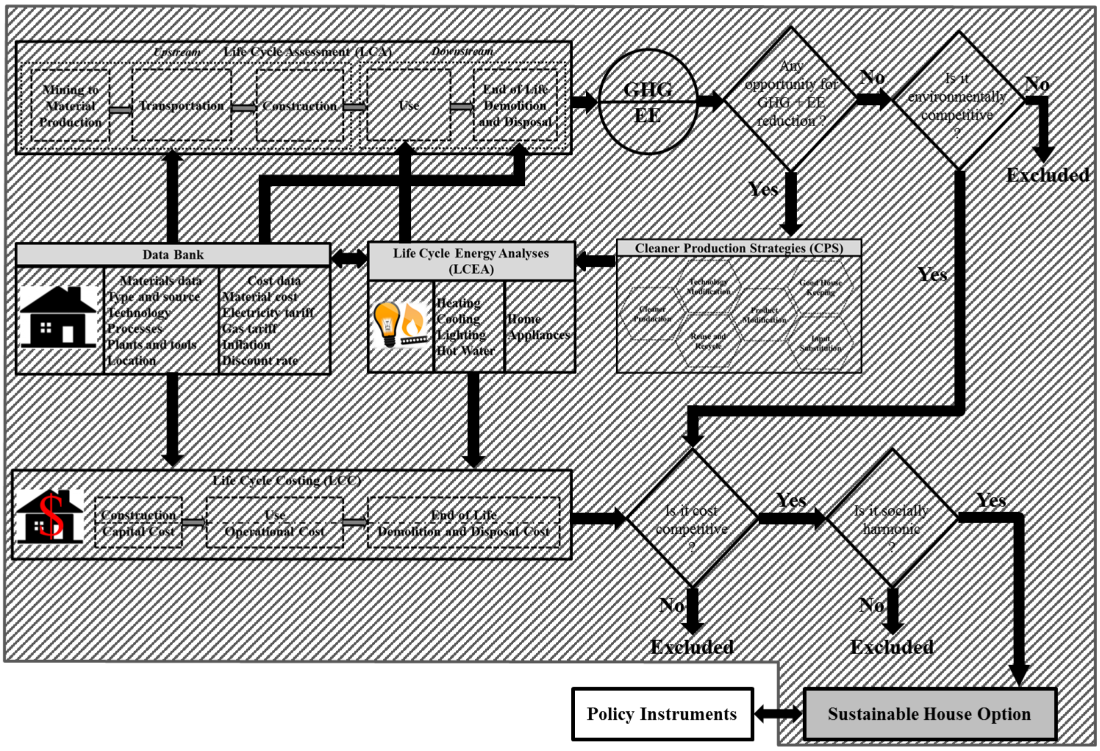


Figure 3.13 LCM framework: Part 5 - Policy instruments

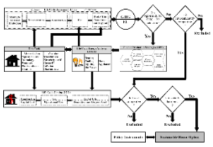
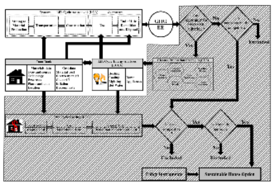
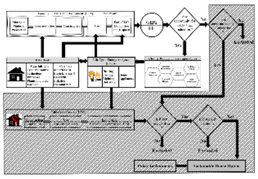
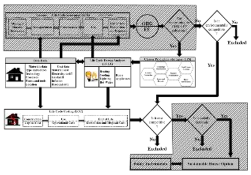
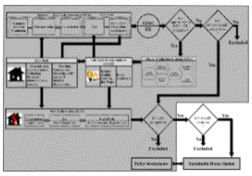
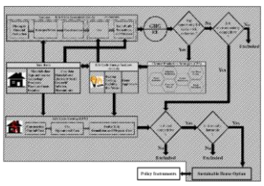
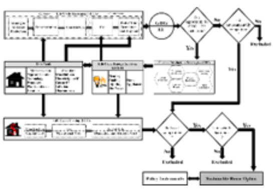
3.8 Conclusion

This chapter describes the development and application of life cycle management framework utilized for achieving sustainable building envelope designs for Western Australian houses in different regions. The chapter discusses integration of various tools and approaches such as life cycle assessment (LCA), life cycle costing (LCC), NatHERS accredited tool for operational energy estimation, cleaner production strategies (CPS), climate change impacts, social impacts, and policy barriers including the data bank which consists of building material specific details, relevant codes of practice, geography and meteorology of WA, modes and methods of transportation, construction specific details, including unit costs required for the construction of a house in Western Australia. The striving methods for addressing all the three pillars of sustainability i.e. environment, economy, and society have been extensively discussed while integrating various tools and approaches. The proposed life cycle management framework is capable of visualizing and assessing the performance of cradle-to-grave stages of a typical house from a sustainability point of view in order to achieve the research objectives stated in Section 3.1. Table 3.2 shows the snapshot of the whole framework addressing the research objectives.

A number of mathematical expressions which have been used by various tools and approaches of the framework have been presented to define the complex theoretical relationship between different variables.

The application of the life cycle management frame work has been demonstrated in detail in Chapter 4, 5, and 6 with discussion and supporting data.

Table 3.2 Summary of development and implementation of LCM framework to achieve research objectives

LCM framework	LCM framework stage / research objectives
	**Development of LCM framework** Objective 1: To develop a framework for improving the sustainability performance of houses in Western Australia (Chapter 3)
 	**Implementation of LCM framework: Part 1 – LCA and Part 2 – Cleaner Production Strategies** Objective 2: To estimate the life cycle environmental impacts of construction, use, and disposal of a typical house in Perth using LCA tool (Chapter 4) Objective 3: To identify hotspots and apply appropriate cleaner production strategies (CPS) to mitigate the life cycle environmental impacts associated with identified hotspots for a typical house in Perth (Chapter 4)
  	**Implementation of LCM framework: Part 3 – LCC, Part 4 – Social impacts of the environmental and economic outcome, and Part 5 - Development of Policy Instruments** Objective 4: To estimate the socio-economic implications of the environmentally viable cleaner production options for mitigation of life cycle impacts of a typical house in Perth (Chapter 5)
	**Implementation of LCM framework: Part 1 to 5** Objective 5: To investigate the implication of environmentally, and economically viable options for 17 locations in regional Western Australia to capture the location specific climatic, economic, energy, and policy variations (Chapter 6).

Chapter 4

Energy and environmental assessment for a sustainable house in Perth

4.1 Introduction

This chapter addresses research objectives 2, and 3 by using the LCM framework. LCA tool of LCM framework has been applied to estimate the environmental impacts (GHG emissions and EE consumption) of a typical 4x2x2 (4 bedroom, 2 bath, and 2 garage) single storey detached double clay brick wall house in Perth with, and without temperature increase climate change scenarios that potentially affect the operational energy demand. The life cycle inventory has been developed for mining to material production and construction stages following the design and architectural plans for a typical house and consultation with local Builders. Then an LCI for the operational energy demand (heating, cooling, lighting, hot water, and home appliances) during use stage over a lifespan of 50 years has been developed. The AccuRate software has been used to estimate the location specific operational energy for heating, cooling, hot water, and lighting. The LCI of the end of life stage consisting of demolition and disposal of construction waste to landfill has been developed. The LCI data is entered into SimaPro software to calculate GHG emissions and EE consumption and to determine the inputs or hotspots causing the most impact in terms of the above mentioned indicators. Finally, the cleaner production strategies including good housekeeping, input substitution, product modification, technology modification, and re-use and recycling have been applied to treat the hotspots in order to achieve the maximum level of GHG emissions reduction and EE consumption savings.

4.2 Life cycle inventory of a typical reference house in Perth

The life cycle inventory (LCI) consisting of material and energy inputs is a prerequisite to estimate GHG emissions and embodied energy consumption. LCI consists of Bill of Quantities (BOQ) for materials, transport information, and energy for construction tools and plants during construction stage, energy for end-use appliances during the use stage over a 50 year lifespan, and demolition and disposal information at the end of life stage of a typical 4x2x2 double clay brick wall house in Perth.

4.2.1 Mining to material production, transport, construction, end of life demolition and disposal stages

The mining to material stage consists of BOQ that has been developed using the architectural and structural plans and specifications for a typical house. Table 4.1 presents the mass of materials which have been estimated using Equation 3.1 for the construction of a typical reference house (DB-XX-SG-CT) in Perth with a floor area of 243m^2, wall height of 2.4m, and a conditioned area of 153.6m^2.

Table 4.1 Summary of materials and energy inputs during mining to material production, transportation, construction, and the end of life demolition and disposal stages

Material/Energy*	Unit	Quantity
Sand to make up levels for footings and ground slab	tonnes	35.96
Polythene Sheet	tonnes	0.04
Mesh reinforcement	tonnes	0.63
Ready mix concrete	tonnes	78.35
Metal door frames	tonnes	0.18
Roof Timber	tonnes	4.13
Bat Insulation for Roof	tonnes	0.48
Gyprock boards & cornices	tonnes	1.98
Door shutters	tonnes	0.37
Floor tiles	tonnes	5.47
Wall tiles	tonnes	0.69
External wall - Face bricks (DB-XX)	tonnes	33.29
External wall - Utility bricks (DB-XX)	tonnes	29.32
Internal wall - Utility bricks	tonnes	32.01
Aluminium Windows – single glazed (SG)	tonnes	1.43
Roof Tiles – concrete (CT)	tonnes	14.52
Cement, brickie sand, and lime for mortar	tonnes	11.48
Metal lintels, columns, bracings, wall ties, and structural fixtures	tonnes	0.58
Cement, plaster sand and lime for rendering	tonnes	10.54
Transportation of building materials to site	tkm	8,932.62
Equivalent energy consumption for plants, equipment and hand tools during construction activities	GJ	20.83GJ
Cart away of excavated soil, and construction waste	tkm	2,840.88
Equivalent energy consumption for plants and equipment during end of life demolition activities	GJ	22.72GJ
Transportation of demolition waste from building site to recycler and landfill facilities	tkm	7,189.96

*The detailed calculations of material and energy inputs during each stage are presented in Table D.1 to Table D.4 (Appendix D).

Equation 3.2 has been used to estimate the tkm value of transportation of building materials to the construction site during construction stage (Table 4.1).

In the case of construction stage, the energy consumption for machinery (e.g. bobcat, compactor, loader, and forklift) and tools required for construction of a typical reference house has been estimated using Equation 3.3 and is presented in terms of GJ in Table 4.1.

Similarly, the energy required for the end of life demolition has been estimated using Equation 3.3 and the transportation for the end of life disposal has been estimated using Equation 3.2. Table 4.1 presents the energy required for demolition in terms of GJ and disposal of demolition waste to landfill in terms of tkm.

4.2.2 Use stage – Operational energy

The energy demand for heating, cooling, lighting, and hot water has been estimated over a lifespan of 50 years using AccuRate (V2.3.3.13SP2) software to capture the location specific climatic variations, while the energy demand for home appliances has been estimated using Equation 3.23.

As elaborated in Section 3.3.2.1.4, the dimensions and shapes of the rooms, orientation of each external wall, locations and dimensions of the doors, windows, and openings, layer wise thickness and material details of wall elements, foundation, shape of roof structure, zoning details, shading dimensions, room wise number and type of lighting, wet-area wise sanitary ware and tap ware data, type of water heater, air-conditioning and heating systems of a reference house (DB-XX-SG-CT) in Perth have been entered into AccuRate software to estimate location specific energy consumption.

Perth falls under climate zone 5, NatHERS zone 13, and hot water region 3. To take advantage of natural ventilation and solar energy, 8 alternative orientations (Morrissey, Moore and Horne 2011) have been used for the simulation of model to estimate the annual energy demand for heating, cooling, lighting, and hot water for the house. A sample report generated by the AccuRate software showing the heating and cooling energy demand for a typical reference house (DB-XX-SG-CT) for east orientation is presented in Figure D.1 (Appendix D). While the heating and cooling energy demand for 50 years life cycle of a typical reference house in Perth has been calculated by multiplying the annual energy demand per m^2 of conditioned floor area of the house by total conditioned floor area of the house and then multiplied by the number of years. The lighting and hot water energy demand for 50 years life cycle of a typical reference house have been calculated by multiplying the annual energy demand per house by a number of years.

It appears that the energy demand for heating and cooling for a typical reference house (DB-XX-SG-CT) in Perth is the lowest for east orientation and the highest for south orientation (Figure 4.1).

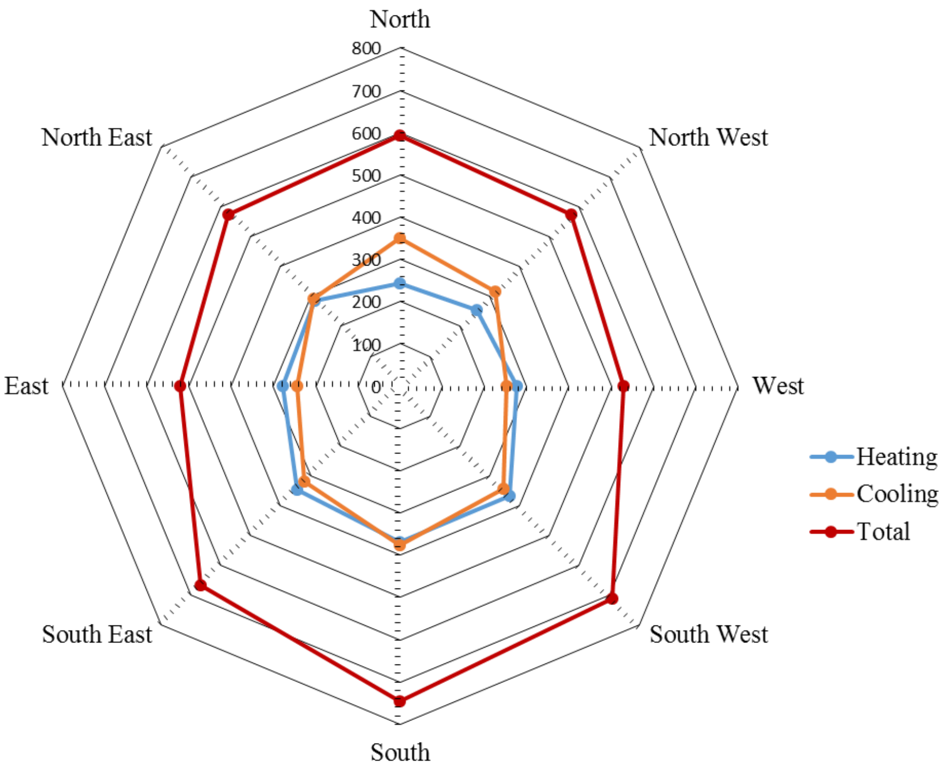


Figure 4.1 Life cycle heating and cooling energy demand of a typical house for 8 orientations

In addition to aforementioned energy demand, the life cycle energy demand for home appliances such as television, refrigerator, washing machine, cloth dryer, dish washer, cook top, oven, microwave, computer, toaster, kettle, mixer/grinder, coffee maker, iron, vacuum cleaner, range hood, and set top box of a typical reference house (DB-XX-SG-CT) has been estimated using Equation 3.23 and the detailed breakdown of calculation is presented in Table D.5 (Appendix D).

Thus, the life cycle operational energy demand for heating, cooling, lighting, hot water, and home appliances of a typical reference house in Perth for all 8 alternative orientations has been summarised and presented in Table 4.2.

Table 4.2 Summary of stage wise life cycle energy demand for a typical reference house (DB-XX-SG-CT) house in Perth for 8 orientations

Orientation	**Heating GJ**	**Cooling GJ**	**Lighting GJ**	**Hot water GJ**	**Home Appliances GJ**	**Total GJ**	**Low to high % variation**
North	243.46	350.21	320.35	1,130.50	717.00	2,761.51	2.68%
South	367.87	377.09	320.35	1,130.50	717.00	2,912.81	8.31%
East	278.78	242.69	320.35	1,130.50	717.00	2,689.32	0.00%
West	277.25	251.14	320.35	1,130.50	717.00	2,696.23	0.26%
North East	284.93	291.07	320.35	1,130.50	717.00	2,743.85	2.03%
North West	254.98	317.95	320.35	1,130.50	717.00	2,740.78	1.91%
South East	346.37	320.26	320.35	1,130.50	717.00	2,834.47	5.40%
South West	366.34	344.83	320.35	1,130.50	717.00	2,879.02	7.05%

The life cycle operational energy consumption varies from 2,689GJ for east orientation to 2,913GJ for south orientation for a typical reference house in Perth. The variation in the life cycle operational energy demand between east and west orientations is only 0.26%, while the variation between east and north-east and north-west orientations is within 2%. In comparison to the east orientation, the operational energy consumption for the remaining orientations is up to 8.3% higher. These results support the application of passive design principles for temperate climate in southern hemisphere, and it is therefore beneficial to have the longer walls of the house facing solar north (i.e. house facing towards east or west) so that the exposure to sun during summer is minimized, and is maximized during winters in order to reduce the dependency on artificial heating and cooling (Morrissey, Moore and Horne 2011; McGee, Reardon and Clarke 2013; Ambrose and Newton 2008). Another Australian study suggests that the house facing either the east or west orientation gains adequate solar access from the north while reducing the hot summer exposure to east and west ends of a house (Luxmoore, Jayasinghe and Mahendran 2005).

For a typical reference house in Perth, the energy demands for water heating, home appliances, heating, cooling, and lighting are found to vary between 39%-42%, 25%-

27%, 9%-13%, 9%-13%, and 11%-12% of life cycle energy demand of the house (Figure 4.2).

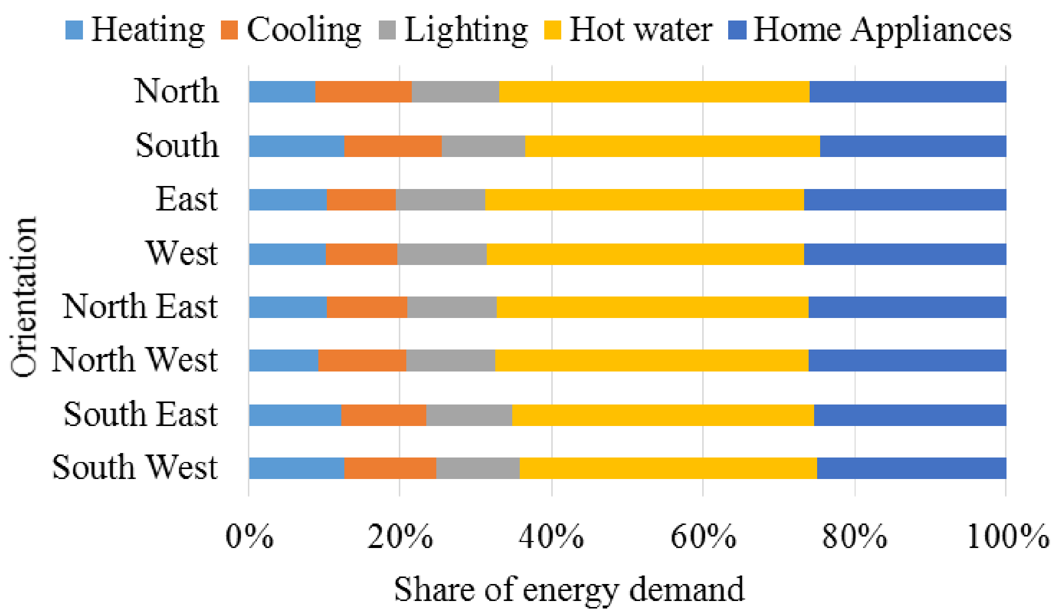


Figure 4.2 Orientation wise life cycle operational energy demand for a typical reference house (DB-XX-SG-CT) in Perth

The annual household energy demand of a typical reference house in Perth, which vary between 54GJ and 58GJ is comparable with the results of other Australian studies. The annual South Australian household energy consumption varies from 44.48GJ (Saman 2013) to 48.1GJ (Berry and Marker 2015a), based on actual monitoring of energy consumption over a period of 2 years. On the other hand, Crawford (2014) estimated the annual energy consumption of a household in Melbourne as 44.91GJ on the basis of the average energy bills of three consecutive years. Moore (2014) reported an average annual energy demand of a 6 star house in Melbourne as high as 54.72GJ. In the case of whole Australia, the average annual household energy consumption was predicted to be around 47GJ by the year 2015-2016 (DEWHA 2008b). The reason for slight variation between these results and current study could possibly be due to inter-state climatic differences resulting in variation in the energy consumption for heating, cooling, and hot water and also due to the inherent properties of the building envelope (Ren et al. 2013; Swan and Ugursal 2009; Lai and Wang 2011; Aldawi 2013). Another reason may be the difference in the methods used to estimate energy demand for end user appliances in these studies (DEWHA 2008b).

The east orientation has been considered as optimum orientation throughout this analysis because it offers the lowest life cycle operational energy demand for a reference house in Perth.

The aforementioned energy consumption estimate has not taken into account the changes in cooling energy demand due to temperature increase as an impact of climate change. Therefore a low CC impact scenario, where the annual cooling energy consumption is expected to increase by a minimum of 2% to 3% during 2010 -2030 and 5% to 8% during 2030-2065, and a high CC impact scenario, where the annual cooling energy consumption is expected to increase by a maximum of 9% to 14% during 2010 -2030 and 27% to 47% during 2030-2065 have been considered (Guan 2009; Ren, Chen and Wang 2011; Wang, Chen and Ren 2010). The operational energy demand for cooling over a 50 year lifespan of a reference house in Perth could increase by 6.11%% to 24% as a consequence of temperature rise (Figure 4.3).

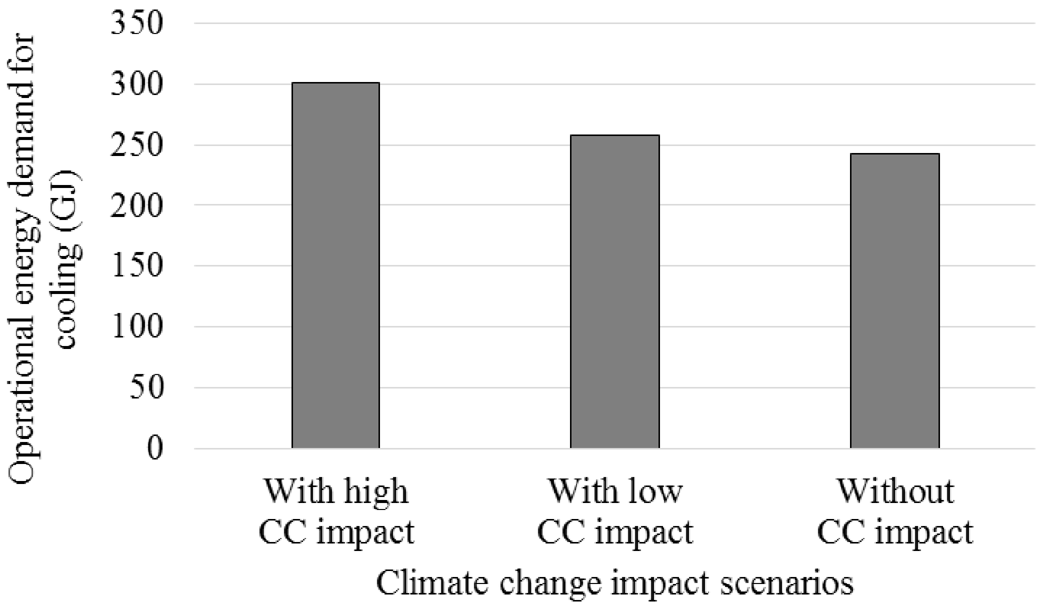


Figure 4.3 Operational energy demand for cooling for a typical reference house (DB-XX-SG-CT) in Perth under climate change impact scenarios

4.3 Estimation of GHG emissions and EE consumption of a typical reference house in Perth

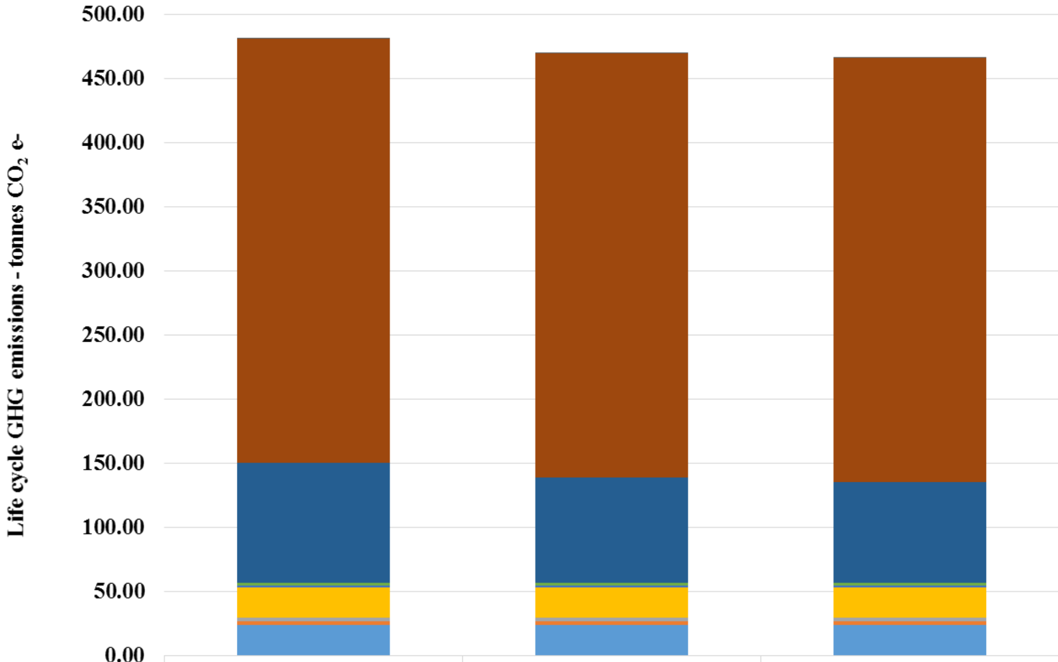
The GHG emissions and EE consumption of a typical reference house (DB-XX-SG-CT) in Perth for East orientation under three climate change impact scenarios have been estimated by entering LCI data into SimaPro software. The detailed procedure has been elaborated in Chapter 3.

4.3.1 GHG emissions

The LCA results show that the total life cycle GHG emissions from mining to material production, transportation, construction, use, and end of life demolition and disposal stages for a typical reference house (DB-XX-SG-CT) in Perth are 467tonnes CO_2 e-, 471tonnes CO_2 e-, and 482tonnes CO_2 e- for no, low, and high climate change impact scenarios respectively (Figure 4.4). Stage wise results of GHG emissions for a reference house for 8 orientations under 3 climate change impact scenarios are presented in Table D.6 to Table D.8 (Appendix D).

The life cycle GHG emissions of a typical reference house (DB-XX-SG-CT) in Perth without climate change impact scenario have been estimated as 467tonnes CO_2 e-. The mining to material production (53.05tonnes CO_2 e-), transportation (1.64tonnes CO_2 e-), construction (2.43tonnes CO_2 e-), use (409.21tonnes CO_2 e-), and the end of life demolition and disposal (0.77tonnes CO_2 e-) stages contribute to 11.36%, 0.35%, 0.52%, 87.61%, and 0.16% of the life cycle GHG emissions respectively. The results show that the use stage is the biggest contributor to life cycle GHG emissions followed by the mining to material stage, while all other stages together contribute to less than 2% of the life cycle GHG emissions.

The use stage of the building has been found to contribute between 85% and 90% of the total environmental impacts (Buyle, Braet and Audenaert 2012; Adalberth, Almgren and Petersen 2001). A study by Zhang, Shen, and Zhang (2013) found that the use and maintenance stage of the building accounts for around 98% of the life cycle air emissions (e.g. CO_2, CH_4, N_2O, SO_2, and NO_x), while other stages such as mining to material production, transportation, construction, and demolition contribute to remaining life cycle air emissions. A study by Cuéllar-Franca and Azapagic (2012) found that the use stage, mining to material production and construction, and the end of life stages of a building contribute to 90%, 9%, and 1% of the life cycle environmental impacts.



	With high CC impact	With low CC impact	Without CC impact
End of life demolition and disposal	0.77	0.77	0.77
Use - Non Thermal (HW/HAp/Lgt)	330.91	330.91	330.91
Use - Thermal (Heat/cool)	93.15	82.03	78.30
Construction	2.43	2.43	2.43
Transportation	1.64	1.64	1.64
M to M Production - Non Envelope Elements	22.93	22.93	22.93
M to M Production - Envelope - Roof	3.49	3.49	3.49
M to M Production - Envelope - Window	2.92	2.92	2.92
M to M Production - Envelope - Wall	23.71	23.71	23.71

Figure 4.4 Life cycle GHG emissions for a typical reference house (DB-XX-SG-CT) in Perth under climate change impact scenarios

In addition to the chosen system boundary and functional unit for life cycle assessment of a building, the region specific material, energy, and climatic data including the social behaviour, practices, and assumptions influence the life cycle environmental impact results and, hence the scope for comparison in terms of absolute values is limited.

The energy consumption for heating, cooling, lighting, hot water, and home appliances during 50 years of use stage seem to be the main reason for the highest emissions during use stage (Ortiz-Rodríguez, Castells and Sonnemann 2010; Rossi et al. 2012; Islam, Jollands and Setunge 2015). The use of energy intensive materials (e.g. concrete, steel, aluminium, and clay bricks) seems to be the reason for second highest GHG emissions during mining to material production stage. (Li et al. 2013; Carre 2011a). The transportation, construction, and the end of life demolition and disposal stages contribute to only around 2% of life cycle GHG emissions. Further investigation is made into the use and mining to material production stages which are responsible for the highest life cycle GHG emissions to find out the material or energy inputs causing these impacts known as hotspots.

Hotspot analysis

The use stage is contributing to 87.65% (highest) followed by mining to material production stage which is contributing to 11% (second highest) of the life cycle GHG emissions of a typical reference house in Perth.

Use stage

Figure 4.5 is the outcome of flow network in SimaPro that gives the activity wise breakdown of GHG emissions of the house during use stage wherein home appliances that accounted for the largest share (45%) of the total use stage GHG emissions thus considered being the most significant hotspot.

The detailed breakdown of GHG emissions for all 8 orientations under 3 climate change impact scenarios for use stage has been presented in Table D.9 (Appendix D).

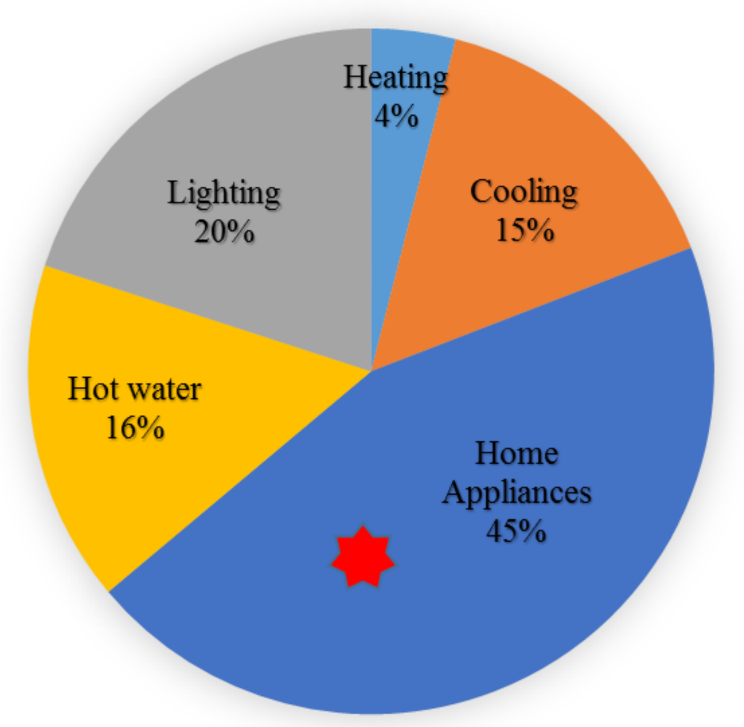


Figure 4.5 Breakdown of GHG emissions during use stage

Whilst the hot water has been found to be the hotspot in terms of life cycle household energy demand (i.e. 40% share of total household energy), it accounts for only 16% of the total GHG emissions. This is because of the use of natural gas for hot water, which has a relatively lower emission factor (i.e. 58.3 kg CO_2 e-/GJ) compared to the emission factor of grid electricity (i.e. 255kg CO_2 e-/GJ) which is used for home appliances. These results are similar to the recent Australian study, which found that the home appliances are responsible for 45% of the life cycle GHG emissions during use stage (Bengtsson, Craggs and Dowse 2014).

Mining to material production stage

The mining to material stage is contributing to the second highest (11.36%) life cycle GHG emissions. Figure 4.6 a) shows the breakdown of GHG emissions of the house during mining to material production at component (e.g. wall, roof, window, and non-envelope) level wherein wall component has been found to have 45% (largest share) of the GHG emissions during mining to material production stage followed by non-envelope, roof, and window components respectively. Upon further breakdown at material (e.g. concrete, brick, glass) level, it has been found that clay bricks and concrete are the top two carbon intensive materials with 35%, and 20% of the GHG emissions during mining to material production stage respectively (Figure 4.6 b). The remaining materials such as ceramic tiles, doors, mortar, roof tiles, steel, timber, and windows altogether contributed to 45% of the GHG emissions.

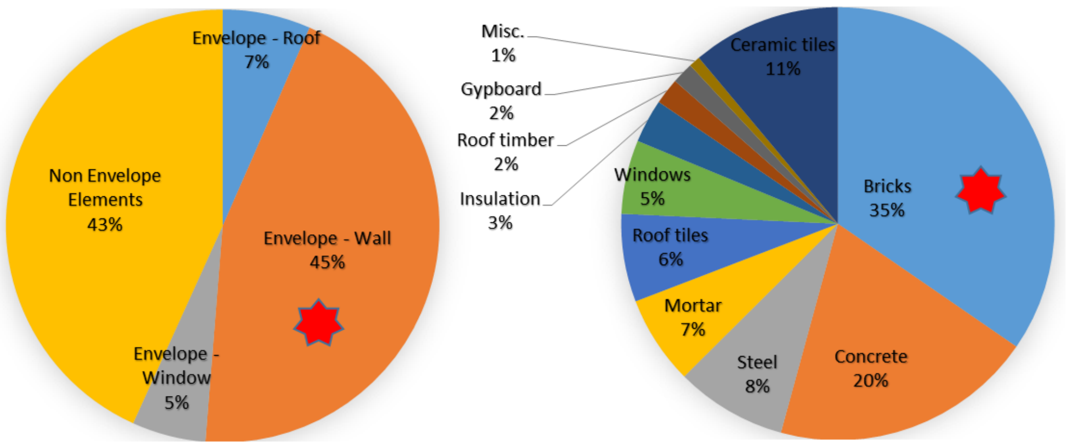


Figure 4.6 Breakdown of GHG emissions during mining to material production stage a) at component level, and b) at material level

Whilst the carbon intensities of some materials such as steel (3.18tonnes CO_2 e-/tonnes), windows (2.04tonnes CO_2 e-/tonnes), gypboard (429kg CO_2 e-/tonnes), and roof tiles (240kg CO_2 e-/tonnes) are higher than the bricks (194kg CO_2 e-/tonnes) and concrete (133kg CO_2 e-/tonnes), their contribution to GHG emissions is much lower than bricks and concrete. This is because of the large mass of bricks (94.62tonnes) and concrete (78.5tonnes), constituting a total share of 66% of the gross mass of all materials required for the construction of a typical reference house in Perth (Table 4.1). The variation in upstream processes of these materials is another reason for the variation in carbon intensities. A process flow chart confirms that the clay bricks and concrete are two major contributors to GHG emissions during mining to material production stage of a typical reference house in Perth (Figure 4.7).

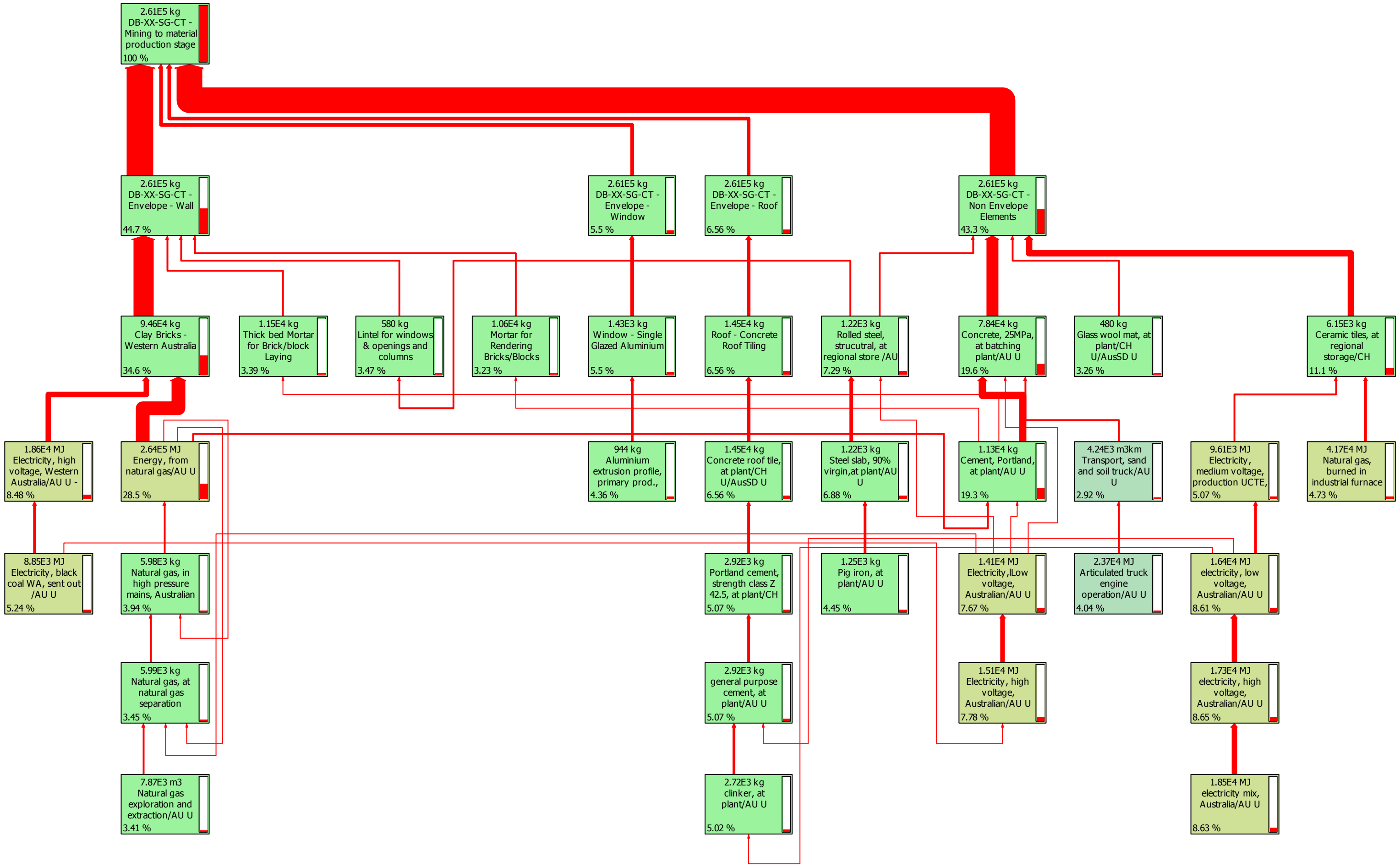


Figure 4.7 Flow chart showing percentage breakdown of GHG emissions (53.05tonnes CO_2 e-) during mining to material production stage of a typical reference house in Perth

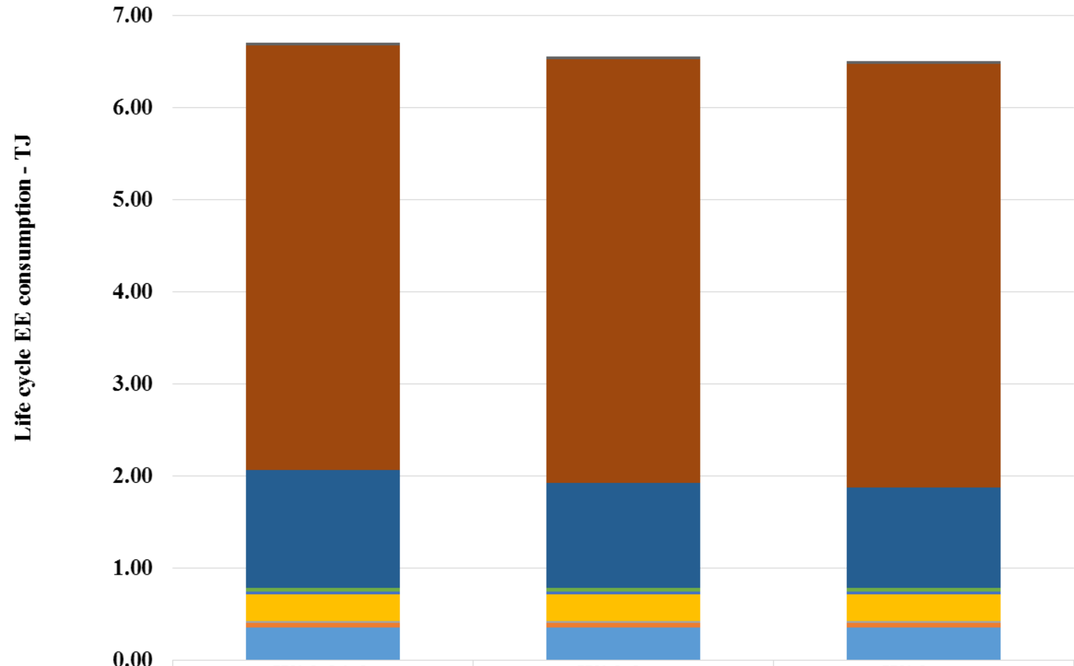
4.3.2 EE consumption

Similar to GHG emissions, the LCA results show that the life cycle EE consumption from mining to material production, transportation, construction, use, and end of life demolition and disposal stages of a typical reference house (DB-XX-SG-CT) in Perth are 6.5TJ, 6.54TJ, and 6.7TJ for without and with (low, and high) climate change impact scenarios respectively (Figure 4.8). Stage wise results of EE consumption for a typical reference house for 8 orientations under 3 climate change impact scenarios are presented in Table D.10 to Table D.12 (Appendix D).

The life cycle EE consumption of a typical reference house (DB-XX-SG-CT) in Perth without climate change impact scenario has been estimated as 6.5TJ. The mining to material production (0.71TJ) transportation (0.02TJ), construction (0.04TJ), use (5.7TJ), and the end of life demolition and disposal (0.03TJ) stages contribute to 10.97%, 0.35%, 0.62%, 87.59%, and 0.46% of the life cycle EE consumption respectively. The results show that the use stage is the biggest contributor to life cycle EE consumption followed by the mining to material stage, while all other stages together contribute to less than 2% of the life cycle EE consumption.

Frischknecht et al. (2015) reported that the use phase of the building contributes to 84% of the life cycle cumulative energy demand. The contribution of use stage of a university building was 87% of the life cycle embodied energy consumption (Biswas 2014). An Australian study found that the construction and the end of life stages of the buildings contribute between 4% and 18% of life cycle cumulative energy demand, while the use stage contributes between 82% and 96% of life cycle cumulative energy demand (Iyer-Raniga and Wong 2012). The above studies confirm the validity of the current analysis.

Similar to GHG emissions, the energy consumption for heating, cooling, lighting, hot water, and home appliances over a lifespan of 50 years seems to be the main reason for the highest EE consumption during use stage (Crawford 2014; Sartori and Hestnes 2007; Fay, Treloar and Iyer-Raniga 2000). The use of energy intensive materials (e.g. concrete, steel, aluminium, and clay bricks) appears to be the reason for the second highest EE consumption during mining to material production stage. (Zabalza Bribián, Valero Capilla and Aranda Usón 2011; Treloar et al. 2001; Cabeza et al. 2013).



	With high CC impact	With low CC impact	Without CC impact
End of life demolition and disposal	0.03	0.03	0.03
Use - Non Thermal (HW/HAp/Lgt)	4.60	4.60	4.60
Use - Thermal (Heat/cool)	1.29	1.14	1.09
Construction	0.04	0.04	0.04
Transportation	0.02	0.02	0.02
M to M Production - Non Envelope Elements	0.29	0.29	0.29
M to M Production - Envelope - Roof	0.02	0.02	0.02
M to M Production - Envelope - Window	0.05	0.05	0.05
M to M Production - Envelope - Wall	0.35	0.35	0.35

Figure 4.8 Life cycle EE consumption of a typical reference house (DB-XX-SG-CT) in Perth under climate change impact scenarios

The transportation, construction, and the end of life demolition and disposal stages contribute to around 1.25% of total EE consumption.

The use and mining to material production stages, which are responsible for the highest life cycle EE consumption have been further investigated to find out the material or energy inputs causing these impacts known as hotspots.

Hotspot analysis

The use stage is found to be the highest contributor (87.75%) to the life cycle EE consumption of a typical reference house in Perth followed by mining to material production stage contributing to second highest (11%) life cycle EE consumption.

Use stage

Figure 4.9 is the outcome of flow network in SimaPro that gives the activity wise breakdown of EE consumption of the house during use stage wherein home appliances that accounted for the largest share (42%) of the total use stage EE consumption has thus been considered to be the largest hotspot.

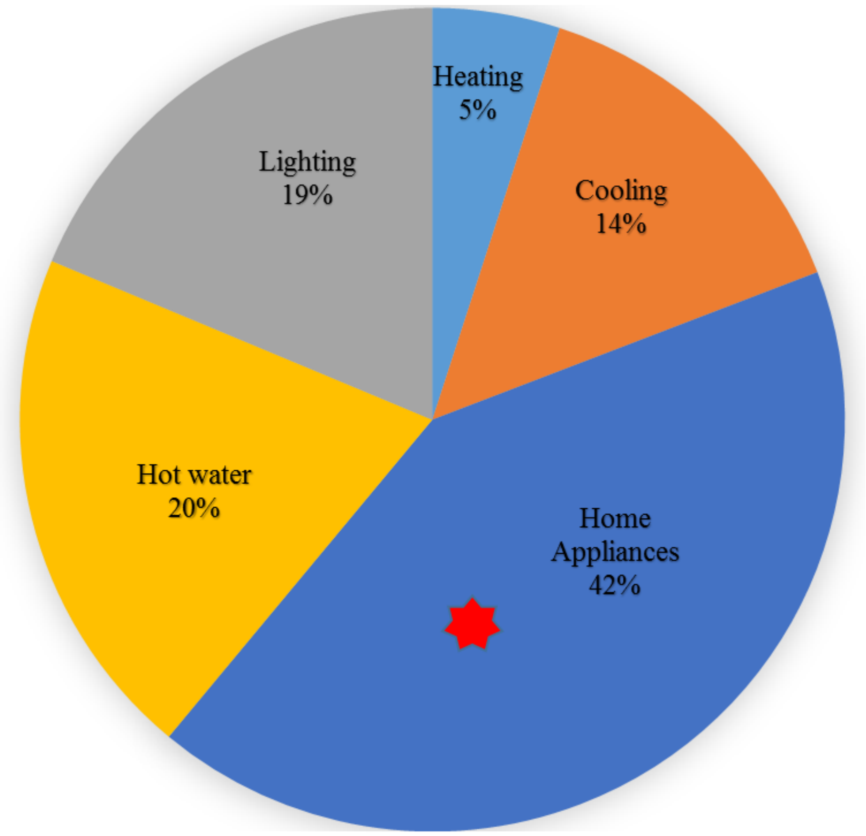


Figure 4.9 Breakdown of EE consumption during use stage

The detailed breakdown of EE consumption for all 8 orientations under 3 climate change impact scenarios for use stage is presented in Table D.13 (Appendix D). Though in terms of life cycle energy demand, the hot water has been found to be the hotspot (i.e. 40% share of total household energy), its share of the EE consumption is only 20% because of the use of natural gas for hot water, which has relatively lower energy intensity (1.02GJ/GJ) compared to the energy intensity of grid electricity (3.33GJ/GJ) which is used for home appliances.

Mining to material production stage

The mining to material stage is contributing to 11% (second highest) of total EE consumption. Figure 4.10 a) shows the breakdown of EE consumption of the house during mining to material production at component (e.g. wall, roof, window, and non-envelope) level wherein wall component has been found to have 49% (largest share) of the life cycle EE consumption during mining to material production stage followed by non-envelope, roof, and window components respectively. Upon further breakdown at material (e.g. concrete, brick, glass) level, it is found that the clay bricks and concrete are the top two energy intensive materials with 42%, and 14% of the EE consumption during mining to material production stage respectively (Figure 4.10 b)). All remaining materials such as ceramic tiles, doors, mortar, roof tiles, steel, timber, and windows altogether contributed to 44% of the EE consumption.

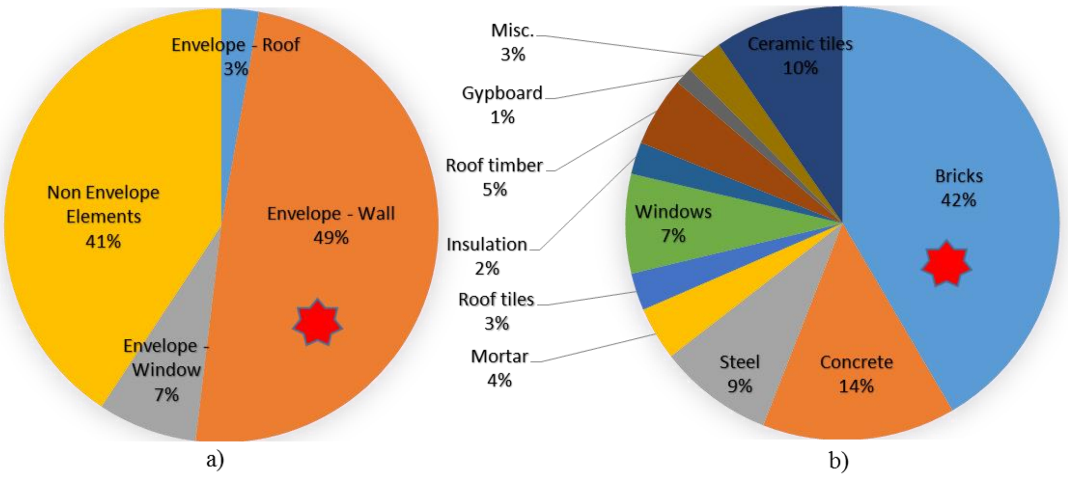


Figure 4.10 Breakdown of EE consumption during mining to material production stage at a) component level, and b) at material level

Whilst the energy intensity of some materials such as steel (43.9GJ/tonnes), windows (37GJ/tonnes), and gypboard (4.77GJ/tonnes) is higher than the bricks (3.3GJ/tonnes), and concrete (1.3GJ/tonnes) but their contribution to EE consumption is far less than the bricks and concrete. This is because the bricks (94.62tonnes), and concrete (78.5tonnes) constitute a share of 66% of the gross mass of all materials required for the construction of a typical reference house in Perth (Table 4.1), they are consuming high embodied energy. The variation in upstream processes of these materials is another reason for the variation in energy intensities.

A process flow chart confirms that the clay bricks and concrete are two major contributors to EE consumption during mining to material production stage of a typical reference house in Perth (Figure 4.11).

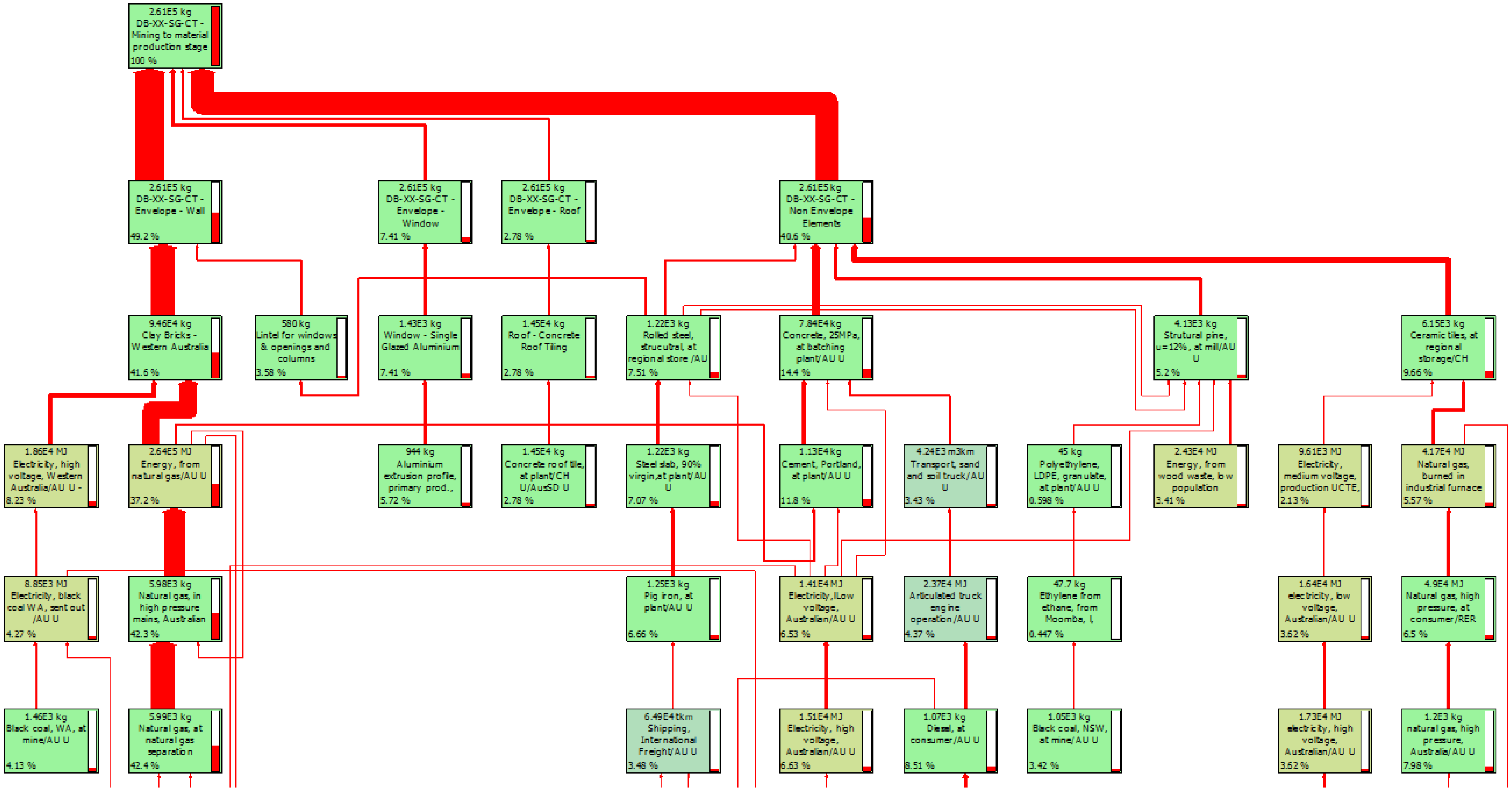


Figure 4.11 Flow chart showing percentage breakdown of EE consumption (0.71TJ) during mining to material production stage of a typical reference house in Perth

4.3.3 Uncertainty analysis

The uncertainty analysis has been conducted that assesses the impact of the uncertainties associated with the source and quality of the input variables on the GHG emissions and EE consumption results to improve the reliability of the results.

A Monte Carlo Simulation (MCS), which is embedded within SimaPro 8.05.13 software, has been employed for 1000 iterations at the 95% confidence level to determine the uncertainty ranges. The calculated GHG emissions and EE consumption values are very close to the corresponding mean and median values where the coefficient of variation values are 2.86%, and 2.21% respectively, which indicates a small degree of uncertainty (Grant 2009; Biswas and Cooling 2013; Lo, Ma and Lo 2005; Biswas and Naude 2016; Mohammed et al. 2016).

The uncertainty histograms from MCS for 1000 iterations at the 95% confidence level for GHG emissions and EE consumption for East facing typical reference house (DB-XX-SG-CT) show a normal distribution (Figure 4.12).

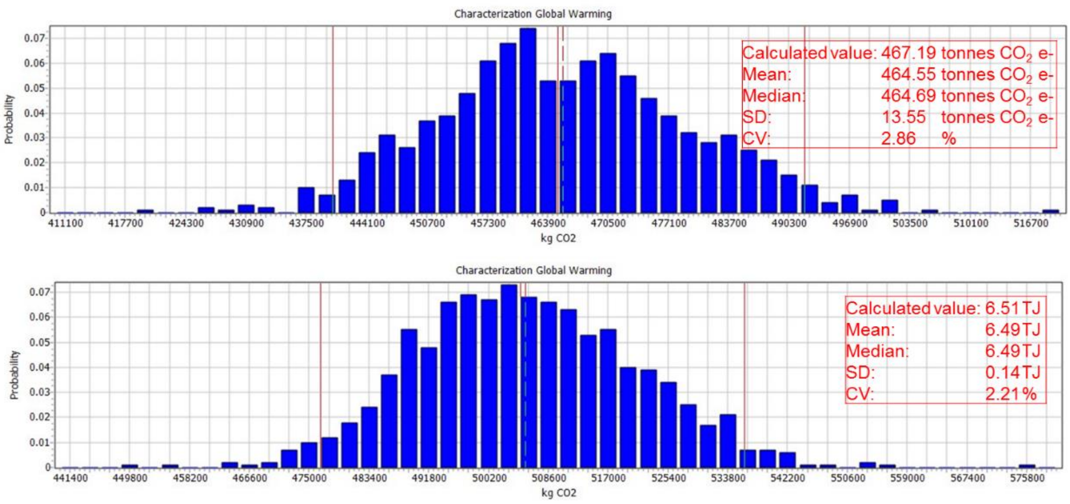


Figure 4.12 Uncertainty histograms for GHG emissions and EE consumption of an East facing typical reference house in Perth

4.3.4 Summary of GHG emissions and EE consumption results for a reference house (DB-XX-SG-CT) in Perth

The findings of GHG emissions and EE consumption assessment of a typical reference house (DB-XX-SG-CT) in Perth have been summarised for identification and implementation of appropriate cleaner production strategies (CPS) to mitigate the impacts to achieve the research objectives as follows:

- The use stage of a typical reference house in Perth has the highest life cycle GHG emissions and EE consumption followed by mining to material production stage.
- During use stage, the home appliances cause the maximum GHG emissions and EE consumption impacts.
- During mining to material production stage, the clay bricks cause the highest GHG emissions and EE consumption impacts followed by concrete.
- The life cycle GHG emissions and EE consumption of a typical reference house in Perth could increase up to 10% due to change in the orientation of the house.
- The life cycle GHG emissions and EE consumption of a typical reference house in Perth could increase up to 5% due to increase in temperature as a result of climate change impacts.

4.4 Application of cleaner production strategies

The materials or energy inputs contributing to the significant portion of GHG emissions and embodied energy impacts during the life cycle stages of a typical reference clay brick wall house in Perth have been identified as hotspots. The relevant CPS options, which can potentially be implemented to treat the hotspots, have been selected on the basis of the resource availability and technical viability so as not to affect the structural performance of the house (Table 4.3).

To evaluate the viability of these recommended cleaner production options, the revised GHG emissions and EE consumption impacts for a typical reference house in Perth have been re-estimated for each strategy as discussed in the following section.

Table 4.3 Cleaner production strategies (CPS) for treating hotspots

Hotspots	Type of CPS	Options recommended
Electricity consumption by home appliances	Technology modification	Integrating grid connected roof top solar PV with electricity utility
Natural gas consumption for hot water	Technology modification	Integrating roof top solar water heater (SWH) with gas water heater
Electricity and natural gas consumption for cooling and heating	Good house keeping	Selecting the optimum orientation to maximize the solar access
	Product modification	Replacing single glazed windows with double glazed windows
	Product modification	Replacing concrete roof tiles with alternative roof material
Energy intensive clay bricks	Product modification	Replacing clay brick walls with alternative walls

4.4.1 Integration of grid connected roof top solar PV with electricity utility

The solar radiation is the most abundant energy resource on earth and annual solar radiation falling on Australia is approximately 58 million petajoules (PJ), which is approximately 10,000 times Australia's annual energy consumption. Australia's vast solar energy resource is largely untapped and in 2011-12, it accounted only 0.2% of total energy consumption (Geoscience-Australia and BREE 2014; Bahadori and Nwaoha 2013). The solar photovoltaic cells in solar PV system convert the sunlight into electricity and only about 15% of the houses in Australia have rooftop solar PV with a total installed capacity of 4,130MW_p (BREE 2014; APVI 2015).

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. At present, 1.5kW_p to 3kW_p roof top solar PV systems are commonly used by WA households (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 4x2x2 double brick house is adequate to accommodate the solar panels of up to 3kW_p (i.e. around 22 m^2) capacity (SEP 2015).

The average daily electricity production data of 1kW$_p$, 1.5kW$_p$, and 3kW$_p$ roof top solar PV systems in Perth has been obtained from PV-GC spread sheet document produced by Clean Energy Council (CEC) (CEC 2011). The amount of electricity that can be generated using 1kW$_p$, 1.5kW$_p$, and 3kW$_p$ solar PV systems over the lifespan of the house has been calculated for a typical reference house in Perth including the remaining amount of grid electricity required to meet total household electricity demand. The amount of electricity that would be generated by 1kW$_p$, 1.5kW$_p$, and 3kW$_p$ roof top solar PV during the life cycle of the house is 80MWh, 120MWh, and 241MWh respectively. The integration of 1kW$_p$ and 1.5kW$_p$ solar PV would generate enough electricity to reduce the use of grid electricity by 40% and 60% for home appliances over the lifespan of 50 years. However, the integration of a 3kW$_p$ solar PV would not only completely reduce the use of grid electricity for home appliances but the excess electricity would reduce the use of grid electricity for lighting also by 47% (Figure 4.13).

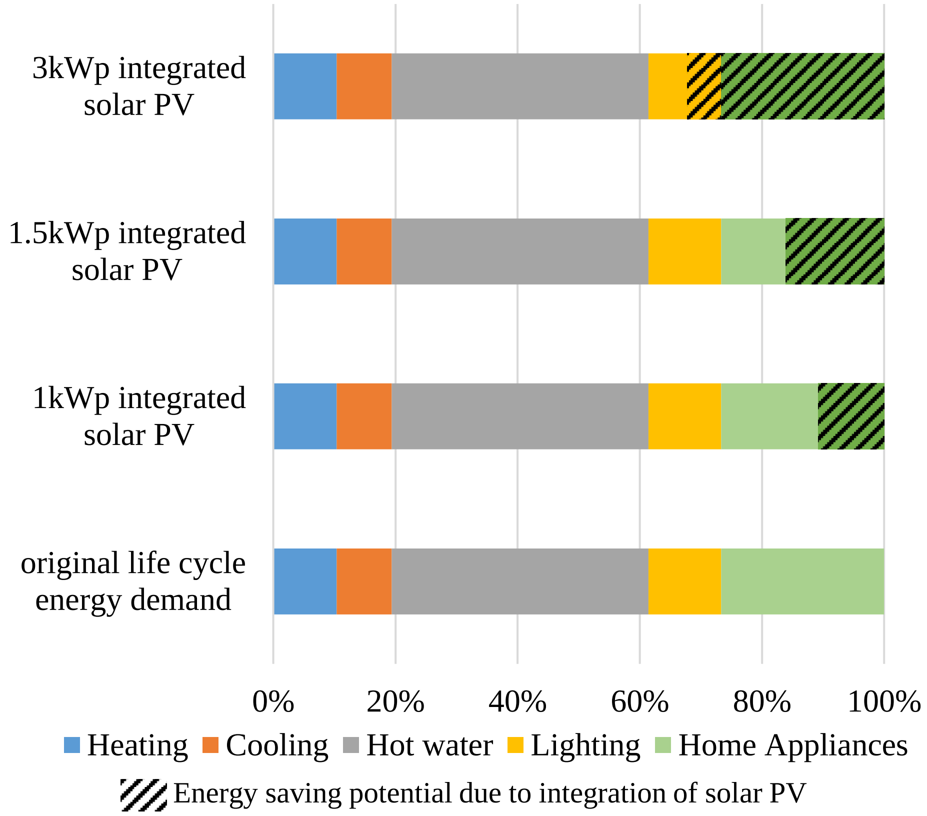


Figure 4.13 Life cycle energy saving potential due to integration of roof top solar PV

The revised operational energy inputs for all the three solar PV options have been entered into SimaPro for calculating the GHG emissions and EE consumption impacts of integration of grid connected roof top solar PV and to assess the viability of this cleaner production strategy.

Table 4.4 shows that the life cycle GHG emissions savings associated with 40%, and 60% substitution of grid electricity for home appliances using solar PV electricity produced by a $1kW_p$, and $1.5kW_p$ roof top solar PV systems would be 71tonnes CO_2 e- and 104tonnes CO_2 e- respectively. A $3kW_p$ roof top solar PV would not only reduce the GHG emissions of grid electricity for home appliances (183tonnes CO_2 e-) by 100%, but the GHG emissions of grid electricity for lighting (17tonnes CO_2 e-) also could be reduced by 21%. The embodied energy consumption saving can range from 0.94TJ for a $1kW_p$ roof top solar PV system to 2.68TJ for a $3kW_p$ roof top solar PV system.

Table 4.4 GHG emissions and EE consumption associated with roof top solar PV systems including their GHG emissions and EE consumption saving potential

Item	**1kW**	**1.5kW**	**3kW**
Life cycle GHG emissions associated with solar PV (tonnes CO_2 e-)	2.36	7.08	21.25
Life cycle GHG saving potential due to solar PV integration (tonnes CO_2 e-)	71.43	103.61	200.14
Life cycle EE consumption associated with solar PV (TJ)	0.02	0.07	0.2
Life cycle EE consumption saving potential due to solar PV integration (TJ)	0.94	1.37	2.68

Due to integration of $1kW_p$, $1.5kW_p$, and $3kW_p$ roof top solar PV, the reduced GHG emissions during use stage of a typical reference house in Perth would be 338tonnes CO_2 e-, 306tonnes CO_2 e-, and 209tonnes CO_2 e- respectively, which are 83%, 75%, and 51% of the GHG emissions during use stage without roof top solar PV system respectively (Figure 4.14). Similar to GHG emissions, the reduced EE consumption during use stage of a typical reference house in Perth due to integration of $1kW_p$, $1.5kW_p$ and $3kW_p$ roof top solar PV would be 4.75TJ, 4.32TJ, and 3.01TJ respectively, which are 83%, 76%, and 53% of the EE consumption during use stage without roof top solar PV system respectively (Figure 4.15).

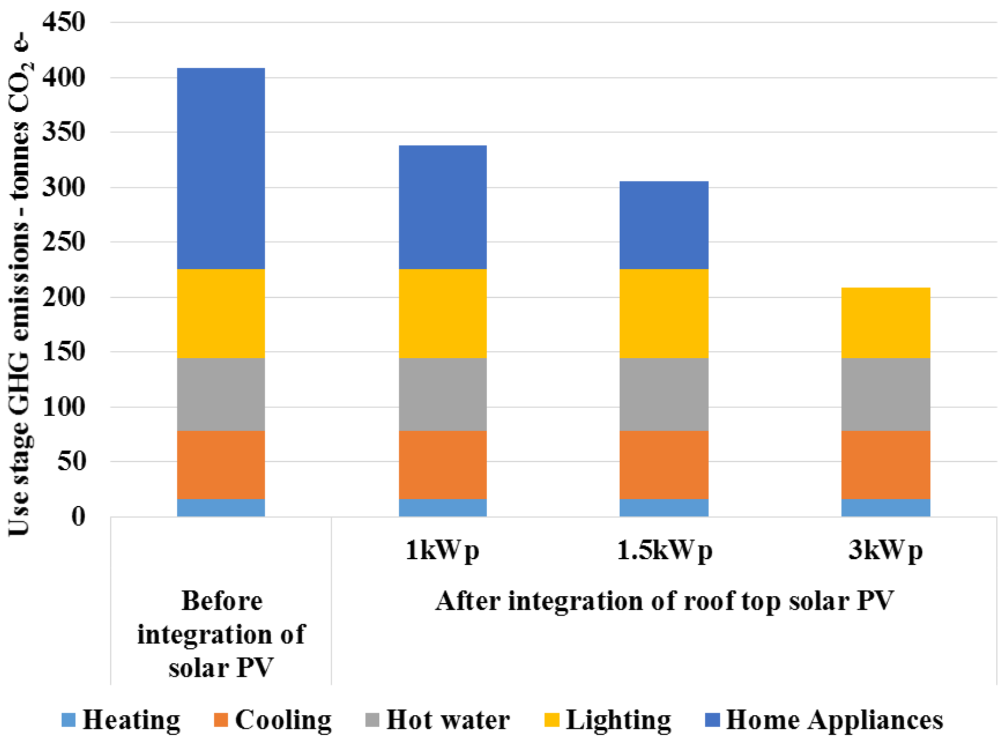


Figure 4.14 Use stage life cycle GHG emissions before and after integration of roof top solar PV

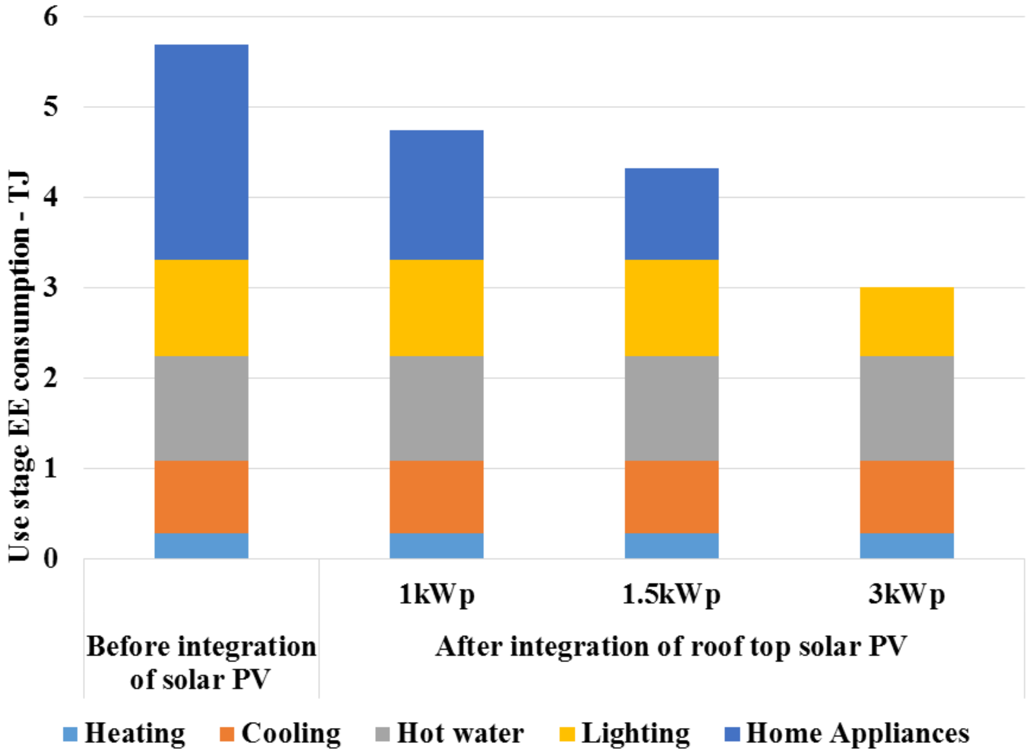


Figure 4.15 Use stage life cycle EE consumption before and after integration of roof top solar PV

GHG emissions and EE consumption mitigation values associated with the use of roof top solar PV could potentially be influenced by the type of technology (e.g. monocrystalline, polycrystalline, and thin film), location specific solar insolation, module efficiency, and the energy mix of the country where these products are manufactured and also where they are being used and hence there is limited opportunity for comparison of results of current study with other studies in terms of absolute values. However studies in Australia and elsewhere (Cucchiella and D'Adamo 2012; Peng, Lu and Yang 2013; Kannan et al. 2006) have confirmed that the use of roof top solar PV system has proved to be an effective strategy to mitigate the environmental impacts of fossil fuel based electricity.

Since the measurement of electricity consumption for cooling, lighting and home appliances of the house through the metering system is beyond the scope of this research, the credit associated with the reduction in electricity consumption due to the use of roof top solar PV has been given to home appliances at the first instance followed by the lighting.

The integration of grid connected roof top solar PV (1kW$_p$ to 3kW$_p$) would reduce both GHG emissions and EE consumption of a typical reference house in Perth by 15% to 43%, and 14% to 41% of the life cycle GHG emissions and EE consumption respectively.

4.4.2 Integration of roof top solar water heater with gas based water heater

Solar water heater is considered as an ecological method for domestic water heating which not only reduces the demand for fossil fuel based energy but also reduces GHG emissions (De Laborderie et al. 2011; Hernandez and Kenny 2012). Australia’s annual average solar radiation is more than 14MJ/m^2, which shows that there is a high potential for solar water heater application for houses (ABARE 2010). However till 2014, only around 900,000 (10% of the total housing stock in Australia) houses in Australia had installed solar water heaters (CEC 2014; BREE 2014).

The flat plate type solar water heater with thermosiphon circulation, that is most commonly used type in Australia (Lovegrove and Dennis 2006; DRET 2013) has been considered as a cleaner production strategy to reduce the demand for natural gas for a storage type gas hot water system of a typical reference house in Perth.

The hot water module in AccuRate housing energy rating tool that consists of the information on solar radiation and reticulated water temperature for all climate zones 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 20º has been considered for simulation as the same matches with the roof pitch of the house thus avoiding any additional requirements of supporting structure (Riedy, Milne and Ryan 2013).

A simulation has been carried out for all seven solar collector azimuths (0°, 30°, 60°, 90°, 270°, 300° and 330°) while maintaining the collector slope at 20º. From the simulation results, it is found that a maximum amount of life cycle gas saving would be obtained for positioning the collector at an azimuth angle of 330° for the house in Perth (Figure 4.16). The amount of energy in the form of natural gas that can be conserved due to the integration of solar water heater for water heating during the life cycle of the house in Perth would be between 616GJ to 737GJ (i.e. 54% to 65% of total life cycle energy demand for water heating). Considering the maximum energy saving potential, the solar water heater integrated with gas based storage type water heater and a solar collector with an azimuth angle of 330°, the recommended azimuth angle range (Riedy, Milne and Ryan 2013) has been utilized for further analysis.

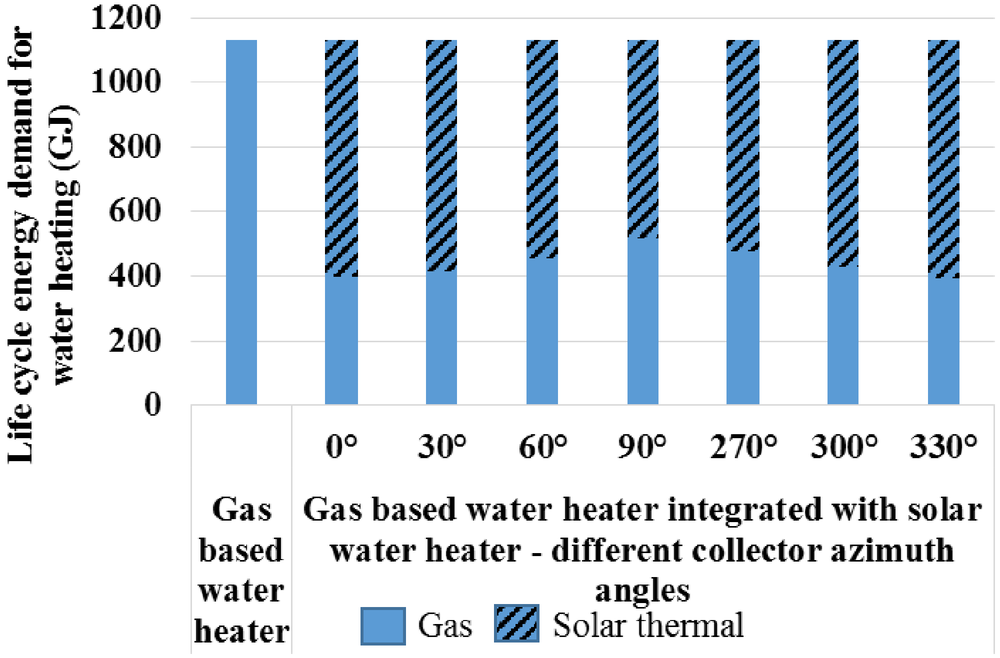


Figure 4.16 Life cycle energy demand for water heating with and without solar water heater

The revised operational energy inputs for water heating have been inserted into SimaPro for calculating the GHG emissions and EE consumption impacts due to the integration of roof top solar water heater and to assess the viability of this cleaner production strategy.

Due to integration of roof top solar water heater, the reduced GHG emissions during use stage of a typical reference house in Perth would be 386tonnes CO_2 e- (i.e. 94% of the GHG emissions during use stage without solar water heater (Figure 4.17)

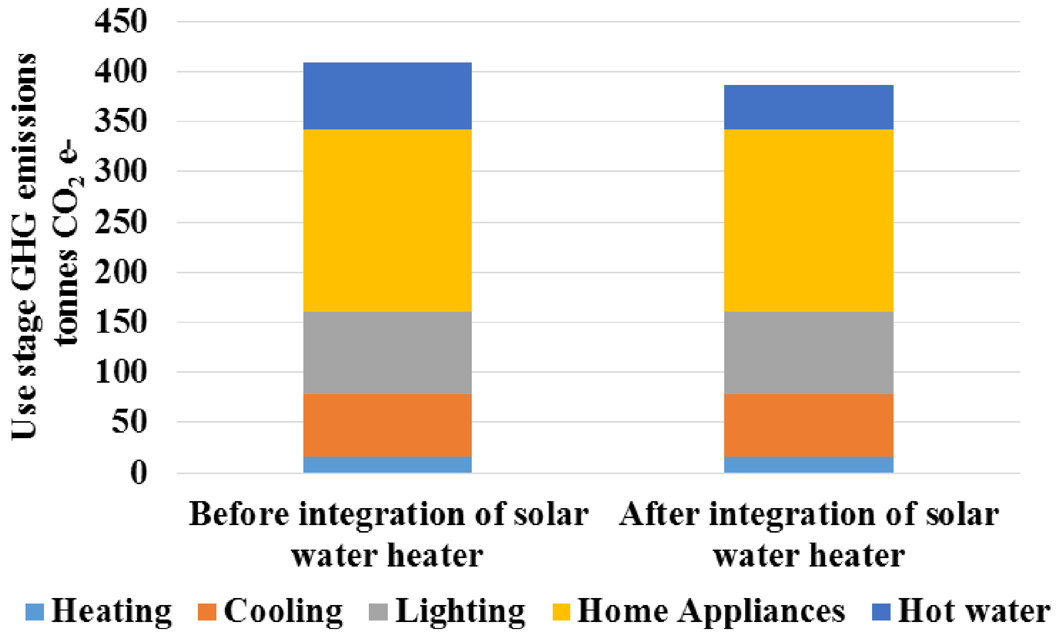


Figure 4.17 Use stage life cycle GHG emissions before and after integration of roof top solar water heater

Similar to GHG emissions, the reduced EE consumption during use stage of a typical reference house due to the integration of roof top solar water heater would be 5.09TJ (i.e. 89% of the EE consumption during use stage without solar water heater) (Figure 4.18).

Similar to roof top solar PV system, GHG emissions and EE consumption mitigation values associated with the roof top solar water heater could potentially be influenced by the technology (e.g. type of solar collector, auxiliary fuel, collector orientation, location specific solar radiation, module efficiency, and the energy mix of the country where they are manufactured and hence there is limited opportunity for comparison of results of this study with other studies in terms of absolute values.

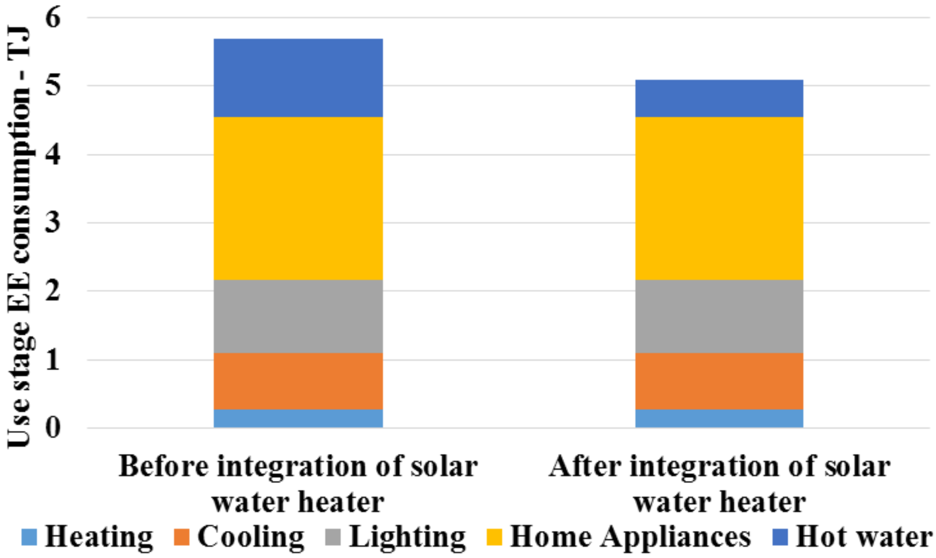


Figure 4.18 Use stage life cycle EE consumption before and after integration of roof top solar water heater

However, recent Australian and international studies have confirmed that the use of roof top solar water heater has proved to be an effective strategy to mitigate the environmental impacts associated with the use of fossil fuel based energy for water heating (Zambrana-Vasquez et al. 2015; Koroneos and Nanaki 2012; Crawford et al. 2003). A recent Australian study reported that the GHG emissions reduction potential of a roof top solar water heater is relatively low compared to roof top solar PV system as the former substitutes the natural gas whose emission factor is lower than one fourth of the emission factor of grid electricity substituted by the latter (Ren, Chen and Wang 2011).

The integration of solar water heater with gas based water heater would reduce the GHG emissions and EE consumption of a typical reference house in Perth by 5%, and 9% of the life cycle GHG emissions and EE consumption respectively.

4.4.3 Optimum orientation of a house to gain from natural ventilation

An easily achievable GHG emissions mitigation (or fetch the low hanging fruit concept) by cleaner production strategy has already been considered at the initial energy modelling stage to select the optimum orientation of a typical reference house in Perth based on its life cycle energy demand (Section 4.2.2). In order to estimate the variation in the GHG emissions and EE consumption due to different orientations of a typical reference house in Perth and to assess the implications of this cleaner production strategy, heating and cooling energy inputs for all 8 orientations (Table 4.2) have been inserted into SimaPro software.

Table 4.2 reveals that the orientation of the house has an influence on the operational energy demand for heating and cooling, which may vary up to 8.3% of the operational energy demand from an optimum (East) to worst (South) orientation in Perth. GHG emissions during use stage could increase by up to 39.52tonnes CO_2 e- (i.e. 10% of the use stage GHG emissions of East facing house) due to change in orientation (Figure 4.19). The operational energy for heating and cooling of a typical reference house in Perth vary from 243GJ to 368GJ, and 243GJ to 377GJ for optimum and worst orientations respectively, while the corresponding GHG emissions vary from 14 to 21tonnes CO_2 e-, and 62 to 96tonnes CO_2 e- respectively.

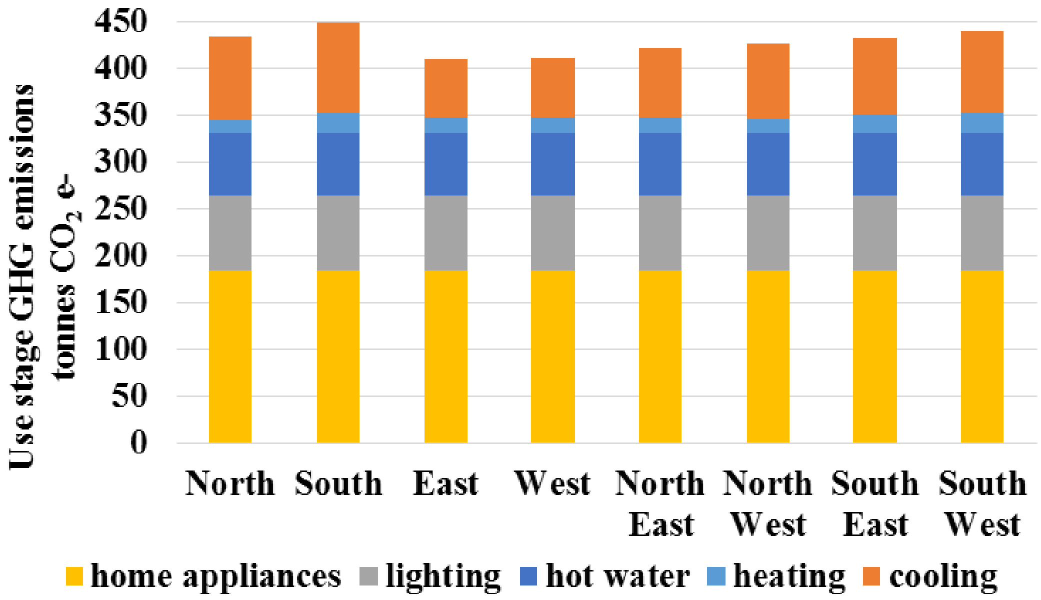


Figure 4.19 Use stage life cycle GHG emissions of a typical reference house in Perth for 8 orientations

Similar to GHG emissions, the house orientation has a significant bearing on the EE consumption. The EE consumption during use stage could increase by up to 0.54TJ (i.e. up to 9% of the use stage EE consumption of east facing house) due to change in orientation (Figure 4.20) from optimum to worst. The EE consumption associated with the operational energy for heating and cooling could vary from 0.25 to 0.38TJ, and 0.81 to 1.25TJ respectively due to the change in orientation from optimum to worst.

The finding is similar to other Australian studies which confirmed that the East or West facing house in Perth with properly planned living spaces will require minimum mechanical heating, and cooling and thus will improve the energy efficiency of the house (Peterkin 2009; Newton, Tucker and Ambrose 2000).

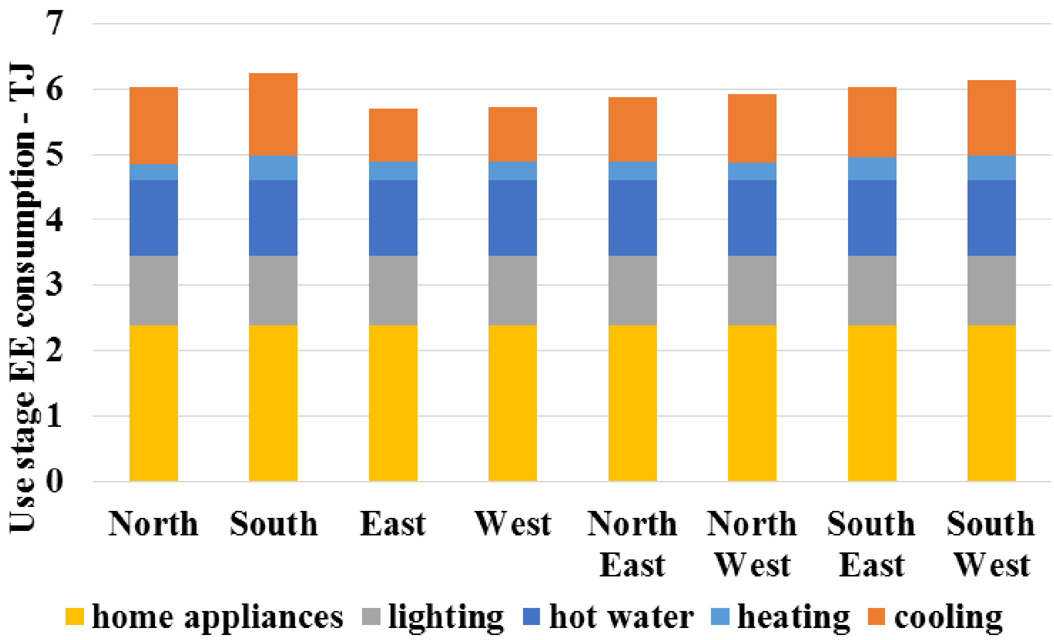


Figure 4.20 Use stage life cycle EE consumption for 8 orientations

GHG emissions and EE consumption of a typical reference house in Perth could rise up to 8.46%, and 8.31% of the life cycle GHG emissions, and EE consumption respectively due to change from optimum to worst orientation.

4.4.4 Replacing building envelope elements with alternative elements

The replacements of single glazed windows with double glazed windows, concrete roof tiles with terracotta tiles, and metal sheet and clay brick walls with alternative walls including the substitution of virgin materials with by-products and recyclates have been considered as cleaner production strategy to mitigate the GHG emissions and EE consumption impacts associated with mining to material production stage. These important building elements together constitute the building envelope (Sadineni, Madala and Boehm 2011), which separates the indoor environment of the house from the outdoor environment and is influenced by various technological, and climatic factors while satisfying the functional and structural requirements (Iwaro and

Mwasha 2013; Zeng et al. 2011), and hence the alternative building elements have been grouped together for further analysis as described in Chapter 3 (section 3.4).

Total 53 alternative envelope combinations have been developed using the alternative wall, window, and roof options while maintaining the same architectural features for all alternative envelope options (Figure 4.21).

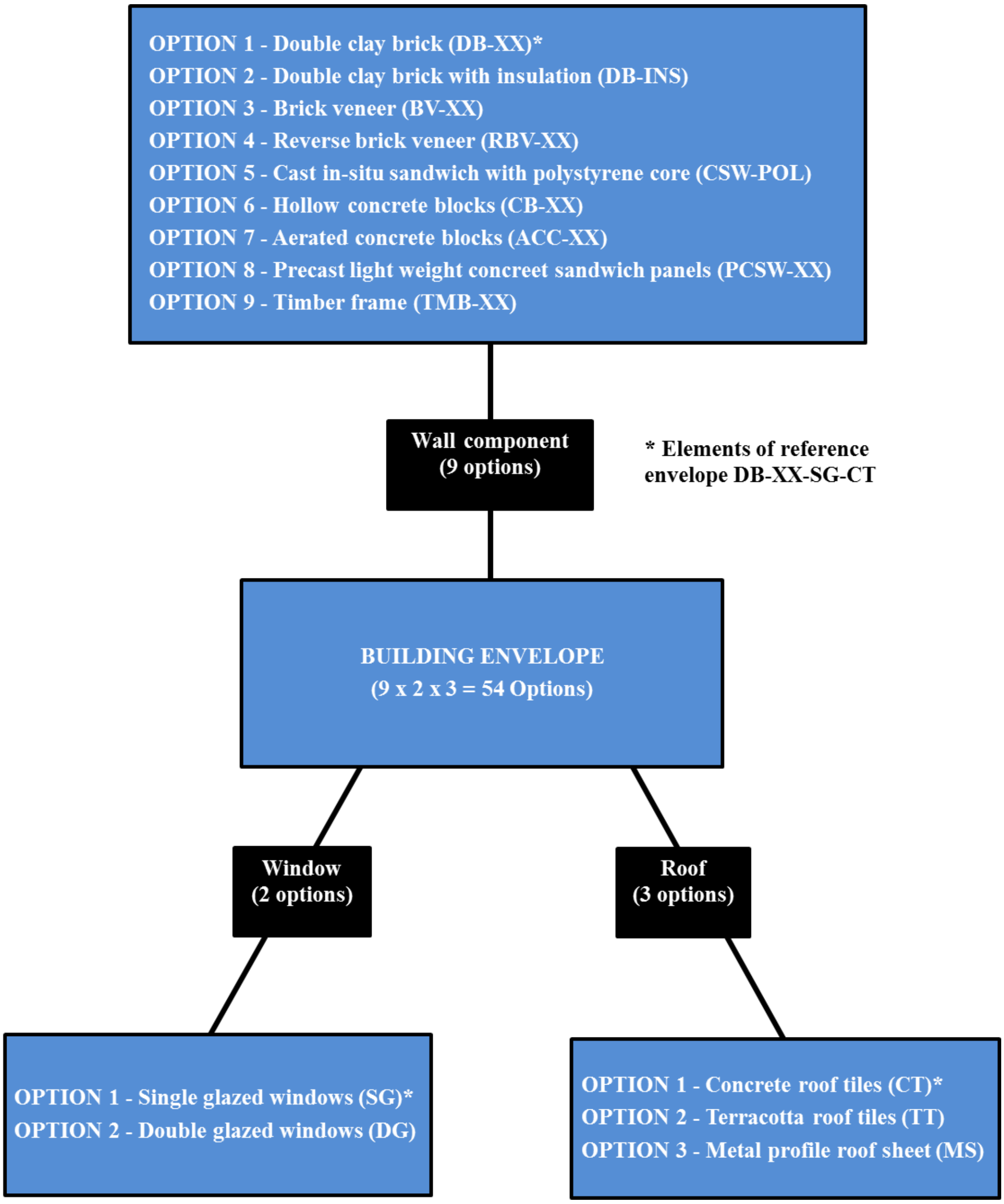


Figure 4.21 Alternative envelope options consisting of wall, window, and roof elements

The bulk of the operational energy required by a house is utilized to compensate the thermal energy losses or gains through the building envelope, and so any improvements in thermal performance of envelope materials provide significant energy and GHG emissions reduction opportunities (Bambrook, Sproul and Jacob 2011; Sadineni, Madala and Boehm 2011; Lai and Wang 2011). The increased amount of EE consumption due to the use of some high thermal performance materials in the building envelope can be compensated through savings of operational energy during use stage (Verbeeck and Hens 2010). The placement of thermal mass and its insulation are the most important elements for reducing operational energy demand in order to achieve the energy efficiency (Gregory et al. 2008).

Any attempt to replace the building envelope materials of a typical house in Perth, which are around 51% of the gross weight of all building materials used for the construction of the house (Table 4.1) requires the update of life cycle inventory with new materials and associated energy consumptions. Some of these materials may have to be procured from different sources thus the transportation requirement may alter with new inputs and transport distances (Equation 3.2). The change of envelope material may have impacts on the energy required during construction and end of life demolition including on transportation requirement for end of life disposal. In order to estimate the GHG emissions and EE consumption impacts of the alternative envelope options and to evaluate the viability of this cleaner production strategy, the life cycle assessment process has been carried out for 53 alternative options as has been done for a reference house (DB-XX-SG-CT) in Perth.

The material and energy inputs associated with mining to material production till the end of life demolition and disposal stages for all alternative envelope options for a typical reference house in Perth have been estimated while complying with the deemed to satisfy design requirements of Australian Building Code Board (ABCB 2015a) and satisfying the functional performance. Secondly, the new envelope material data has been utilized for estimation of heating and cooling operational energy demand of a typical house in Perth for all envelope options using AccuRate software. The building envelope has no influence on the operational energy demand for lighting, hot water, and home appliances as described in Section 3.3.2.1.4 and hence they are considered to be unchanged. Finally, the LCI data for each envelope option is inserted into SimaPro to calculate their GHG emissions and EE consumption impacts.

4.4.4.1 Estimation of revised material and energy inputs during mining to material production, transport, construction, use and the end of life demolition and disposal stages

Mining to material production stage

The material inputs for all alternative envelopes during mining to material stage have been estimated using Equation 3.1 following architectural design and structural plans of the reference house in Perth. The detailed Bill of materials for all alternative envelope options are presented in Table D.14 (Appendix D). The gross weights of all building materials for alternative envelope options including reference envelope are presented in Table 4.5. Gross weights of the building materials of 50 alternative envelope options are up to 41% less than the gross weight of building materials of the reference envelope, while the gross weights of only 3 alternative envelope options are more than the reference envelope (Figure 4.22).

Table 4.5 Gross weight of all building materials for the construction of the house for alternative envelope options

Options	Gross weight of all building materials (tonnes)					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	261.45*	258.55	248.56	261.94	259.04	249.05
DB-INS	261.65	258.75	248.76	262.15	259.24	249.25
BV-XX	201.73	198.83	188.84	202.22	199.32	189.33
RBV-XX	247.72	244.81	234.83	248.21	245.31	235.32
CB-XX	232.61	229.71	219.72	233.11	230.20	220.21
ACC-XX	189.33	186.43	176.44	189.83	186.92	176.93
PCSW-XX	181.12	178.21	168.22	181.61	178.70	168.71
TMB-XX	166.79	163.88	153.89	167.28	164.38	154.39
CSW-POL	213.98	211.08	201.09	214.47	211.57	201.58

* Reference envelope option

The main reason for the variation in the gross weights of different envelopes is due to the use of materials having different densities (e.g. brick-1950kg/m^3, concrete-

2400kg/m^3, timber-900kg/m^3) and their corresponding volumes along with associated sundry materials to achieve same architectural and structural requirements as the reference house (Monahan and Powell 2011). For example, 27.88m^3 of concrete will be needed for wall element CSW-POL, whereas 48.52m^3 of bricks will be required for wall elements DB-XX, and DB-INS and 17.68m^3 of timber will be required for TMB-XX wall element for the construction of a typical reference house in Perth. The difference in terms of materials and gross weight would affect the thermal performance of the building envelope, and cause variability in GHG emissions and EE consumption as discussed in following sections.

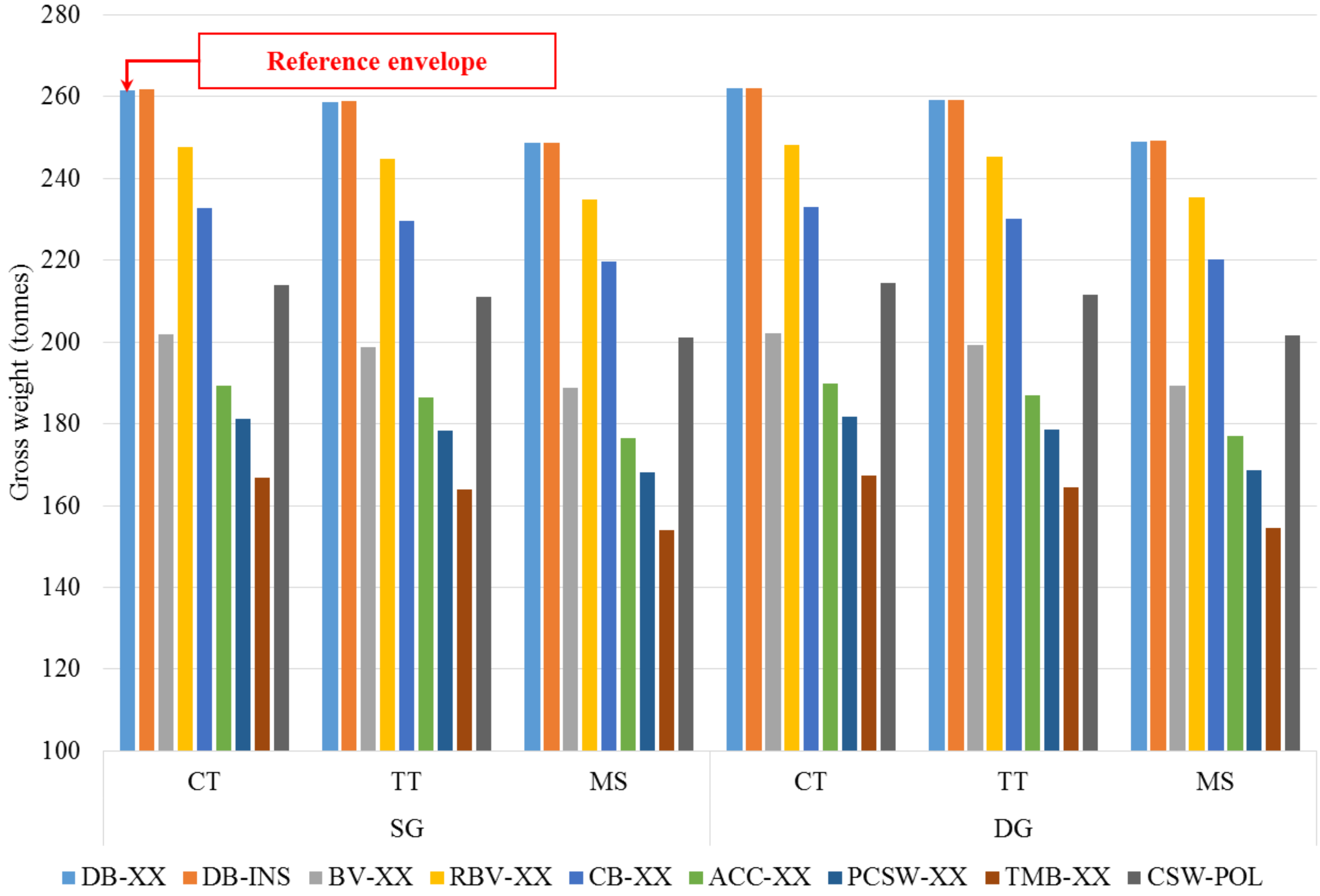


Figure 4.22 Gross weight of building materials for all envelope options

Transportation stage

The material inputs for alternative envelope options not only vary significantly but they are sourced from different locations. As a result, tonnes-km values (tkm) of these materials for different envelope options will vary the transportation of building materials to the construction site during the construction stage of the house in Perth has been estimated using Equation 3.2 and is presented as tkm in Table 4.6. The detailed break-down of transportation of each material for alternative envelope options are presented in Table D.15 (Appendix D). The tkm values for the building materials for 50 alternative envelopes are up to 40% less than the tkm of building materials for the reference envelope (Figure 4.23). The same 3 envelope options, which had more gross weights also, have more tkm than reference envelope. Therefore the use of materials of different mass causes this variation in tkm (e.g. brick-94.62tonnes, concrete-66.91tonnes, concrete blocks-63.62tonnes, ACC blocks-26.5tonnes, and timber-15.91tonnes) and their corresponding distances from the source to the construction site (Li et al. 2013; Cole 1998).

Table 4.6 tkm of all building materials for the construction of the house for alternative envelope options

Options	**Transportation of materials to construction site (tkm)**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	8,932.62*	8,845.50	8,545.81	8,947.37	8,860.25	8,560.56
DB-INS	8,938.63	8,851.51	8,551.82	8,953.39	8,866.27	8,566.58
BV-XX	6,832.75	6,745.63	6,445.94	6,847.51	6,760.39	6,460.70
RBV-XX	8,458.83	8,371.71	8,072.02	8,473.59	8,386.47	8,086.78
CB-XX	8,073.82	7,986.70	7,687.00	8,088.57	8,001.45	7,701.76
ACC-XX	6,614.30	6,527.18	6,227.49	6,629.06	6,541.94	6,242.25
PCSW-XX	6,228.54	6,141.42	5,841.73	6,243.30	6,156.18	5,856.49
TMB-XX	5,722.74	5,635.62	5,335.93	5,737.50	5,650.38	5,350.69
CSW-POL	7,138.49	7,051.37	6,751.68	7,153.25	7,066.13	6,766.43

***** Reference envelope

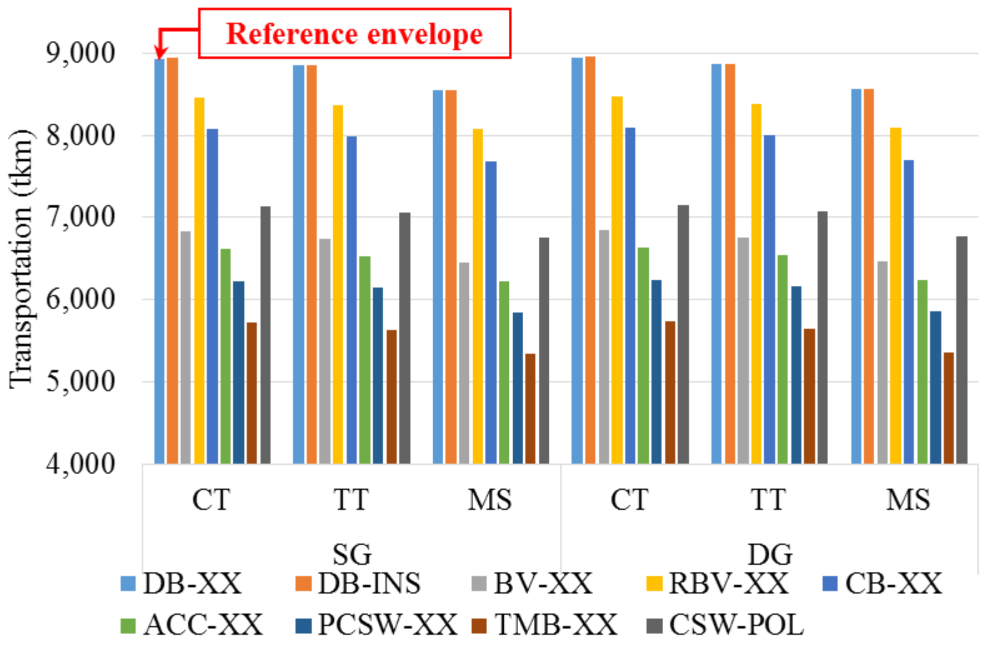


Figure 4.23 tkm of building materials for all envelope options

Construction stage

The energy consumption for machinery (e.g. bobcat, compactor, loader, and forklift) and tools required for the construction of the house for alternative envelope options has been estimated using Equation 3.3 and is presented in terms of equivalent energy (GJ) in Table 4.7.

Table 4.7 Equivalent energy consumption for plant, equipment, and hand tools during construction stage for alternative envelope options

Options	**Equivalent energy consumption during construction stage (GJ)**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	20.83*	20.83	19.49	20.83	20.83	19.49
DB-INS	22.19	22.19	20.85	22.19	22.19	20.85
BV-XX	32.36	32.36	31.02	32.36	32.36	31.02
RBV-XX	27.65	27.65	26.31	27.65	27.65	26.31
CB-XX	27.65	27.65	26.32	27.65	27.65	26.32
ACC-XX	20.83	20.83	19.49	20.83	20.83	19.49
PCSW-XX	41.16	41.16	39.83	41.16	41.16	39.83
TMB-XX	41.23	41.23	37.86	41.23	41.23	37.86
CSW-POL	14.09	14.09	12.74	14.09	14.09	12.74

***** Reference envelope

The detailed break-down of energy estimation for plants, equipment, and hand tools required the construction of a typical house for alternative envelope options is presented in Table D.16 (Appendix D).

The energy required during the construction stage of a typical reference house in Perth for 36 alternative envelope options is up to 98% more than the reference envelope, while the construction stage for 10 alternative envelope options require up to 39% less energy compared to reference envelope. The energy required during construction stage for 7 envelopes is same as the reference envelope. The main reason for the variation in the energy requirement for construction stage of different envelopes is due to the use of different construction methods and type of tools including their duration of use (Guggemos and Horvath 2005; Yan et al. 2010). For example, the mortar mixer is used for brick walls and rendering, while the shotcrete pump is required for cast in-situ concrete sandwich walls. On the other hand, timber walls require the use of hand tools for a longer duration, but in the case of concrete block, the lifting requirement is more due to the weight of individual block compared to clay bricks.

In the case of disposal of construction waste, the tkm of construction waste from the construction site to landfill during the construction stage of the house in Perth for all alternative envelope options have been estimated using Equation 3.2 and are presented in Table 4.8.

Table 4.8 tkm for disposal of construction waste for alternative envelope options

Options	**Transportation for disposal of construction waste during construction stage (tkm)**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	2,840.88*	2,840.88	2,765.88	2,840.88	2,840.88	2,765.88
DB-INS	2,840.88	2,840.88	2,765.88	2,840.88	2,840.88	2,765.88
BV-XX	2,090.88	2,090.88	2,015.88	2,090.88	2,090.88	2,015.88
RBV-XX	2,465.88	2,465.88	2,390.88	2,465.88	2,465.88	2,390.88
CB-XX	2,840.88	2,840.88	2,765.88	2,840.88	2,840.88	2,765.88
ACC-XX	2,465.88	2,465.88	2,390.88	2,465.88	2,465.88	2,390.88
PCSW-XX	2,090.88	2,090.88	2,015.88	2,090.88	2,090.88	2,015.88
TMB-XX	2,090.88	2,090.88	2,015.88	2,090.88	2,090.88	2,015.88
CSW-POL	1,903.38	1,903.38	1,828.38	1,903.38	1,903.38	1,828.38

***** Reference envelope

The detailed break-down of tkm of construction waste for all alternative envelope options is presented in Table D.16 (Appendix D).

The tkm for the construction waste disposal of a typical reference house in Perth for 42 alternative envelope options is up to 36% less than the tkm for the reference envelope, while 11 alternative envelope options have same tkm value as that for the reference envelope. The main reason for the variation in the tkm of construction waste disposal for different envelopes is due to the generation of different amount of construction, and packaging waste for different materials during handling and construction activities. In addition, some building materials are more susceptible to damage during the construction process as Carre (2011b) found that the construction waste is proportional to the mass of the materials used for the construction. For example, in the case of wall elements using clay bricks, a considerable amount of bricks is wasted due to improper handling and cutting to suit to architectural requirements (Forsythe and Máté 2007; Crossin, Hedayati and Clune 2014).

The end of life demolition and disposal stage

Similar to the construction stage, the energy requirement for plants and equipment during the end of life demolition stage has been estimated using Equation 3.3. Table 4.9 presents the energy requirement for plants and equipment during the end of life demolition stage in terms of equivalent energy (GJ). The detailed break-down of energy consumption for plants, and equipment required for alternative envelope options is presented in Table D.17 (Appendix D).

The energy required for plants and equipment during the end of life demolition stage of a typical reference house in Perth for 36 alternative envelope options is up to 62% more than the energy required for the reference envelope, while 10 alternative envelope options require 15% less energy compared to that for the reference envelope. The energy required for the end of life demolition stage for 7 alternative envelopes is same as the reference envelope. The main reason for the variation in energy required for demolition activities is due to the difference in mass and nature of each material and material separation from composite elements (Winistorfer et al. 2005; Scheuer, Keoleian and Reppe 2003). For example, brick walls require less energy for demolition than the concrete walls due to relatively weaker mortar joints. Similarly, timber walls or composite elements (e.g. brick veneer, reverse brick veneer, light weight concrete panels) walls require more energy for separation of the materials and loading into trucks than the brick walls where no separation is needed.

Table 4.9 Equivalent energy consumption for plant, and equipment during the end of life demolition stage for alternative envelope options

Options	**Equivalent energy consumption for plant, and equipment for demolition during end of life stage (GJ)**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	22.72*	22.72	22.04	22.72	22.72	22.04
DB-INS	22.72	22.72	22.04	22.72	22.72	22.04
BV-XX	24.08	24.08	23.4	24.08	24.08	23.4
RBV-XX	24.08	24.08	23.4	24.08	24.08	23.4
CB-XX	26.73	26.73	26.05	26.73	26.73	26.05
ACC-XX	20.07	20.07	19.39	20.07	20.07	19.39
PCSW-XX	31.43	31.43	30.75	31.43	31.43	30.75
TMB-XX	23.46	23.46	22.78	23.46	23.46	22.78
CSW-POL	36.74	36.74	36.06	36.74	36.74	36.06

***** Reference envelope

Similar to tkm for building materials and disposal of construction waste, the disposal of demolition waste at the end of life stage has been estimated using Equation 3.2. Table 4.10 presents the tkm for the end of life disposal of demolition waste to a landfill site. The detailed break-down of tkm of demolition waste to recyclers and landfill site for alternative envelope options is presented in Table D.17 (Appendix D).

The tkm for the demolition waste disposal of a typical reference house in Perth for 50 alternative envelope options is up to 41% less than the reference envelope, while only 3 alternative envelope options have higher tkm compared to the reference envelope. The main reason for the variation in the tkm of demolition waste for different envelopes is due to the different mass of building materials used during the construction of the house (Guggemos and Horvath 2005; Ramesh, Prakash and Shukla 2013).

Table 4.10 tkm for disposal of demolition waste for alternative envelope options

Options	Transportation for disposal of demolition waste during end of life stage (tkm)					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	7,189.96*****	7,110.10	6,835.38	7,203.48	7,123.62	6,848.91
DB-INS	7,195.47	7,115.61	6,840.90	7,209.00	7,129.14	6,854.43
BV-XX	5,547.59	5,467.73	5,193.01	5,561.11	5,481.25	5,206.54
RBV-XX	6,812.26	6,732.40	6,457.68	6,825.78	6,745.92	6,471.21
CB-XX	6,396.89	6,317.03	6,042.31	6,410.42	6,330.56	6,055.83
ACC-XX	5,206.71	5,126.85	4,852.13	5,220.24	5,140.38	4,865.66
PCSW-XX	4,980.69	4,900.83	4,626.12	4,994.22	4,914.36	4,639.64
TMB-XX	4,586.67	4,506.81	4,232.10	4,600.20	4,520.34	4,245.62
CSW-POL	5,884.44	5,804.58	5,529.86	5,897.96	5,818.10	5,543.39

***** Reference envelope

Use stage – operational energy

The operational energy consumption for heating and cooling during use stage of a house is highly influenced by the thermal performance and characteristics (e.g. material density, insulation, windows, dimensions, and orientation) of the envelope materials and climatic conditions (Ross Maher 2011; Aldawi, Alam, Date, et al. 2013; Gregory et al. 2008; Lam et al. 2005; Iwaro and Mwasha 2013), which necessitates the re-estimation of the heating and cooling energy demand for the reference house for all alternative envelope options. The energy demand for home appliances, hot water, and lighting of the house is not affected by the properties of the building envelope (Ross Maher 2011; Swan and Ugursal 2009) hence they are considered to be unchanged for the house for reference envelope as well as for alternative envelope options.

Similar to reference house (DB-XX-SG-CT), the energy demand for heating, and cooling has been estimated using AccuRate (V2.3.3.13SP2) software. The revised material inputs (e.g. insulation, concrete blocks, ACC blocks, terracotta roof tiles, double glazed windows) for all alternative envelope elements (e.g. wall, window, roof) have been inserted into AccuRate software. The East facing house has been utilized for model simulation for all alternative envelope options to estimate the annual energy demand for heating and cooling. Similar to the reference envelope, the heating and cooling energy demand for 50 years life cycle of a typical reference house in Perth for all alternative envelope options has been calculated by multiplying the annual energy demand per m^2 of conditioned floor area of the house by total conditioned floor area of house and then multiplied by the number of years and is presented in Table 4.11.

The life cycle operational energy demand for heating and cooling during use stage of a typical reference house in Perth for 37 alternative envelope options is up to 49% less than the reference envelope, while the life cycle operational demand for heating and cooling for 16 alternative envelope options is more than that of the reference envelope (Figure 4.24).

Table 4.11 Life cycle operational energy demand for heating and cooling for alternative envelope options

Options	**Life cycle operational energy demand for heating and cooling (GJ)**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	521.47*	519.94	519.17	450.82	450.05	452.35
DB-INS	364.03	362.50	364.03	299.52	300.29	301.06
BV-XX	466.18	463.10	466.94	377.09	374.02	380.93
RBV-XX	369.41	365.57	368.64	304.13	301.82	304.90
CB-XX	866.30	864.77	866.30	781.06	777.98	778.75
ACC-XX	384.77	382.46	384.77	312.58	309.50	313.34
PCSW-XX	636.67	634.37	636.67	539.90	536.06	539.14
TMB-XX	569.09	566.78	574.46	477.70	477.70	482.30
CSW-POL	326.40	325.63	327.17	267.26	263.42	268.80

***** Reference envelope

The main reason for the variation in the life cycle operational energy demand for heating and cooling for alternative envelope options is due to the fact that the envelopes consisting of key elements such as clay bricks, concrete, insulation, timber, aerated concrete, light weight concrete, fibre board, metal sheet, terracotta, aluminium, and glass demonstrate different levels of thermal performance under the same geometrical design and climatic conditions. This is due to the inherent thermal mass of the materials (i.e. the ability of material to absorb and store heat energy) (Baggs and Mortensen 2006), and the overall heat transfer coefficient of materials (i.e. U value)

(Table 4.12). The U value refers to the rate of heat transfer due to conduction, convection, and radiation through a given thickness of the material (Al-Homoud 2005). Also, the thickness of material and the degree of insulation controls the rate at which heat is absorbed and released through thermal mass.

Table 4.12 Thermal mass and U values of various envelope elements

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

*Source: (AccuRate 2015; Reardon, McGee and Milne 2013)

This study finds that the CSW-POL-DG-TT envelope option comprising of cast in-situ concrete sandwich walls (CSW-POL) of high thermal mass (i.e. with a very low U value of 0.36W/m^2K), double glazed windows (i.e. with a moderate U value of 4.8W/m^2K), and terracotta roof tiles (i.e. moderate thermal mass and medium U value of 5.47W/m^2K) has the lowest life cycle operational energy demand for heating and cooling (263.42GJ). On the other hand, the envelope CB-XX-SG-MS comprising of hollow concrete block wall (CB-XX) of low thermal mass (i.e. with a high U value of 2.7W/m^2K,) single glazed windows (i.e. very high U value of 6.7W/m^2K), and metal sheet roof of very low thermal mass (i.e. very high U value of 6.3W/m^2K) has the highest life cycle operational energy demand for heating and cooling (866.30GJ).

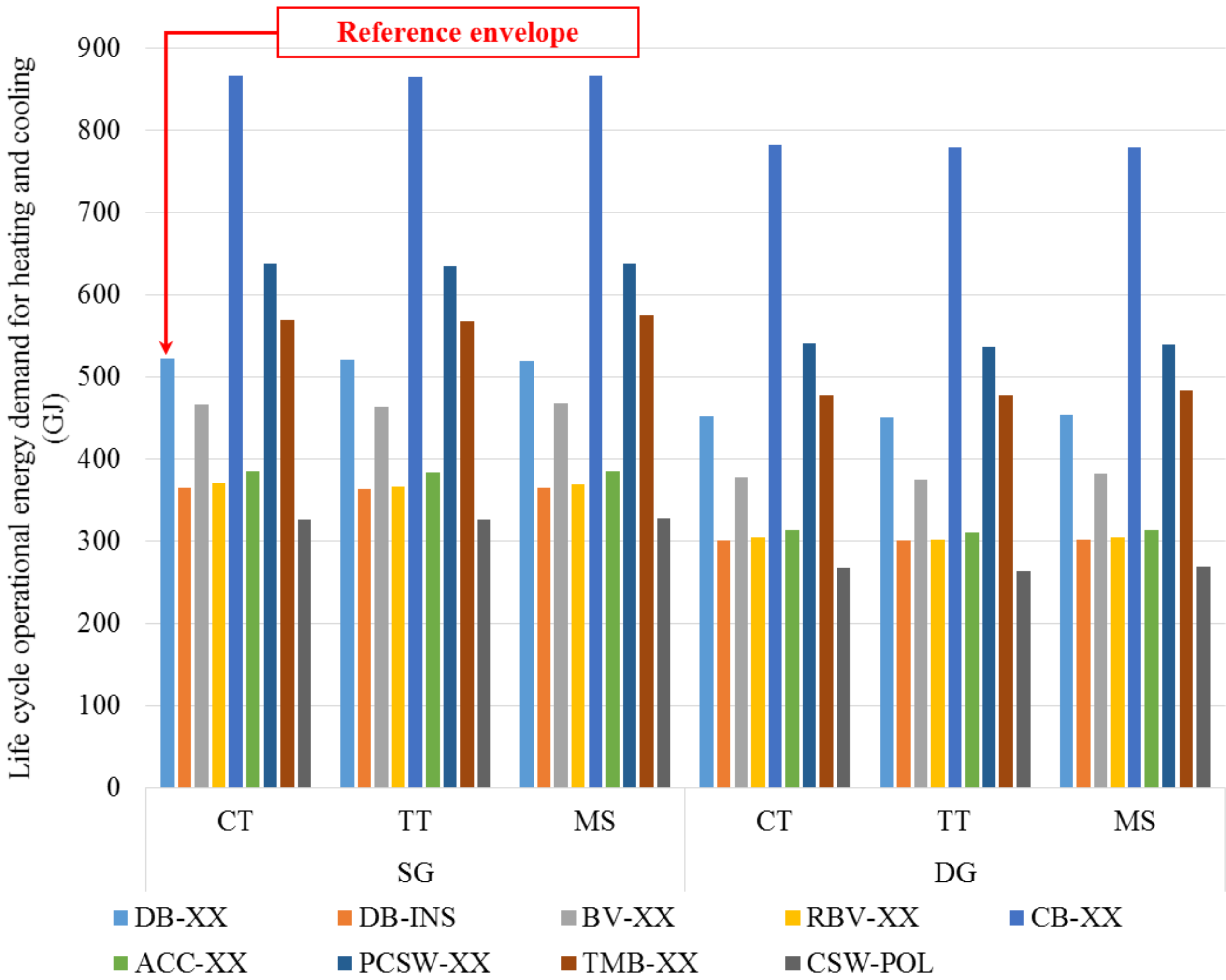


Figure 4.24 Life cycle operational energy demand for heating and cooling for all alternative envelope options

As compared to the reference envelope (DB-XX-SG-CT), the life cycle operational energy demand for heating and cooling for envelope option CSW-POL-DG-TT has reduced by 49.5%, while the gross weight also has reduced by 19%. On the other hand, the life cycle operational energy demand for heating and cooling in the case of envelope option CB-XX-SG-MS has increased by 66%, even though the gross weight has reduced by 16%. This demonstrates that the gross weight has no influence on the operational energy for heating and cooling.

This research confirms that the change in roof material does not appear to affect the thermal performance of the envelope significantly and so the life cycle operational energy demand for heating and cooling (±5GJ) because the U values of these three types of roof vary slightly and in all cases, the roof space is insulated (Crawford, Czerniakowski and Fuller 2010; Reardon and Downton 2013a).

The replacement of single glazed (U value of 6.7W/m2K) windows with double glazed (U value of 4.8W/m2K) windows appear to offer a wide range of savings for alternative envelope options. For example, the life cycle operational energy demand for heating and cooling reduces from 58 to 98 GJ due to the replacement of single glazed window with a double glazed window for different wall elements of the envelope. This variation in energy saving potential is because of the fact that the performance of the window as an element of a house envelope does not only depend on its own thermal properties but it also depends on other multiple factors, including architectural design (i.e. location of the windows), and climatic conditions which have direct impacts on the performance of windows (Peter Lyons, Chris Reardon and Tracey Gramlick 2013; Aldawi, Alam, Date, et al. 2013).

For similar architectural design and climatic conditions for all envelope options, the performance of windows is controlled by its own U value and the thermal properties of wall elements. The replacement of single glazed windows with double glazed windows has been found to be more beneficial for wall elements (BV-XX, CB-XX, PCSW-XX, and TMB-XX) of relatively lower thermal mass, while in the case of the wall elements (CSW-POL, RBV-XX, DB-INS DG, and ACC-XX) of relatively higher thermal mass, the replacement appears not to make significant change. Another study reported that the energy saving potential of the use of double glazed windows vary significantly with wall properties and the placement of the window that is governed by the type of wall system (Singh and Garg 2009). To determine the total life cycle operational energy demand of a typical reference house in Perth for all alternative envelope options, the heating and cooling energy for all alternative envelope options over a lifespan of 50 years has been added to the operational energy for home appliances, hot water, and lighting of the reference house, which remains same for all alternative envelope options (Table 4.13).

Table 4.13 Life cycle operational energy demand for heating, cooling, lighting, hot water, and home appliances of a typical reference house for alternative envelope options

Options	Life cycle operational energy demand (GJ)					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	2,689.32*	2,687.79	2,687.02	2,618.67	2,617.90	2,620.20
DB-INS	2,531.88	2,530.35	2,531.88	2,467.37	2,468.14	2,468.91
BV-XX	2,634.03	2,630.95	2,634.79	2,544.94	2,541.87	2,548.78
RBV-XX	2,537.26	2,533.42	2,536.49	2,471.98	2,469.67	2,472.75
CB-XX	3,034.15	3,032.62	3,034.15	2,948.91	2,945.83	2,946.60
ACC-XX	2,552.62	2,550.31	2,552.62	2,480.43	2,477.35	2,481.19
PCSW-XX	2,804.52	2,802.22	2,804.52	2,707.75	2,703.91	2,706.99
TMB-XX	2,736.94	2,734.63	2,742.31	2,645.55	2,645.55	2,650.15
CSW-POL	2,494.25	2,493.48	2,495.02	2,435.11	2,431.27	2,436.65

***** Reference envelope

The revised material and energy data for all alternative envelope options has been utilized for estimation of GHG emissions and EE consumption.

4.4.4.2 Estimation of GHG emissions and EE consumption of alternative envelopes in Perth

Once the inventories have been developed for all alternative envelopes, as discussed in the aforementioned sections, the material and energy inputs for mining to material production, transportation, construction, use, and end of life demolition and disposal for alternative envelope options for the construction of a reference house in Perth have been entered into SimaPro software to estimate the GHG emissions and EE consumption saving potential due to replacement of conventional building envelope with alternative building envelopes.

Total GHG emissions

The stage wise breakdown of life cycle GHG emissions of a reference house in Perth for alternative envelope options is presented in Table D.18 (Appendix D). The results show that the life cycle GHG emissions of a reference house in Perth for 53 alternative envelope options vary from a minimum of 428tonnes CO_2 e- for CSW-POL-DG-CT option (cast in-situ sandwich wall with polystyrene insulation core, double glazed windows and concrete roof tiles), which is 8.3% less than the reference envelope option to a maximum of 530tonnes CO_2 e- for PCSW-XX-SG-MS option (pre-cast light weight concrete sandwich wall with single glazed windows and metal sheet roof), which is 13.5% more than the that of the reference envelope option (467.1tonnes CO_2 e- for DB-XX-SG-CT or clay brick wall without insulation, single glazed windows and concrete roof tiles) (Table 4.14).

Table 4.14 Life cycle GHG emissions for alternative envelope options

Options	**Life cycle GHG emissions tonnes CO_2 e-**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	467.10*	467.63	468.08	453.81	454.59	455.83
DB-INS	449.61	450.05	451.09	437.95	438.98	439.83
BV-XX	471.39	471.59	473.07	454.21	454.41	456.77
RBV-XX	455.91	455.91	457.19	444.05	444.45	445.73
CB-XX	511.03	511.47	512.67	494.38	494.43	495.43
ACC-XX	470.90	471.29	472.37	457.58	457.78	459.25
PCSW-XX	528.51	528.75	529.99	509.52	509.52	510.96
TMB-XX	480.82	481.21	483.38	463.20	464.18	465.57
CSW-POL	438.35	439.14	440.02	428.37	428.37	430.24

* Reference envelope

The main reason for this variation in GHG emissions across these envelope options is due to the variation in their corresponding operational energy consumption for heating and cooling during use stage and the gross mass including carbon intensities of their material components during mining to material production stage. Total 30 envelope options are found to have life cycle GHG emissions reduction potential, whereas the remaining 23 envelopes have more life cycle GHG emissions than the reference envelope.

GHG emissions – Use stage

As the building envelope has no influence over the life cycle energy consumption for lighting, hot water, and home appliances of the house, the life cycle GHG emissions associated with these activities remains the same (331tonnes CO_2 e-) for all envelope options. The life cycle GHG emissions associated with the operational energy consumption for heating and cooling of a typical reference house in Perth for alternative envelopes vary from a minimum of 45tonnes CO_2 e- for CSW-POL-DG-TT option (cast in-situ sandwich wall with polystyrene insulation core, double glazed windows and terracotta roof tiles), which is 43% less than the life cycle GHG emissions of reference envelope option to a maximum of 132tonnes CO_2 e- for CB-XX-SG-MS option (concrete block walls with single glazed windows and metal sheet roof), which is 69% more than the life cycle GHG emissions of reference envelope option (78.24tonnes CO_2 e- for DB-XX-SG-CT or clay brick wall without insulation, single glazed windows and concrete roof tiles) (Table 4.15).

Table 4.15 Life cycle GHG emissions associated with operational energy for heating and cooling for alternative envelope options

Options	**Life cycle GHG emissions for heating and cooling tonnes CO_2 e-**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	78.24*	77.70	77.80	64.28	64.09	64.98
DB-INS	59.37	58.83	59.52	47.13	47.18	47.68
BV-XX	87.88	87.10	88.23	70.13	69.34	71.26
RBV-XX	60.75	59.77	60.70	48.31	47.72	48.66
CB-XX	131.95	131.41	132.26	114.72	113.79	114.44
ACC-XX	67.70	67.11	67.85	53.80	53.01	54.15
PCSW-XX	113.11	112.37	113.27	93.55	92.56	93.65
TMB-XX	105.99	105.41	107.37	87.80	87.80	88.98
CSW-POL	56.42	56.23	56.77	45.86	44.88	46.40

* Reference envelope

The main reason for this variation in GHG emissions for these envelope options is due to their inherent thermal properties resulting in the variation in operational energy consumption for heating and cooling (Table 4.11). Only 32 envelope options are found to have the GHG emissions reduction potential (up to 8.3%) during use stage, while the remaining 21 envelopes have up to 13.5% more GHG emissions than the reference envelope.

GHG emissions - Mining to material production stage

The GHG emissions associated with mining to material production stage of a typical reference house in Perth for alternative envelopes vary from a minimum of 38tonnes CO_2 e- for TMB-XX-SG-CT option (timber frame wall with single glazed windows and concrete roof tiles), which is 28% less than that of reference envelope option to a maximum of 81tonnes CO_2 e- for PCSW-XX-DG-MS option (pre-cast light weight concrete sandwich wall with single glazed windows and metal sheet roof), which is 52% more than the reference envelope option (53.11tonnes CO_2 e- for DB-XX-SG-CT or clay brick wall without insulation, single glazed windows and concrete roof tiles) (Table 4.16).

Table 4.16 GHG emissions associated with mining to material production stage for alternative envelope options

Options	**GHG emissions from mining to material production stage tonnes CO_2 e-**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	53.11*	54.11	54.68	53.69	54.69	55.26
DB-INS	54.31	55.31	55.88	54.89	55.89	56.46
BV-XX	47.51	48.51	49.08	48.09	49.09	49.66
RBV-XX	59.01	60.01	60.58	59.59	60.59	61.16
CB-XX	42.81	43.81	44.38	43.39	44.39	44.96
ACC-XX	68.01	69.01	69.58	68.59	69.59	70.16
PCSW-XX	78.71	79.71	80.28	79.29	80.29	80.86
TMB-XX	38.32	39.32	39.89	38.90	39.90	40.47
CSW-POL	46.91	47.91	48.48	47.49	48.49	49.06

***** Reference envelope

The main reason for this variation in GHG emissions for these envelope options is due to the variation in their corresponding gross mass (Table 4.5) and the carbon footprints of materials (e.g. concrete roof tiles - 240kg CO_2 e-/tonnes, steel sheet roof – 3.11tonnes CO_2 e-/tonnes, ACC blocks – 475 kg CO_2 e-/tonnes, concrete block – 165 kg CO_2 e-/tonnes, gypboard – 429 kg CO_2 e-/tonnes) used for the construction (Monahan and Powell 2011; Ramesh, Prakash and Shukla 2010). Only 24 envelope options are found to have GHG emissions reduction potential during the mining to material production stage, while the remaining 29 envelopes have equal or more GHG emissions than the reference envelope.

A structurally sound house with reduced material content does not necessarily has low GHG emissions. This research found that the house with the highest GHG emissions during mining to material production stage (PCSW-XX-DG-MS) is 35.5% lighter than the reference house (261tonnes), and a similar situation has been found in the case of the house with the lowest GHG emissions during mining to material production stage (TMB-XX-SG-CT) (i.e. 36.21% less than the reference house). Although the mass of building materials for the envelope option (PCSW-XX-DG-MS) is 35.5% less than the reference house, but this envelope option is made of materials with high energy intensity such as light weight concrete (6.7MJ/kg), galvanized steel track (38MJ/kg), fibre cement boards (13.7MJ/kg), polymer modified thin bed mortar and skim coat (23.7MJ/kg), and metal roof sheet (43.9MJ/kg) resulting in the highest GHG emissions during mining to material production stage.

GHG emissions - Transportation, construction, and the end of life stages

The GHG emissions associated with transportation, construction, and the end of life stages of a typical reference house in Perth for alternative envelope options vary from a minimum of 4tonnes CO_2 e- for CSW-POL-SG/DG-MS option (cast in-situ sandwich wall with polystyrene insulation core, single/double glazed windows and metal sheet roof), which is 4% less than the reference envelope option to a maximum of 5.7tonnes CO_2 e- for PCSW-XX-DG-CT option (pre-cast light weight concrete sandwich wall with double glazed windows and concrete roof tiles), which is 18% more than the reference envelope option (4.83tonnes CO_2 e- for DB-XX-SG-CT or clay brick wall without insulation, single glazed windows and concrete roof tiles) (Table 4.17).

Table 4.17 Total GHG emissions associated with transportation, construction, and end of life stages for alternative envelope options

Options	Life cycle GHG emissions from transportation, construction, and end of life - tonnes CO_2 e-					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	4.83*	4.81	4.59	4.83	4.82	4.59
DB-INS	4.93	4.91	4.69	4.93	4.91	4.69
BV-XX	4.99	4.98	4.75	5.00	4.98	4.85
RBV-XX	5.15	5.13	4.91	5.15	5.13	4.91
CB-XX	5.27	5.25	5.03	5.27	5.25	5.03
ACC-XX	4.19	4.17	3.94	4.19	4.18	3.95
PCSW-XX	5.68	5.67	5.44	5.69	5.67	5.45
TMB-XX	5.50	5.48	5.12	5.50	5.49	5.12
CSW-POL	4.01	4.00	3.77	4.02	4.00	3.77

***** Reference envelope

The main reason for this variation in GHG emissions for these envelope options is due to the difference in their gross weights (Table 4.5), distances between material sources and the construction site (e.g. concrete, bricks, timber, concrete roof tiles, and metal roof sheet) (Table 4.6, Table 4.8, and Table 4.10), plus the energy consumed by the plant and equipment (i.e. fork lift, mortar mixer, and hand tools) for their assembly and disassembly including the recyclability potential of demolition material (Table 4.7 and Table 4.9). Only 19 envelope options are found to have GHG emissions reduction potential during transportation, construction, and end of life stages whereas remaining 34 envelopes are having equal or increased life cycle GHG emissions as compared to the reference envelope.

Cause diagnosis of GHG emissions

Further investigation of envelope elements (e.g. wall, window, roof tiles) for the alternative envelope options found that the GHG emissions saving benefits between 10.4 and 19.8tonnes CO_2 e- during use stage due to replacement of single glazed windows (SG) with double glazed windows (DG) outweighs the additional emission of 0.6tonnes CO_2 e- associated with the mining to material production of double glazed windows. The replacement of concrete roof tiles (CT) with terracotta tiles (TT) has been found to increase the GHG emissions by 1tonne CO_2 e- during mining to material production stage mainly due to the fact that terracotta tiles (3.7MJ/kg) are more energy intensive than concrete tiles (1.79MJ/kg), but during use stage this replacement reduces the GHG emissions by 0.54 to 0.98tonnes CO_2 e-. Similarly, the replacement of concrete roof tiles (CT) with metal sheet roof (MS) has been found to not only increase the GHG emissions by 1.57tonnes CO_2 e- during mining to material production stage due to very high energy intensiveness (43.9MJ/kg), but the GHG emissions during operational energy (heat/cool) application also increases up to 1.37tonnes CO_2 e-.

During Mining to material production stage, the alternative wall elements BV-XX, CB-XX, TMB-XX, and CSW-POL for single/double glazed windows and concrete/terracotta/metal roof options reduces the GHG emissions up to 14.8tonnes CO_2 e- as compared with reference wall element (DB-XX), while the wall options DB-INS, RBV-XX, ACC-XX, and PCSW-XX causes an increase of the GHG emissions up to 25.6tonnes CO_2 e-. However, during use stage, this pattern changes drastically. For example, during use stage, the wall elements DB-INS, RBV-XX, ACC-XX, and CSW-POL for single/double glazed windows and concrete/terracotta/metal roof options reduce the GHG emissions up to 21.8tonnes CO_2 e-, while the wall elements BV-XX, CB-XX, PCSW-XX, and TMB-XX cause an increase of the GHG emissions up to 53.71tonnes CO_2 e-.

Though the mining to material production stage GHG emissions for wall options BV-XX, CB-XX, and TMB-XX are less than the reference wall element due to their low material mass, but the GHG emissions during use stage are more than the reference wall due to their lower thermal mass. On the other hand, during mining to material production stage, the wall options DB-INS, RBV-XX, ACC-XX are causing more GHG emissions due to their high material mass, but during use stage, their GHG emissions are less than the reference wall due to high thermal mass. In the case of envelope option PCSW-XX, the GHG emissions during mining to material production as well as use stage are more than the reference wall due to high material mass, and moderate thermal mass. The wall element CSW-POL is the only option for where the GHG emissions during mining to material production and use stage both are less than the reference wall (DB-XX) because this option is not only able to reduce the material mass but demonstrates better thermal properties as compared to reference wall.

The GHG emissions results of all 53 alternative envelope options have been grouped into total 7 bands based on their potential for GHG emissions reduction or increase with respect to the reference envelope DB-XX-SG-CT (Figure 4.25).

Of these bands, 3 bands (i.e. <1%, >1% <5%, and >5% <10%) have GHG emissions reduction potential, while 4 bands (i.e. <1%, >1% <5%, >5% <10%, and >10% <15%) have more GHG emissions than the reference envelope.

	No. of options	Range	Envelope options
Reduction	9	>5% <10%	CSW-POL-SG/DG-CT/TT/MS, DB-INS-DG-CT/TT/MS
	18	>1% <5%	ACC-XX-DG-CT/TT/MS, BV-XX-DG-CT/TT/MS, DB-INS-SG-CT/TT/MS, DB-XX-DG-CT/TT/MS, RBV-XX-SG/DG-CT/TT/MS
	3	<1%	TMB-XX-DG-CT/TT/MS
			DB-XX-SG-CT (reference envelope)
Increase	6	<1%	ACC-XX-SG-CT/TT, BV-XX-SG-CT/TT, DB-XX-SG-MS/TT
	5	>1% <5%	TMB-XX-SG-CT/TT/MS, ACC-XX-SG-MS, BV-XX-SG-MS
	9	>5% <10%	CB-XX-SG/DG-CT/TT/MS, PCSW-XX-DG-CT/TT/MS
	3	>10% <15%	PCSW-XX-SG/CT/TT/MS

Figure 4.25 Alternative envelope options with their potential of life cycle GHG emissions reduction or increase

The Figure 4.25 shows that there are 30 envelope options that have a life cycle GHG emissions reduction potential of up to 10% of the life cycle GHG emissions of a typical reference house in Perth, while 23 envelope options are causing more life cycle GHG emissions than the reference house.

Total 9 envelope options are found to have life cycle GHG emissions reduction potential between 5% and 10%, while 18 envelope options have the moderate life cycle GHG emissions reduction potential between 1% and 5%.

There are only 3 envelope options that have life cycle GHG emissions reduction potential of less than 1%. On the other hand, 6 envelope options are found to cause a slight increase (<1%) of life cycle GHG emissions. Total 14 envelope options are found to increase the life cycle GHG emissions between 1% and 10%, while 3 envelope options are causing 10% to 15% more life cycle GHG emissions. The reasons for this variation have already been discussed in the previous parts of this section.

Comparison of results with other studies

As discussed in Section 4.3.1, the life cycle environmental impact results are influenced by the chosen system boundary, functional unit, material specification, the region specific energy, and climatic data, and the assumptions and hence the scope for comparison of the results of other studies with the current study is limited in terms of absolute values. However, the pattern of GHG emissions reduction or increase due to alternative envelopes is closely matching with other studies. A LCA study of a single glazed window house over a lifespan of 50 years for different envelope options such as double brick, insulated double brick, brick veneer, reverse brick veneer, and timber frame in Melbourne, Brisbane, and Newcastle confirmed that the reverse brick veneer, and insulated double brick wall houses had lower life cycle GHG emissions (between1% and 4%) than that of the double brick wall house, while the timber wall and brick veneer houses had more life cycle GHG emissions (between1% and 4%) than the double clay brick wall house (Rouwette 2010). Another LCA study of a house with alternative wall systems, double glazed windows and concrete roof tiles in Brisbane confirmed that the life cycle GHG emissions of timber wall and ACC block wall houses were lower than the life cycle GHG emissions of double rick wall house (Islam et al. 2014). A similar LCA study of a Portuguese house with alternative exterior walls, double glazed windows and insulated reinforced concrete slab roof confirmed that the life cycle GHG emissions of ACC block, reverse brick veneer, and timber wall houses were lower than the life cycle GHG emissions of the double brick wall house (Monteiro and Freire 2012).

Total EE consumption

The stage wise breakdown of life cycle EE consumption of a typical reference house in Perth for alternative envelope options is presented in Table D.19 (Appendix D). Similar to GHG emissions, the results show that the life cycle EE consumption of a typical reference house in Perth for 53 alternative envelope options vary from a minimum of 5.93TJ for CSW-POL-DG-CT option (cast in-situ sandwich wall with polystyrene insulation core, double glazed windows and concrete roof tiles), which is 8.8% less than the reference envelope option to a maximum of 7.15TJ for PCSW-XX-SG-MS option (pre-cast light weight concrete sandwich wall with single glazed windows and metal sheet roof), which is 9.9% more than that of the reference envelope option (6.51TJ for DB-XX-SG-CT or clay brick wall without insulation, single glazed windows and concrete roof tiles) (Table 4.18). The main reason for this variation in EE consumption for these envelope options is due to the difference in operational energy consumption for heating and cooling during use stage and the initial embodied energy of materials during mining to material production stage. Total 36 envelope options are found to have the life cycle EE consumption reduction potential, whereas remaining 17 envelopes are causing more or equal life cycle EE consumption compared to the reference envelope.

Table 4.18 Total life cycle EE consumption for alternative envelope options

Options	Total life cycle EE consumption - TJ					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	6.51*	6.51	6.55	6.33	6.34	6.38
DB-INS	6.26	6.27	6.31	6.10	6.12	6.16
BV-XX	6.44	6.44	6.49	6.21	6.22	6.27
RBV-XX	6.25	6.25	6.29	6.09	6.10	6.14
CB-XX	7.02	7.03	7.07	6.80	6.80	6.84
ACC-XX	6.45	6.46	6.50	6.27	6.28	6.32
PCSW-XX	7.10	7.10	7.15	6.85	6.85	6.89
TMB-XX	6.56	6.56	6.62	6.32	6.34	6.38
CSW-POL	6.06	6.08	6.12	5.93	5.93	5.98

* Reference envelope

EE consumption – Use stage

The life cycle EE consumption for operational energy for lighting, hot water, and home appliances remain the same (4.6TJ) for all envelope options. The life cycle EE consumption associated with operational energy for heating and cooling of a typical reference house for alternative envelopes vary from a minimum of 0.6TJ for CSW-POL-DG-TT option (cast in-situ sandwich wall with polystyrene insulation core, double glazed windows and terracotta roof tiles), which is 43.8% lower than the reference envelope option to a maximum of 1.8TJ for CB-XX-SG-MS option (concrete block walls with single glazed windows and metal sheet roof), which is 68.6% more than the reference envelope DB-XX-SG-CT option (1.09TJ) (Table 4.19). The main reason for this variation in EE consumption for these envelope options is due to the difference in their corresponding operational energy for heating and cooling (Table 4.11) caused by their inherent thermal properties. During use stage, total 31 envelope options are found to have the life cycle EE consumption reduction potential, whereas remaining 22 envelopes are causing an equal or increased life cycle EE consumption as compared to the reference envelope.

Table 4.19 Life cycle EE consumption associated with operational energy for heating and cooling for alternative envelope options

Options	Life cycle EE consumption for heating and cooling - TJ					
	SG-CT	SG-TT	SG-MS	DG-CT	DG-TT	DG-MS
DB-XX	1.09*	1.08	1.09	0.90	0.90	0.91
DB-INS	0.82	0.81	0.82	0.65	0.65	0.66
BV-XX	1.19	1.18	1.19	0.95	0.94	0.96
RBV-XX	0.84	0.82	0.83	0.67	0.66	0.67
CB-XX	1.84	1.83	1.84	1.61	1.59	1.60
ACC-XX	0.92	0.91	0.92	0.74	0.72	0.74
PCSW-XX	1.54	1.53	1.54	1.28	1.26	1.28
TMB-XX	1.43	1.42	1.45	1.19	1.19	1.20
CSW-POL	0.77	0.77	0.77	0.63	0.61	0.63

* Reference envelope

EE consumption – Mining to material production stage

The EE consumption associated with the mining to material production stage of a typical reference house in Perth for alternative envelopes is found to vary from a minimum of 0.42TJ for TMB-XX-SG-CT option (timber frame wall with single glazed windows and concrete roof tiles), which is 41% lower than the EE consumption of that the reference envelope option to a maximum of 0.91TJ for PCSW-XX-DG-MS option (pre-cast light weight concrete sandwich wall with single glazed windows and metal sheet roof), which is 27.15% more than the reference envelope option (0.71TJ) (Table 4.20). As discussed earlier, the main reason for this variation in EE consumption for these envelope options is due to the difference in the gross weight (Table 4.5) and energy intensity of their material components (Cabeza et al. 2013; Praseeda, Reddy and Mani 2015). Overall, only 24 envelope options found to have EE consumption reduction potential during mining to material production stage, while the remaining 29 envelopes are causing an equal or increased EE consumption as compared to the reference envelope.

Table 4.20 EE consumption associated with mining to material production stage for alternative envelope options

Options	EE consumption for mining to material production - TJ					
	SG-CT	SG-TT	SG-MS	DG-CT	DG-TT	DG-MS
DB-XX	0.71*	0.73	0.76	0.72	0.74	0.77
DB-INS	0.74	0.75	0.79	0.75	0.76	0.80
BV-XX	0.55	0.57	0.60	0.56	0.58	0.61
RBV-XX	0.71	0.72	0.76	0.72	0.73	0.77
CB-XX	0.47	0.49	0.52	0.48	0.50	0.53
ACC-XX	0.84	0.86	0.89	0.85	0.87	0.90
PCSW-XX	0.85	0.86	0.90	0.86	0.87	0.91
TMB-XX	0.42	0.44	0.47	0.43	0.44	0.48
CSW-POL	0.60	0.61	0.65	0.61	0.62	0.66

***** Reference envelope

As discussed earlier, the reduced material content does not necessarily mean a low EE consumption. The envelope option with the highest EE consumption during mining to material production stage (PCSW-XX-DG-MS) is 35.5% lighter than the reference envelope option (261tonnes), but the EE consumption is 27% more than the reference envelope. In the case of the lowest EE consumption during mining to material production stage, the envelope option TMB-XX-SG-CT is not only 36% lighter than the reference envelope, but the EE consumption is also 41% less than the reference envelope.

Although the total mass of building materials for envelope option (PCSW-XX-DG-MS) is 35.5% less than the total material mass of reference house, the EE consumption is 27% more than the reference envelope option. This is due to the fact that this envelope option is made of materials, which have significantly high embodied energy contents such as light weight concrete (6.7MJ/kg), galvanized steel track (38MJ/kg), fibre cement boards (13.7MJ/kg), polymer modified thin bed mortar and skim coat (23.7MJ/kg), and metal roof sheet (43.9MJ/kg) (Milne and Reardon 2013).

EE consumption - Transportation, construction, and the end of life stages

The EE consumption associated with transportation, construction, and the end of life stages of a typical reference house in Perth for alternative envelope options vary from a minimum of 0.08TJ for ACC-XX-SG/DG-MS option (aerated concrete block wall, single/double glazed windows and metal sheet roof), which is 18.6% lower than the reference envelope option to a maximum of 0.11TJ for PCSW-XX-SG/DG-CT/TT/MS and CB-XX-SG/DG-CT/TT options (pre-cast light weight concrete sandwich wall with single/double glazed windows and concrete tile, terracotta tile, metal sheet roof), which is 12.6% more than that of the reference envelope option (0.1TJ) (Table 4.21).

Table 4.21 Total EE consumption associated with tkm, construction, and the end of life stages for alternative envelope options

Options	**Total EE consumption for tkm, construction, and the end of life TJ**					
	SG-CT	**SG-TT**	**SG-MS**	**DG-CT**	**DG-TT**	**DG-MS**
DB-XX	0.10	0.10	0.10	0.10	0.10	0.10
DB-INS	0.10	0.10	0.10	0.10	0.10	0.10
BV-XX	0.10	0.10	0.10	0.10	0.10	0.10
RBV-XX	0.10	0.10	0.10	0.10	0.10	0.10
CB-XX	0.11	0.11	0.10	0.11	0.11	0.10
ACC-XX	0.09	0.09	0.08	0.09	0.09	0.08
PCSW-XX	0.11	0.11	0.11	0.11	0.11	0.11
TMB-XX	0.10	0.10	0.10	0.10	0.10	0.10
CSW-POL	0.09	0.09	0.09	0.09	0.09	0.09

***** Reference envelope

As discussed earlier, the main reason for this minor variation in EE consumption for these envelope options is due to the difference in their material gross weight (Table 4.5), distances between material sources and the construction site (e.g. concrete, bricks, timber, concrete roof tiles, and metal roof sheet) (Table 4.6, Table 4.8, and Table 4.10), plus the energy consumed by the plant and equipment (i.e. fork lift, mortar mixer, and hand tools) for assembly and disassembly including the recyclability potential of demolition material (Table 4.7 and Table 4.9). Total 12 envelope options are found to have life cycle EE consumption reduction potential during transportation, construction, and the end of life stages whereas remaining 41 envelopes are having equal or increased life cycle EE consumption as compared to the reference envelope.

Cause diagnosis of EE consumption

The further investigation of the envelope components (e.g. wall, window, roof) for the alternative envelope options reveal that the EE consumption saving benefits between 0.14TJ and 0.26TJ during use stage due to the replacement of SG with DG outweighs the additional EE consumption of 0.01TJ associated with the double glazed windows. The replacement of concrete roof tiles (CT) with terracotta tiles (TT) has been found to increase the EE consumption by 0.02TJ, mainly due to the fact that terracotta tiles (3.7MJ/kg) are more energy intensive than concrete tiles (1.79MJ/kg), but this replacement reduces the EE consumption during use stage by 0.01TJ resulting into a zero net affect. Similarly, the replacement of concrete roof tiles (CT) with metal sheet roof (MS) not only increases the EE consumption during mining to material production stage by 0.05TJ because of very high energy intensiveness (43.9MJ/kg) of metal sheet roof, but the EE consumption during use stage increases up to 0.02TJ.

During mining to material production stage, alternative wall elements BV-XX, CB-XX, TMB-XX, and CSW-POL for single/double glazed windows and concrete/terracotta/metal roof options reduce the EE consumption up to 0.29TJ as compared to reference wall element (DB-XX), while the wall options DB-INS, ACC-XX, and PCSW-XX result in an increase of the EE consumption up to 0.13TJ. The EE consumption for wall element RBV-XX is found to be same as the reference wall element DB-XX. However, during use stage, this pattern does not remain same. For example, during use stage, the wall elements DB-INS, RBV-XX, ACC-XX, and CSW-POL for single/double glazed windows and concrete/terracotta/metal roof options reduces the EE consumption up to 0.32TJ, while the EE consumption for wall elements BV-XX, CB-XX, PCSW-XX, and TMB-XX increases up to 0.74TJ.

The above results suggest that materials of high thermal performance should be preferred regardless of their initial embodied energy because the additional embodied energy invested in high thermal performance materials can easily be recovered from the operational energy savings during use stage (i.e. heating and cooling). A similar conclusion was drawn by other studies as they found that 20%-50% of the operational energy savings were attained due to the use of insulation, additional glazing, and high thermal mass materials (Verbeeck and Hens 2010; Ramesh, Prakash and Shukla 2010; Crawford, Czerniakowski and Fuller 2010).

Similar to GHG emissions results, all 53 alternative envelope options have been grouped into total 6 bands based on their potential of EE consumption reduction or increase with respect to the reference envelope DB-XX-SG-CT (Figure 4.26). There are 3 bands under EE consumption reduction potential (i.e. <1%, >1% <5%, and >5% <10%), while the envelope options causing more EE consumption than the reference envelope have been grouped under 3 bands (i.e. <1%, >1% <5%, and >5% <10%).

	No. of options	**Range**	**Envelope options**
Reduction	**12**	>5% <10%	CSW-POL-SG/DG-CT/TT/MS, DB-INS-DG-CT/TT/MS, RBV-XX-DG-CT/TT/MS
	19	>1% <5%	ACC-XX-DG-CT/TT/MS, BV-XX-DG-CT/TT/MS, BV-XX-SG-CT, DB-INS-SG-CT/TT/MS, DB-XX-DG-CT/TT/MS, RBV-XX-SG-CT/TT/MS, TMB-XX-DG-CT/TT/MS
	5	<1%	ACC-XX-SG-CT/TT/MS, BV-XX-SG-TT/MS
			DB-XX-SG-CT (reference envelope)
Increase	**4**	<1%	DB-XX-SG-MS/TT, TMB-XXSG-CT/TT
	3	>1% <5%	CB-XX-DG-CT/TT, TMB-XX-SG-MS
	10	>5% <10%	CB-XX-DG-MS, CB-XX-SG-CT/TT/MS, PCSW-XX-SG/DG-CT/TT/MS

Figure 4.26 Alternative envelope options with their potential of life cycle EE consumption reduction or increase

Figure 4.26 shows that there are 36 envelopes that have life cycle EE consumption reduction potential of up to 10% of the life cycle EE consumption of a typical reference house in Perth, while 17 envelope options are causing an increase of life cycle EE consumption compared to reference envelope. Total 12 envelopes are found to have life cycle EE consumption reduction potential between 5% and 10%, while 19 envelope options have a moderate life cycle EE consumption reduction potential between 1% and 5. There are only 5 envelope options that are found to have a life cycle EE consumption reduction potential of less than 1%. On the other hand, 4 envelope options are causing a slight increase (<1%) in the life cycle EE consumption, while 3 envelope options are found to increase the life cycle EE consumption between 1% and 10%. Ten envelope options are causing an increase in life cycle EE consumption between 10% and 15%. The reasons for this variation have already been discussed in the previous parts of this section.

The EE consumption saving does not always translate into GHG emissions reduction. Interestingly, from the life cycle GHG emissions and EE consumption results of alternative envelope options, it is found that more number (i.e. 36) of envelope options have EE consumption reduction potential than the number (i.e. 30) of envelope options that have GHG emissions reduction potential. This is because of the fact that the reduction in EE consumption does not mean that it is avoiding only the energy sources having higher carbon footprints. For example, the carbon footprint of grid electricity is 255.5 kg CO_2 e-/GJ, while the carbon footprint of natural gas is only 58.3 kg CO_2 e-/GJ.

As seen in Figure 4.24, and Table 4.11, the operational energy for heating and cooling for 37 alternative envelope options is up to 49% less than the reference envelope, the remaining envelope options do not have operational energy reduction potential because of their heating and cooling demand. The total energy value for heating, and cooling may be less or more than the reference envelope, but the GHG emissions and EE consumptions will be highly influenced by the share of electricity and natural gas for cooling and heating respectively. For alternative envelope options, it was found that the heating energy (i.e. use of natural gas) vary between 34% and 57%, while the cooling energy (i.e. use of grid electricity) vary between 43% and 66%. This means that even if the total operational energy for heating, and cooling of a particular envelope option is less than the reference case (53% for heating, and 47% for cooling), the higher share of electricity powered cooling energy demand than the reference case may lead to higher GHG emissions compared to the EE consumption.

Comparison of results with other studies

As discussed in Section 4.3.1, the life cycle environmental impact results vary due to the use of different system boundaries, functional units, the region specific material, energy, and climatic data including the assumptions and hence the scope for comparison of the results of other studies with current study is limited in terms of absolute values. However, the pattern of reduction or increase of EE consumption due to the use of alternative envelopes is comparable with other studies. An LCA study of double glazed windows and concrete roof tiled house for alternative wall systems in Brisbane confirmed that the life cycle EE consumptions of timber wall and ACC block wall houses were lower than the double brick wall house (Islam et al. 2014). Another study on LCEA of building construction assemblies for a typical Australian house confirmed that the brick veneer wall and concrete roof tiles had 13%, and 17.65% less life cycle EE consumptions than the timber wall and steel sheet roof respectively(Crawford, Czerniakowski and Fuller 2010).

Kibert (2008) suggested that the minimization of construction and demolition (C&D) waste influences the sustainable development of buildings. Saghafi and Hosseini Teshnizi (2011), and Aye and Hes (2012) also echoed similar views and suggested that recycle and re-use of C&D waste is also an effective way to reduce the environmental impacts and increase the resource efficiency of buildings. Lawania, Sarker, and Biswas (2015) demonstrated the environmental benefits of substitution of virgin materials with by-products and recyclates for the construction of a house in WA. The following section discusses the opportunities to further reduce the GHG emissions and EE consumption associated with the mining to material production stage.

Use of by-products and recycled materials

The concrete used for ground slab and footings has been found to be a second largest hotspot during mining to material production stage as each tonne of concrete is responsible for 133kg CO_2 e- GHG emissions, and 1.31GJ of EE consumption. About 78.4tonnes of concrete is required for the ground slab and footings of a typical reference house in Perth for all alternative envelope options but there is an additional 66.9tonnes of concrete required for the wall element CSW-POL option. The partial replacement of cement, aggregate and sand in the conventional concrete by different combinations of by-products such as fly ash (FA), ground granulated blast furnace slag (GGBFS), recycled crushed aggregates (RCA), and manufactured sand (MFS) has been considered as one of the cleaner production strategies to mitigate the GHG emissions and EE consumption impacts associated with the production of concrete during mining to material production stage.

As per Australian Cement Industry Federation report, the GHG emission intensity of cement production during 2012–2013 was 700 kg CO_2 e- per tonne (CIF 2014).

Therefore, it is necessary that the cement in concrete be substituted with supplementary cementitious materials (SCM) having low carbon footprint while still maintaining the structural performance and integrity. FA and GGBFS have been found to be suitable SCM for the production of concrete (CCAA 2012). Fly ash which is a pozzolanic material hardens by reacting with the calcium hydroxide that is released during the hydration of portland cement but GGBFS react with water to form hardened binder in the presence of portland cement due to its latent hydraulicity (CCAA 2012).

The second major element of concrete is crushed rock aggregate which involves highly energy intensive crushing process. The use of RCA produced from C&D waste has been found not only help reduce the GHG emissions associated with energy consumption and landfill area but it reduces the air-borne CO_2 emissions as well (CCAA 2013). The third major element of concrete is fine aggregate or natural sand. The MFS, a by-product of crushed rock aggregate has been found to be a suitable substitute to scarce natural sand resources (CCAA 2013) by avoiding additional processing in relation to quarrying and transporting natural sand. Though the conversion process of MFS to workable sand requires energy for processing, it is still worth to investigate the environmental benefits due to the replacement of natural sand with MFS.

On the basis of the thorough literature review as explained in Sections 2.5.3.5 and 2.5.3.6, following conclusions have been drawn for developing compositions of concrete utilizing FA, GGBFS, RCA and MFS with conventional materials:

- Up to 30% of cement, 40% of natural aggregate (NA), and 40% of natural sand (NS) could be substituted with fly ash (FA), GGBFS, recycle concrete aggregate (RCA) and manufactured sand (MFS) respectively. However, in order to maintain the acceptable structural performance, some minor adjustments in concrete mix design will be needed for these combinations.

- The market conditions and changes to production processes may affect the constant supply of by-products and therefore a number of structurally sound compositions should be considered to suit to any fluctuations in supply during the time of resource scarcity. Accordingly, seventy two possible combinations of concrete mix designs (one current/conventional + seventy one alternatives) have been considered to determine the possible GHG emissions saving implications due to the use of by-products.

The cementitious material has been divided into six groups designated as 100% OPC, 70% OPC + 30% FA, 70% OPC + 20% FA + 10% GGBFS, 70% OPC + 15% FA + 15% GGBFS, 70% OPC + 10% FA + 20% GGBFS, and 70% OPC + 30% GGBFS. Each of these cementitious group has been used in combination of four aggregate groups designated as 100% NA, 60% NA + 40% RCA, 70% NA + 30% RCA, and 80% NA + 20% RCA, where these aggregate groups are further sub-divided into three sand groups each and designated as 100% NS, 60% NS + 40% MFS, and 80% NS + 20% MFS respectively. Therefore, total 71 (72 - original) alternative compositions of concrete have been considered for estimation of GHG emissions and EE consumption impacts associated with the substitution of input materials (Figure 4.27).

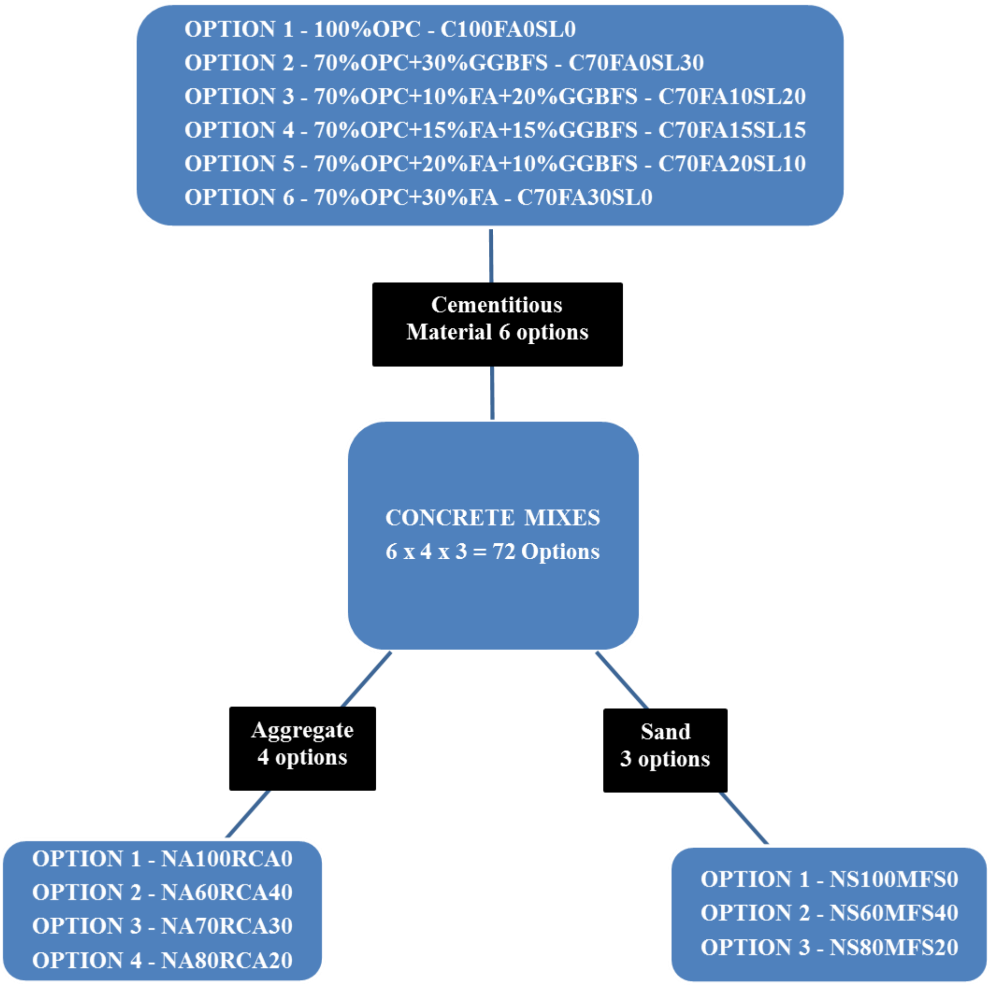


Figure 4.27 Alternative concrete mixes

The material composition data for 71 alternative concrete mixes has been entered in SimaPro software following Table D.20 (Appendix D) to estimate the GHG emissions and EE consumption impacts associated with input substitution. GHG emissions associated with the production of 1 tonnes of concrete for 71 alternative compositions are presented in Table D.21 (Appendix D). The results show that 69 alternative compositions of concrete mix offer the GHG emissions reduction up to 25.9% compared to the conventional concrete mix, while only 2 alternative compositions of concrete mix have more GHG emissions than the conventional concrete mix (Figure 4.28).

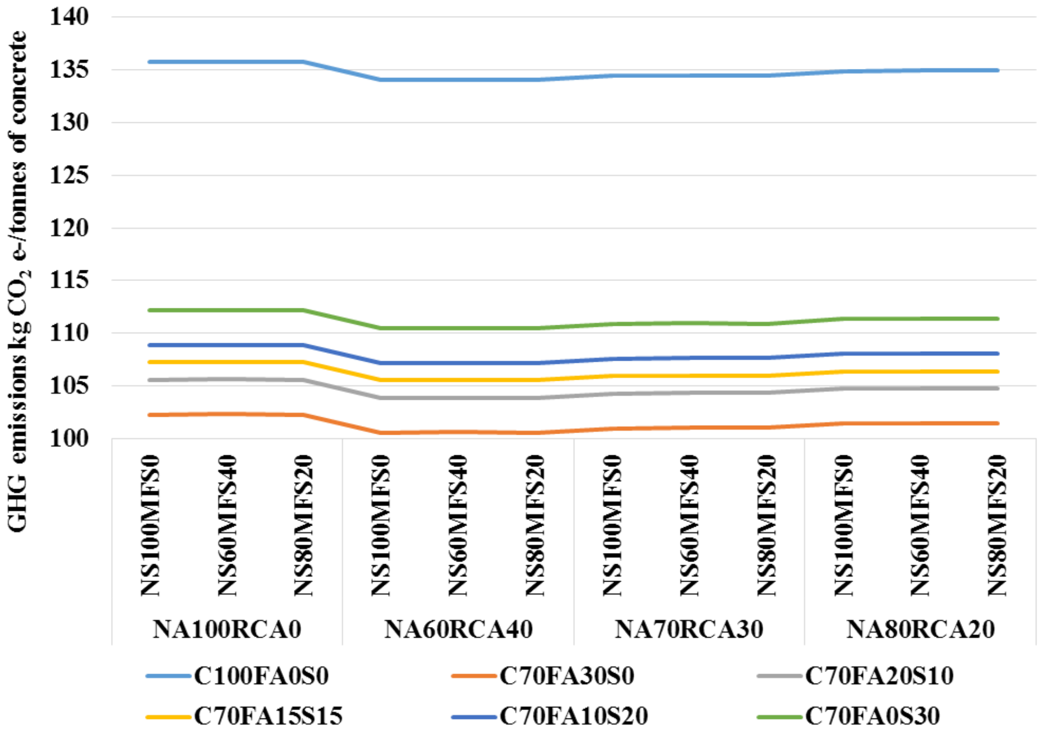


Figure 4.28 GHG emissions of concrete mixes for alternative material compositions

The results of EE consumption associated with the production of 1 tonnes of concrete for 71 alternative compositions are presented in Table D.22 (Appendix D). The results show that 69 alternative compositions of concrete mix offer an EE consumption reduction up to 23% compared to the conventional concrete mix, while only 2 alternative compositions of concrete mix have more EE consumption than the conventional concrete mix (Figure 4.30).

From these results, it is observed that the concrete with a composition of C70FA30S0-NA60RCA40-NS100MFS0 (70% OPC + 30% FA + 60% NA + 40% RCA + 100% NS) has the highest potential of GHG emissions reduction and EE consumption saving.

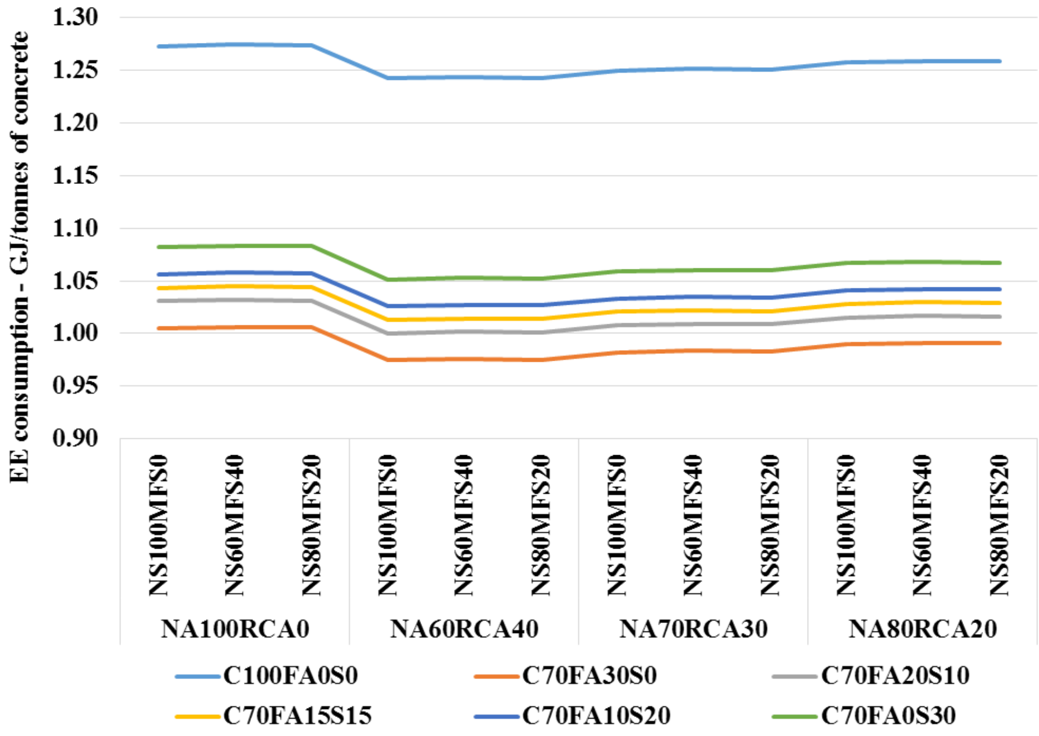


Figure 4.29 EE consumption of concrete mixes for alternative material compositions

GGBFS and FA are by-products but FA has been found to have slightly more GHG emissions reduction potential because, in the case of GGBFS, an additional energy is required for grinding of blast furnace slag. For concrete mixes with 100% OPC, the changes in aggregate and sand compositions have a minor impact on emissions. However, once the cement is partially replaced by SCM, the GHG emissions and EE consumption reduces significantly. This clearly shows that the partial replacement of cement can substantially reduce the EE consumption in the concrete.

For concrete mixes with various cementitious and aggregate compositions, an insignificant increase in GHG emissions (<0.02%) and EE consumption (<0.11%) has been observed when NS is partially replaced by MFS. The reason for this increase is that an additional energy is required for making MFS suitable for use in concrete, (O’Flynn 2000). However, there are also benefits from the minimization of the associated waste and natural resource depletion (Marinković et al. 2010).

GHG emissions and EE consumption impacts associated with the use of concrete required for all envelope elements have been estimated by multiplying the GHG emissions and EE consumption per tonnes of concrete composition i.e. C70FA30S0-NA60RCA40-NS100MFS0, which is offering the highest GHG emissions and EE consumption by the mass of concrete required for all alternative envelope options. It is found that the GHG emissions could be reduced by 2.76tonnes CO_2 e- due to the use of by-product and recyclates in concrete for ground slab and footing for all envelope options. Additional 2.35tonnes CO_2 e- GHG emissions could be reduced, if the by-product and recyclates are used in concrete for 6 envelope options having cast in-situ concrete (CSW-POL) wall elements (Figure 4.30).

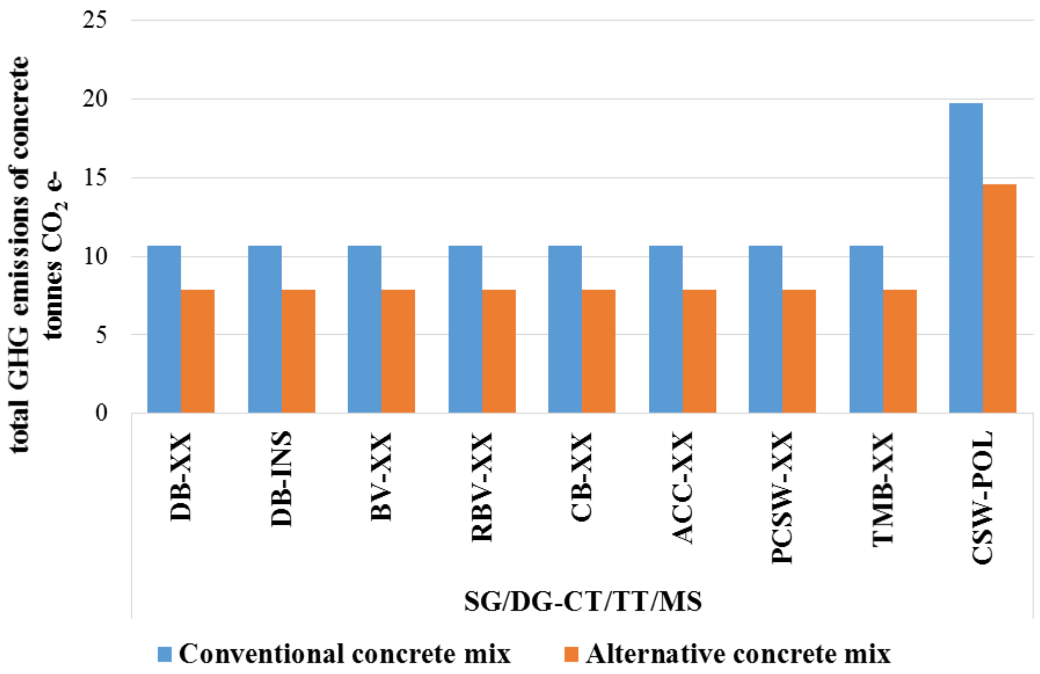


Figure 4.30 GHG emissions reduction potential associated with concrete for alternative envelope options

Similar to GHG emissions reduction potential, the EE consumption could reduce by 0.02TJ due to the use of by-product and recyclates in concrete for ground slab and footing for all envelope options. An additional 0.02TJ of EE consumption could be reduced, if the by-product and recyclates are used in concrete for 6 envelope options having cast in-situ concrete (CSW-POL) wall elements (Figure 4.31).

The 6 most efficient envelope options CSW-POL-SG/DG-CT/TT/MS, in terms of their life cycle GHG emissions reduction, and EE consumption saving potential use the polystyrene insulation as core and so there is an opportunity to replace the polystyrene core with polyethylene terephthalate (PET) foam core manufactured from post consumed PET bottles, which may further reduce the GHG emissions and EE consumption.

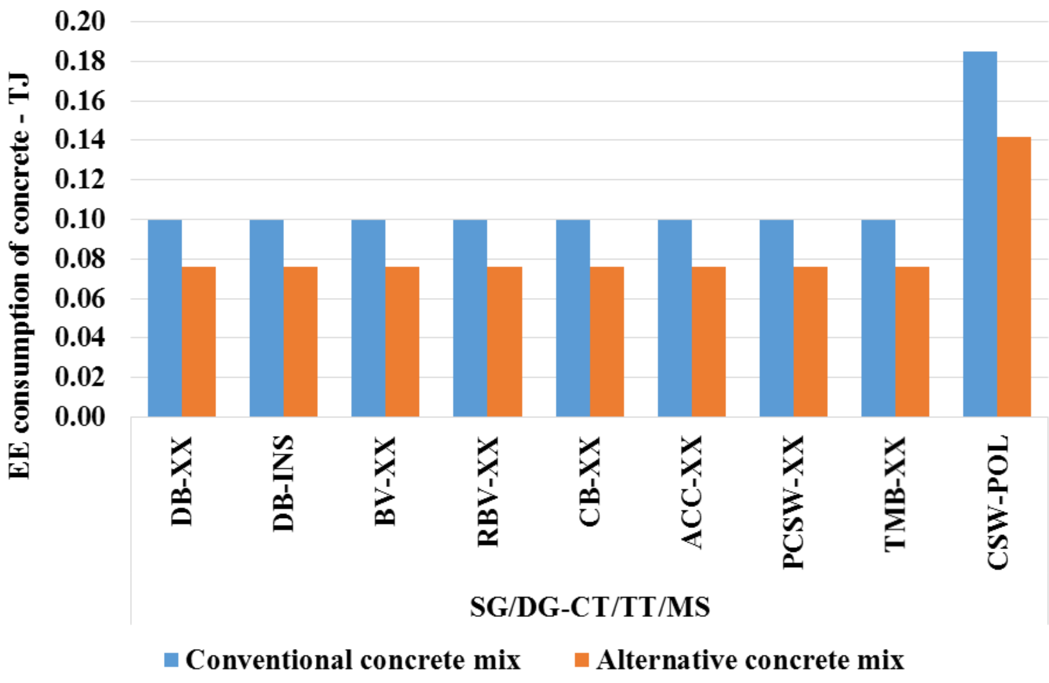


Figure 4.31 EE consumption reduction potential associated with concrete for alternative envelope options

Various recent studies suggest that post consumed plastic bottles made of polyethylene terephthalate (PET) could potentially be used either as an ingredient of concrete or as a replacement of polystyrene core (Foti 2011; Intini and Kühtz 2011; Saikia and de Brito 2012). In normal conditions, PET is considered as a non-degradable material and the known micro-organisms can not consume it due to its large molecules (Awaja and Pavel 2005). A study by Japon, Leterrier, and Månson (2000) suggested that recycling of post consumed PET bottles into PET foam provides a durable insulation core for sandwich structures. According to Australian national plastics recycling survey held in 2013–2014, the recovery and recycling rate of PET bottles was 54.8% (APC 2014). Therefore, the use of post consumed plastic bottles by building sector provides an opportunity to increase the waste recovery, and reduce the demand for landfill area.

The use of PET foam as the core can not only reduce the use of non-renewable petroleum based virgin polystyrene but it also improves the thermal performance of the walls compared to virgin polystyrene insulation core (Intini and Kühtz 2011; Lawania and Biswas 2016). The AccuRate software has been used to estimate the energy impacts of this substitution. The energy results show that there is an opportunity to reduce life cycle operational energy demand for heating and cooling of the house by 13GJ – 17.7GJ (Figure 4.32), if the polystyrene insulation core is replaced by PET foam core for envelope options CSW-POL-SG/DG-CT/TT/MS.

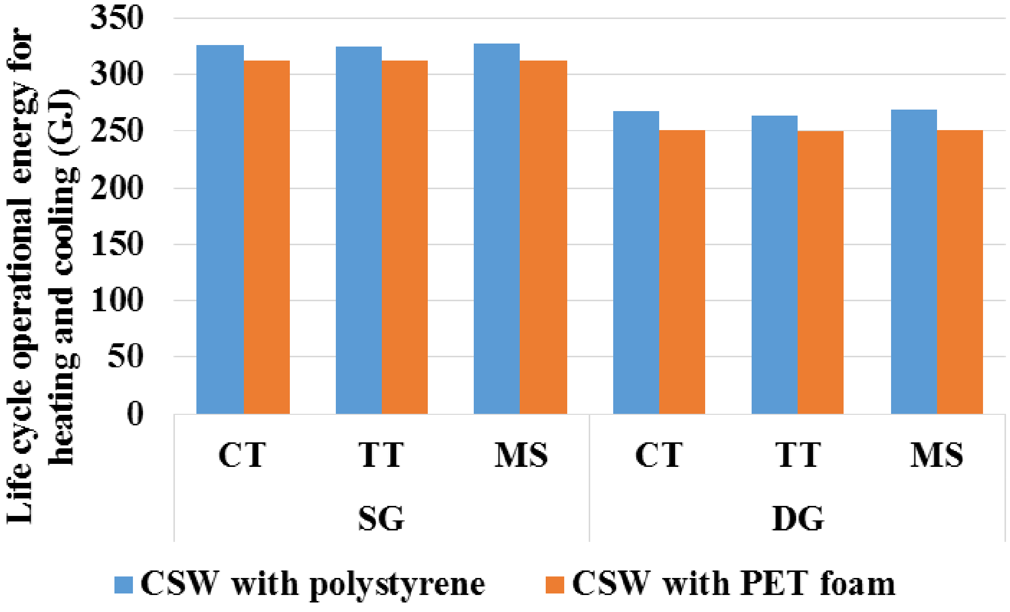


Figure 4.32 Life cycle operational energy for heating and cooling due to substitution of polystyrene and PET foam core

The revised material and energy inputs have been entered in SimaPro software to estimate the GHG emissions and EE consumption impacts associated with this substitution during mining to material production, transportation, and use stages. The results show that this substitution could reduce GHG emissions and EE consumption by 1.9tonnes CO2 e-, and 0.06TJ respectively.

The above analysis for the introduction of PET foam is based on the assumption that this substitution will provide equal or better structural performance compared to polystyrene insulation core. However, there is no published laboratory or field data on the structural performance of PET foam core for cast in-situ sandwich wall system and hence the above saving potential is not considered for further analysis in this study. However, this substitution may be implemented after due diligence.

Use of fibre reinforced polymer sections

The reference envelope options and all except 6 alternative envelope options require galvanized metal lintels and columns to comply with the structural design requirements according to the nature of wall elements used for the construction of the house (Table 4.5). The 6 envelope options (CSW-POL-SG/DG-CT/TT/MS) does not require any galvanized metal lintels and columns (Poluraju and Rao 2014; Lee et al. 2006). The quantity of galvanized material for these envelope options vary from 0.06tonnes to 0.58tonnes. The galvanized metal lintels have been found to have significantly high carbon intensity of 3.18tonnes CO_2 e-/tonnes. These galvanized metal lintels could be replaced with light weight fibre reinforced polymer (FRP) sections, which will eliminate the requirement of crane for placement of heavy metal lintels during the construction stage. The use of FRP material is increasing for various applications in building sector including strengthening of heritage buildings (Zhao and Zhang 2007; Hollaway 2010; Kendall 2007). The recent experimental and analytical studies of FRP sections under Western Australian conditions have demonstrated that the FRP sections, in spite of being categorised as a brittle material have significant residual strength, and resilience even under varying thermal conditions (Russo et al. 2015, 2016). However, the environmental and economic impacts associated with this substitution for WA conditions are still unknown hence this substitution has not been considered for further analysis in this study.

4.4.5 Uncertainty analysis

From the detailed investigation into GHG emissions and EE consumption impacts of alternative envelope options, it appears that each envelope has its own unique material characteristics, composition, and mass and therefore the uncertainties associated with the assumptions and considerations of these variables cannot be ruled out. Each envelope group has 6 alternative options where they vary with each other with the change in the type of windows and roof coverings (Figure 4.21). The major impact within these 6 alternative options under each envelope group is in terms of operational energy consumption, where the quantum of energy is only changing while there is no change in the characteristic of energy. However, the material and energy inputs are varying significantly for all alternative envelope groups (Table 4.5, and Table 4.11). In order to estimate the uncertainties associated with the input variables and also to predict their impact on the GHG emissions and EE consumption due to changes in characteristics of materials, one alternative envelope option from each group as listed below has been selected for the uncertainty analysis using the Monte Carlo Simulation (MCS) of SimaPro software.

- DB-INS-SG-CT
- BV-XX-SG-CT
- RBV-XX-SG-CT
- CB-XX-SG-CT
- ACC-XX-SG-CT
- PCSW-XX-SG-CT
- TMB-XX-SG-CT
- CSW-POL-SG-CT

The calculated GHG emissions and EE consumption values are very close to the corresponding mean and median values for alternative envelope options where the coefficient of variation values indicates a very small degree of uncertainty (Table 4.24).

Table 4.22 Summary of coefficient of variations (GHG and EE) for alternative envelope options

Envelope Option	**Coefficient of Variations (CV)**	
	GHG	**EE**
DB-INS-SG-CT	2.86%	2.18%
BV-XX-SG-CT	3.06%	2.37%
RBV-XX-SG-CT	2.85%	2.17%
CB-XX-SG-CT	3.12%	2.38%
ACC-XX-SG-CT	3.07%	2.67%
PCSW-XX-SG-CT	4.24%	3.28%
TMB-XX-SG-CT	3.08%	2.45%
CSW-POL-CT	3%	2.28%

The uncertainty histograms from Monte Carlo simulations for 1000 iterations at the 95% confidence level for GHG emissions and EE consumption for the reference house with alternative envelope options show a normal distribution (Figure 4.33 to Figure 4.40).

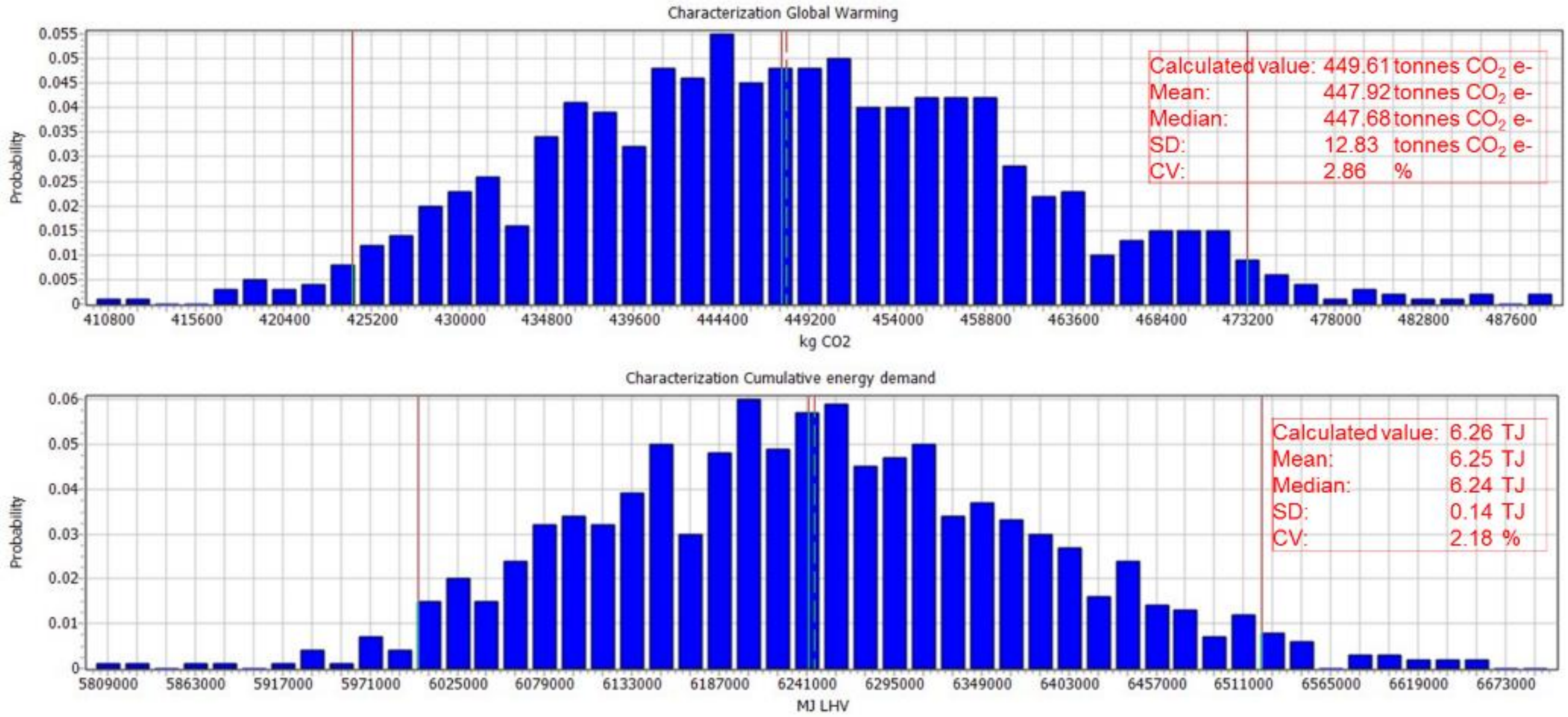


Figure 4.33 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for DB-INS-SG-CT envelope

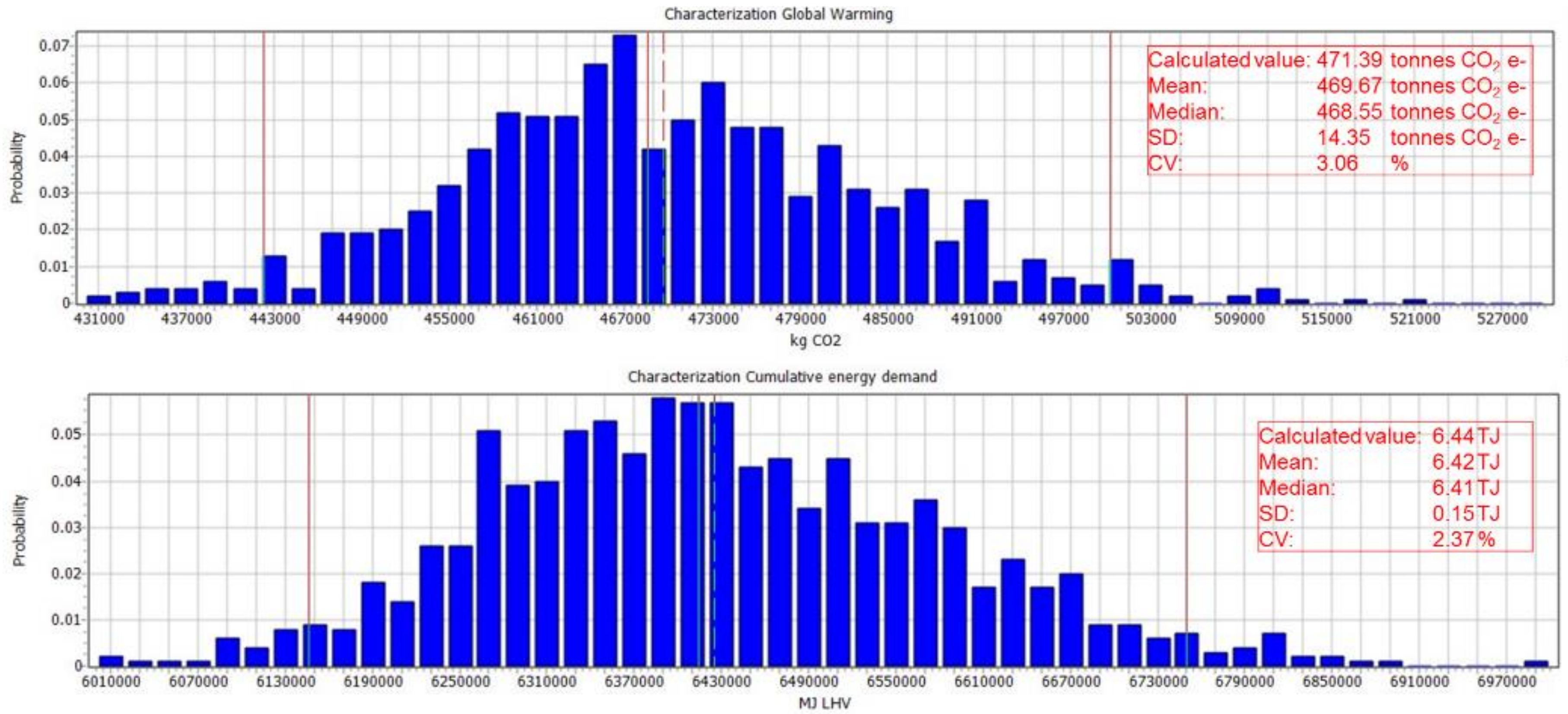


Figure 4.34 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for BV-XX-SG-CT envelope

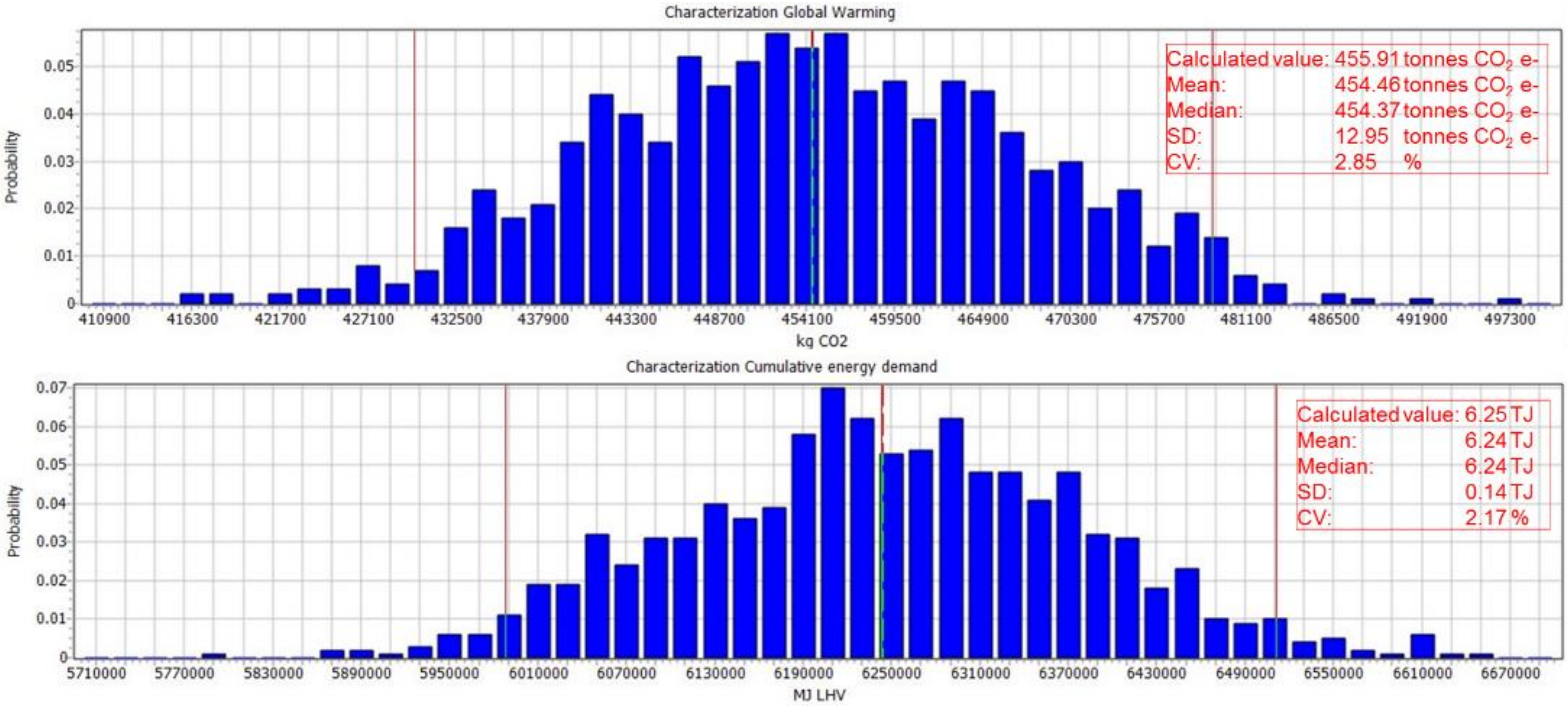


Figure 4.35 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for RBV-XX-SG-CT envelope

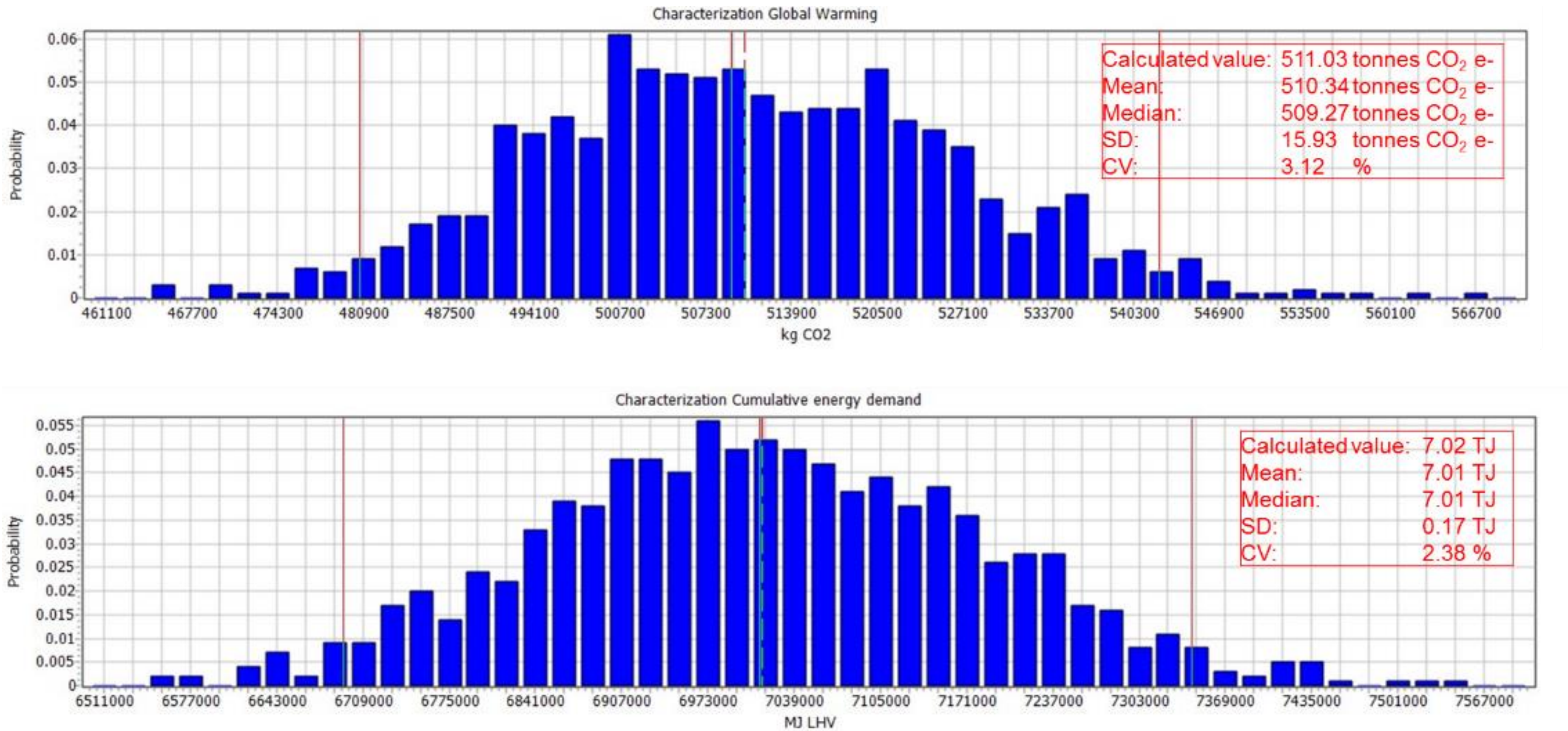


Figure 4.36 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for CB-XX-SG-CT envelope

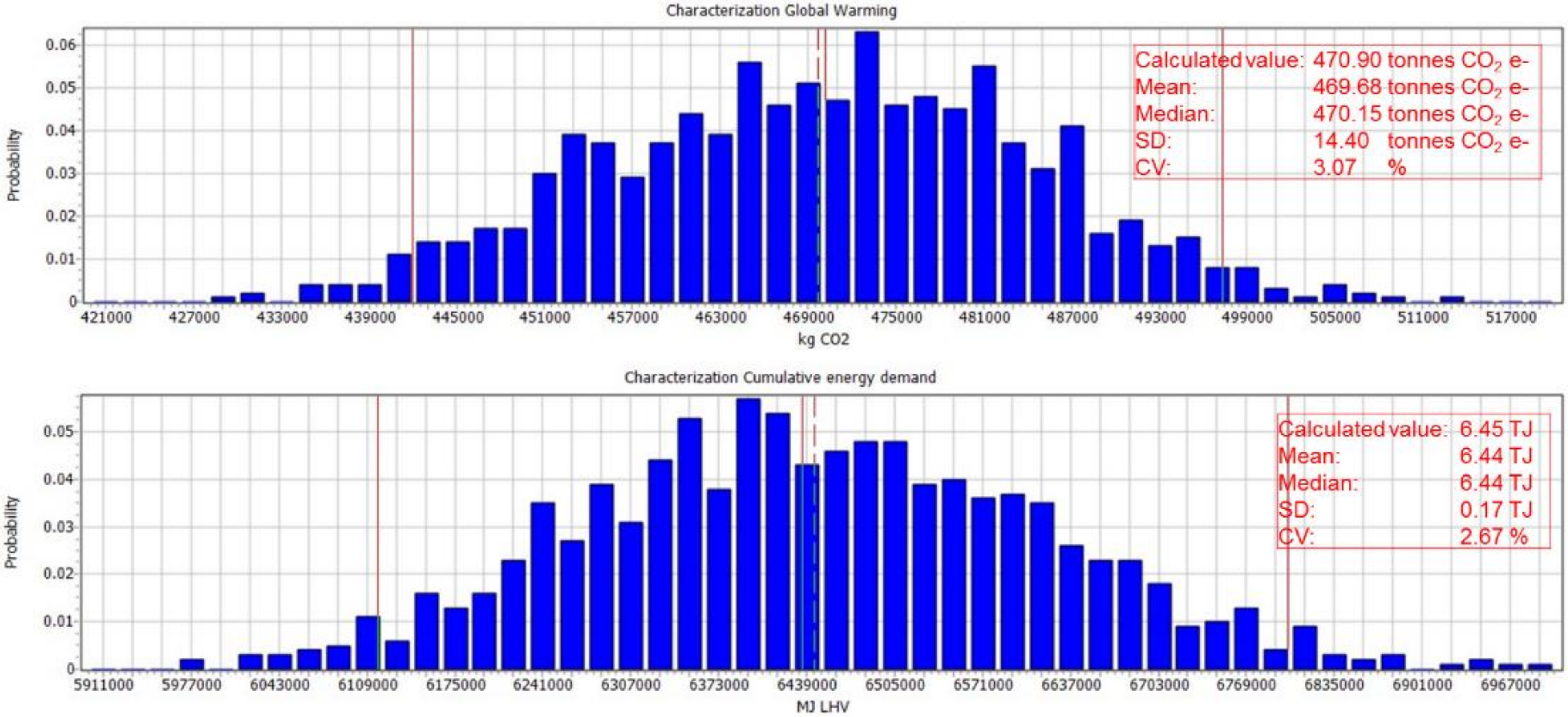


Figure 4.37 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for ACC-XX-SG-CT envelope

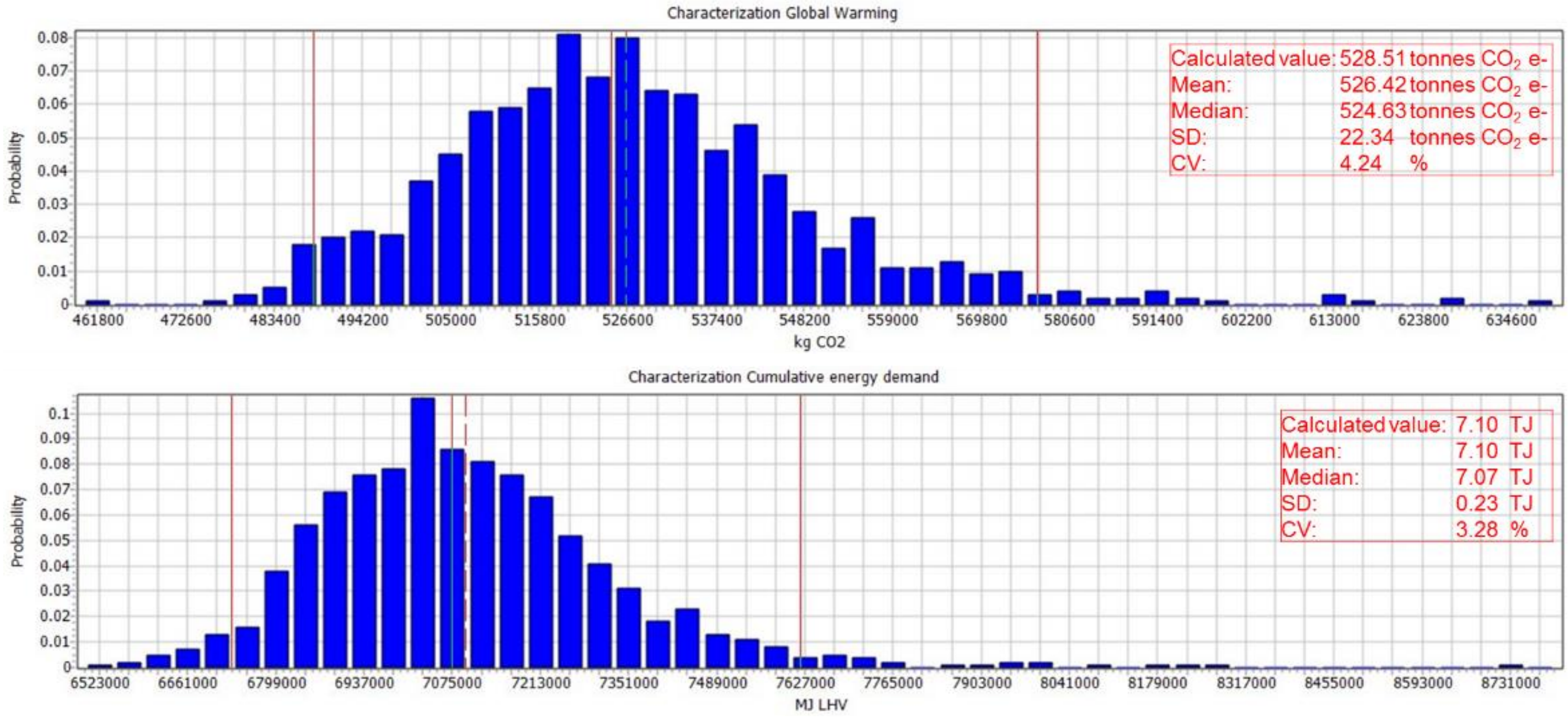


Figure 4.38 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for PCSW-XX-SG-CT envelope

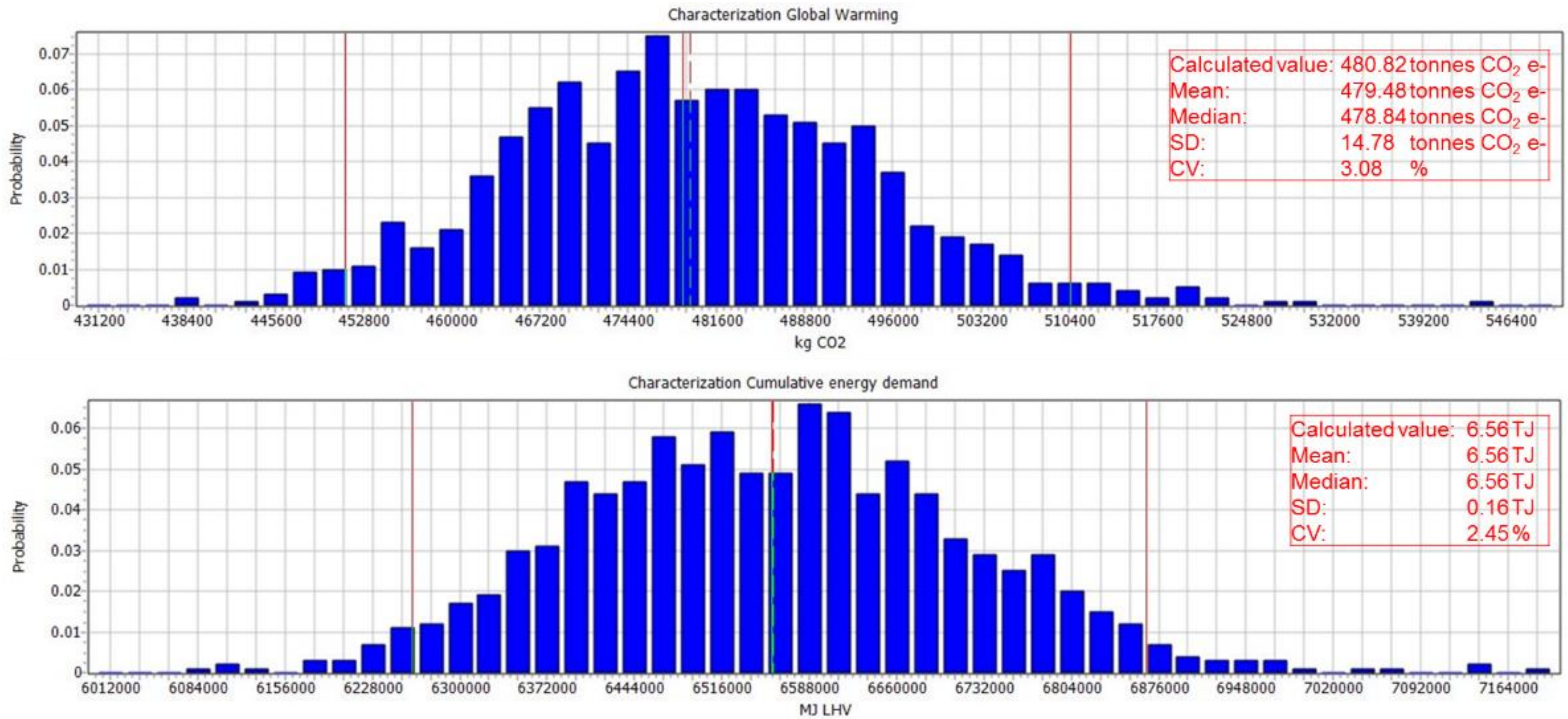


Figure 4.39 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for TMB-XX-SG-CT envelope

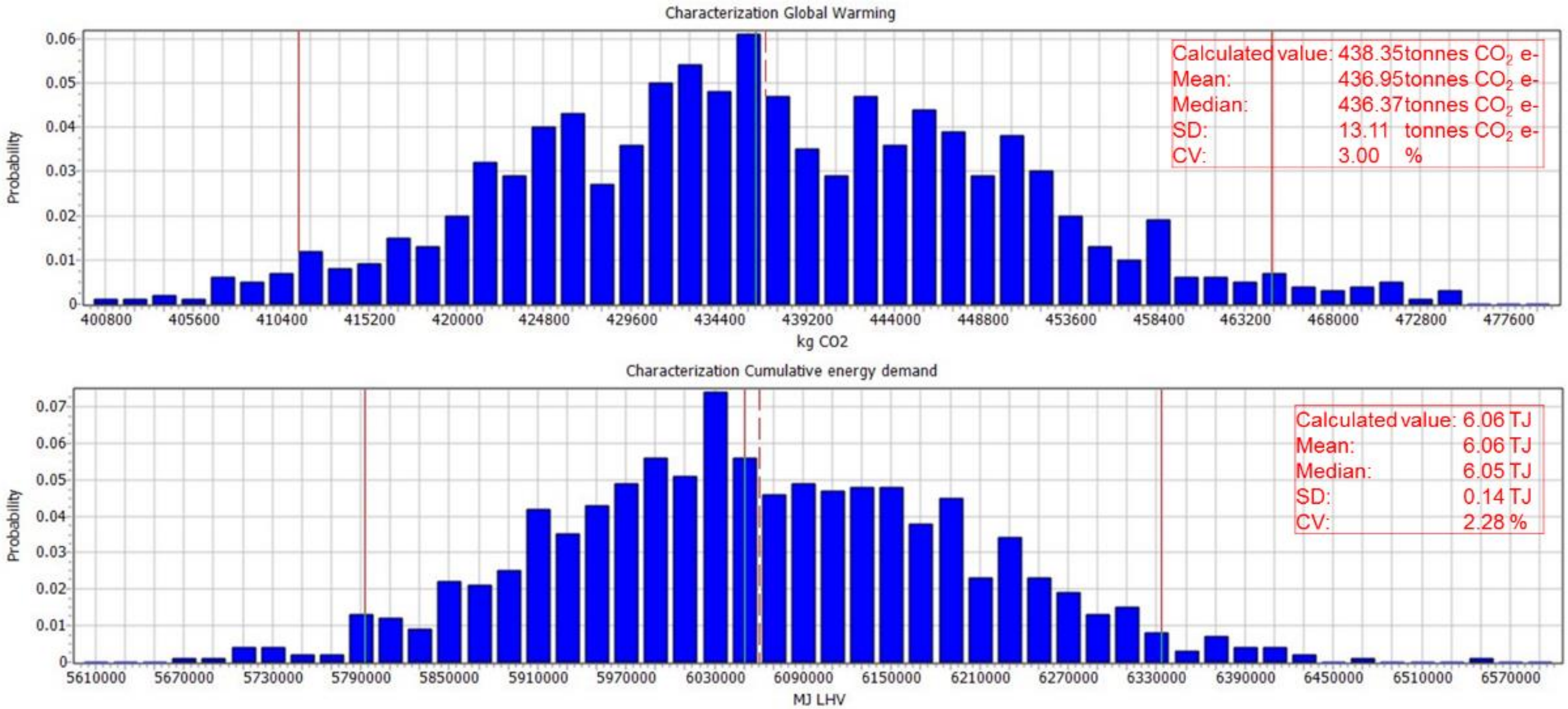


Figure 4.40 Uncertainty histogram for GHG emissions and EE consumption of a typical reference house in Perth for CSW-POL-SG-CT envelope

The above results show an increased level of confidence and robustness in the life cycle assessment results and provide transparency (Guo and Murphy 2012) and a better basis of comparison between alternative envelope options (Niero et al. 2014). The calculated values of GHG emissions for these envelope options are between 0.14% and 0.40% of the mean values. In the case of EE consumption, the calculated values are between 0.0% and 0.31% of the mean values. The coefficient of variation of these envelope options for GHG emissions varies from 2.85% and 4.24%, while the CVs for EE consumption vary from 2.17% and 3.28%. All these results show the statistical validity of the current LCA. However, the CVs of GHG emissions are relatively higher than those of EE consumption. This may be because of the fact that GHG emissions deal with a number gases, while there is only a single value of energy as input. Various studies have confirmed that the LCA results with CV values less than 5% are statistically viable (Grant 2009; Biswas and Cooling 2013; Lo, Ma and Lo 2005; Biswas and Naude 2016; Mohammed et al. 2016).

4.4.6 Sensitivity analysis

Unlike the uncertainty analysis, which essentially estimates the uncertainties within the background inventories based on a probability distribution, the sensitivity analysis is useful for investigation of the magnitude of the effect of known uncertainties or assumptions in isolation (Carre, Crossin and Clune 2013; Bragança and Mateus 2012; Björklund 2002). In this current study, the sensitivity of effect of orientation change of the house on life cycle operational energy demand for heating and cooling and impact of climate change on life cycle operational energy demand for cooling for alternative envelope options have been evaluated.

Sensitivity to change in orientation

In a large residential sub-division, it may not be practically possible to have all the houses having a precise optimum orientation (Yıldız and Arsan 2011) and hence it is important to investigate the sensitiveness of the results of alternative envelope options due to change in orientation. Based on the findings of the optimum orientation for a typical reference house in Perth (Section 4.2.2, and Section 4.4.3), the life cycle operational energy demand for heating and cooling of a typical house for alternative envelope options including associated GHG emissions and EE consumption impacts were estimated for the East orientation only (Section 4.4.4), which had the lowest life cycle operational energy demand for heating and cooling. The reference house with South orientation was found to have not only the highest operational energy for heating and cooling, but the GHG emissions and EE consumptions were also the highest. Therefore, AccuRate software and SimaPro software have been utilized for estimation of life cycle operational energy for heating and cooling, as well as associated GHG emissions and EE consumptions of a typical house for alternative envelope options for remaining orientations. It is found that still the South facing house for all alternative envelope options has the highest life cycle operational energy demand for heating and cooling as well as the highest GHG emissions and EE consumption. The results of life cycle operational energy for heating and cooling, as well as associated GHG emissions and EE consumption of a typical reference house for all alternative envelope options for East and South orientations, are presented in Table D.23 (Appendix D).

Sensitivity to change in orientation - Operational energy for heating and cooling for alternative envelope options

As discussed in Sections 4.2.2, and 4.4.3, the life cycle operational energy demand for heating and cooling of a typical reference envelope (DB-XX-SG-CT) may increase up to 42.9% due to the change in orientation (from optimum East facing to worst South facing). The results show that the increase of life cycle operational energy demand for heating and cooling due to the change in orientation from East to South vary from 173GJ (up by 65%) for CSW-POL-DG-CT/TT/MS options to 260GJ (up by 33%) for CB-XX-DG-CT/TT/MS options. The change in orientation has the minimum influence on heating energy (an increase of 20%) for options CB-XX-SG/DG-CT/TT/MS, while the heating energy (an increase of about 53%) for envelope options DB-INS-DG-CT/TT/MS, and RBV-XX-DG-CT/TT/MS is highly influenced due to the change in orientation. On the other hand, the change in orientation has the minimum influence on cooling energy (an increase of 36%) for options TMB-XX-SG-CT/TT/MS, while the cooling energy (an increase of about 83%) for options DB-INS-DG-CT/TT/MS, and RBV-XX-DG-CT/TT/MS is highly influenced due to change. In the case of total energy for heating and cooling, the options CB-XX-SG-CT/TT/MS with an increase of 29% are found to be the least sensitive to orientation change, while the envelope options DB-INS-DG-CT/TT/MS and RBV-XX-DG-CT/TT/MS with an increase of about 68% are highly sensitive to orientation change (Figure 4.41).

The main reason for sensitiveness of highly insulated envelopes with double glazed windows such as DB-INS-DG-CT/TT/MS, and RBV-XX-DG-CT/TT/MS to orientation change is due to the fact that the envelope's insulation behaves as a double edged sword and becomes counter-productive beyond a certain point because during winter, it enhances the envelope's ability to retain the heat, while during summer, the dissipation of unwanted heat is prevented by the same insulation (Wang, Gwilliam and Jones 2009; Masoso and Grobler 2008). Bellamy (2014) and Pacheco, Ordóñez, and Martínez (2012) reported that the relationship between the level of envelope's insulation and its energy performance for different orientations is non-linear. Similarly, the double glazed windows help in reducing the solar radiation entering the house, which is beneficial during summer but the same is detrimental during winter (Florides et al. 2002; Li, Yang and Lam 2013). This confirms that each envelope will perform differently under same climatic conditions.

The envelope options with low or nil insulation, and very low thermal mass such as CB-XX-SG-CT/TT/MS and TMB-XX-Sg-CT/TT/MS are less sensitive to the change in orientation, because they are unable to retain and dissipate the heat to take advantage of minimizing the mechanical heating and cooling irrespective of orientation (Kordjamshidi 2011). The similar trend of variation in operational energy demand for heating and cooling due to change in orientation for envelopes with different levels of insulation has been confirmed by Vijayalaxmi (2010), where the increase of energy between East and South orientations is minimum for insulated envelope options and maximum for uninsulated envelope options. Andersson et al. (1985) confirmed that the change in orientation can significantly influence the energy use in a moderately well-insulated house. Also a study by Crawford, Czerniakowski, and Fuller (2011) reported that the relative ranking of operational energy demand for heating and cooling for alternative envelopes does not change with the change in orientation (i.e. if envelope A has lower energy demand for a particular orientation with respect to envelope B then this remains valid for all other orientations), however the variation in the operational energy demand for heating and cooling due to change in orientation is different for each envelope.

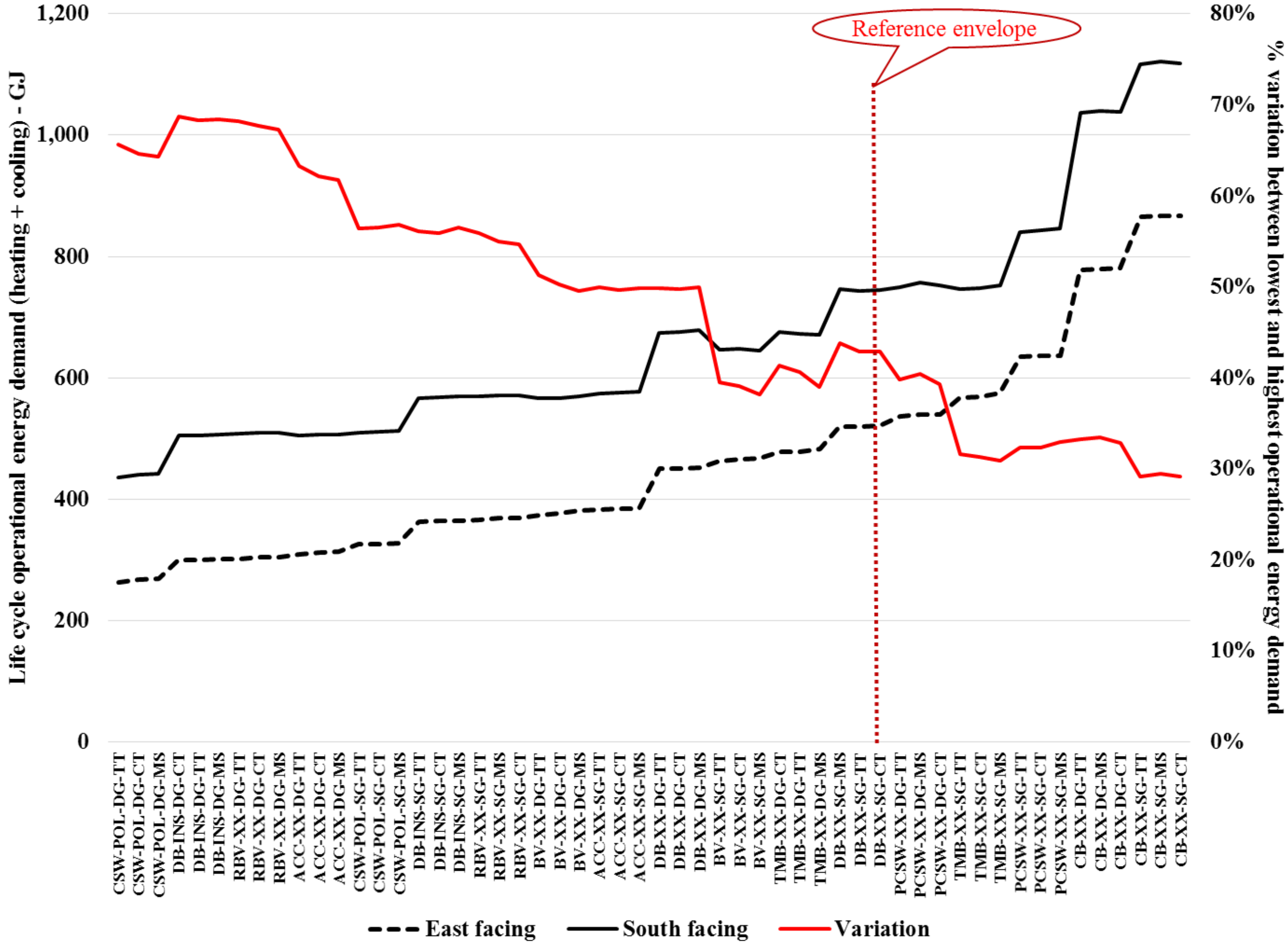


Figure 4.41 Sensitivity to change in orientation on operational energy for heating and cooling for alternative envelope options

Despite of the high sensitivity of well insulated envelope options to the change in orientation, the inclusion of insulation and double glazed windows (envelopes DB-INS-DG-CT/TT/MS and RBV-XX-DG-CT/TT/MS) provide significant savings of around 42% (for East orientation) and 32% (for South orientation) of the total operational energy demand for heating and cooling in comparison to the reference envelope (DB-XX-SG-CT). These results are supported by other studies which have recommended the inclusion of insulation and double glazed windows as an effective measure to reduce the operational energy demand for heating and cooling (Morrissey, Moore and Horne 2011; Jaber and Ajib 2011; Serghides and Georgakis 2012; Florides et al. 2002; Bambrook, Sproul and Jacob 2011; Cheung, Fuller and Luther 2005).

Sensitivity to change in orientation - GHG emissions for alternative envelope options

To analyse the sensitiveness of the change in orientation of alternative envelopes to GHG emissions and EE consumption, the revised operational energy data for heating and cooling were entered into the LCIs of these envelope options in SimaPro software. The results of GHG emissions and EE consumption associated with the operational energy demand for heating and cooling for alternative envelope options for East and South orientations are presented in Table D.23 (Appendix D). GHG emissions associated with the operational energy for heating and cooling for reference envelope (DB-XX-SG-CT) changes from 78tonnes CO_2 e- to 118tonnes CO_2 e- (an increase of 50.51%) due to change in orientation. Similar to the operational energy, the GHG emissions impacts associated with operational energy for heating and cooling for highly insulated envelope options DB-INS-DG-CT/TT/MS, and RBV-XX-DG-CT/TT/MS are highly sensitive to the change in orientation (an increase of about 78%), while the GHG emissions impacts for envelope options (CB-XX-SG-CT/TT/MS) are least sensitive to change in orientation (an increase of 36%) (Figure 4.42).

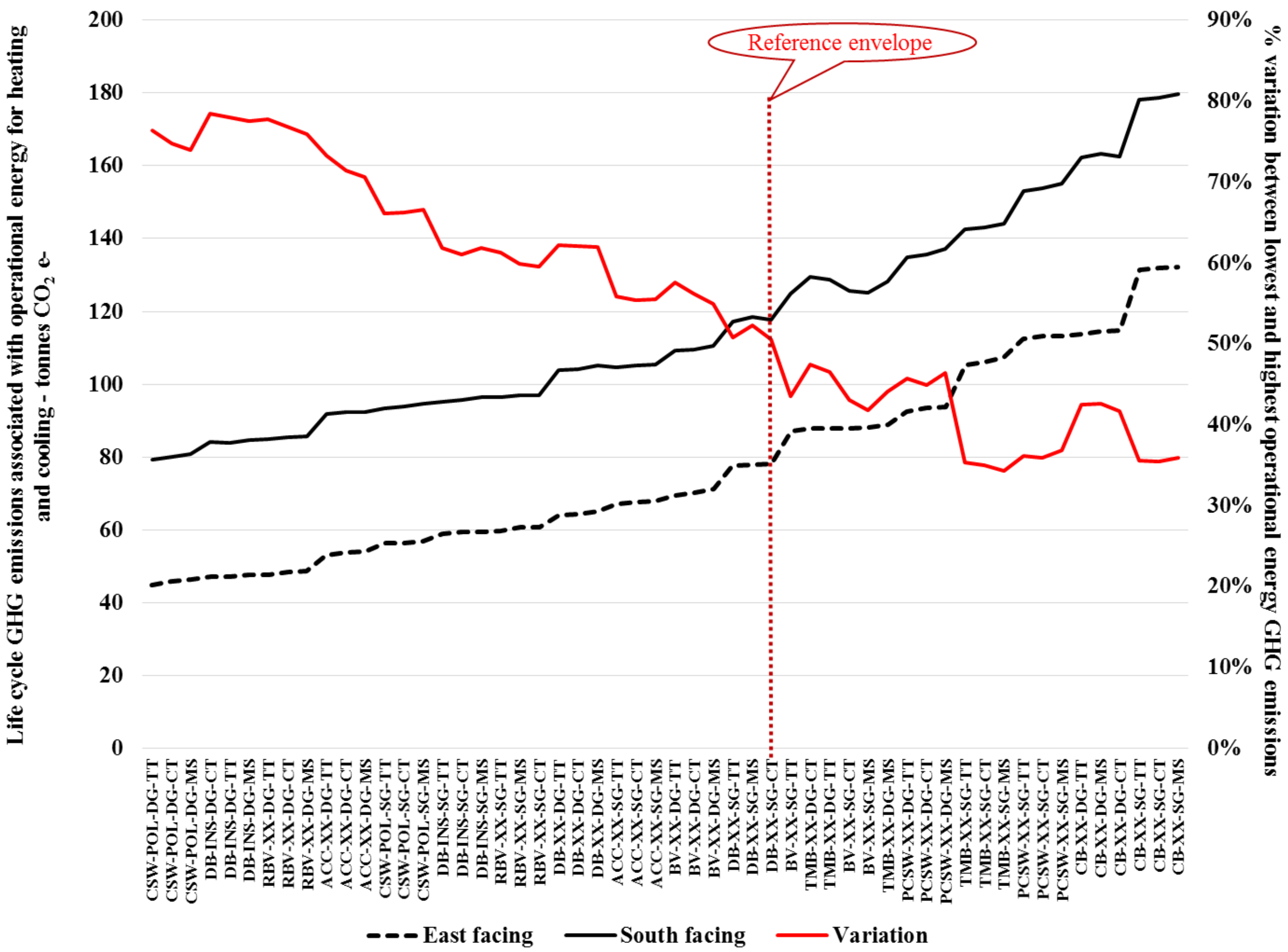


Figure 4.42 Sensitivity to change in orientation on GHG emissions associated with operational energy for heating and cooling for alternative envelopes

Sensitivity to change in orientation - EE consumption for alternative envelope options

The EE consumption associated with the operational energy for heating and cooling for reference envelope (DB-XX-SG-CT) changes from 1.09TJ to 1.63TJ (an increase of 49.27%). The EE consumption associated with the operational energy for heating and cooling for highly insulated envelope options DB-INS-DG-CT/TT/MS, and RBV-XX-DG-CT/TT/MS is highly sensitive to the change in orientation (an increase of about 77%), the EE consumption for envelope options (CB-XX-SG-CT/TT/MS) is least sensitive to change in orientation (an increase of 35%) (Figure 4.43)

Despite the high sensitivity of well insulated envelope options to the change in orientation, the inclusion of insulation and double glazed windows (envelopes DB-INS-DG-CT/TT/MS and RBV-XX-DG-CT/TT/MS) provide the GHG emissions reduction and EE consumption saving of around 39% (for East orientation) and 28% (for South orientation) in comparison with the reference envelope (DB-XX-SG-CT). Table D.23 (Appendix D), shows that the patterns of change of operational energy for heating and cooling, associated GHG emissions, and EE consumption for alternative envelope options are not uniform (Figure 4.44) due to the change in orientation from East to South. This is because of the fact that an increase or decrease of each GJ of heating (i.e. use of natural gas) and cooling (i.e. grid electricity) energy has different impacts. For example, one GJ of natural gas for heating causes 58.3 kg CO_2 e- GHG emissions, while one GJ of grid electricity for cooling causes 255.5kg CO_2 e- GHG emissions.

The results of the sensitivity analysis show that the operational energy for heating, and cooling, GHG emissions, and EE consumption of a typical house in Perth for energy efficient envelope options (CSW-POL-DG-CT/TT/MS) remain the lowest in all orientations, which demonstrate their adaptability to change in orientation. Findings of other studies tend to confirm the above results (Morrissey, Moore and Horne 2011; Crawford and Fuller 2011; Verbeeck and Hens 2010; Cuéllar-Franca and Azapagic 2012).

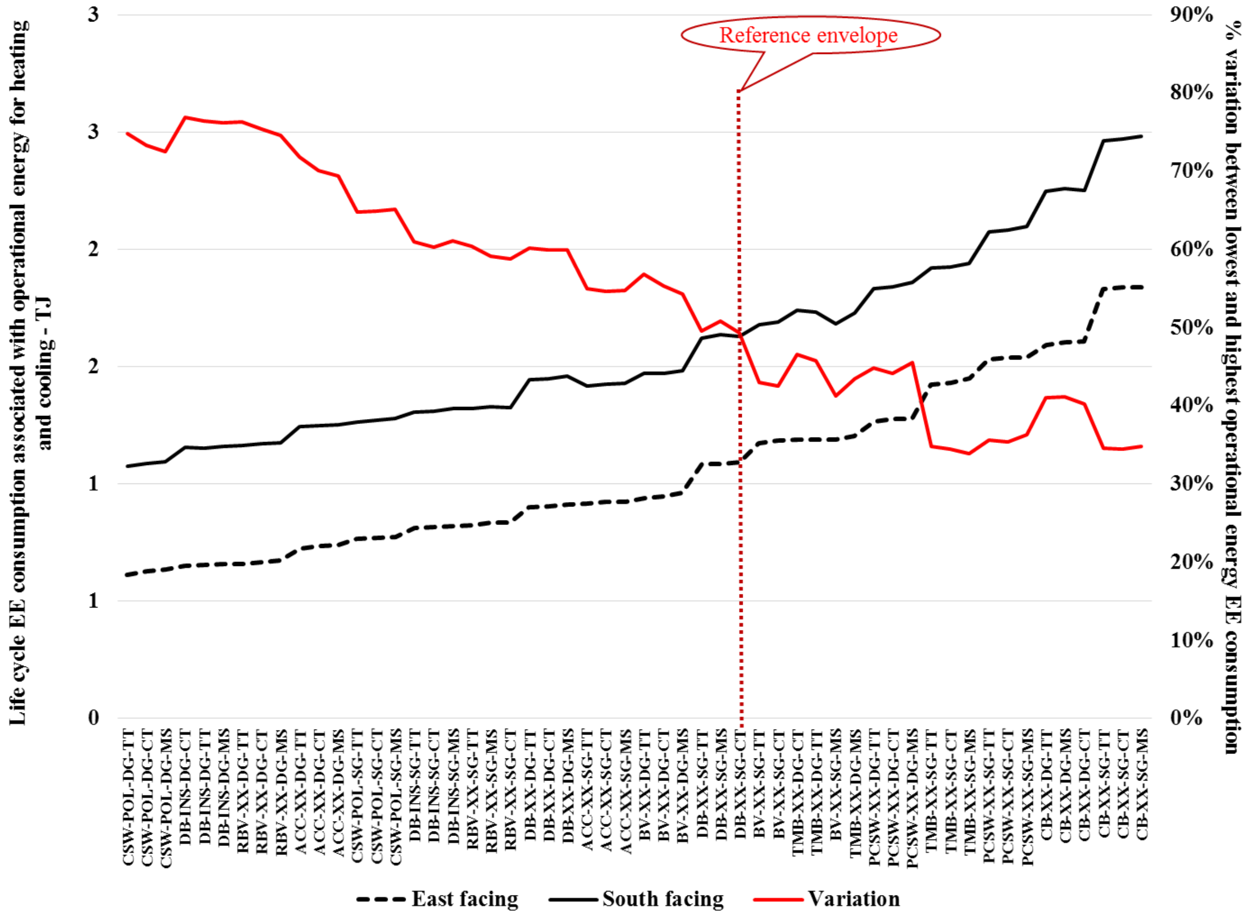


Figure 4.43 Sensitivity to change in orientation on EE consumption associated with operational energy for heating and cooling for alternative envelope

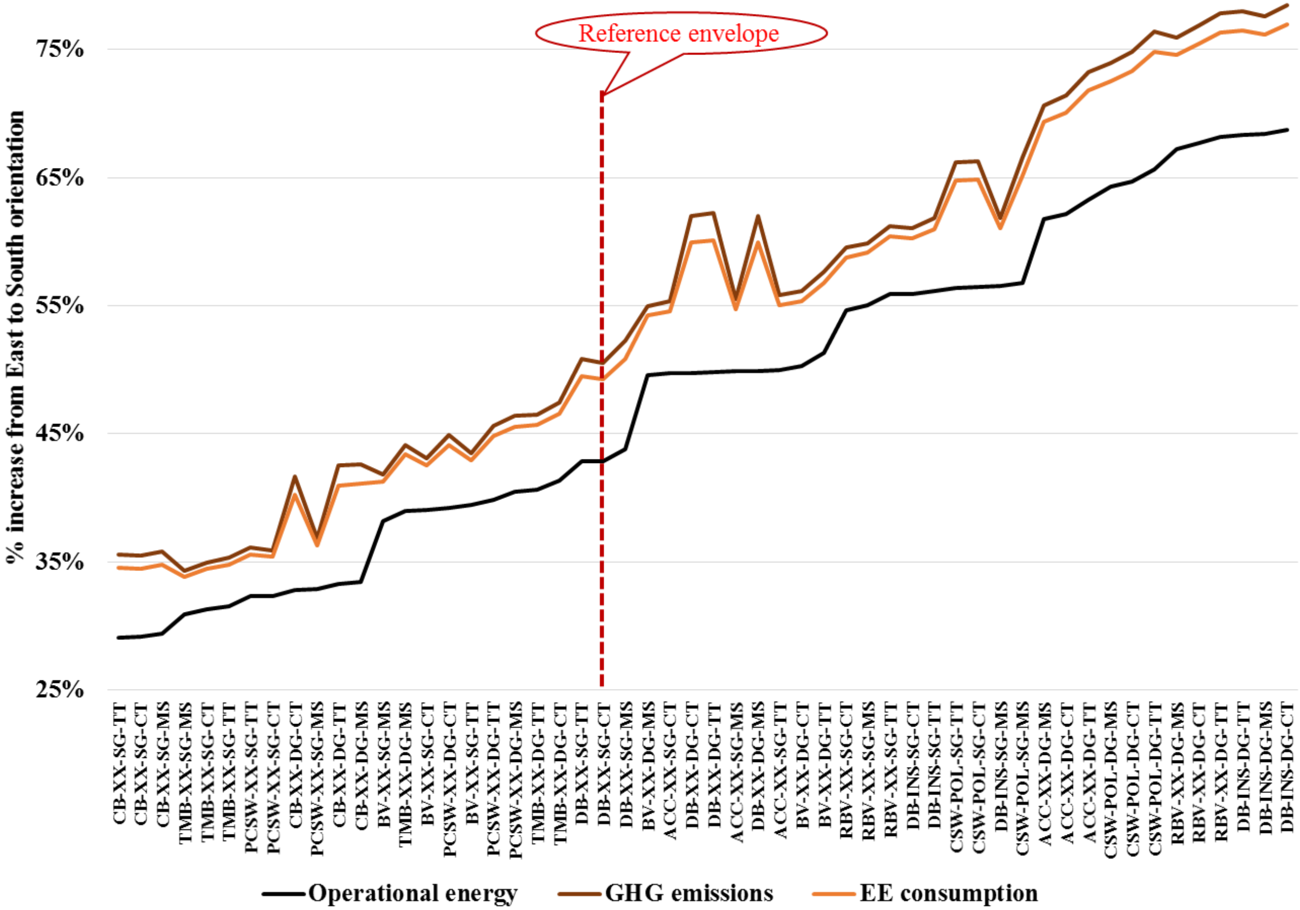


Figure 4.44 Percentage increase of operational energy for heating and cooling, associated GHG emissions, and EE consumption for alternative envelopes due to change in orientation

Sensitivity to temperature rise due to climate change impact on cooling energy demand for alternative envelope options

The recent studies have reported that there is an increasing trend of rising temperature and discomfort during summer that results in an increased operational energy demand for cooling (Lam et al. 2010). Therefore, it is important that the alternative house designs are adaptable to temperature rise due to climate change and minimize the vulnerability of the occupants from the effects of temperature rise (Ingwersen et al. 2013; Roberts 2008). Li, Yang, and Lam (2012) and Ren, Chen, and Wang (2011) reported that the houses, where operational energy demand is dominated by cooling will be most affected due to temperature rise and so the electricity demand for cooling may increase. Thus the investigation into the impact of temperature rise on the life cycle operational energy demand for cooling for alternative envelopes is deemed essential (Holmes and Hacker 2007; Chan 2011).

The impacts of temperature rise on the cooling energy of a typical house for reference envelope (DB-XX-SG-CT) were analysed in Section 4.2.2. The annual cooling energy consumption is expected to increase by a minimum of 2% to 3% during 2010 -2030, and 5% to 8% during 2030-2065 under low CC impact scenario, while for high CC impact scenario, the annual cooling energy consumption is expected to increase by a maximum of 9% to 14% during 2010 -2030, and 27% to 47% during 2030-2065 (Guan 2009; Ren, Chen and Wang 2011; Wang, Chen and Ren 2010; CSIRO 2001; Whetton et al. 2005). The life cycle cooling energy demand of a reference house in Perth for alternative envelope options could increase by 6% to 24% as a result of the temperature rise (Table D.24, Appendix D). It has been found that even under high CC impact scenario, the life cycle operational energy for cooling for highly insulated/double glazed envelope options DB-XX-DG-CT/TT/MS, DB-INS-SG/DG-CT/TT/MS, ACC-XX-DG-CT/TT/MS, and CSW-POL-SG/DG-CT/TT/MS will be lower than or equal to the life cycle operational energy for cooling without CC impacts for reference envelope DB-XX-SG-CT (Figure 4.45).

The above findings confirm that the energy efficient house will be least affected by temperature rise due to climate change impacts and is an appropriate climate change adaptation strategy (Bambrick et al. 2011; Crawley 2008; Guan 2012).

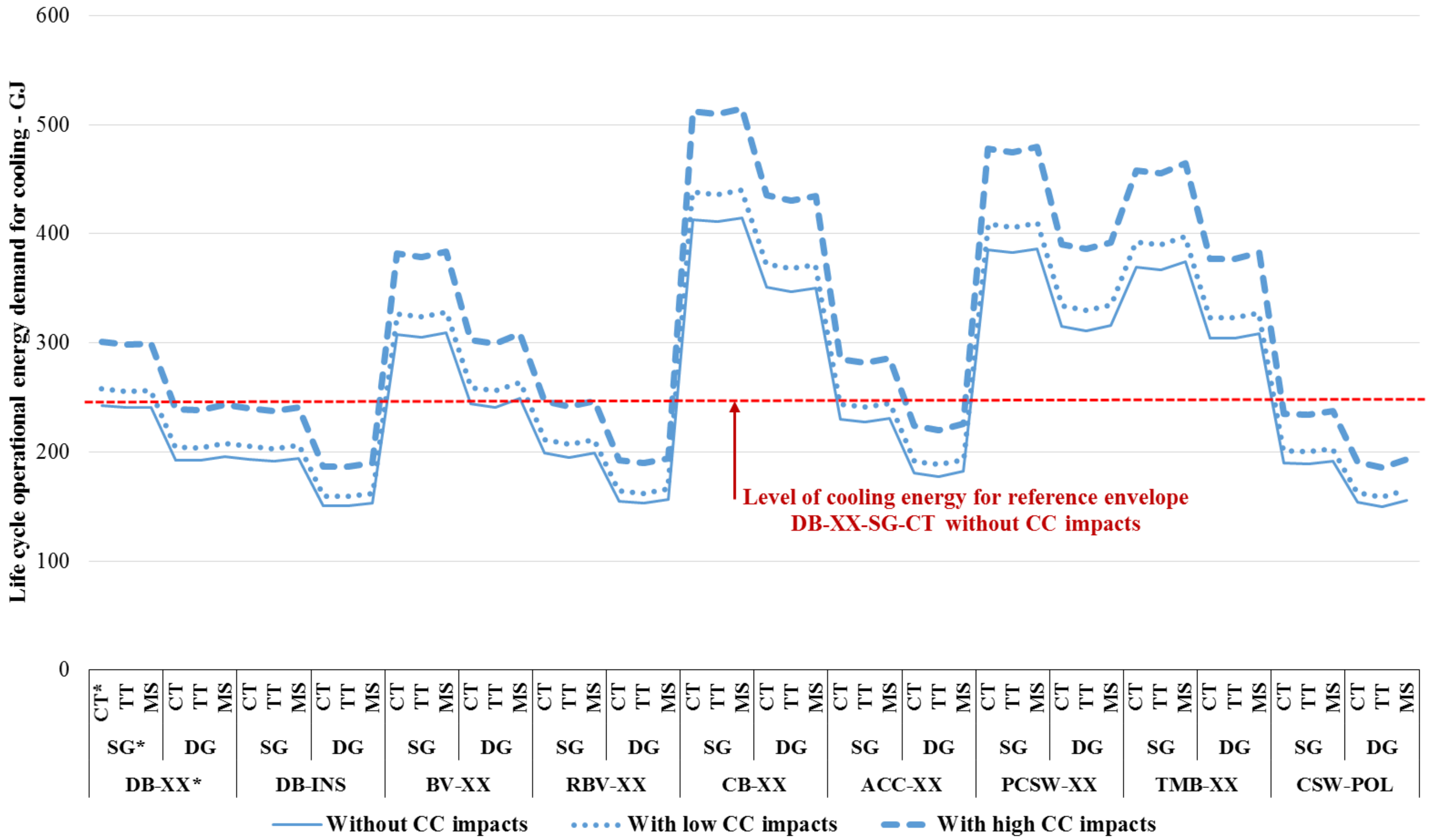


Figure 4.45 Impact of temperature rise on life cycle operational energy for cooling of a typical house for alternative envelope options

The life cycle GHG emissions and EE consumption associated with the operational energy for cooling for alternative envelope options under climate change impact scenarios have been presented in Table D.25, and Table D.26 (Appendix D). Even under high CC impact scenario, the life cycle GHG emissions (Figure 4.46) and EE consumption (Figure 4.47) associated with the operational energy for cooling for highly insulated/double glazed envelope options DB-XX-DG-CT/TT/MS, DB-INS-SG/DG-CT/TT/MS, ACC-XX-DG-CT/TT/MS, and CSW-POL-SG/DG-CT/TT/MS will be lower than or equal to the life cycle GHG emissions and EE consumption associated with the operational energy for cooling without CC impacts for reference envelope DB-XX-SG-CT.

The above findings confirm that as a consequence of temperature rise due to climate change impacts, the increased use of air-conditioning will have adverse impact on energy consumption, and GHG emissions of a building, which can be significantly mitigated through inclusion of energy efficiency measures (Sanders and Phillipson 2003; Xu et al. 2012; Wan et al. 2012).

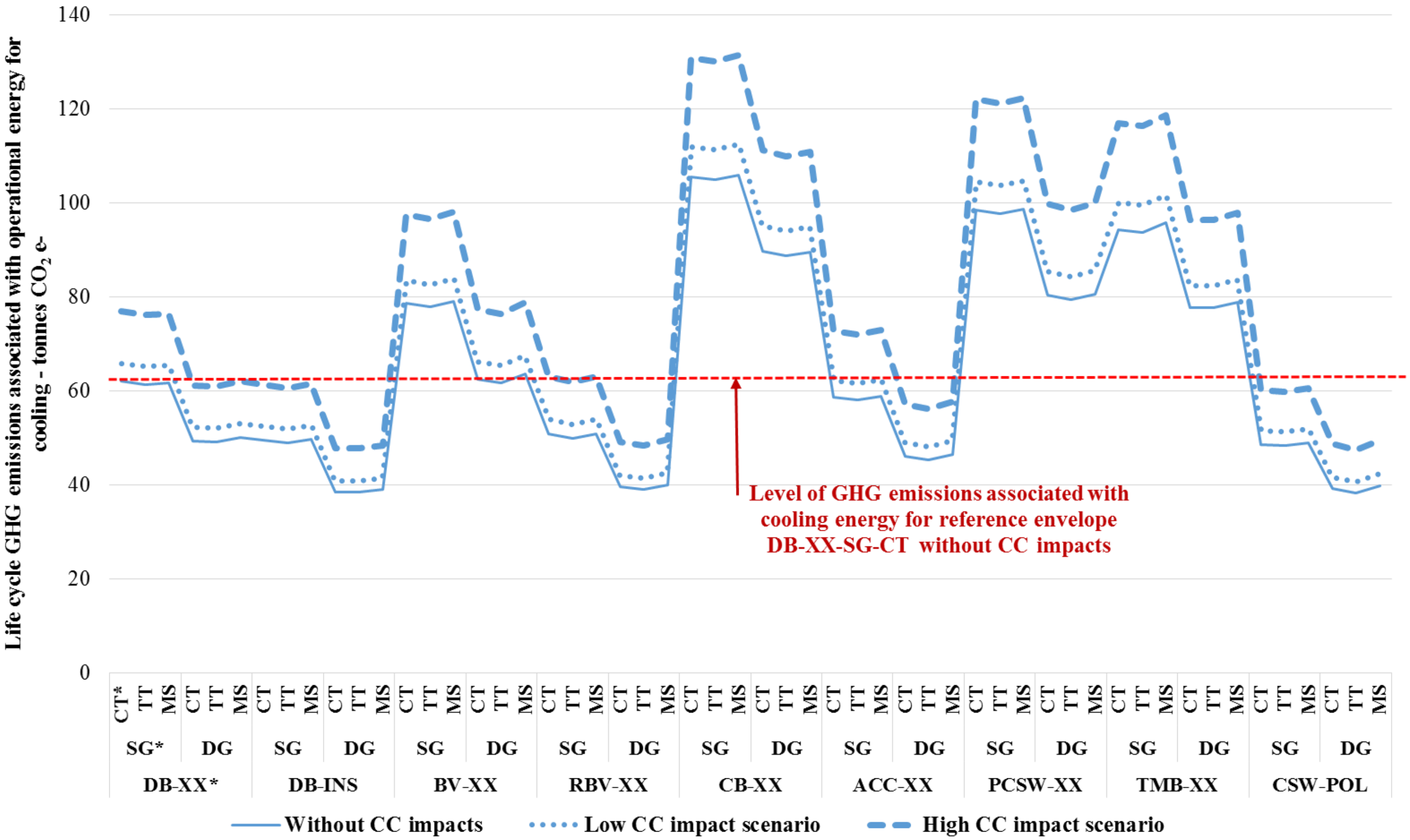


Figure 4.46 Impact of temperature rise on life cycle GHG emissions associated with the operational energy for cooling of a typical house for alternative envelope options

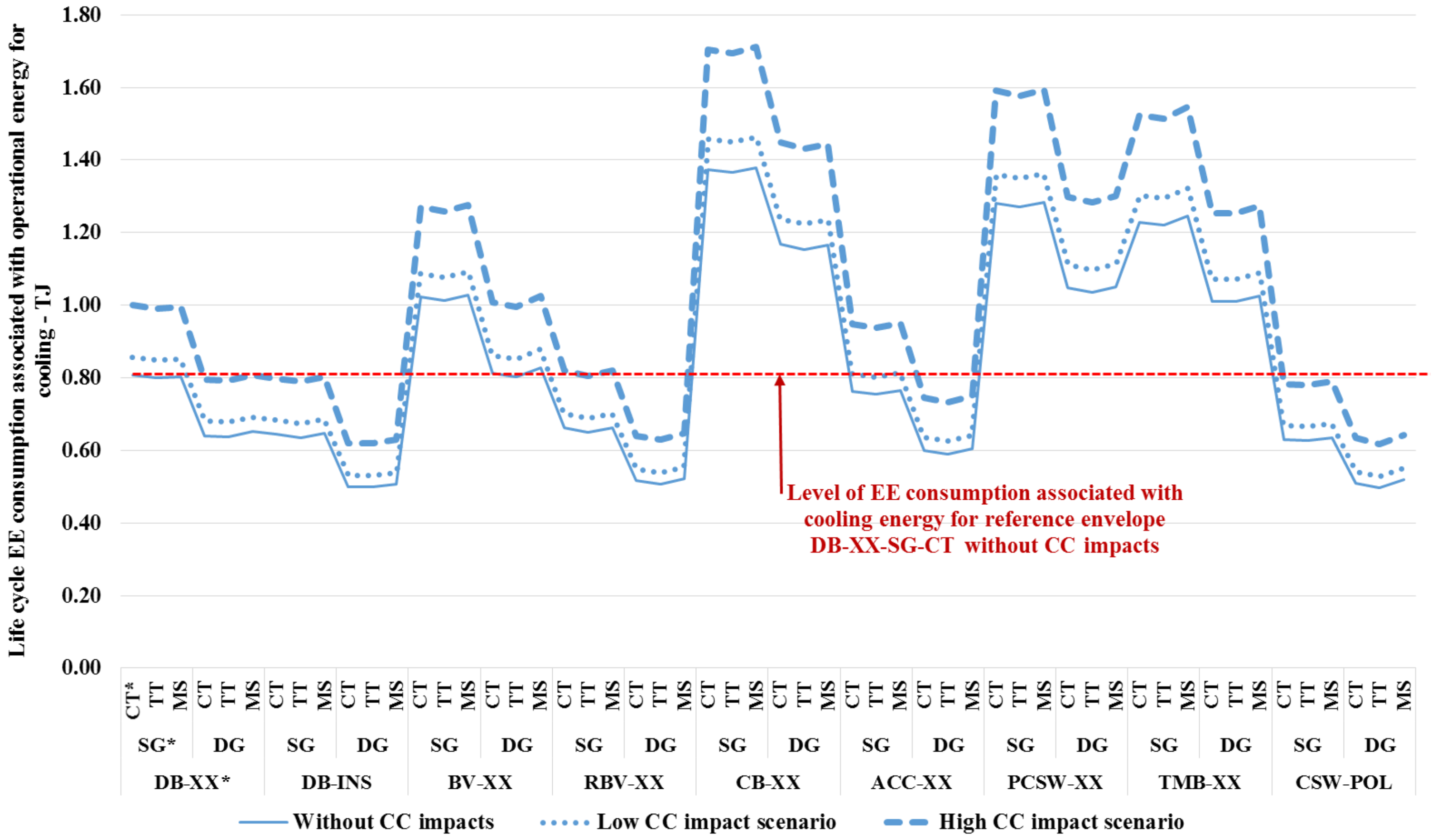


Figure 4.47 Impact of temperature rise on life cycle EE consumption associated with the operational energy for cooling of the house for alternative envelope options

Sensitivity to technological advancements and improvement of energy efficiency of appliances

The houses have long lifespan and the technological advancements and an improvement of energy efficiency of appliances (e.g. air-conditioner, heater, TV, refrigerator, computer, and oven) that may take place during this lifespan are unpredictable and is beyond the scope of this research and hence the same technologies have been considered throughout the lifespan. Moreover, various studies suggest that the technological advancements and energy efficiency improvement policies have not been as effective as they were believed to be because of rebound effect, where the actual energy consumption has been increasing over recent decades despite the energy efficiency improvements (Jin 2007; Gillingham et al. 2013; Herring 2006; Sorrell, Dimitropoulos and Sommerville 2009; Burgess and Nye 2008). Whilst, the efficiency of electrical and electronic home appliances is increasing, the number, as well as the type of appliances, are also increasing (e.g. multiple and big screen LED TVs as compared to old TV, more computers) (Herring and Roy 2007). Brännlund, Ghalwash, and Nordström (2007) suggested that an exogenous technological progress, in terms of increase in energy efficiency may not essentially help to lower the energy consumption and hence lower the associated emissions. For example, the replacement of high wattage incandescent lamps with lower wattage compact fluorescent lamp (CFL) should ideally be reducing the electricity consumption but many occupants feel that because it is now costing them less, they may use it for a longer duration to enhance safety and security. Another example is refrigerators, which are getting bigger and bigger in their storage capacity and thus are being utilized for storage of food which even does not require storage at a cool temperature (Wilhite and Norgard 2004).

The energy consumption pattern of home appliances is a complex function of occupant's behaviour and interaction (DEWHA 2008a; ABS 2014) and the impact of technological advancement and improvements in energy efficiency of home appliances will be uniform for all alternative envelope options due to aforementioned uncertainties. The impacts of technological advancements and improvements in energy efficiency of home appliances have not been considered for this study. Moreover, Greening, Greene, and Difiglio (2000) suggested that in the absence of stringent polices, a significant portion of technologically achievable energy and GHG emissions savings may be lost due to the rebound effect.

Since the energy consumption due to rebound effect is unlikely to be changed significantly, the introduction of renewable energy as a replacement for the conventional energy is expected to make a reduction in GHG emissions. Therefore this study considered supply side improvement using roof top solar PV and solar water heater instead of demand side technological improvement. However, there is a limitation that the efficiency improvement of solar PV in future has not been considered for this study.

4.4.7 Summary of GHG emissions and EE consumption reduction potential due to implementation of above CPS

Summary of GHG emissions

The GHG emissions results of the implication of cleaner production strategies to treat the hotspots (materials or energy inputs contributing to the significant portion of GHG emissions impacts) during the life cycle stages of a typical reference clay brick wall house in Perth have been summarised in Table D.27 (Appendix D). The cumulative GHG emissions reduction potential offered by all CPS have been assigned a positive (+) or negative (-) ranking with respect to the GHG emissions reduction potential of the reference envelope option having roof top solar PV, solar water heater, and green concrete (i.e. ranking 0). A study by Bender and Stinson (1984) reported that effectiveness ranking of impact evaluation can be expressed in terms of "+" (i.e. effective), and "–" (i.e. worsen impacts). The range of positive (+) rankings is based on the effective and most effective performance relations, and indicate that how an alternative mitigation option is better than other options, while the negative (-) rankings indicate as to how an alternative option is worse than other (Rossi, Cancelliere and Giuliano 2005). The results show that out of total 53 alternative options, 30 options have more GHG emission reduction potential than the reference case (i.e. ranking 0), while 23 options provide less GHG emissions. Following Qureshi and Harrison (2001), the 30 alternative options having more GHG reduction potential have been assigned positive rankings from +1 (most effective) to +30 (least effective), while the negative rankings from -1 (least worse) to -23 (most worse) have been assigned to 23 alternative options having less GHG emissions reduction potential (Table 4.23).

Table 4.23 Summary of GHG reduction potential of CPS and their rankings

Envelope options				**GHG savings potential tonnes CO_2 e-**				**Cumulative GHG reduction tonnes CO_2 e-**	**Ranking + (effective) - (worse)**
				Changes in envelope	**Roof top solar PV 3kW$_p$**	**Solar water heater**	**Green concrete**		
DB	**XX**	**SG**	**CT**	N.A	-200.14	-22.7	-2.76	-225.60	0
			TT	0.44	-200.14	-22.7	-2.76	-225.16	**-1**
			MS	0.89	-200.14	-22.7	-2.76	-224.71	**-2**
		DG	**CT**	-13.38	-200.14	-22.7	-2.76	-238.98	**+16**
			TT	-12.59	-200.14	-22.7	-2.76	-238.19	**+19**
			MS	-11.35	-200.14	-22.7	-2.76	-236.95	**+20**
DB	**INS**	**SG**	**CT**	-17.57	-200.14	-22.7	-2.76	-243.17	**+13**
			TT	-17.13	-200.14	-22.7	-2.76	-242.73	**+14**
			MS	-16.09	-200.14	-22.7	-2.76	-241.69	**+15**
		DG	**CT**	-29.23	-200.14	-22.7	-2.76	-254.83	**+7**
			TT	-28.20	-200.14	-22.7	-2.76	-253.80	**+8**
			MS	-27.36	-200.14	-22.7	-2.76	-252.96	**+9**
BV	**XX**	**SG**	**CT**	4.20	-200.14	-22.7	-2.76	-221.40	**-5**
			TT	4.40	-200.14	-22.7	-2.76	-221.20	**-6**
			MS	5.88	-200.14	-22.7	-2.76	-219.72	**-8**
		DG	**CT**	-12.97	-200.14	-22.7	-2.76	-238.57	**+17**
			TT	-12.78	-200.14	-22.7	-2.76	-238.38	**+18**
			MS	-10.42	-200.14	-22.7	-2.76	-236.02	**+23**
RBV	**XX**	**SG**	**CT**	-11.28	-200.14	-22.7	-2.76	-236.88	**+21**
			TT	-11.28	-200.14	-22.7	-2.76	-236.88	**+22**
			MS	-10.00	-200.14	-22.7	-2.76	-235.60	**+24**
		DG	**CT**	-23.13	-200.14	-22.7	-2.76	-248.73	**+10**
			TT	-22.74	-200.14	-22.7	-2.76	-248.34	**+11**
			MS	-21.46	-200.14	-22.7	-2.76	-247.06	**+12**
CB	**XX**	**SG**	**CT**	43.85	-200.14	-22.7	-2.76	-181.75	**-18**
			TT	44.29	-200.14	-22.7	-2.76	-181.31	**-19**
			MS	45.48	-200.14	-22.7	-2.76	-180.12	**-20**
		DG	**CT**	27.20	-200.14	-22.7	-2.76	-198.40	**-12**
			TT	27.24	-200.14	-22.7	-2.76	-198.36	**-13**
			MS	28.24	-200.14	-22.7	-2.76	-197.36	**-14**

Envelope options				GHG savings potential tonnes CO_2 e-				Cumulative GHG reduction tonnes CO_2 e-	Ranking + (effective) - (worse)
				Changes in envelope	Roof top solar PV 3kW$_p$	Solar water heater	Green concrete		
ACC	**XX**	**SG**	**CT**	3.71	-200.14	-22.7	-2.76	-221.89	**-3**
			TT	4.11	-200.14	-22.7	-2.76	-221.49	**-4**
			MS	5.19	-200.14	-22.7	-2.76	-220.41	**-7**
		DG	**CT**	-9.60	-200.14	-22.7	-2.76	-235.20	**+25**
			TT	-9.40	-200.14	-22.7	-2.76	-235.00	**+26**
			MS	-7.93	-200.14	-22.7	-2.76	-233.53	**+27**
PCSW	**XX**	**SG**	**CT**	61.32	-200.14	-22.7	-2.76	-164.28	**-21**
			TT	61.57	-200.14	-22.7	-2.76	-164.03	**-22**
			MS	62.80	-200.14	-22.7	-2.76	-162.80	**-23**
		DG	**CT**	42.34	-200.14	-22.7	-2.76	-183.26	**-15**
			TT	42.34	-200.14	-22.7	-2.76	-183.26	**-16**
			MS	43.77	-200.14	-22.7	-2.76	-181.83	**-17**
TMB	**XX**	**SG**	**CT**	13.63	-200.14	-22.7	-2.76	-211.97	**-9**
			TT	14.02	-200.14	-22.7	-2.76	-211.58	**-10**
			MS	16.19	-200.14	-22.7	-2.76	-209.41	**-11**
		DG	**CT**	-3.98	-200.14	-22.7	-2.76	-229.58	**+28**
			TT	-3.00	-200.14	-22.7	-2.76	-228.60	**+29**
			MS	-1.62	-200.14	-22.7	-2.76	-227.22	**+30**
CSW	**POL**	**SG**	**CT**	-28.84	-200.14	-22.7	-5.11	-256.79	**+4**
			TT	-28.05	-200.14	-22.7	-5.11	-256.00	**+5**
			MS	-27.16	-200.14	-22.7	-5.11	-255.11	**+6**
		DG	**CT**	-38.82	-200.14	-22.7	-5.11	-266.77	**+1**
			TT	-38.82	-200.14	-22.7	-5.11	-266.77	**+2**
			MS	-36.95	-200.14	-22.7	-5.11	-264.90	**+3**

The matrix shows that the CPS options such as a 3kW$_p$ grid connected roof top solar PV, integration of water heater with roof top solar water heater, and replacement of concrete with green concrete for a reference house with DB-XX-SG-CT envelope in Perth have a combined GHG emissions reduction potential of 225.6tonnes CO_2 e- (i.e. 48.3% of the life cycle GHG emissions of reference house without CPS). Once the changes in envelope elements (wall, roof, and window) are also included, then the combined GHG emissions reduction potential could be between 162.8tonnes CO_2 e- and 266.8tonnes CO_2 e- (Figure 4.48) according to the envelope characteristics.

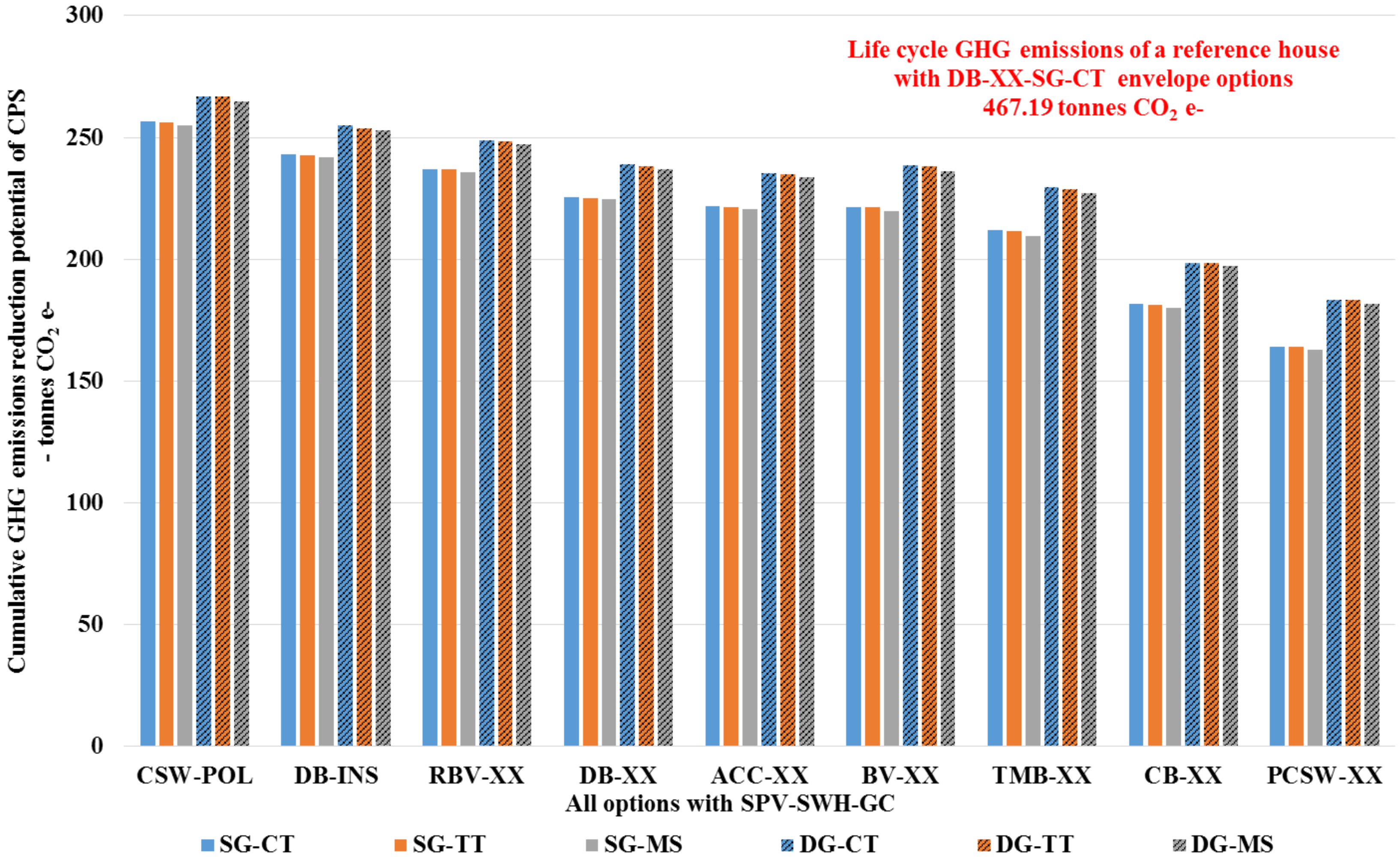


Figure 4.48 Cumulative GHG emission reduction potential of various CPS for a typical house in Perth

The GHG emissions reduction potential due to change in roof element (i.e. concrete tiles to terracotta tiles or metal profile sheet) of a reference envelope (DB-XX-SG-CT) has been found to be low (ranking -1 and -2), while the change in window element (single glazed windows to double glazed windows) increases the GHG emissions reduction potential (ranking +16, +19, and +20).

The CPS options CSW-POL-DG/SG-CT/TT/MS-SPV-SWHGC for a typical house in Perth, which are ranked between +1 and +6 have been found to have the highest GHG emissions reduction potential of 54.5% and 57% of life cycle GHG emissions of reference house (DB-XX-SG-CT) (Figure 4.49). The CPS options DB-INS-DG-CT/TT/MS-SPV-SWH-GC, and RBV-XX-DG-CT/TT/MS-SPV-SWH-GC are next best performers (rankings of +7 to +12) due to their life cycle GHG emissions reduction potential between 53% and 54% of life cycle GHG emissions of reference house. The CPS options CB-XX-SG-CT/TT/MS-SPV-SWH-GC, and PCSW-XX-SG-CT/TT/MS-SPV-SWH-GC have been found to be ranked between -18 and -23 due to their lowest GHG emissions reduction potential between 35% and 38% of life cycle GHG emissions of reference house. It is interesting to note that the inclusion of a 3kWp grid connected roof top solar PV, integration of water heater with roof top solar water heater, and replacement of concrete with green concrete itself provide around 48.3% of life cycle GHG reduction for a reference house, therefore any other CPS options offering the life cycle GHG emissions reduction of less than 48.3% are not viable options (Figure 4.49).

Some other CPS options such as DB-INS-SG-CT/TT/MS-SPV-SWH-GC (ranked +13 to +15), DB-XX-DG-CT/TT/MS-SPV-SWH-GC (ranked +16, +19, and +20), BV-XX-DG-CT/TT/MS-SPV-SWH-GC (ranked +17, +18, and +23), and RBV-XX-SG-CT/TT/MS-SPV-SWH-GC (ranked +21, +22, and +24) have been found to have more or less similar performance while offering an average GHG emissions reduction of 51% of the life cycle GHG emissions of reference house (DB-XX-SG-CT) in Perth.

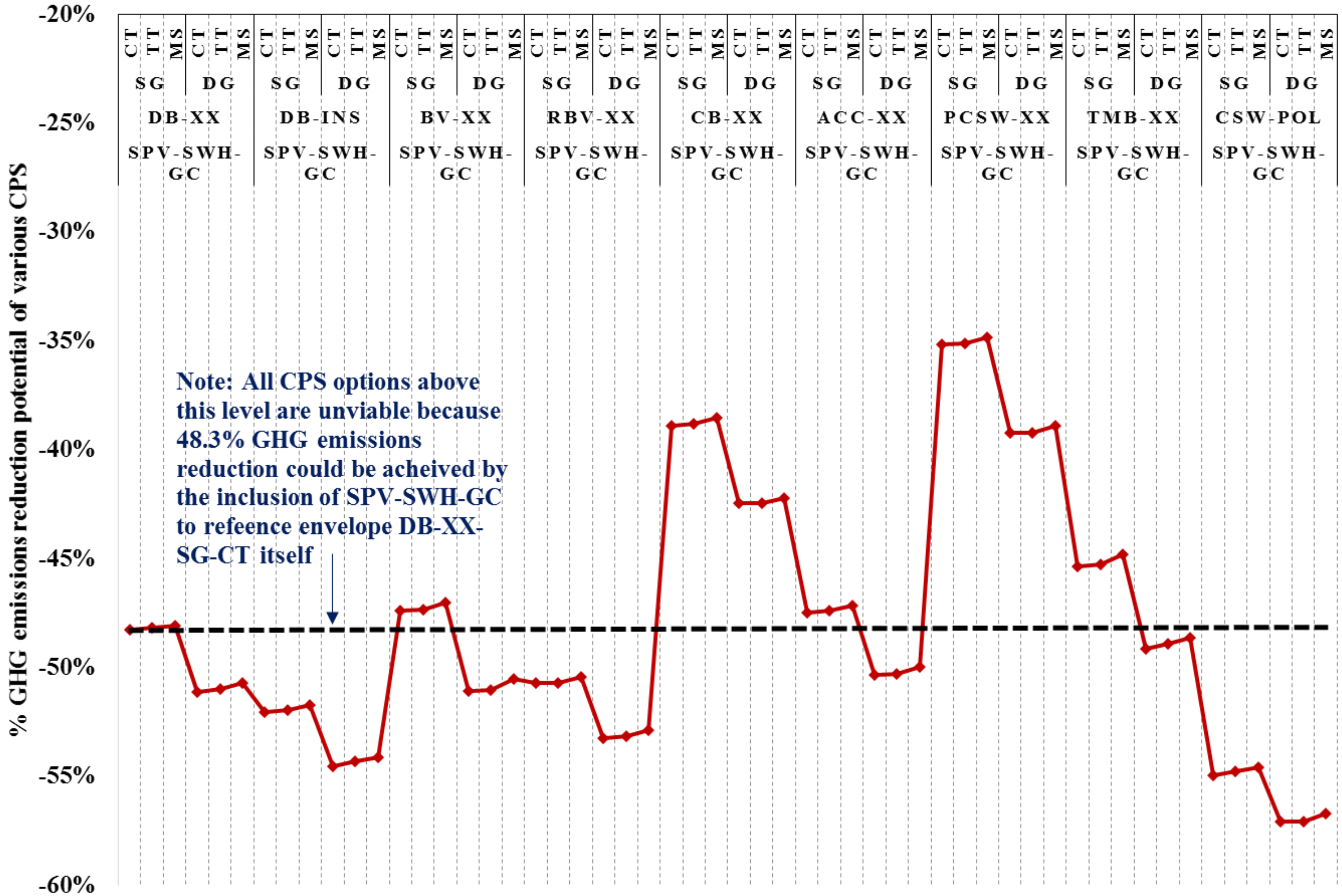


Figure 4.49 GHG emission reduction potential of various CPS for a typical reference house in Perth

Summary of EE consumption

The EE consumption results of the implication of cleaner production strategies to treat the hotspots during the life cycle stages of the reference clay brick wall house in Perth have been summarised in Table D.28 (Appendix D). As discussed earlier, the CPS options have been assigned a positive (+) or negative (-) ranking with respect to the EE consumption saving potential of the reference envelope option having roof top solar PV, solar water heater, and green concrete (i.e. ranking 0). Out of total 53 options, 36 options have more EE consumption saving potential than the reference case (i.e. ranking 0), while 17 options provide less EE consumption saving. the 36 alternative options having more EE consumption saving potential have been assigned positive rankings from +1 (most effective) to +36 (least effective), while the negative rankings from -1 (least worse) to -17 (most worse) have been assigned to 17 alternative options having less EE consumption saving potential (Table 4.24).

The matrix shows that the CPS options such as a 3kW$_p$ grid connected roof top solar PV, integration of water heater with roof top solar water heater, and replacement of concrete with green concrete for a reference house with envelope DB-XX-SG-CT in Perth have a combined EE consumption saving potential of 3.3TJ (i.e. 50.7% of the life cycle EE consumption of reference house without CPS). Once the changes in envelope elements (wall, roof, and window) are also included, then the combined EE consumption saving potential could be between 2.7TJ and 3.9TJ (Figure 4.50) according to the envelope characteristics. The combined EE consumption saving potential due to change in roof element (i.e. concrete tiles to terracotta tiles or metal profile sheet) of a reference envelope (DB-XX-SG-CT) has been found to be low (ranking -1 and -2), while the change in window element (single glazed windows to double glazed windows) increases the combined EE consumption saving potential (ranking +26, +28, and +30).

Table 4.24 Summary of EE consumption saving potential of CPS and their rankings

Envelope changes				EE consumption savings potential - TJ				Cumulative EE consumption saving - TJ	Ranking + (effective) - (worse)
				Changes in envelope	Roof top solar PV 3kWp	Solar water heater	Green concrete		
DB	**XX**	**SG**	**CT**	N.A	-2.68	-0.6	-0.02	-3.30	0
			TT	+0.01	-2.68	-0.6	-0.02	-3.29	**-1**
			MS	+0.04	-2.68	-0.6	-0.02	-3.26	**-2**
		DG	**CT**	-0.18	-2.68	-0.6	-0.02	-3.48	**+26**
			TT	-0.17	-2.68	-0.6	-0.02	-3.47	**+28**
			MS	-0.12	-2.68	-0.6	-0.02	-3.42	**+30**
DB	**INS**	**SG**	**CT**	-0.25	-2.68	-0.6	-0.02	-3.55	**+17**
			TT	-0.24	-2.68	-0.6	-0.02	-3.54	**+18**
			MS	-0.20	-2.68	-0.6	-0.02	-3.50	**+23**
		DG	**CT**	-0.40	-2.68	-0.6	-0.02	-3.70	**+9**
			TT	-0.39	-2.68	-0.6	-0.02	-3.69	**+10**
			MS	-0.35	-2.68	-0.6	-0.02	-3.65	**+12**
BV	**XX**	**SG**	**CT**	-0.07	-2.68	-0.6	-0.02	-3.37	**+31**
			TT	-0.06	-2.68	-0.6	-0.02	-3.36	**+32**
			MS	-0.01	-2.68	-0.6	-0.02	-3.31	**+35**
		DG	**CT**	-0.29	-2.68	-0.6	-0.02	-3.59	**+13**
			TT	-0.29	-2.68	-0.6	-0.02	-3.59	**+14**
			MS	-0.23	-2.68	-0.6	-0.02	-3.53	**+20**
RBV	**XX**	**SG**	**CT**	-0.26	-2.68	-0.6	-0.02	-3.56	**+15**
			TT	-0.25	-2.68	-0.6	-0.02	-3.55	**+16**
			MS	-0.21	-2.68	-0.6	-0.02	-3.51	**+22**
		DG	**CT**	-0.41	-2.68	-0.6	-0.02	-3.71	**+6**
			TT	-0.41	-2.68	-0.6	-0.02	-3.71	**+8**
			MS	-0.36	-2.68	-0.6	-0.02	-3.66	**+11**
CB	**XX**	**SG**	**CT**	+0.51	-2.68	-0.6	-0.02	-2.79	**-12**
			TT	+0.52	-2.68	-0.6	-0.02	-2.78	**-13**
			MS	+0.56	-2.68	-0.6	-0.02	-2.74	**-14**
		DG	**CT**	+0.29	-2.68	-0.6	-0.02	-3.01	**-6**
			TT	+0.29	-2.68	-0.6	-0.02	-3.01	**-7**
			MS	+0.33	-2.68	-0.6	-0.02	-2.97	**-8**
ACC	**XX**	**SG**	**CT**	-0.05	-2.68	-0.6	-0.02	-3.35	**+33**
			TT	-0.05	-2.68	-0.6	-0.02	-3.35	**+34**
			MS	-0.01	-2.68	-0.6	-0.02	-3.31	**+36**
		DG	**CT**	-0.23	-2.68	-0.6	-0.02	-3.53	**+19**
			TT	-0.23	-2.68	-0.6	-0.02	-3.53	**+21**

Envelope changes				EE consumption savings potential - TJ				Cumulative EE consumption saving - TJ	Ranking + (effective) - (worse)
				Changes in envelope	Roof top solar PV 3kWp	Solar water heater	Green concrete		
			MS	-0.18	-2.68	-0.6	-0.02	-3.48	**+25**
PCSW	**XX**	**SG**	**CT**	+0.59	-2.68	-0.6	-0.02	-2.71	**-15**
			TT	+0.60	-2.68	-0.6	-0.02	-2.70	**-16**
			MS	+0.64	-2.68	-0.6	-0.02	-2.66	**-17**
		DG	**CT**	+0.34	-2.68	-0.6	-0.02	-2.96	**-9**
			TT	+0.34	-2.68	-0.6	-0.02	-2.96	**-10**
			MS	+0.39	-2.68	-0.6	-0.02	-2.91	**-11**
TMB	**XX**	**SG**	**CT**	+0.05	-2.68	-0.6	-0.02	-3.25	**-3**
			TT	+0.06	-2.68	-0.6	-0.02	-3.24	**-4**
			MS	+0.11	-2.68	-0.6	-0.02	-3.19	**-5**
		DG	**CT**	-0.18	-2.68	-0.6	-0.02	-3.48	**+24**
			TT	-0.17	-2.68	-0.6	-0.02	-3.47	**+27**
			MS	-0.12	-2.68	-0.6	-0.02	-3.42	**+29**
CSW	**POL**	**SG**	**CT**	-0.44	-2.68	-0.6	-0.04	-3.76	**+4**
			TT	-0.43	-2.68	-0.6	-0.04	-3.75	**+5**
			MS	-0.39	-2.68	-0.6	-0.04	-3.71	**+7**
		DG	**CT**	-0.58	-2.68	-0.6	-0.04	-3.90	**+1**
			TT	-0.57	-2.68	-0.6	-0.04	-3.89	**+2**
			MS	-0.52	-2.68	-0.6	-0.04	-3.84	**+3**

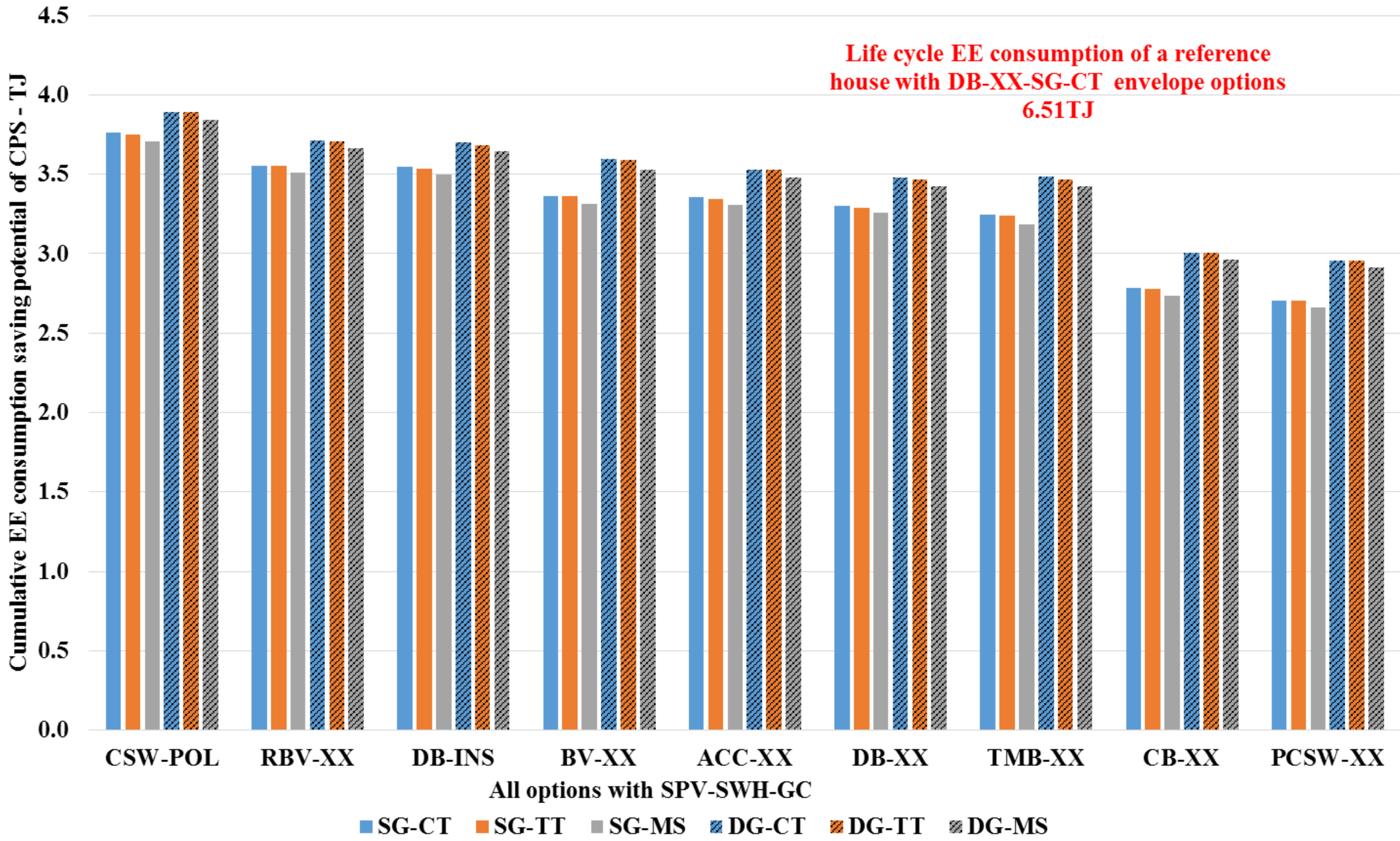


Figure 4.50 Cumulative EE consumption saving potential of various CPS for a typical house in Perth

The CPS options CSW-POL-DG/SG-CT/TT/MS-SPV-SWH-GC for a typical house in Perth, which are ranked between +1 and +5 including +7 have been found to have the highest EE consumption saving potential between 57% and 60% of life cycle EE consumption of a reference house (DB-XX-SG-CT) (Figure 4.51). The CPS options RBV-XX-DG-CT/TT/MS-SPV-SWH-GC, and DB-INS-DG-CT/TT/MS-SPV-SWH-GC are the next best performers (ranked between +6 and +12) due to their EE consumption saving potential between 56% and 57% of life cycle EE consumption of reference house. The CPS options CB-XX-SG-CT/TT/MS-SPV-SWH-GC and PCSW-XX-SG-CT/TT/MS-SPV-SWH-GC have been found to be ranked between -12 and -17 due to their lowest EE consumption saving potential of a reference house.

It is interesting to note that the inclusion of a 3kWp grid connected roof top solar PV, integration of water heater with roof top solar water heater, and replacement of concrete with green concrete itself provide around 50.7% of EE consumption saving for a typical reference house, therefore any other CPS options offering the EE consumption saving of less than 50.7% are not viable options (Figure 4.51).

Some other CPS options such as BV-XX-DG-CT/TT/MS-SPV-SWH-GC (ranked +13, +14, and +20), RBV-XX-SG-CT/TT/MS-SPV-SWH-GC (ranked +15, +16, and +22), DB-INS-SG-CT/TT/MS-SPV-SWH-GC (ranked +17, +18, and +23), and ACC-XX-DG-CT/TT/MS-SPV-SWH-GC (ranked +19, +21, and +25) have been found to have more or less similar performance while offering an average EE consumption saving of 54% of the life cycle EE consumption of reference house (DB-XX-SG-CT) in Perth.

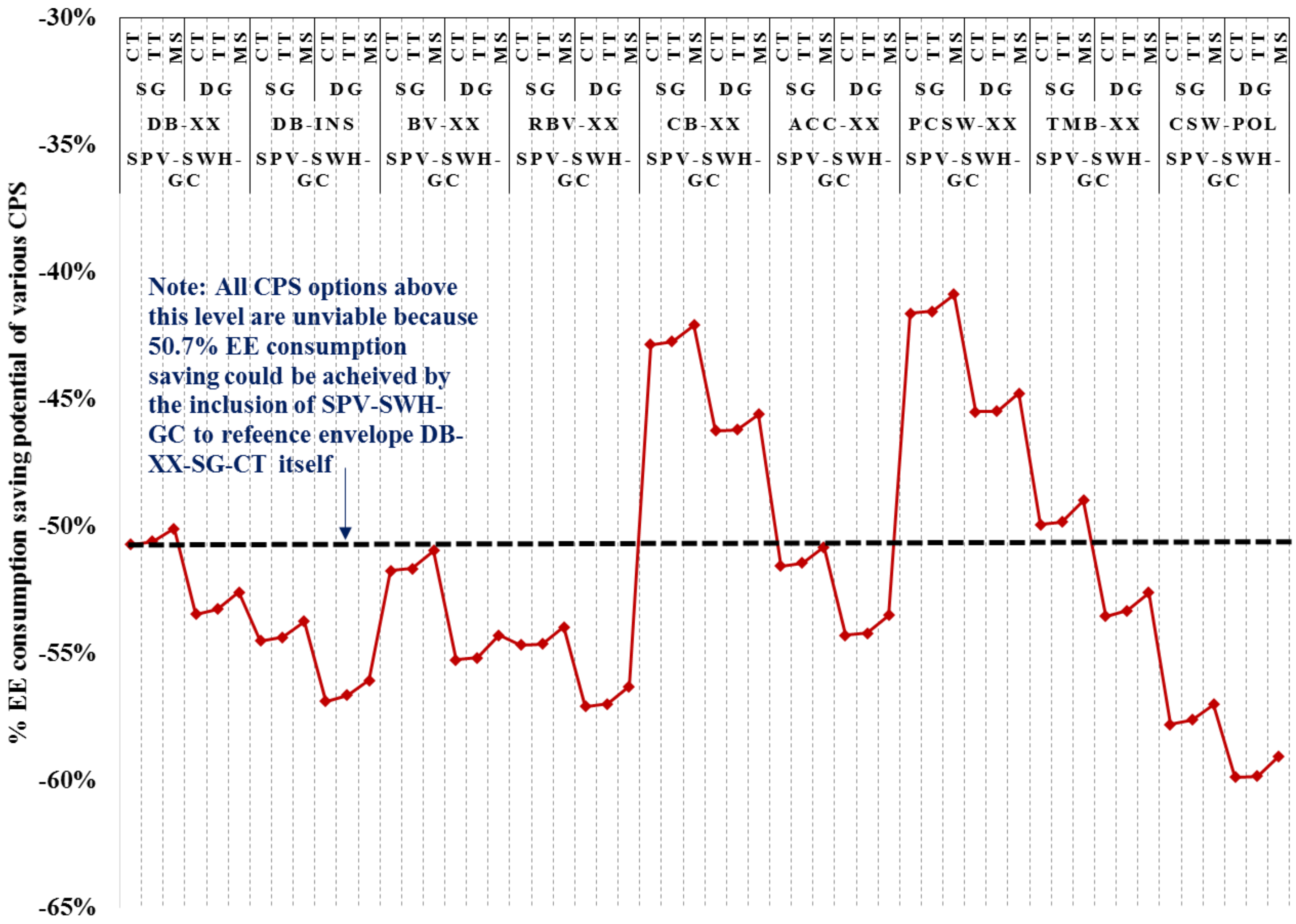


Figure 4.51 EE consumption saving potential of various CPS for a typical house in Perth

Key findings

The key findings derived from this chapter are summarized as following:

1. A typical detached single storey double clay brick wall house in Perth has 467tonnes CO_2 e- of life cycle GHG emissions and 6.51TJ of life cycle EE consumption. The use stage and mining to material production stages are the hotspots accounting for almost 99% of the total life cycle impacts.

2. The temperature rise due to climate change impact could increase the life cycle GHG emissions and EE consumption impacts up to 5%.

3. Optimum orientation has been found to be the first step to reduce the life cycle operational energy demand for heating and cooling of a house and hence the associated environmental impacts. The change from optimum to worst orientation may cause an increase in life cycle energy consumption for heating and cooling by 50% and also the associated GHG emissions and EE consumptions may increase by 55%.

4. Installation of a $3kW_p$ roof top solar PV and integration of gas based water heater with roof top solar water heater have been found to be most effective cleaner production strategies as the life cycle GHG emissions and EE consumption may be reduced to up to 50%.

5. The change in house envelope consisting of roof, windows, and wall elements may have positive or negative impacts depending upon the thermal performance of materials. The use of alternative envelope can increase the life cycle GHG emissions of a typical house up to 13.5% and also can decrease the GHG emissions up to 8%, while the increase of EE consumption could go up to 10% and the same could decrease up to 9%.

6. The replacement of the envelope of a reference house with all options of cast in-situ concrete sandwich walls with polystyrene core has been found to be the most effective cleaner production strategy.

7. The replacement of cementitious materials and aggregates with supplementary cementitious materials and recycled aggregates, and manufactured sand has

been found to be an effective cleaner production strategy, because, in addition to the environmental impacts reduction, it provides an opportunity for resource reduction as well.

8. The uncertainties associated with material and energy input data for all building components used for life cycle assessment have been found to be acceptable (between 2% to 4%).

9. Envelope elements having high thermal performance are more sensitive to change in orientation but are highly adaptable to climate change impacts.

The following chapter (Chapter 5) discusses as to whether the environmentally viable options having GHG and EE consumption reduction potential are cost effective. The LCC component of LCM framework has been applied to evaluate the cost effectiveness of various mitigation strategies.

Chapter 5

Socio-economic implications of cleaner production strategies

5.1 Introduction

This chapter applies LCC of LCM framework to estimate the life cycle cost of a typical 4x2x2 (4 bedroom, 2 bath, and 2 garage) single storey detached reference house in Perth and thirty including environmentally viable cleaner production options as presented in Table E.1 (Appendix E) in order to find the options for cost-effective mitigation of GHG emissions and EE consumption.

The life cycle cost of a reference house in Perth including construction, operational energy (heating, cooling, hot water, home appliances, and lighting), and the end of life demolition and disposal stages has been estimated using the life cycle inventory data in Chapter 4. The life cycle cost of a reference house in Perth for all environmentally viable cleaner production options has been estimated and then the environmentally viable options with present values (PV) less than the reference one have been determined as economically feasible options followed by a sensitivity analysis for a range of economic instruments have been carried out to achieve the right strategies for policy makers. Finally, the social implications of the environmentally and economically feasible CPS options have been analysed.

5.2 Life cycle costing of reference house in Perth

For economic analysis, all material and energy inputs, which were utilized for the LCI for LCA analysis have been considered for this LCC analysis to maintain the consistency of assessment, therefore the unit prices of all material and energy inputs required for the life cycle stages (cradle to grave) of the house have been sourced from construction cost guide (Rawlinsons 2015) for estimation of capital cost, and from utility service providers (DOF 2015d; Alintaenergy 2015) for estimation of operational costs. Originally, the costs have been estimated in Australian Dollar which were then converted to American Dollar or US$ (1AUD = 0.7229US$).

The units prices and amount of inputs in the LCI are used in the MS Excel spread sheet to estimate the cost of materials, transport, construction, operational energy (heating, cooling, home appliances, hot water, and lighting), and the end of life demolition and disposal of a typical house in Perth.

The estimated costs of materials, transport, construction, operational energy (heating, cooling, home appliances, hot water, and lighting), and the end of life demolition and disposal of a typical house in Perth have been converted to their present value (PV) using inflation and discount rates (Equation 3.40). Finally, the life cycle cost of the house has been calculated using Equation 3.41 and a sensitivity for a discount factor on life cycle cost has been carried out.

5.2.1 Life cycle cost

The estimation by engineering procedures method that was discussed in Section 3.5, has been used to estimate the capital cost (i.e. material, transport, and labour cost for construction of a house), operational cost (i.e. electricity for cooling, home appliances, and lighting and natural gas for hot water and heating), and the end of life demolition and disposal of a reference house in Perth. Similar to LCA analysis, the cost of 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 as well as the cost of land have been excluded from this LCC analysis (Section 3.3.1).

The present values of capital cost (i.e. material, transport, and construction), operational cost (i.e. electricity for cooling, home appliances, and lighting and natural gas for heating and hot water), and the end of life demolition and disposal cost are added using Equation 3.43 to determine the life cycle cost of the reference house, which is found to be US$211,439.50, and breakdown is presented in Figure 5.1.

The capital cost (US$160,007.00) has been found to have the highest share (75.7%) of life cycle cost of the house followed by operation cost (US$49,735.00, i.e. 23.5%). The end of life demolition and disposal cost (US$1,697.50) is negligible, which is only less than 1% of the life cycle cost of the house. This trend is contrary to GHG emissions and EE consumption wherein the operational stage has the highest share (87% of total impacts) while remaining 13% of total impacts are attributed to construction and end of life demolition and disposal stages.

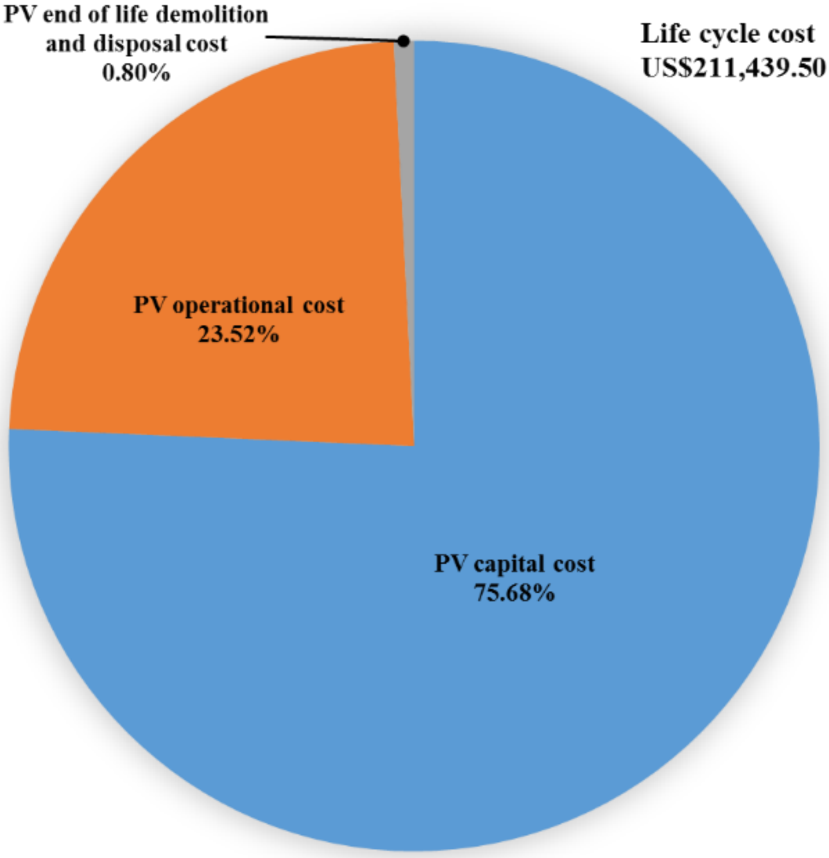


Figure 5.1 Breakdown of life cycle cost for a reference house in Perth

This is because of the fact that the operational cost and the end of life demolition and disposal costs are future costs, which have been discounted to present value, whereas, in the case of capital cost, the initial cost itself is a present value (Pelzeter 2007). The construction of a house is a set of activities requiring a number of building materials and components (i.e. concrete, brick, roof timber, windows, ceiling, and tiles), use of plants and tools (i.e. excavator, loader, and crane), and labour for assembly of individual components at construction site where they have different pricing patterns depending upon material and labour intensity, and durability. Therefore, the capital cost is higher than the operational cost (i.e. the cost of electricity and natural gas only).

The breakdown of capital cost has been presented in Table E.2 (Appendix E). It has been found that the cost of building envelope consisting of wall, window and roof elements has the biggest share of 61% of the total capital cost of the house (Figure 5.2).

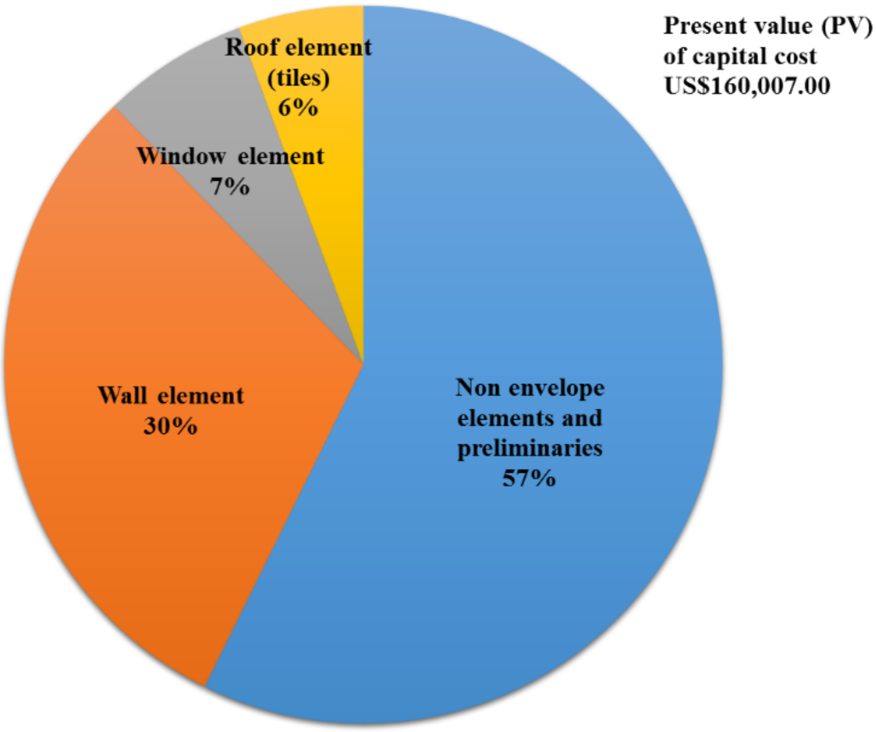


Figure 5.2 Breakdown of capital cost of a typical reference house in Perth

The cost of wall element has a share of 30% of capital cost followed by window and roof elements with shares of 7%, and 6% of capital cost, respectively. Similar to the GHG emissions and EE consumption impacts, the cost of wall element has been found to be the hotspot, because of the use of expensive clay bricks including associated laying cost.

The breakdown of present value of operational cost for electricity for cooling, home appliances, and lighting and natural gas for heating, and hot water for the reference house for 50 years lifespan that has been estimated using current utility tariff structure (DOF 2015d; Alintaenergy 2015) has been presented in Table E.3 (Appendix E). The future costs of these energy utilities have been determined by escalating the current price by an inflation rate of 3% per year (RBA 2015) and then the escalated price has been discounted to convert the dollar value of cost of different time horizons to present value at the discount rate of 7% per year (as per latest recommendations of Infrastructure Australia (IA 2016)), while considering the year 2015 as the base year. A discount rate of 7% has also been utilized by other recent economic studies in Western Australia (Blackwell et al. 2010; Flugge and Abadi 2006; Breheny et al. 2006; DRDL 2012; Gurung and Mahendran 2002).

It is found that the cost of electricity for home appliance has the biggest share (36% of operational cost), followed by hot water (29% of operational cost). The costs of lighting, cooling, and heating have been found to be 16%, 12%, and 7% of the operational cost, respectively (Figure 5.3). The energy costs for home appliances and hot water are found to be the hotspots, which is the case for GHG emissions and EE consumption impacts. The main reason for the higher cost share for home appliances and hot water is due to the fact that these activities consume a substantial amount of energy (i.e. 27%, and 42% of the total energy demand, respectively).

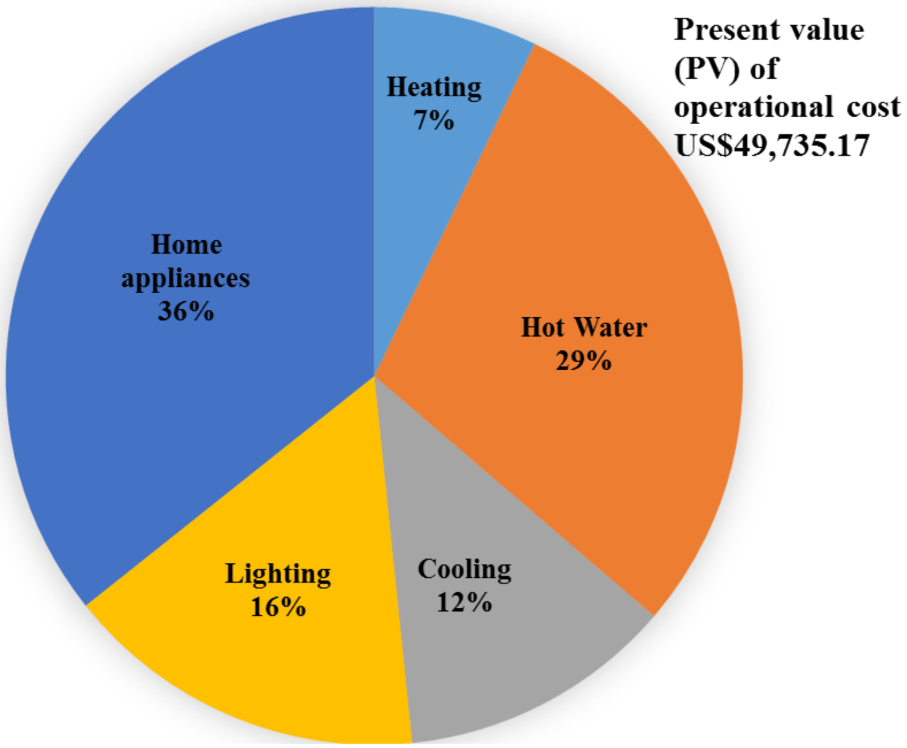


Figure 5.3 Breakdown of operational cost for a typical reference house in Perth

The breakdown of the present value of end of life demolition and disposal cost for the reference house is presented in Table E.4 (Appendix E). It is found from published literature that from the year 2018 onwards, the Western Australian government has decided to increase the landfill levy rate to AUD70.00 per tonnes of inert construction and demolition (C&D) waste from its current rate of AUD40.00 per tonnes of inert C&D waste (DER 2015). The landfill levy rate of AUD70.00 also has been included in the end of life demolition and disposal cost.

The findings are comparable to other life cycle cost studies wherein the contribution of initial cost is the highest as compared to operational cost because the future operational and end of life demolition and disposal costs diminish due to discounting to a present value (Gurung and Mahendran 2002; Pelzeter 2007). A local life cycle costing study of a double storey brick veneer house in Queensland had found that the construction cost contributed to 83% of life cycle cost (Islam, Jollands and Setunge 2015).

5.2.2 Sensitivity analysis of variables for economic analysis

Sensitivity of LCC to discount rate

As discussed in Section 5.2.1, the present values of operational and the end of life demolition and disposal costs of a reference house in Perth have been estimated using a discount rate of 7%. As the discount rate allows the comparisons of costs over different timescales, Infrastructure Australia recommends to undertake sensitivity testing of the results for discount rates of 4% and 10% respectively (IA 2016). Based on these recommendations, a sensitivity analysis of the life cycle cost of a reference house has been performed for different discount rates and the results are presented in Table 5.1. It has been found that the lowest discount rate of 4% results in an increased level of deferred cash flow, while the highest discount rate of 10% has an opposite effect.

Table 5.1 Present values of life cycle stages of reference house in Perth under different discount rates

Discount rate (DR) scenarios (1AUD = 0.7229US$)	**Present values in US$**			**Life cycle cost US$**
	Capital cost	**Operational cost**	**End of life demolition and disposal cost**	
Discount rate - 7%	160,006.77	49,735.17	1,697.49	211,439.43
% share	***75.67%***	***23.52%***	***0.80%***	100.00%
Discount rate - 4%	160,006.77	89,546.63	7,036.06	256,589.46
% share	***62.36%***	***34.90%***	***2.74%***	100.00%
Discount rate - 10%	160,006.77	32,142.30	425.95	192,575.02
% share	***82.66%***	***16.69%***	***0.22%***	100.00%

It appears that the change in discount rate has a significant impact on operational cost and the end of life demolition and disposal cost thus results in an increased or a decreased life cycle cost of the house. Due to change in discount rate to 4%, the life cycle cost of a reference house would increase by 21.35% of the life cycle cost of a reference house with 7% discount rate, whereas due to change in discount rate to 10% the life cycle cost of reference house would reduce by 8.9%.

Even though the absolute value of capital cost does not get affected due to change in discount rate, but the percentage share of capital cost changes while still accounting for the highest share of life cycle cost (Figure 5.4).

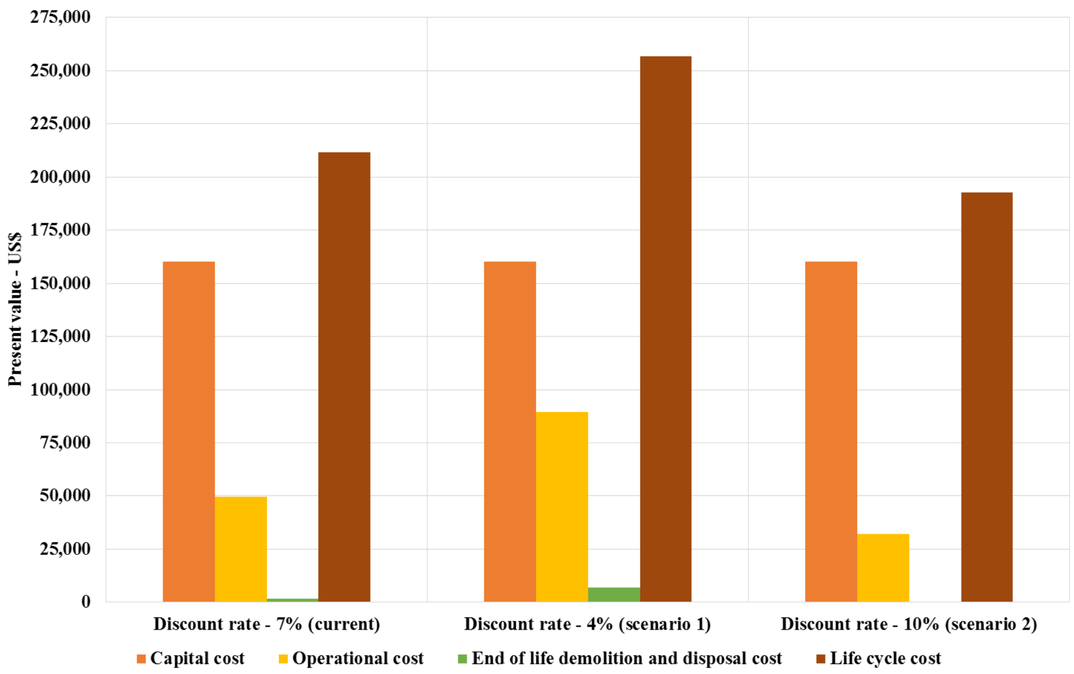


Figure 5.4 Sensitivity of life cycle cost for a reference house in Perth to different discount rates

The findings are similar to other studies. While, Zachariah (2004) and Kurnitski et al. (2011) reported that the life cycle cost is sensitive to discount rate, Real (2010) and Moore and Morrissey (2014) suggested that lower discount rates have a higher influence on future costs in the life cycle costing. The life cycle costing is sensitive to the discount rate, but as this study compares various options for their environmental and economic performance, so the impact of discount rate will be same for all options.

Sensitivity of LCC to probable carbon tax

Whilst, the carbon tax in Australia has been repealed in 2014 due to political compulsions, the re-enactment of a carbon tax may happen due to increasing global concern about climate change as being reported by media based on the feedback from various political parties (Hunt 2015). A number of countries such as Canada, Chile, Denmark, Finland, France, Iceland, Ireland, Japan, Mexico, Norway, South Africa, Sweden, Switzerland and the United Kingdom have carbon tax or emissions trading schemes in different forms (CTC 2015; Alexandre Kossoy et al. 2015) and there is a broad consensus that the carbon tax is the most comprehensive and efficient policy to limit the GHG emissions (Donald Marron 2015; BP 2016). Studies suggest that the electricity producers and natural gas distributors pass all the carbon cost burden to the consumers, which results in an increase of the operational cost (Kneifel 2010). It is, therefore, important to evaluate the impact of probable carbon tax on the life cycle cost of the reference house in Perth.

In Australia, this time the carbon tax may change from fixed price to floating price and is expected to be around AUD38.00 per tonnes of GHG emissions (Hunt 2015). While the carbon tax has no influence on the capital cost and the end of life demolition and disposal cost, the impact of anticipated carbon tax on the operational cost of the reference house has been evaluated. The annual GHG emissions associated with the electricity (for cooling, home appliances, and lighting) and natural gas (for heating and hot water) of a reference house in Perth have been utilized to estimate the cost of probable carbon tax. The present value of carbon tax for a typical house in Perth for a lifespan of 50 years has been estimated to be US$4,926.40 (i.e. 9.91% of operational cost without a carbon tax) at 3% inflation rate and 7% discount rate. In the case of 4% and 10% discount rates, the present value of carbon tax would be US$8,869.81, and US$3,183.77 respectively. Due to the implication of carbon tax, the life cycle cost of the reference house in Perth (under 7% discount rate and 3% inflation rate) would increase by 2.33%. The carbon tax under 4% and 10% discount rates would increase the life cycle cost by 3.46%, and 1.65%, respectively (Figure 5.5). The analysis shows that the sensitiveness of the life cycle costing to a carbon tax is quite low.

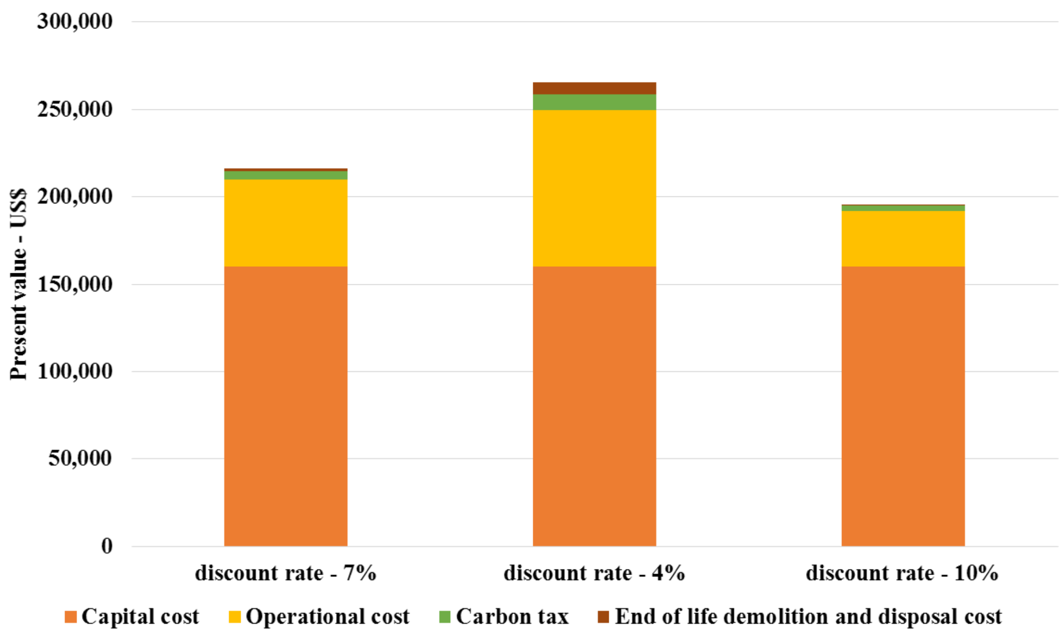


Figure 5.5 Sensitivity of life cycle cost of a typical reference house in Perth to carbon tax

The economic impacts of environmentally viable options involving cleaner production strategies on the life cycle cost of a reference house in Perth have been discussed in the following section.

5.3 Cost-effectiveness of environmentally viable CPS options

The economic feasibility of all environmentally viable options involving CPS such as a grid connected 3kW$_p$ roof top solar PV, integration of gas based water heater with roof top solar water heater, alternative envelope options, and replacement of conventional concrete with green concrete (as summarised in Section 4.4.7) for a reference house in Perth have been investigated using life cycle costing. Similar to the life cycle costing in the previous section, the unit prices of materials in AUD have been obtained from construction cost guide (Rawlinsons 2015) for estimation of capital costs of all alternative envelope options and then converted to USD to present analytical results to both national and international readers.

The present values of capital and replacement costs of a grid connected 3kW$_p$ roof top solar PV and roof top solar water heater have been estimated using current market prices (Solarchoice 2015, Solare, WA 2015; Advanced Solar Technology, WA 2015; Solaire Connect, WA 2015) for an inflation rate of 3% per year (RBA 2015) and a discount rate of 7% per year (IA 2016). Based on the published literature and also the information sourced from the industry, the lifespan of roof top solar PV has been considered as 25 years (i.e. one replacement during life cycle of the house) (Kannan et al. 2006; Schwartfeger and Miller 2015; Mitscher and Rüther 2012), and a 13 years lifespan has been considered for the solar water heater (3 replacements during life cycle of the house) (Zambrana-Vasquez et al. 2015; Ardente et al. 2005; Otanicar and Golden 2009). The present value of operational cost for electricity for cooling, home appliances, and lighting and natural gas for heating, and hot water has been estimated using current utility tariff structure (DOF 2015d; Alintaenergy 2015). The end of life demolition and disposal cost estimation includes the landfill levy rate of AUD70.00 per tonnes of inert waste disposal (DER 2015).

The breakdown of life cycle cost (i.e. capital cost, operational cost, and the end of life cost) of a reference house in Perth using CPS has been presented in Table E.5 (Appendix E). It has been found that the environmentally viable CPS could offer a maximum LCC reduction up to US$33,169.85 i.e. 15.70% of the LCC of the reference house, while only one option has been found to increase the LCC by US$1,407.40 (i.e. 0.7%). The cleaner production option CSW-POL-SG-CT-SPV-SWH-GC, which offers the maximum LCC reduction has been found to have the 4th rank in terms of environmental performance (life cycle GHG emissions reduction of 256.79tonnes CO_2 e- (i.e. 54.96%), and EE consumption saving of 3.76TJ (i.e. 57.81%) compared to the reference house). The option ACC-XX-DG-TT-SPV-SWH-GC causing an increase of LCC has the poor rankings of 26th for GHG emissions (i.e. 50.3% reduction potential) and 21st for EE consumption (i.e. 54.22% saving potential) respectively (Figure 5.6).

The inclusion of a grid connected 3kWp roof top solar PV, integration of gas based water heater with roof top solar water heater, and replacement of conventional concrete with green concrete (SPV-SWH-GC) for a reference house (DB-XX-SG-CT) in Perth has been found to offer not only the single largest GHG emissions reduction of 225.6tonnes CO_2 e- (Table 4.23) as well as EE consumption saving of 3.3TJ (Table 4.24), but also offers a single largest LCC reduction of US$18,372.82. The main reason for this massive reduction is the use of a 3kW$_p$ roof top solar PV (241MWh of electricity saving), and solar water heater (737GJ of natural gas saving) (Sections 4.4.1, and 4.4.2).

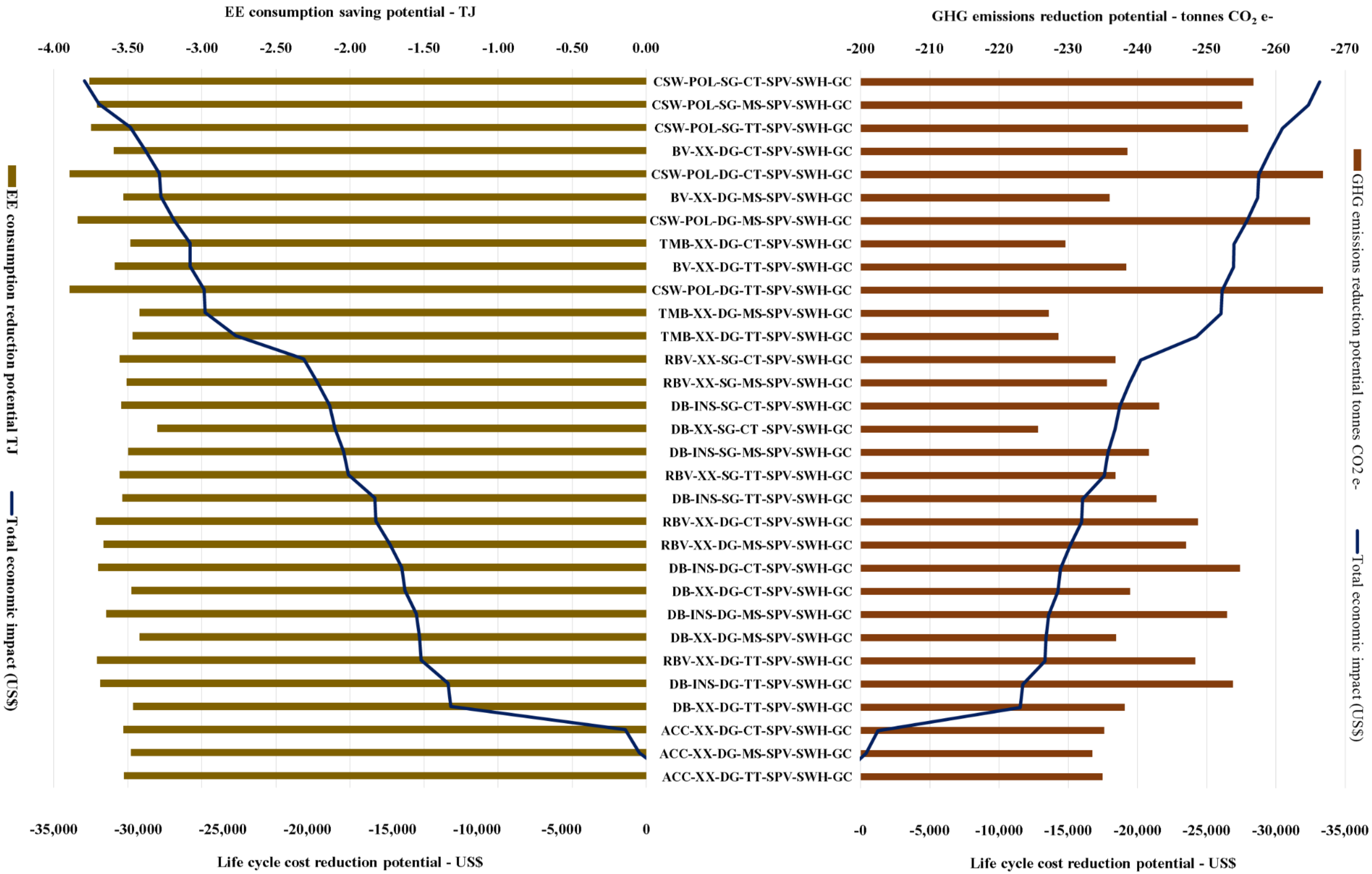


Figure 5.6 Life cycle cost reduction potential of environmentally viable cleaner production strategies

Similar to the GHG emissions and EE consumption (Section 4.4.7), any other CPS option offering an LCC reduction of less than US$18,372.82 would be considered an economically unviable option. The results show that 15 environmentally viable CPS options ACC-XX-DG-CT/TT/MS-SPV-SWH-GC, DB-INS-SG-TT/MS-SPV-SWH-GC, DB-INS-DG-CT/TT/MS-SPV-SWH-GC, RBV-XX-SG-TT-SPV-SWH-GC, RBV-XX-DG-CT/TT/MS-SPV-SWH-GC, and DB-XX-DG-CT/TT/MS-SPV-SWH-GC have lower economic benefit as compared to the benefits achieved by inclusion of SPV-SWH-GC alone, and thus these options do not make economic sense. The economic analysis of all CPS options has been discussed in detail in following sections.

5.3.1 Economic analysis of alternative envelope options

The LCC of a typical house for a given envelope option consists of the capital cost (design and supervision charges, Government fees, material, transportation of material to construction site, labour charges for assembly including cost for all tools, plants and machinery), operational cost (electricity and natural gas charges for heating, cooling, lighting, hot water, and home appliances) over the lifespan of the house, and the end of life demolition and disposal costs (Keoleian, Blanchard and Reppe 2000; Islam, Jollands and Setunge 2015; Standard 2014). The capital, operational, and the end of life costs of a typical reference house in Perth have been analysed in the following sections.

5.3.1.1 Economic analysis of capital costs for alternative envelope options

The breakdown of capital cost for environmentally viable envelope options has been presented in Table E.6 (Appendix E). The capital cost for these envelope options has been found to vary from 74.7% to 79.3% of the LCC of the house. As compared to capital cost (US$160,006.77) of a reference envelope house (DB-XX-SG-CT) in Perth, the capital cost for alternative envelope options vary from a minimum of US$148,303.41 (i.e. a reduction of 7.3%) for CSW-POL-SG-CT to a maximum of US$183,418.58 (i.e. an increase of 14.6%) for ACC-XX-DG-TT (Figure 5.7).

It has been found that 12 envelope options such as CSW-POL-SG/DG-CT/TT/MS, TMB-XX-DG-CT/TT/MS, and BV-XX-DG-CT/TT/MS have lower capital costs than the reference envelope house, while remaining 18 envelope options such as DB-XX-

DG-CT/TT/MS, DB-INS-SG/DG-CT/TT/MS, RBV-XX-SG/DG-CT/TT/MS, and ACC-XX-DG-CT/TT/MS have higher capital costs. The main reason for the higher capital costs of these envelope options is due to the additional cost incurred for materials such as wall insulation (DB-INS and RBV-XX options), fibre cement board (RBV-XX options), and double glazed windows (DB-INS-DG, DB-XX-DG, RBV-XX-DG and ACC-XX-DG options).

Out of these 18 envelope options, 12 options (DB-XX-DG-CT/TT/MS, DB-INS-SG/DG-CT/TT/MS, and RBV-XX-SG/DG-CT/TT/MS) have a capital cost difference of up to 6.5% of the capital cost of a reference envelope, while 6 options (ACC-XX-DG-CT/TT/MS) are up to 14.6% more expensive. While the double glazed windows are 52.4% more expensive than the single glazed windows, the terracotta roof tiles, and metal roof sheet are 30.2%, and 9.30% more expensive than the concrete roof tiles respectively.

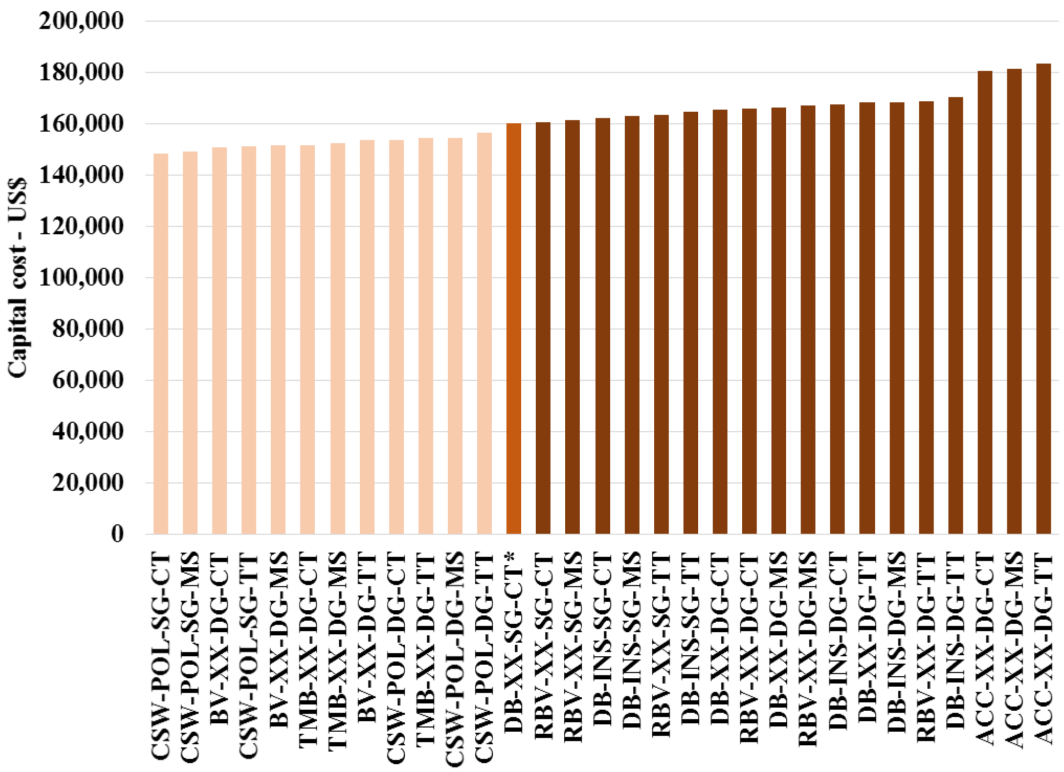


Figure 5.7 Capital costs of environmentally viable envelope options

In the case of 12 envelope options with lower capital costs, 10 envelope options have capital costs up to 6% lower than that of the reference envelope, while only 2 envelope options (CSW-POL-SG-CT/MS) offer a capital cost reduction of up to 7.3%. The main reason for capital cost reduction of these envelope options is due to the cost of wall elements wherein the bricks and associated materials as well as labour costs have been either completely eliminated (e.g. CSW and TMB options), or reduced significantly (e.g. BV options) (Figure 5.8).

The capital costs of wall elements CSW-POL, TMB-XX and BV-XX are up to 30% less than the reference wall element (DB-XX), while the wall elements RBV-XX and DB-INS have up to 4.5% more capital costs compared to the reference wall element. The capital cost of wall element ACC-XX has been found to be 31% more than the reference wall element.

The capital cost of non-envelope elements (e.g. foundation, ground slab, roof timber, ceiling, doors, and ceramic tiles) and preliminaries (e.g. council fee, working drawings, engineering drawings) is same (US$91,674.05) for a reference envelope as well as the alternative envelope options because there is no change in type and consumption pattern of materials.

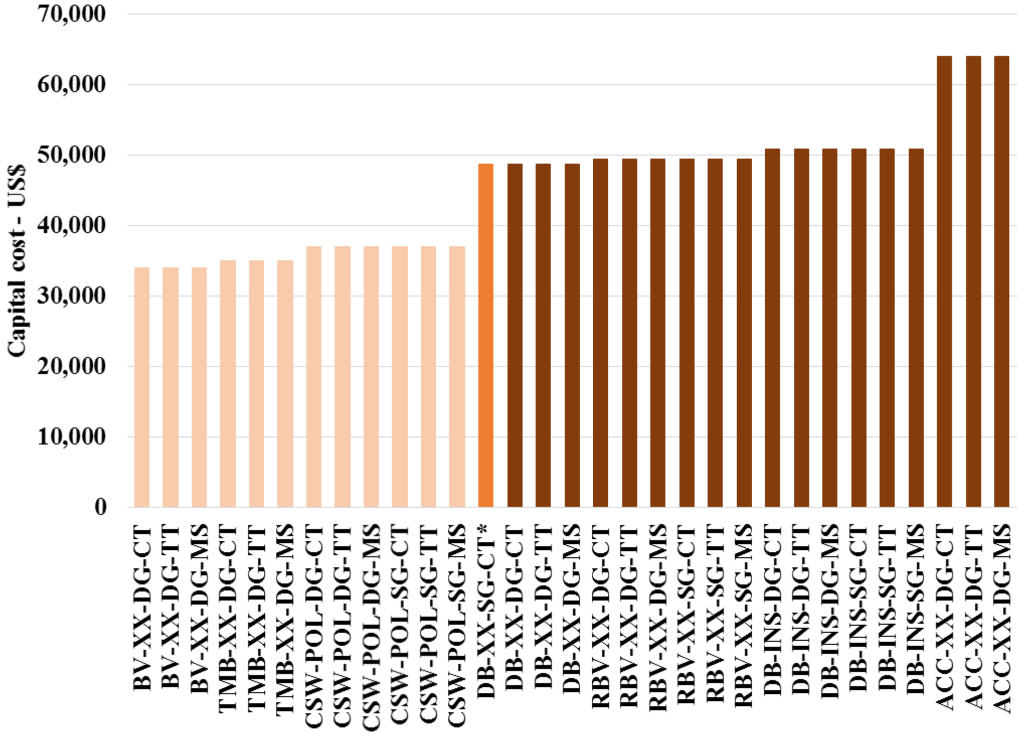


Figure 5.8 Capital costs of wall elements of environmentally viable envelope options

5.3.1.2 Economic analysis of operational costs for alternative envelope options

The envelope elements have an influence on the operational energy demand for heating and cooling of the house during use stage (Section 4.4.4.1). The operational cost of the house for these envelope options has been found to vary from 20.1% to 24.6% of the LCC of a reference house. The life cycle operational energy demand for heating and cooling of a reference house during use stage could be reduced up to 49.5% due to the replacement of envelope (wall, window, and roof) (Table 4.11). The economic viability associated with the change in operational energy demand have been analysed for alternative envelope options (Table E.7, Appendix E). As compared to the operational cost (US$49,735.16) of a reference house (DB-XX-SG-CT) in Perth, the operational cost for alternative envelope options vary from a minimum of US$45,770.80 (i.e. a reduction of 8%) for CSW-POL-DG-TT to a maximum of US$50,043.09 (i.e. an increase of 0.6%) for TMB-XX-DG-MS (Figure 5.9).

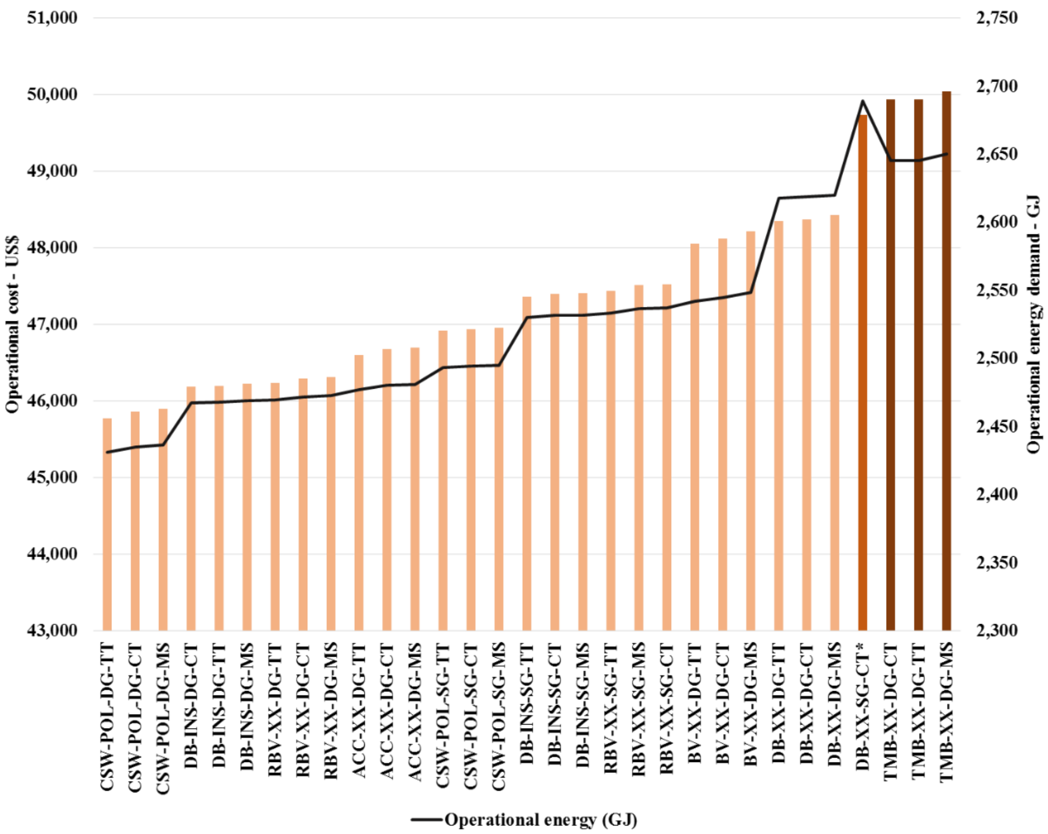


Figure 5.9 Operational cost of environmentally viable envelope options

The main reason for the operational cost reduction is due to the reduction of operational energy consumption for heating and cooling due to the thermal performance of the envelope options. The pattern of changes in operational energy shows that the envelope option CSW-POL-DG-TT having the lowest operational cost has the lowest energy demand. In the case of envelope options TMB-XX-DG-CT/TT/MS, the operational costs are higher than the operational cost for reference envelope (DB-XX-SG-CT), even though the operational energy demand for these envelope options has been about 1.6% less than the reference envelope. This is because, the natural gas demand for heating for envelope options TMB-XX-DG-CT/TT/MS is around 7.45% less than that of the reference envelope, while the electricity demand for cooling is 4.8% more than the reference envelope. Even though the energy saving in terms of natural gas is more than the additional energy in terms of electricity, the natural gas saving does not result in the overall cost saving, and the overall operational cost is more than the reference envelope (Alintaenergy 2015; DOF 2015b). This is because the price of natural gas (¢14.2/unit till 12 units average per day and ¢12.8/unit thereafter (1unit = 1kWh)) is almost half of the price of electricity (¢ 25.7/unit (1unit=1kWh)).

5.3.1.3 Economic analysis of the end of life demolition and disposal costs for alternative envelope options

The breakdown of the end of life demolition and disposal costs for environmentally viable envelope options is presented in Table E.8 (Appendix E). The end of life demolition and disposal cost for these envelope options has been found to vary from 0.6% to 0.9% of the LCC of a reference house. As compared to the end of life demolition and disposal cost of US$1,697.49 for reference house (DB-XX-SG-CT) in Perth, the end of life demolition and disposal cost for alternative envelope options vary from a minimum of US$1,309.02 (i.e. a reduction of 22.9%) for TMB-XX-DG-MS to a maximum of US$1,738.27 (i.e. an increase of 2.4%) for CSW-POL-DG-CT (Figure 5.10).

Whilst it has been found that the gross weights of envelope options CSW-POL-SG/DG-CT/TT/MS are up to 23% less than the reference envelope (DB-XX-SG-CT), the end of life demolition and disposal costs are up to 2.4% more than the end of life demolition and disposal cost of a reference house. This is because the wall element of these envelope options is made of concrete, and all the walls of the house are monolithically interconnected thus requiring additional energy for demolition, which in fact makes the demolition more costly than the reference envelope which is made of brick walls requiring relatively less energy for demolition. On the other hand, the demolition of envelope options TMB-XX-DG-CT/TT/MS requires the lowest energy than the brick walls because there are hard cementitious materials thus the demolition is less costly than the reference envelope house.

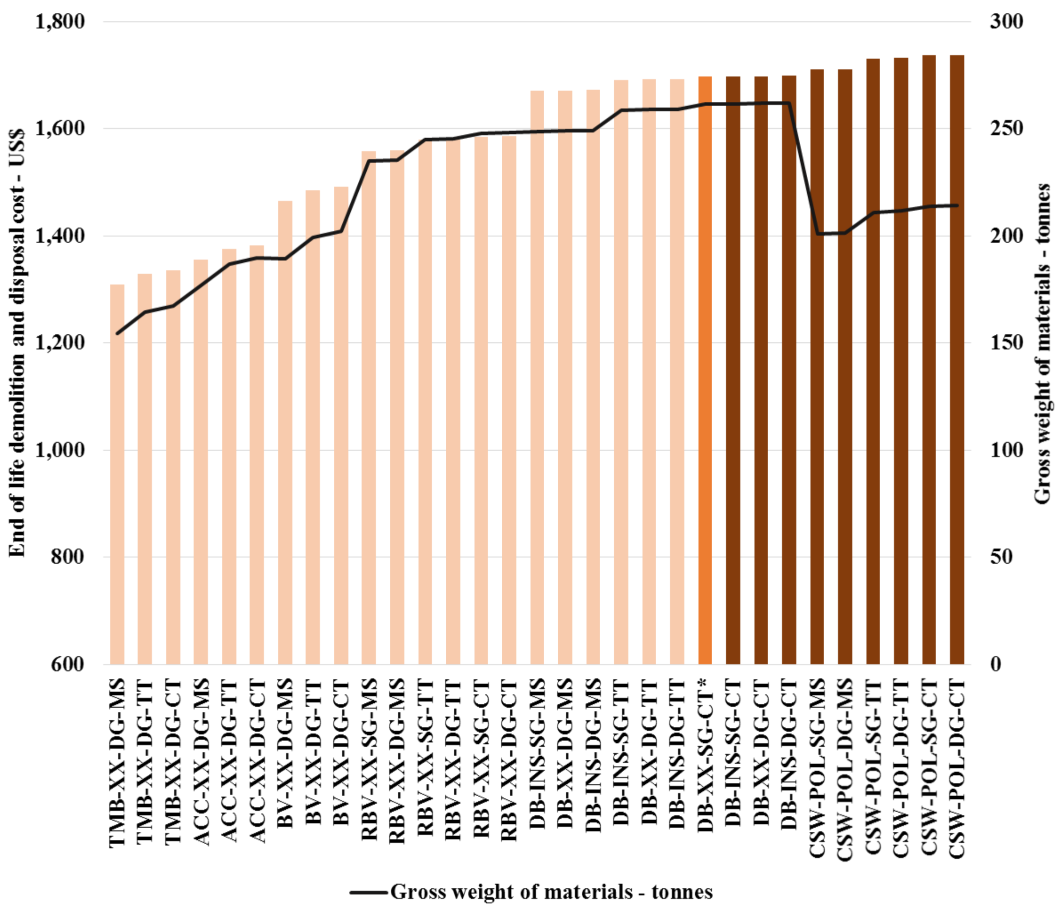


Figure 5.10 The end of life demolition and disposal costs of environmentally viable envelope options

5.3.1.4 Summary of economic analysis of alternative envelope options

As the envelope elements (wall, window, and roof) have an influence on the operational energy demand for heating and cooling of the house during use stage (Section 4.4.4.1), therefore it is important to analyse the cost effectiveness of each element individually.

Wall elements

The LCC results for all the environmentally viable envelope options DB-XX-DG-CT/TT/MS, DB-INS-SG/DG-CT/TT/MS, BV-XX-DG-CT/TT/MS, RBV-SG/DG-CT/TT/MS, ACC-XX-DG-CT/TT/MS, TMB-XX-DG-CT/TT/MS, and CSW-POL-SG/DG-CT/TT/MS show that the wall elements CSW-POL, BV-XX, and TMB-XX offer a net economic saving between US12,600.00 and US$15,000.00. Although the wall elements CSW-POL, and BV-XX offer both capital and operational cost saving, the wall element TMB-XX offers only capital cost saving (Figure 5.11). The main reason for the capital cost reduction of these wall elements is due to avoidance or minimization of clay bricks. The wall elements DB-INS, and RBV-XX offer less economic benefits compared to previous 3 options, while the capital cost of wall element ACC-XX is more than the reference wall element DB-XX.

Although the use of wall element TMB-XX offers a significant capital cost saving benefit but the associated GHG emissions are the highest amongst the wall elements due to the use of more energy for heating and cooling. Similarly, the wall element BV-XX has been found to offer almost no GHG emissions reduction. The wall element CSW-POL offers a maximum GHG emissions reduction, while the wall elements DB-INS, and RBV-XX offer a moderate GHG emissions reduction with a small amount of economic benefits. The wall element ACC has been found to have more GHG emissions than the reference wall element DB-XX. Some wall elements offer low economic and environmental benefits but with different windows and roof element combinations, their performance may be slightly different as discussed earlier.

Window elements

The replacement of single glazed (SG) windows with double glazed (DG) windows would result in an average operational cost saving of US$1,200.00 only for an increased capital cost of US$5,509.00. The savings to investment ratio has been found to be 0.22 (i.e. <1), thus this replacement is not considered as an economically feasible option. A study by Bojić and Yik (2007) also confirmed that the double glazed windows is not an economically feasible option due to lower (<1) savings to investment ratio. Also, Cetiner and Özkan (2005) found that the single glazed options are more cost efficient than the double glazed options because the operational cost saving due to heating and cooling energy reduction during use stage is less than the difference of capital costs of single and double glazed windows.

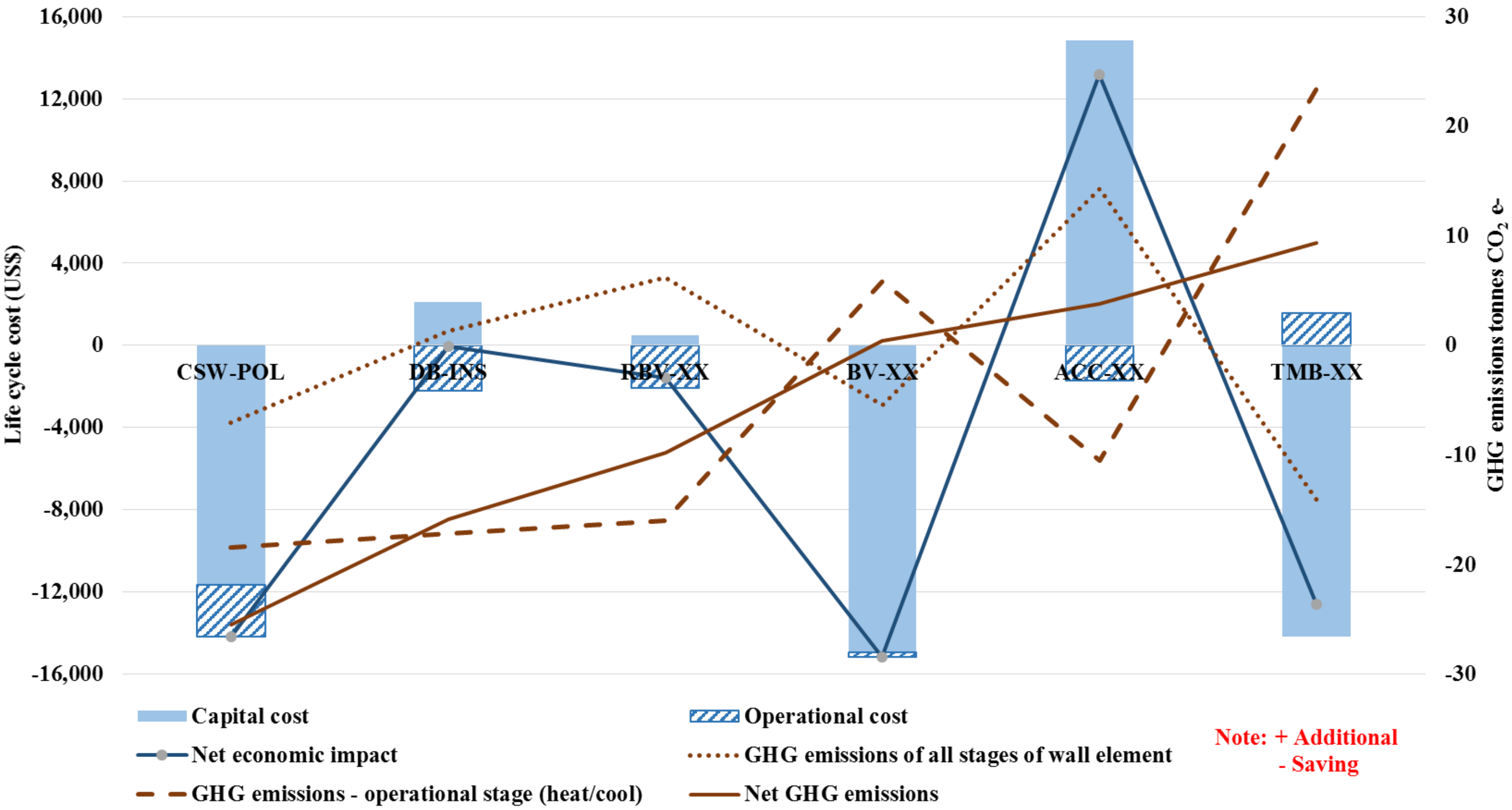


Figure 5.11 Economic performance of wall elements of environmentally viable envelope options with double glazed windows and concrete roof tiles

Whilst, the replacement of SG with DG has been found an economically unviable option, the associated environmental benefits are substantial. The GHG emissions for the production of double glazed windows for a typical reference house in Perth including transport, installation, and the end of life demolition and disposal has been found to be 0.58tonnes CO_2 e- more than the single glazed windows, however, this replacement would reduce the GHG emissions during use stage by about 12tonnes CO_2 e- due to reduction in heating and cooling energy (Section 4.4.4.2).

Roof elements

The average incremental cost associated with the replacement of concrete roof tiles (CT) with terracotta roof tiles (TT), and metal roof sheet (MS) would be US$2,723.00, and US$813.00 respectively, while the replacement of CT with TT would save the operational cost by an average of US$50.00, the operational cost would increase by US$100.00 due to the replacement of CT with MS. The savings to investment ratios of these replacements have been found to be significantly low (i.e. <1), which makes them the economically unfeasible option. A study by Islam et al. (2015) confirmed that the metal roof sheet is not an economically viable option as compared to concrete roof tiles. In addition to economic unviability, the replacement of CT with TT, and MS offers GHG emissions reduction of 0.98tonnes CO_2 e-, and an increase of 1.2tonnes CO_2 e-respectively as compared to the increase of GHG emissions by 1 to 1.3tonne CO_2 e- during production, transport, installation, and the end of life demolition and disposal stages (Section 4.4.4.2). A similar study by the University of Melbourne reported that the environmental and economic performance of tiled roof is slightly better than the metal roof (Jensen 2013). Also, the LCEA study of Crawford, Czerniakowski, and Fuller (2011) showed that the CT are better than the TT and MS.

5.3.2 Economic analysis of integration of a grid connected 3kW$_p$ roof top solar PV system

The breakdown of capital and operational costs of a grid connected 3kW$_p$ roof top solar PV (SPV) for a reference house in Perth that considered the environmentally viable options has been presented in Table E.9 (Appendix E). The economic benefit due to the integration of roof top SPV (US$15,814.44) has been found to be same for all alternative envelope options as the electricity generation performance of a 3kW$_p$

roof top solar PV is independent of design and materials of the building envelope. The capital cost of SPV including one replacement after its lifespan of 25 years has been found to be US$3,806.76, while this integration offers an operational cost saving of US$19,621.20 during use stage (Figure 5.12). The roof top SPV for a reference house in Perth for all environmentally viable options has been found to have savings to investment ratio of more than 5, which shows the very high level of economic performance of this option (Nikolaidis, Pilavachi and Chletsis 2009). The solar PV has also been found to be an economically feasible option by a number of recent studies (Ramadhan and Naseeb 2011; Bazilian et al. 2013; Moosavian et al. 2013).

5.3.3 Economic analysis of integration of gas based water heater with roof top solar water heater system

The breakdown of capital and operational costs of integration of gas based water heater with roof top solar water heater (SWH) for a reference house in Perth for environmentally viable options has been presented in Table E.10 (Appendix E). The economic benefit due to the integration of gas based water heater with SWH for all alternative envelope options varies from a minimum of US$2,389.62 for reference envelope DB-XX-SG-CT to a maximum of US$2,592.59 for envelope option CSW-POL-DG-MS. Unlike SPV, the economic benefit for SWH is not uniform across all envelope options, even though it offers the same amount of energy savings across all envelope options. The reason for this variation in the economic benefits is due to the fact that the unit price of natural gas in WA vary (¢14.2/unit till 12 units average per day and ¢12.8/unit thereafter (1unit = 1kWh)) with the level of consumption of natural gas (Alintaenergy 2015), and as the natural gas is used for heating as well, the economic benefits could vary according to these slabs. The capital cost of SWH including three replacements of SWH after every 13 years has been found to be US$6,062.80, while the integration offers an operational cost saving benefit of a minimum of US$8,452.42 to a maximum of US$8,655.39 during use stage (Figure 5.13).

The integration of gas based water heater with roof top solar water heater (SWH) for a reference house for all environmentally viable options has been found to have savings to investment ratio of more than 1.4, which shows the higher economic performance as confirmed by Nikolaidis, Pilavachi, and Chletsis (2009).

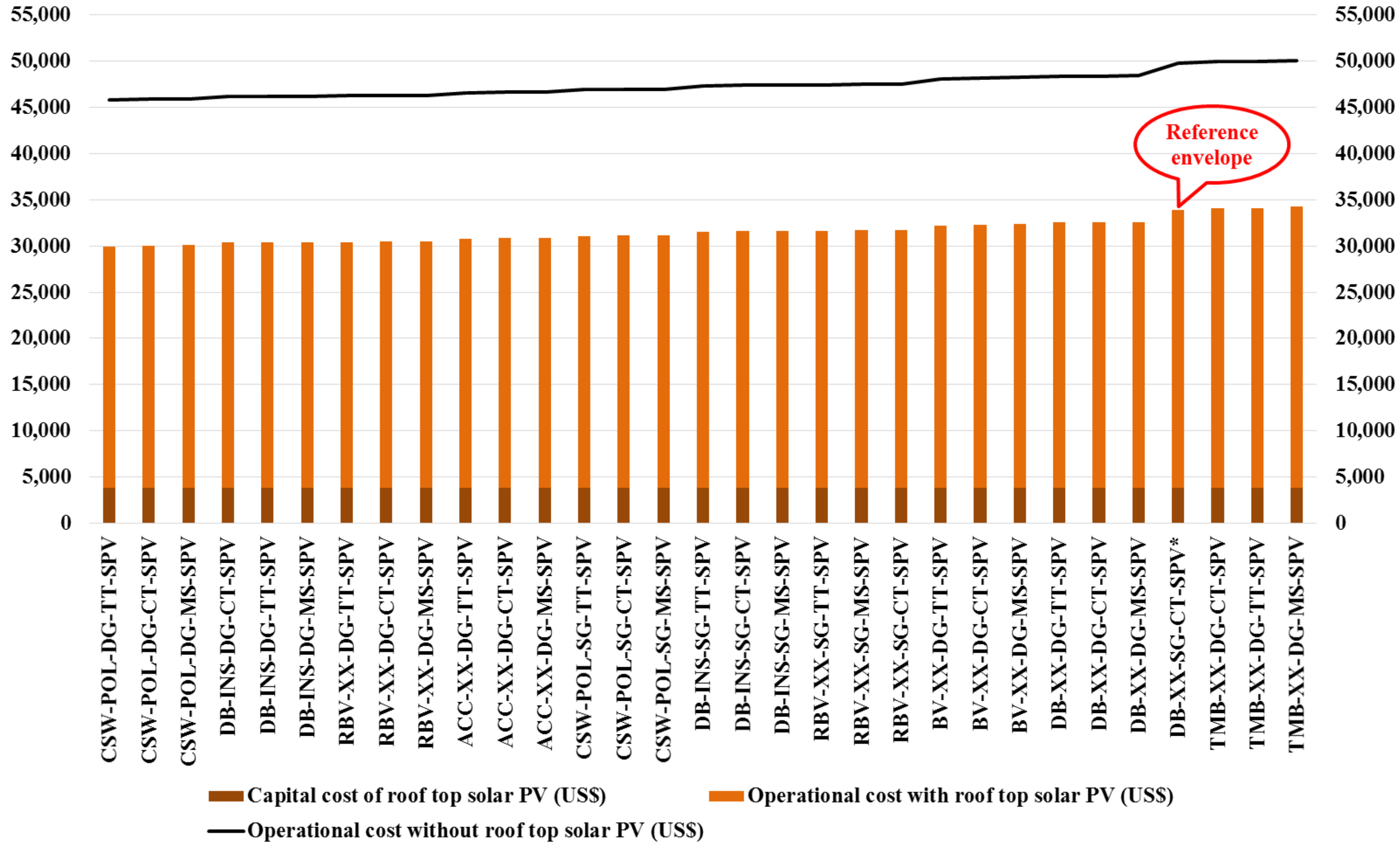


Figure 5.12 Economic implication of the integration of roof top SPV for a reference house for environmentally viable envelope options

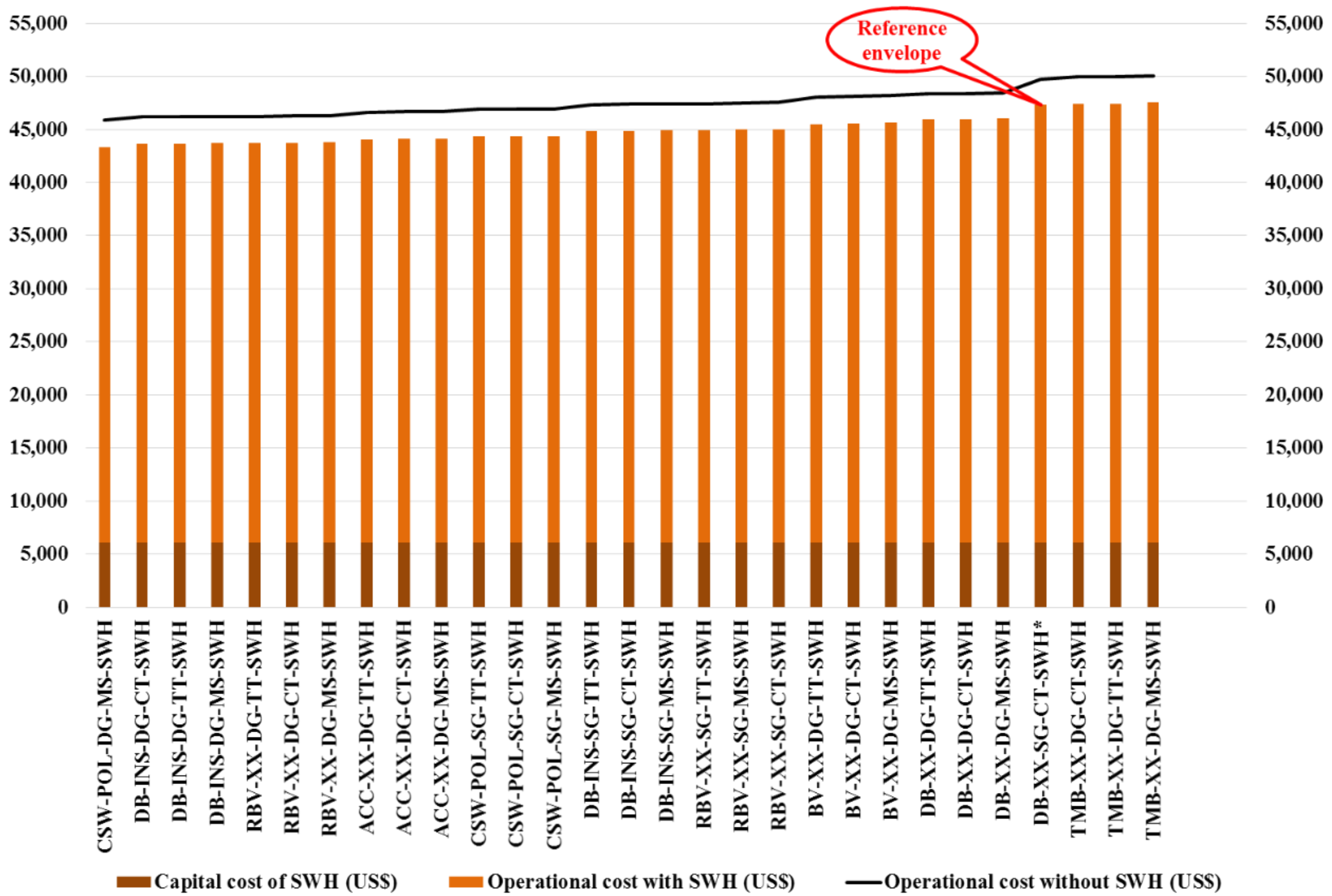


Figure 5.13 Economic implication of the integration of gas based water heater with roof top solar water heater for a reference house for environmentally viable envelope options

The recent studies by Islam, Sumathy, and Ullah Khan (2013) and Kalogirou (2009) confirmed that the use of solar water heater is one of the efficient and cost effective way from energy and environmental conservation perspective.

5.3.4 Economic analysis of replacement of conventional concrete with green concrete

The use of by-products in concrete offers a further GHG emissions saving (Section 4.4.4). The cost implication due to the replacement of conventional concrete with green concrete (GC) (C70FA30S0-NA60RCA40-NS100MS0, i.e. 30% cement replaced by fly ash and 40% aggregate replaced by recycled aggregate) for a reference house in Perth has been presented in Table E.11 (Appendix E). The cost saving due to replacement of conventional concrete with GC vary from a minimum of US$168.76 for the house for envelope options DB-XX-DG-CT/TT/MS, DB-INS-SG/DG-CT/TT/MS, BV-XX-DG-CT/TT/MS, RBV-XX-SG/DG-CT/TT/MS, ACC-XX-DG-CT/TT/MS, and TMB-XX-DG-CT/TT/MS to a maximum of US$327.27 for envelope options of CSW-POL-SG/DG-CT/TT/MS. The cost saving associated with the use of GC is not uniform for across all envelope options because, the concrete requirement for foundation and ground slab (78.35tonnes) for a typical house is same for all envelope options, while the CSW-POL-SG/DG-CT/TT/MS options uses additional 66.91tonnes of concrete for wall element (Figure 5.14).

The use of green concrete (GC) avoids the use of carbon and energy intensive materials such as cement and natural crushed aggregates. The replacement of conventional concrete with green concrete offers only 2.76tonnes CO_2 e- of GHG emissions and 0.2TJ of EE consumption the house for envelope options DB-XX-DG-CT/TT/MS, DB-INS-SG/DG-CT/TT/MS, BV-XX-DG-CT/TT/MS, RBV-XX-SG/DG-CT/TT/MS, ACC-XX-DG-CT/TT/MS, and TMB-XX-DG-CT/TT/MS, a 5.11tonnes CO_2 e- of GHG emissions and 0.04TJ of EE consumption could be reduced by the use of GC for the house for envelope options CSW-POL-SG/DG-CT/TT/MS. However, the use of by products and recycled materials would help in minimizing the natural resource depletion and requirement of landfill area (Lockrey et al. 2016). The replacement of cement with fly ash in concrete has not only the environmental benefits but it provides economic benefits as well (Reiner and Rens 2006; Henry and Kato 2012).

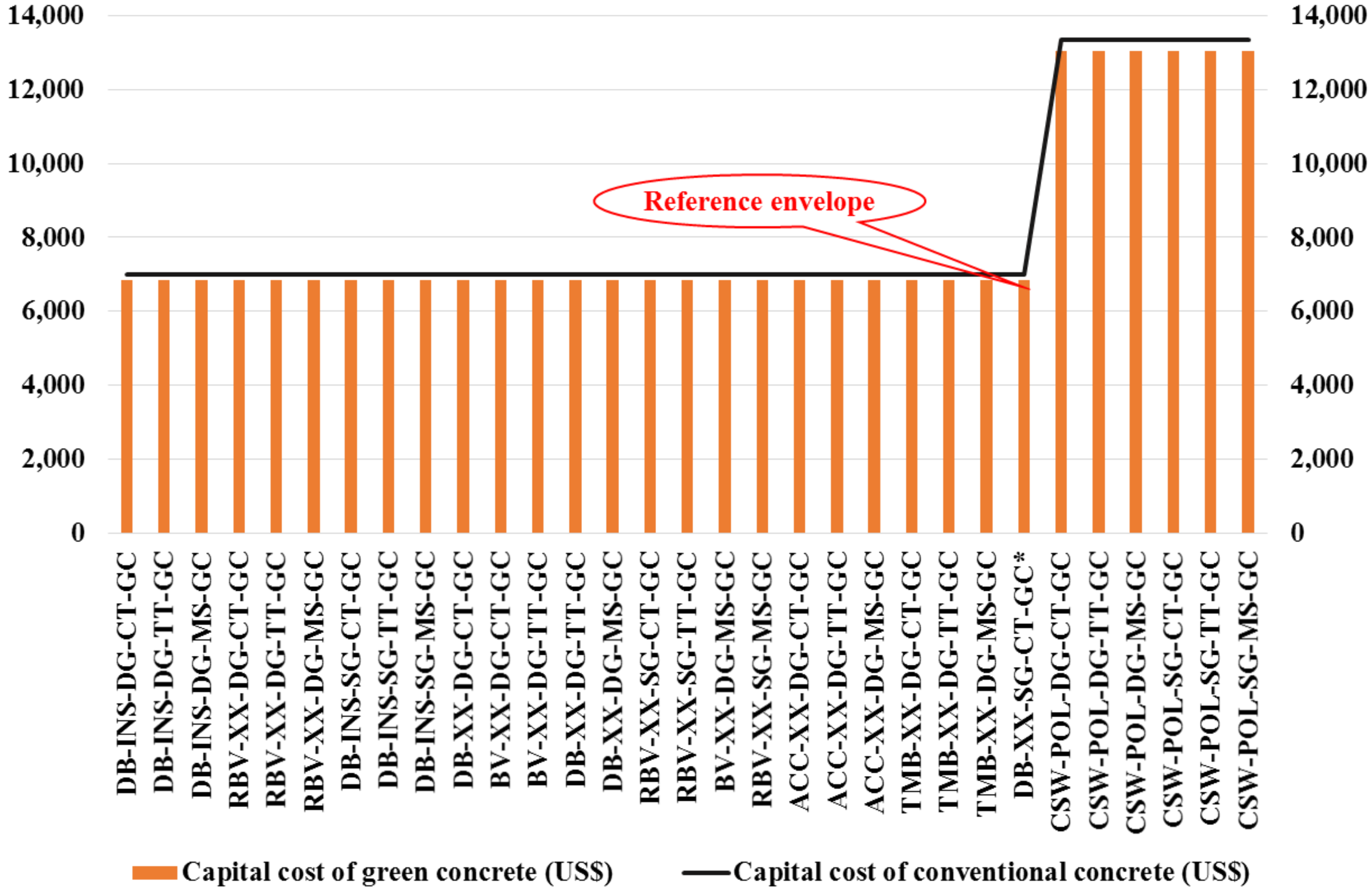


Figure 5.14 Economic implication of the replacement of conventional concrete with green concrete for a reference house for environmentally viable envelope options

5.3.5 Summary of economic analysis of environmentally viable CPS options

The summary of LCC, GHG emissions, and EE consumption results of environmentally feasible options with their relative rankings with respect to the reference house in Perth have been presented in Table E.12 (Appendix E). The LCC, GHG emissions, and EE consumption have different units (e.g. US$, tonnes CO2 e-, and TJ) and scales, therefore in order to make an optimal sustainable decision, a normalization approach has been utilized wherein the actual values of these indicators have been divided by their optimum values to obtain the normalized data (Azapagic and Clift 1999; Huppes and Ishikawa 2005).

The normalized data in Figure 5.15 shows that the cleaner production options CSW-POL-SG/DG-CT/TT/MS-SPV-SWH-GC have LCC, GHG emissions and EE consumption values at unity (i.e. 1) or very close to unity with a minimum spread (as identified by red dotted rectangular area), thus making them optimum sustainable options (i.e. most cost effective with least environmental impacts).

The LCC, GHG emissions, and EE consumption values of CPS options BV-XX-DG-CT/TT/MS-SPV-SWH-GC, and TMB-XX-DG-CT/TT/MS-SPV-SWH-GC are also close to unity but with a wide spread between them. Other CPS options have their normalized LCC, GHG emissions, and EE consumption values away from the unity and with a significant spread between them. However, in most of the cases, the LCC values are close to unity, while GHG emissions and EE consumption values far away from unity. A recent study by Mangan and Oral (2016) has also used a similar method to assess the cost effectiveness of alternative approaches for energy saving and environmental impact reduction of a building.

The relationship between LCC, GHG emissions, and EE consumption for all environmentally and economically feasible CPS options have been identified and analysed in detail to determine the maximum GHG reduction in a cost-effective manner, which is, in fact the key decision criteria for this study. This is supported by the strong sustainability approach, where the priority is given to the environment or ecosystem before the economic and social aspects (Van Den Bergh 2010; Málovics, Csigéné and Kraus 2008).

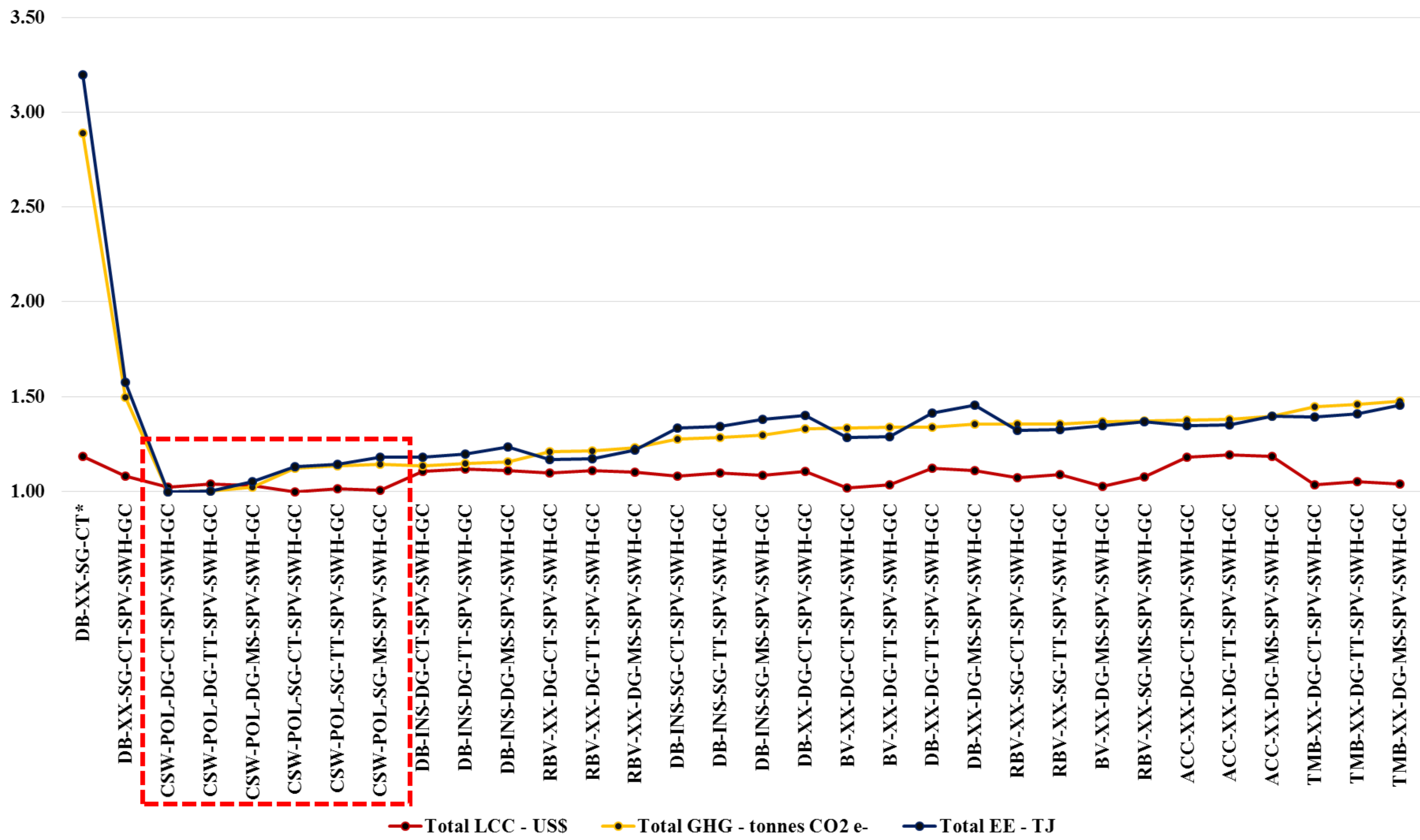


Figure 5.15 Normalized LCC, GHG emissions, and EE consumption results for a reference house in Perth for CPS options

The techno-economic and environmental assessment of alternative CPS options has been summarized as following:

- Envelope options cast in-situ sandwich - polystyrene core – single glazed / double glazed windows – concrete roof tiles /terracotta roof tiles / metal roof sheet – solar PV – solar water heater – green concrete (CSW-POL-SG/DG-CT/TT/MS-SPV-SWH-GC) are the most cost effective options with the highest GHG emissions and EE consumption saving potential.

- The wall element option CSW-POL combined with different window types and roofs has been found to be the most cost effective option, which offers the maximum environmental benefits.

- The double glazed window (DG) option is not economically viable but contributes to substantial environmental benefit.

- The concrete roof tiles (CT), terracotta roof tiles (TT), and metal roof sheet (MS) have been found to offer the same amount of economic and environmental performance.

- The grid connected 3kW$_p$ roof top solar PV (SPV) has been found to be the most cost effective CPS for GHG emissions and EE consumption saving.

- The integration of gas based water heater with roof top solar water heater (SWH) is another efficient and cost effective way to reduce GHG emissions and EE consumption.

- The replacement of conventional concrete with green concrete (C70FA30S0-NA60RCA40-NS100MS0) has been found to offer negligible economic benefit but it offers GHG emissions and EE consumption saving benefits. This CPS option could potentially contribute to the reduction of other impacts such as natural resource depletion and solid waste disposal.

Similar to the reference house, the sensitiveness of the LCC of all CPS options to discount rate and probable carbon tax have been analysed in the following section.

5.3.6 Sensitivity analysis

A sensitivity analysis of LCC results has been performed for the discount rate and the probable carbon tax.

Sensitivity of life cycle cost to discount rate

The present values of replacement costs of SPV, and SWH, operational cost, and the end of life demolition and disposal cost of a reference house in Perth for environmentally viable CPS options have been estimated for a discount rate of 7%. A sensitivity analysis has been performed for different discount rates (i.e. 4%, and 10%) as presented in Table E.13 (Appendix E). The results reveal that the low discount rate of 4% would result in an increase of LCC between 10.9% and 14% as compared to LCC with 7% discount rate, while the high discount rate of 10% would reduce the LCC between 4.5% and 5.8% of the LCC with 7% discount rate (Figure 5.16).

For a discount rate of 7%, the CPS option ACC-XX-DG-TT-SPV-SWH-GC has been found to be an economically unviable option (Figure 5.6) as compared to LCC of a reference house. For a discount rate of 4%, this option also becomes economically viable compared to reference option, while for a discount rate of 10%, all the three variants of this group (i.e. ACC-XX-DG-CT/TT/MS-SPV-SWH-GC) becomes economically unviable. The LCC for environmentally viable CPS options has been found to be sensitive to the discount rates and as compared to their LCC ranking for a discount rate of 7%, the LCC rankings of some of these CPS options for discount rates of 4% and 10% have changed slightly (i.e. one or two rank up or down) as presented in Table E.14 (Appendix E). The main reason for this slight change in ranking with the change in discount rates is due to the fact that each environmentally viable CPS option has a different percentage share of capital, operational, and the end of life costs (Figure 5.17), and the CPS options having higher share of future costs (i.e. the present values of replacement costs of SPV, and SWH, operational cost, and the end of life demolition and disposal cost) are more sensitive to the change in discount rate.

Table E.5 (Appendix E) shows that 15 alternative envelope options offer less economic benefits than the economic benefits achieved by inclusion of SPV-SWH-GC for a reference envelope. The similar trend for LCC of these 15 envelope options has been observed in the case of discount factors of 4% and 10% (Table E.14, Appendix E).

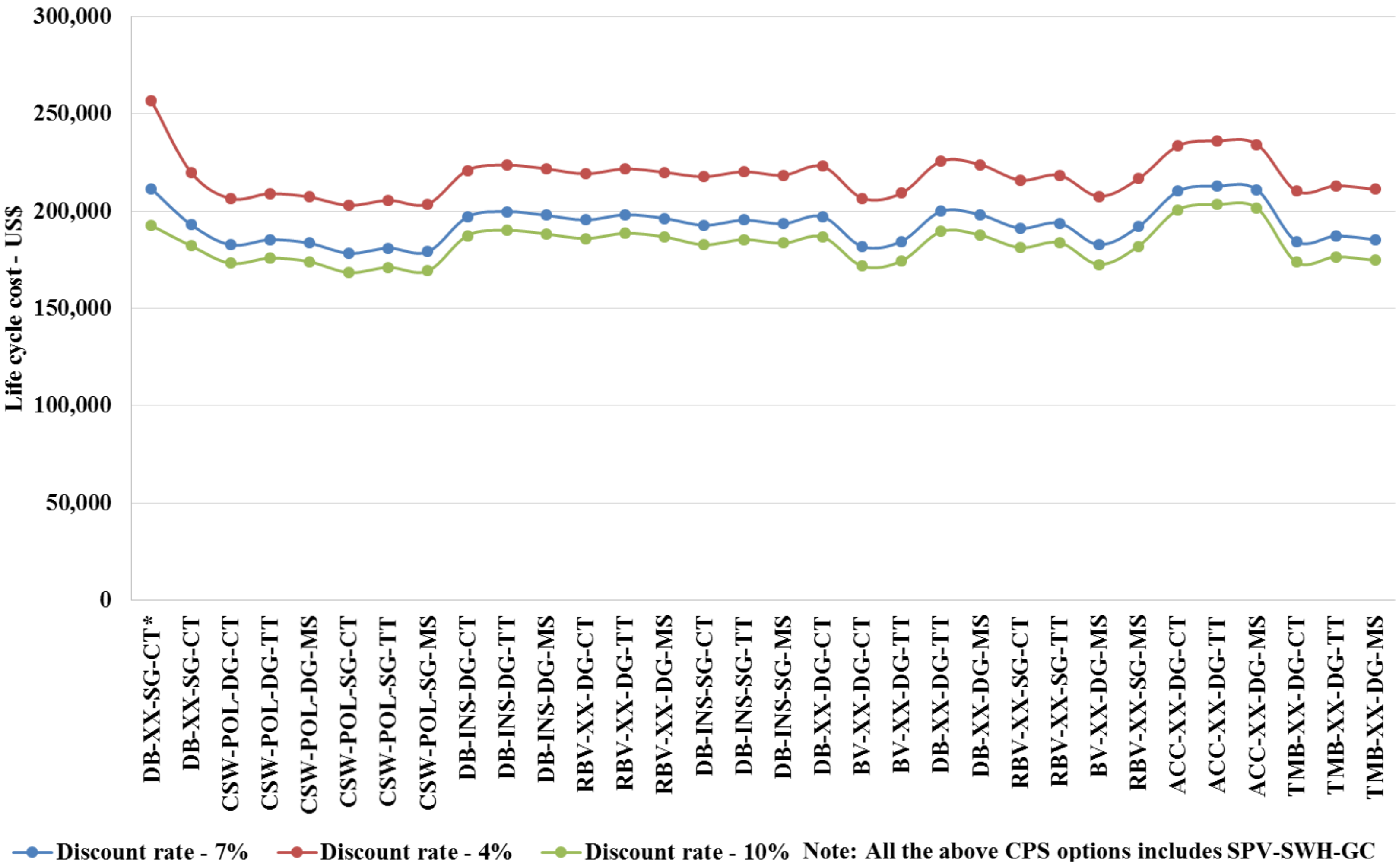


Figure 5.16 Sensitivity of LCC of environmentally viable CPS options to discount rate

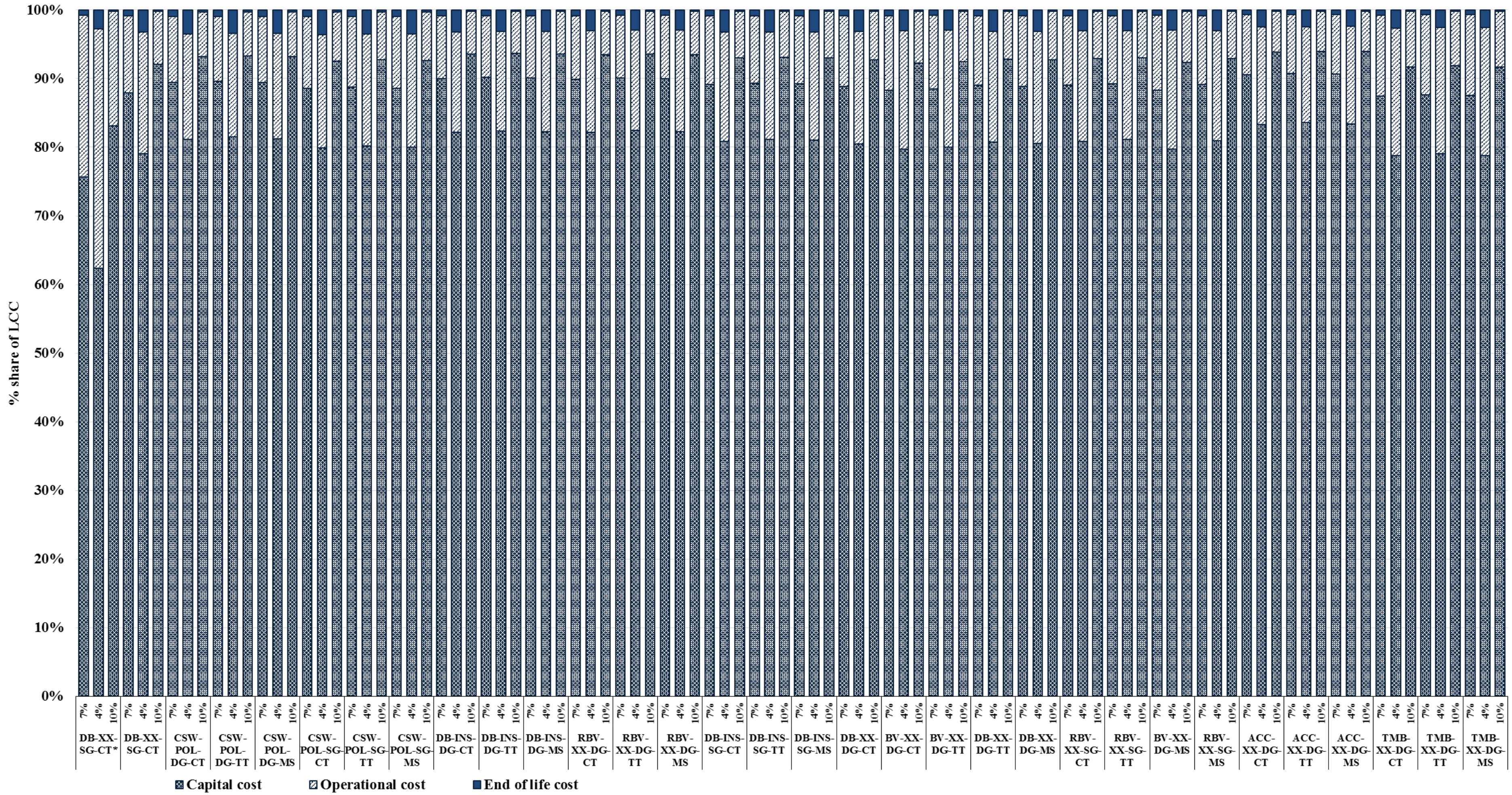


Figure 5.17 Breakdown of LCC for environmentally viable CPS options for different discount rates

Sensitivity of capital cost to discount rate

The capital cost of environmentally viable CPS options, which includes the costs of construction of the house with different envelop options, grid connected 3kW$_p$ roof top solar PV (SPV) including one replacement after 25 years, roof top solar water heater (SWH) including 3 replacements after every 13 years, and the conventional concrete replacement with green concrete has been found to be least sensitive to the change in discount rates to 4% and 10%. This is because, a major portion of the capital cost is the initial investment cost itself, while only a small portion (i.e. replacement costs of SPV and SWH) is a discount rate dependent future cost. Due to change in discount rates, the lowest change i.e. an increase of 10.9% of capital cost for a discount rate of 4%, and a decrease of 4.5% of capital cost for a discount rate of 10% has been observed for CPS option ACC-XX-DG-TT-SPV-SWH-GC, while the highest change has been found for option TMB-XX-DG-CT-SPV-SWH-GC (i.e. an increase of 14% of capital cost for a discount rate of 4%, and a decrease of 5.78% of capital cost for a discount rate of 10%) (Figure 5.18).

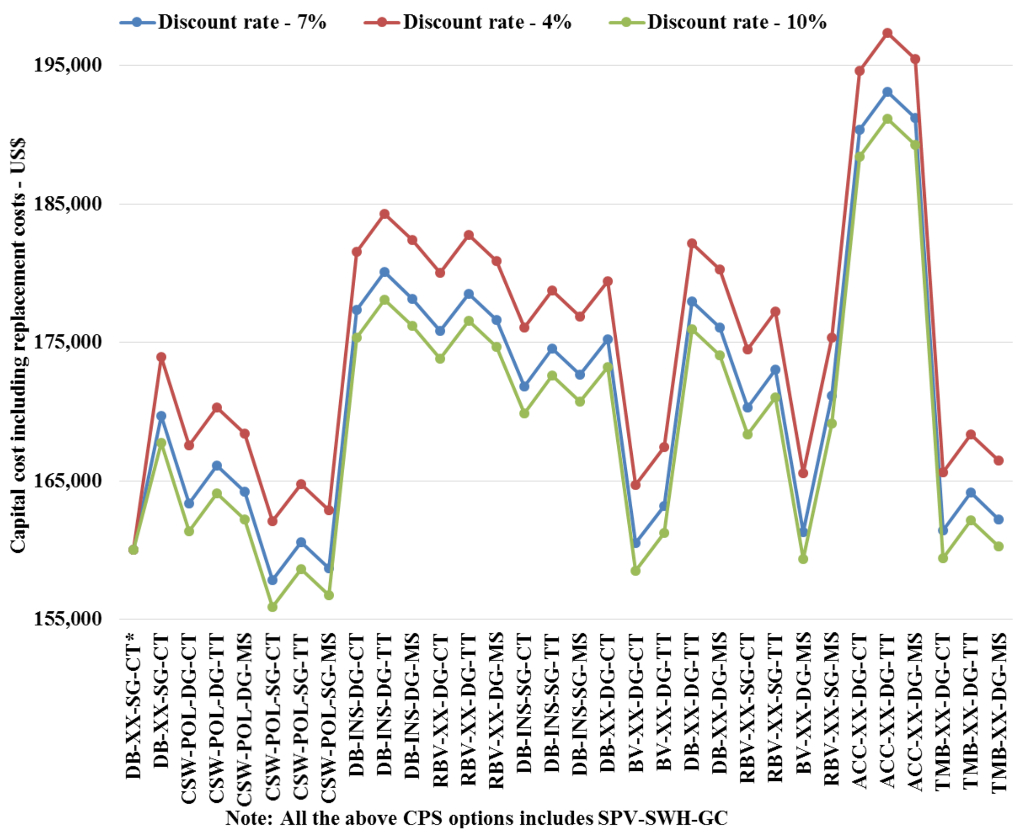


Figure 5.18 Sensitivity of capital cost of environmentally viable CPS options to discount rate

Sensitivity of operational cost to discount rate

The operational cost of a typical house for environmentally viable CPS options, which includes the cost of electricity and natural gas during a 50 year lifespan of the house shows a moderate sensitivity due to the change in discount rates to 4% (i.e. an increase of operational cost by 80.1%) and 10% (i.e. a reduction of operational cost by 35.4%). The main reason for this moderate sensitivity is due to the costs of electricity and natural gas, which are discount rate dependent future costs (Figure 5.19).

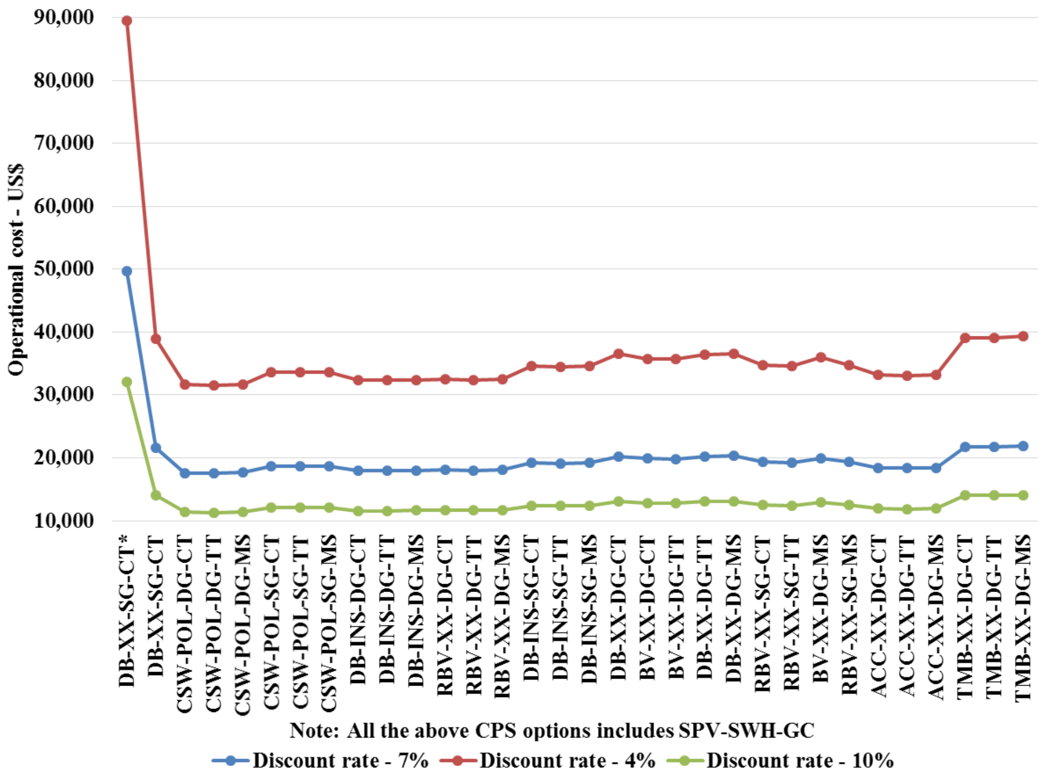


Figure 5.19 Sensitivity of operational cost of environmentally viable cleaner production options to discount rate

Sensitivity of the end of life demolition and disposal cost to discount rate

The end of life demolition and disposal cost of the house for environmentally viable CPS options, which include the cost of demolition and disposal including levy for inert landfill show a very high sensitivity due to change in discount rates to 4% (i.e. an increase of 314.5% of the end of life cost) and 10% (i.e. a reduction of 74.9% of the end of life cost). The main reason for this very high sensitivity is due to the end of life cost, which will incur at the fag end of a 50 year lifespan of the house. In the case of operational cost, the future cost starts right from the end of the first year which goes on till the end of the lifespan, while in this case, the entire cost is a future cost to be incurred after 50 years (Figure 5.20).

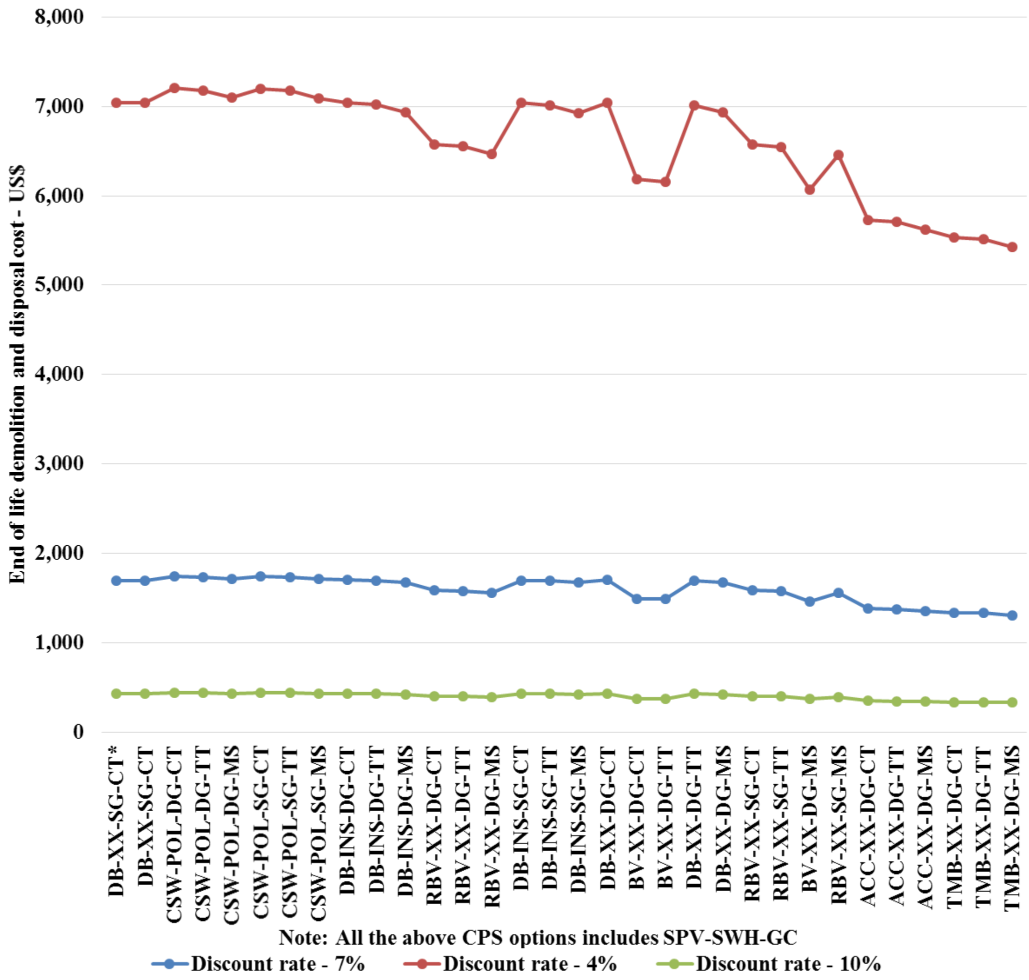


Figure 5.20 Sensitivity of the end of life demolition and disposal cost of environmentally viable CPS options to discount rate

Summary of sensitivity analysis to discount rate

To assess the influence of the change of discount rates (either 4% or 10%) on the decision making, the revised LCC of a typical house for all CPS options has been normalized (Figure 5.21). Similar to the discount rate of 7%, the LCC, GHG emissions, and EE consumption values of CPS options CSW-POL-SG/DG-CT/TT/MS-SPV-SWH-GC are at unity (i.e. 1) or very close to unity with a minimum spread thus making them optimum sustainable options (i.e. most cost-effective with least environmental impacts) even under the discount rates of 4%, and 10%.

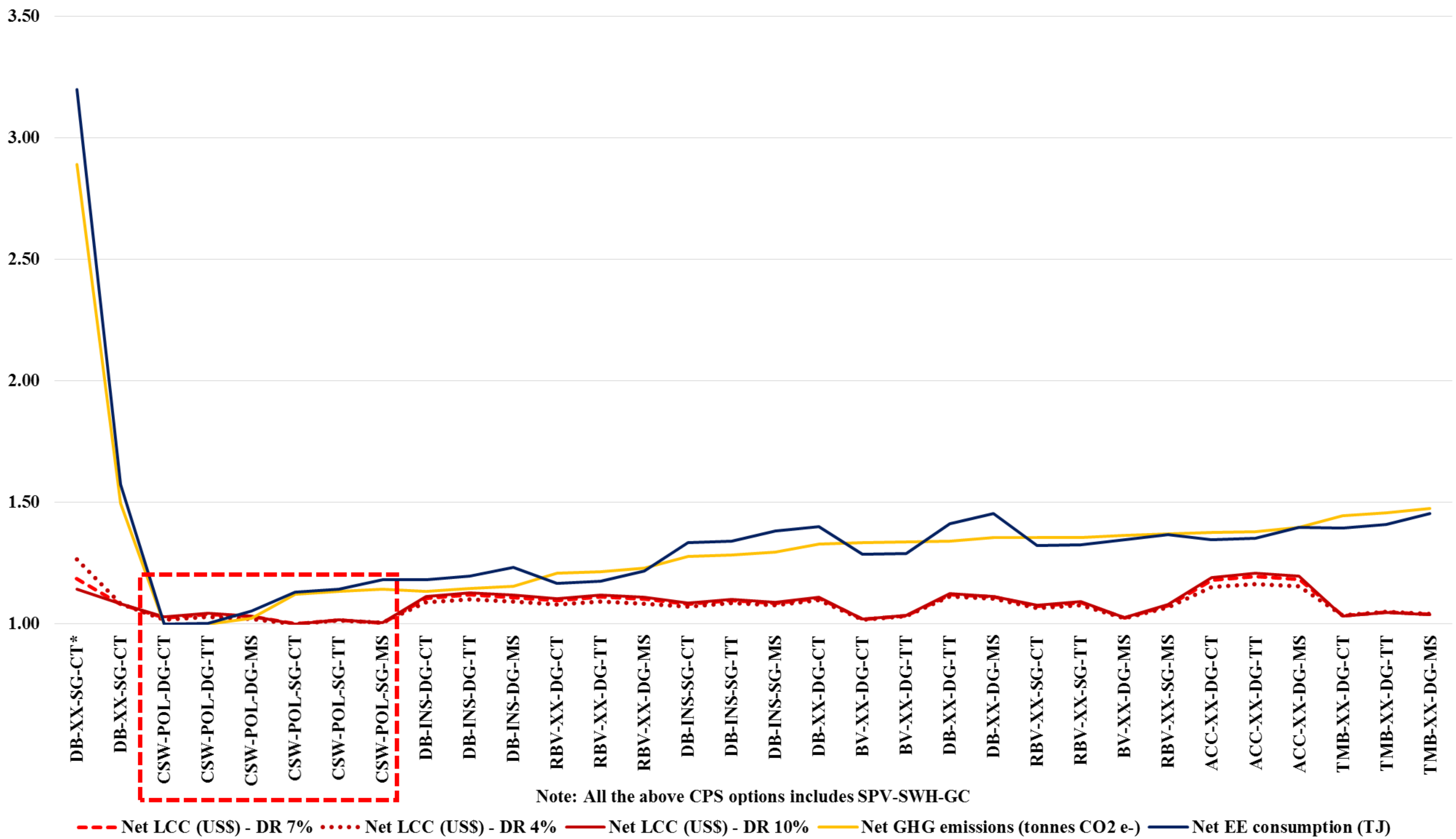


Figure 5.21 Normalized LCC, GHG emissions, and EE consumption results of environmentally viable CPS options for different discount rates

The findings of the sensitivity analysis of the current results are similar to other studies. Val and Stewart (2003) and Ma, Yang, and Lu (2014) confirmed that the discount rate influences the cost effectiveness of various options and also an increase in the discount rate leads to the reduction of LCC. Another study by Ferreira and Santos (2013) confirmed that the capital cost is independent of the discount rate, while the operational cost decrease with the increase of discount rate. The LCC has been found to be sensitive to the discount rates but as the ranking of these CPS options in terms of environmental performance remain the same it does not influence the decision criteria of CPS. For example, the CPS options CSW-POL-SG/DG-CT/TT/MS-SPV-SWH-GC remains the most cost effective environmentally friendly option for all discount rates.

Sensitivity analysis of LCC to probable carbon tax

This analysis has been performed to see that what would happen to the LCC of a typical house for CPS options if the carbon tax is reintroduced by the Government, and also to see as to whether the application of carbon tax as an economic instrument could promote environmentally friendly options. As a result, the impact of probable carbon tax on the LCC of a reference house in Perth for environmentally viable CPS options has been evaluated for different discount rates (Table E.15, Appendix E). The carbon tax has no influence on the capital cost and the end of life demolition and disposal cost but influences the operational cost of environmentally viable CPS options. The imposition of a carbon tax under different discount rate scenarios would increase the operational cost of a typical reference house for alternative CPS options between 10.2% and 10.9%. Also the carbon tax would increase the LCC of a reference house for alternative CPS options between 0.9% and 1.3% for a discount rate of 7%, while the carbon tax under 4% and 10% discount rates would cause an increase of LCC up to 2%, and 0.9% respectively (Figure 5.22).

The analysis shows that the sensitiveness of LCC to a carbon tax is quite low. It appears that the installation of the grid connected 3kW$_p$ roof top solar PV (SPV) and integration of gas based water heater with roof top solar water heater (SWH) itself could reduce the carbon tax significantly (i.e. about 54.8% of the carbon tax of reference house). Similarly, the replacement of a reference envelope by the best envelope options CSW-POL-DG-CT/TT/MS could reduce the carbon tax of a reference house by an additional 8%, while the envelope options DB-INS-DG-CT/TT/MS and RBV-XX-DG-

CT/TT/MS could reduce the carbon tax by an additional 7%. These results are supported by the findings of other studies, which confirmed that the energy efficiency measures for a house would not only reduce the energy cost, and environmental impacts but it would help in reducing the carbon tax as well (Li and Colombier 2009; Lee and Yik 2004; Amstalden et al. 2007; Sumner, Bird and Dobos 2011).

The social implications of environmentally and economically viable CPS options for a reference house in Perth have been discussed in the following section.

5.4 Social implications of environmentally and economically viable CPS options

In order to achieve the goal of sustainable building development as discussed in section 3.6, it is important to evaluate the positive and negative social impacts of the environmentally and economically feasible options using a series of tangible and intangible indicators.

5.4.1 Tangible social indicators

Affordability: The economic analysis results show that the environmentally and economically feasible envelope options CSW-POL-DG-CT/TT/MS for the construction of a typical reference house in Perth have up to 7.3% less capital costs as compared to the capital cost (i.e. US$160,007.00) of the house with reference envelope (DB-XX-SG-CT). These envelope options provide an additional benefit in terms of operational cost saving of up to 8% of the operational cost (US$49,735.00) of the house with reference envelope due to their enhanced thermal performance. However, the end of life demolition and disposal costs of these options are up to 2.4% higher than the reference envelope (US$1,697.50), which is not a significant amount. The installation of a grid connected 3kW_p roof top solar PV (SPV) would attract an initial capital cost of US$2,747.00, which would be recovered within 3.5 years from the operational cost saving. A replacement would occur after 25 years of SPV's lifespan and by that time there would be enough operational cost saving to support the new installation. Overall, this CPS option would result in a net saving of US$15,814.00 over the lifespan of a typical house in Perth.

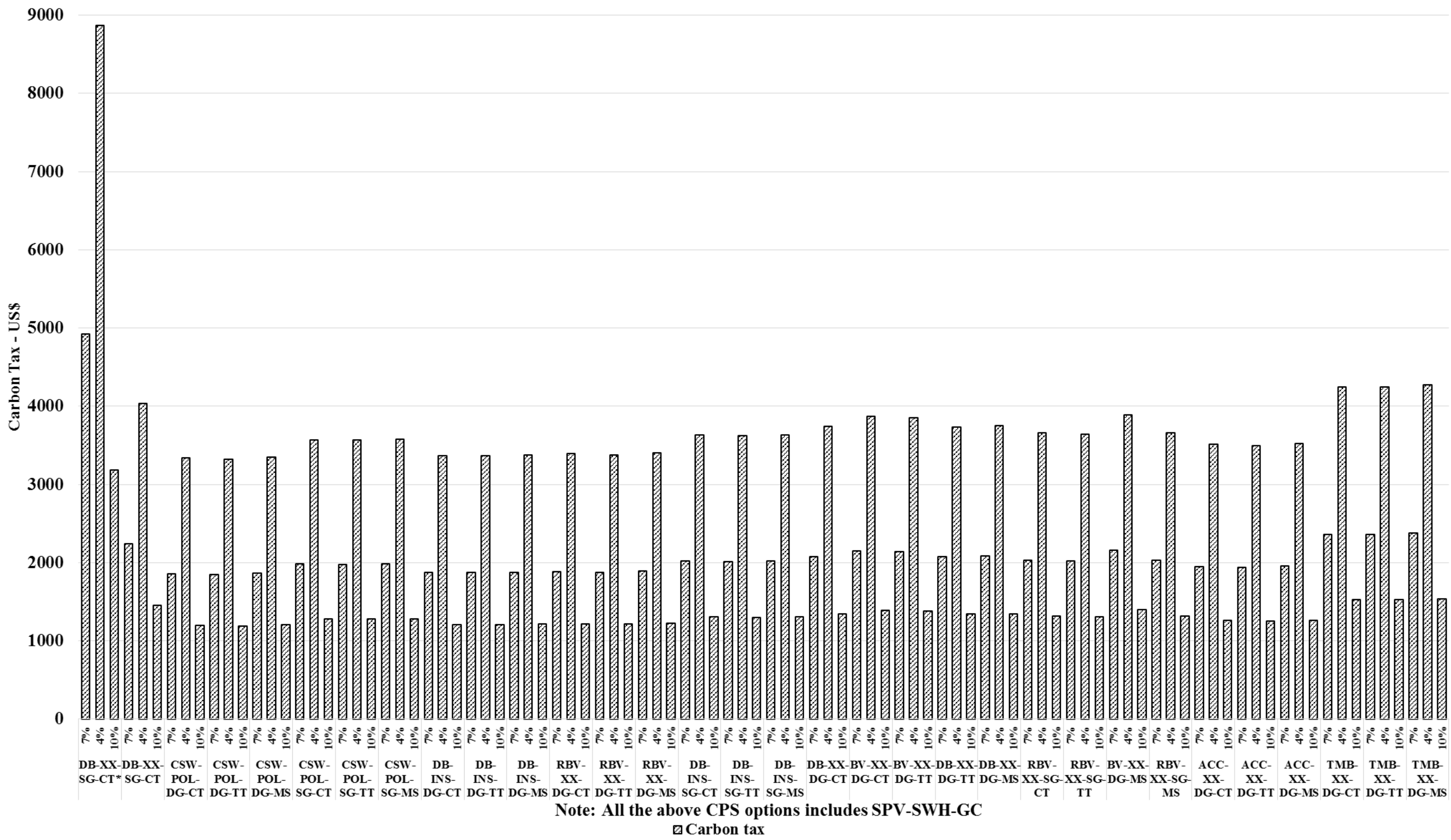


Figure 5.22 Sensitivity of LCC of a reference house in Perth to carbon tax for environmentally viable CPS options under different discount rates

The integration of gas based water heater with roof top solar water heater (SWH) would attract an initial capital cost of US$2,747.00, which would be recovered within 9 years from the operational cost saving. The replacements will occur after every 13 years, and as a whole, this CPS option would result in a net saving of US$2,389.40 00 over the lifespan of a typical house in Perth. The replacement of conventional concrete by green concrete would reduce the capital cost of a reference house by US$327.00. It is interesting to note that even after adding the initial capital costs of SPV and SWH to the capital costs of best options CSW-POL-DG-CT/TT/MS, the total capital costs would be less than the capital cost of the house for reference envelope.

The above analysis demonstrates that the environmentally and economically viable CPS options CSW-POL-DG-CT/TT/MS-SPV-SWH-GC are not only affordable at the initial stage but also due to the amount of operational cost saving they offer during the lifespan of the house further enhances the affordability. Due to the lower capital and operational costs, people from slightly lower income groups would be able to meet the mortgage eligibility criteria and the households would have some surplus money due to operational cost savings, thus reducing the stress of mortgage repayment.

***Employment opportunities*:** As discussed in section 3.6, there is a shortage of skilled masons in Australia, and not many people are willing to enter into this trade because the brick laying activity is a specialized trade requiring hard labour, attention, and onsite precision. Due to its innovative technology and method of construction, there is no requirement of the tedious assembly of small components (i.e. clay bricks) for the environmentally and economically viable wall element option cast in-situ sandwich with polystyrene core (CSW-POL), which makes this option more attractive for trade people. Also because the skeleton of this wall element is factory made (BRANZ 2011), the level of trade skill of people at a construction site is not that high as compared to brick masonry. The skills to assemble these walls at the site could easily be acquired by the existing brick masons. Based on the experience of Middle East and discussion with local builders, it can be concluded that the use of this wall option would not have any adverse impact on the employment opportunities.

In fact, the employment opportunities for other trades in housing sector may improve due to this substitution because the interrelated trades such as electrical, plumbing, and window installation whose productivity gets affected due to the slow assembly of brick walls of a house would be able to finish the work faster and move to new projects.

***Project duration*:** The method and process of construction greatly influence the project duration. As per currents trends and due to shortage of skilled masons in WA, the completion of brick work of a typical house alone takes between three and five months, depending upon the availability of masons (Budget Developments Australia Pty Ltd; Fozdar Technologies Pty Ltd; Innovative Construction Pty Ltd). Because of the nature and method of construction, the CSW-POL wall elements would not take more than a month to complete the walls of a typical house. Recent studies by Wafa (2011), and Mousa and Zidan (2014) confirmed that the cast in-situ sandwich wall construction requires substantially less (up to 50%) of the time of conventional construction. The cast in-situ sandwich wall system has been accepted as an efficient method of construction of modular houses, and sustained shelters in disaster affected areas due to fast construction (Sarcia 2004; Huy 2002). The reduced duration for the construction of walls will result in a continuous work flow for subsequent trades and activities. As discussed earlier, this reduction of time would indirectly help all other trades and may result in more employment opportunities.

***Resource conservation*:** The analysis of material and energy inputs for alternative envelope options (Section 4.4.4.1) show that the material inputs for the environmentally and economically viable wall element CSW-POL are 47.5tonnes less than the reference wall element (DB-XX) (Table 4.5). This material weight reduction has subsequent implications in terms of transportation, construction energy, and waste, and demolition energy and waste disposal. The wall element CSW-POL has been found to reduce the transportation for materials to construction site by 1,794tkm (Table 4.6), energy for tools and plants during construction by 6.75GJ (Table 4.7), transportation of construction waste disposal by 937.5tkm (Table 4.8), and the end of life waste disposal by 1,305.5tkm (Table 4.10) with respect to the reference wall option (DB-XX), while only the energy for tools and plants during the end of life demolition (Table 4.9) has been found to be more (i.e. 14GJ) than the reference wall option. This demonstrates that the environmentally and economically feasible options would not only reduce the material consumption at first hand, they will reduce the fossil fuels due to the reduction of energy. A study by Blismas and Wakefield (2009) confirmed that an energy efficient and innovative method of construction of a house could not only reduce the raw material and energy consumption but could further help in reducing the onsite waste, and the landfill size.

5.4.2 Intangible social indicators

Acceptability: The continual use of the energy intensive clay bricks in Western Australian housing sector is due to its acceptability by the majority of the people as the preferred method of a house construction. Unlike the Eastern States of Australia, light weight wall construction has not been successful in WA due to a perceived fear that it is not a solid and durable method of construction. However the economically and environmentally feasible wall element CSW-POL could overcome this issue because, this system not only provides a solid cementitious surface but it provides additional benefits by creating a monolithic structure, which increases the resistance of a house to fire, flood, and earthquake (Omid Rezaifar 2008; Ricci et al. 2012; Sarcia 2004).

***Human comfort*:** The adverse effects of the increased frequency of intensive heat waves on human comfort could be minimized through climate responsive design of the house. The results of the sensitivity analysis (Section 4.4.6) reveal that even for the worst house orientation, the operational energy demand for heating and cooling of a typical house in Perth for environmentally and economically viable envelope options CSW-POL-SG/DG-CT/TT/MS would be less than that of the reference envelope (DB-XX-SG-CT) (Table D.23, Appendix D). The results further reveal that even under the high impact scenario of temperature rise due to climate change impacts, the operational energy demand for cooling of a typical house for environmentally and economically viable envelope options would still be less than that of the reference envelope option where the impacts of temperature rise are not considered. This demonstrates that even under extreme conditions, the envelope options CSW-POL-SG/DG-CT/TT/MS would have the comfort performance better or equal to that of the performance of reference envelope without those impacts.

5.5 Summary of key findings

The key findings derived from this chapter are summarized as following:

- The LCC of a typical detached single storey double clay brick wall house in Perth is US$211,439.50. The capital, operational, and the end of life costs accounts for 75.7%, 23.5%, and 0.8% of the LCC respectively.
- The cost of building envelope (e.g. wall, window, and roof) has been found to be 43% of the capital cost where the costs of wall, window and roof elements accounts for 30%, 7%, and 6% respectively.
- The energy costs for home appliances, hot water, lighting, cooling, and heating accounts for 36%, 29%, 16%, 12%, and 7% of the operational cost respectively.
- The LCC has been found to be sensitive to the discount rate, while it is least sensitive to the probable carbon tax.
- The environmentally feasible CPS options CSW-POL-SG-CT/TT/MS-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – Single glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – Roof top solar PV – Roof top solar water heater – Green concrete) have been found to have the lowest LCC.
- The capital cost of a typical house for envelope option CSW-POL-SG-CT (cast in-situ sandwich walls – polystyrene insulation core – single glazed windows – concrete roof tiles) is 7.3% less than that of the reference envelope DB-XX-SG-CT (double brick walls – no wall cavity insulation – single glazed windows – concrete roof tiles), while the capital cost of envelope option ACC-XX-DG-TT (aerated concrete block walls – no wall cavity insulation – single glazed

windows – concrete roof tiles) is 14.6% more than the reference envelope. In total, the capital costs for 12 envelope options such as CSW-POL-SG/DG-CT/TT/MS (cast in-situ sandwich walls – polystyrene insulation core – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet), TMB-XX-DG-CT/TT/MS (timber frame walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet), and BV-XX-DG-CT/TT/MS (brick veneer walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet) are less than the reference envelope, while the capital costs for remaining 18 envelope options such as DB-XX-DG-CT/TT/MS (double brick walls – no wall cavity insulation – double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet), DB-INS-SG/DG-CT/TT/MS (double brick walls – wall cavity insulation – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet), RBV-XX-SG/DG-CT/TT/MS (reverse brick veneer walls with infill insulation – no wall cavity insulation – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet), and ACC-XX-DG-CT/TT/MS (aerated concrete block walls – no wall cavity insulation – double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet) are more than the reference envelope.

- The capital costs of wall elements CSW-POL, TMB-XX and BV-XX are up to 30% less than the reference wall element (DB-XX), while the capital costs of remaining wall elements RBV-XX, DB-INS, and ACC-XX are more than the reference wall element.

- The operational cost of a typical house for envelope option CSW-POL-DG-TT is 8% less than the reference envelope DB-XX-SG-CT, while the operational cost for envelope option TMB-XX-DG-MS is 0.6% more than the reference envelope.

- The end of life cost of a typical house for envelope option TMB-XX-DG-MS is 22.9% less than the reference envelope DB-XX-SG-CT, while the operational cost for an envelope option CSW-POL-DG-CT is 2.4% more than the reference envelope.

- The LCC of a typical house is reduced by US$15,814.00 due to the installation of a $3kW_p$ roof top solar PV.
- The LCC of a typical house is reduced by US$2,389.60 due to the integration of gas based water heater with roof top solar water heater.
- The capital cost of a typical house is reduced between US$169 and US$327 due to the use of by-products and recyclates in the concrete for different envelope systems.
- The environmentally and economically feasible CPS options have been found to be affordable, having no impact on the employment opportunities, requiring less time for the construction, and conserving the material and energy resources. In addition, they are found to meet the acceptability criteria and climatically responsible design criteria.

The following chapter (Chapter 6) discusses whether the environmentally and economically viable CPS options in Perth are applicable to 17 locations in regional WA under location specific climatic, economic, energy, and policy variations. Therefore, similar analyses using LCM framework has been conducted for 17 locations in regional WA.

Chapter 6

Regional implications of sustainable options

6.1 Introduction

This chapter discusses the applicability of the LCM framework at the regional level to evaluate the environmental and economic viability of the CPS options applied to a typical 4x2x2 (4 bedroom, 2 bath, and 2 garage) single storey detached house. In this chapter, it was tested as to whether the same cleaner production strategies, which were found to be sustainable in Perth, have the potential to mitigate the life cycle GHG emissions and EE consumption impacts, reduce LCC and enhances the intra, and inter-generational equity benefits (Table E.12, Appendix E).

This chapter discusses the regional characteristics of 17 locations across Western Australia. The life cycle energy analysis of a typical house for various cleaner production options have been performed for these regional locations because, the use stage of a typical house in Perth (i.e. operational energy consumption for heating, cooling, lighting, hot water, and home appliances) has been found to be the major contributor (up to 90%) of the total environmental impacts (Section 4.3.1, 4.3.2). In terms of LCC, the operational cost during use stage is more sensitive due to the future costs. The CPS options, which have been found to be sustainable for Perth, have been assessed for 17 regional locations from environmental and economic perspective. Finally, the sustainable options in 17 regional locations in WA have been discussed.

6.2 Geography and Demography of regional WA

Prior to the assessment of the sustainability aspects of CPS options for a typical house in 17 regional locations in WA, it is important to briefly present the geographical and demographical details of Western Australia that drive the demand for housing.

Western Australia is the largest state of Australia with a diverse climate, history, flora and fauna covering more than 2.5million square kilometres of the area and is one of the most ancient lands on the planet. As per Regional Development Commissions Act 1993, the WA is divided into 10 regions such as Perth metropolitan, Kimberley, Pilbara, Gascoyne, Mid-West, Goldfields-Esperance, Wheatbelt, Peel, South West, and Great Southern (DOP 2015), while Perth metropolitan region is the fastest growing region with almost 80% of WA's population living in this region. Kimberley is the northern most region of WA with Broome, Derby, Wyndham, and Kununurra as main population centres. Pilbara is in the north of WA with Karratha, Port Hedland, and Newman as population centres and dominated by the resources sector. Gascoyne is in the north-west of WA with Carnarvon and Exmouth as population centres. Mid West has a diverse economy, natural environment, and culture with Geraldton, Meekatharra, Wiluna, and Mount Magnet as main population centres. Goldfields-Esperance has diverse rich social, economic and natural environments due to mineral wealth with Kalgoorlie, Esperance, Dundas, Leonora, and Laverton as population centres. Wheatbelt is the agricultural powerhouse of WA with widely dispersed population centres in rural areas. Peel region with Mandurah, Waroona, Byford, and Boddington as population centres is one of the most populated centres outside the Perth metropolitan area and is growing very fast. South West has high population growth with a thriving and diverse export oriented economy with Bunbury, Busselton, Augusta, and Manjimup as population centres. Great Southern has rich indigenous and European heritage with agriculture and tourism based economy with Albany, Denmark, Katanning, Woodanilling as population centres (DOP 2015; DOSD 2015; wa.gov.au 2015).

Out of eight climate zones of Australia, the 17 locations in regional WA falls under five climate zones (1, 3, 4, 5, and 6). The postal code, climate zone, and NatHERS zone data of these locations, which are required by AccuRate software for energy analysis are presented in Table F.1 (Appendix F). Similarly, the Australia is divided into 4 water heating climate regions (Figure 3.6) based on the solar insolation and ground temperature, which affect the temperature of reticulated water (Standard 2008).

For electricity supply, the Albany, Armadale, Augusta, Bunbury, Busselton, Esperance, Geraldton, Joondalup, Kalgoorlie, Mandurah, and Yanchep are connected to SWIS grid, while the electricity generation in Broome, Carnarvon, Mount Magnet, and Newman is gas based and in Kununurra and Laverton it is diesel based (Horizon 2015b; DOF 2015a; Horizon 2015a).

For gas supply, the Albany, Armadale, Bunbury, Busselton, Geraldton, Joondalup, Kalgoorlie, Mandurah, and Yanchep are connected to ATCO's reticulated natural gas network, while the residents of Augusta, Broome, Carnarvon, Esperance, Kununurra, Laverton, Mount Magnet, and Newman use bottled gas (ATCO 2012; DOF 2015c).

Given the climatic as well as energy source variation in these 17 locations in regional WA, the energy consumption and associated GHG emissions and EE consumption could vary which could also vary the CPS. Therefore, it is important to conduct separate estimation for GHG emissions, EE consumption, and LCC of a typical house for these locations. The following section discusses the energy implications of CPS options in 17 regional locations in WA and compares the results with Perth.

6.3 Life cycle energy analysis

As discussed in Section 4.4, the grid connected $3kW_p$ roof top solar PV (SPV), integration of gas based water heater with roof top solar water heater (SWH), and changes in envelop elements (window, roof, and wall) have been found to be the effective CPS options for reducing the operational energy consumption of a reference house in Perth. Also, the orientation of the house has been found to influence the life cycle energy demand for heating and cooling of a house.

The impacts of climatic variation on the energy mitigation potential of these CPS options for 17 locations in regional WA has been evaluated and discussed in following sections.

Impacts of locations on $3kW_p$ grid connected roof top solar PV (SPV) system

The electricity production capacity of a roof top solar PV is highly sensitive to the location specific solar radiations (Kumar Sahu 2015; Arif, Oo and Ali 2013). The average daily electricity production data of a $3kW_p$ roof top solar PV systems for 17 locations under 4 radiation zones has been obtained from PV-GC spread sheet document produced by Clean Energy Council (CEC) (CEC 2011). The amount of electricity which can be generated using a $3kW_p$ roof top solar PV system has been estimated for all 17 locations (Table 6.1). It has been found that the electricity generation capacity of a $3kW_p$ roof top solar PV in Broome, Carnarvon, Kununurra, Laverton, and Newman is 13.6% more than the electricity generation capacity of $3kW_p$ roof top solar PV in Perth, while the electricity generation capacity in Albany, Augusta, and Esperance is 18.2% less than that in Perth. The electricity generation capacity of $3kW_p$ roof top solar PV has been found to be same in Armadale, Bunbury, Busselton, Geraldton, Joondalup, Kalgoorlie, Mandurah, Mount Magnet, and Yanchep has been found to be same as in Perth.

Table 6.1 Electricity generation capacity of roof top solar PV at different locations in regional WA

Location *reference	NatHERS Zone	Solar radiation Zone	Average Daily Production kWh	Average production during 50 years life of house - kWh
Perth*	13	3	13.2	240,900
Albany	58	4	10.8	197,100
Armadale	47	3	13.2	240,900
Augusta	58	4	10.8	197,100
Broome	33	2	15	273,750
Bunbury	54	3	13.2	240,900
Busselton	57	3	13.2	240,900
Carnarvon	4	2	15	273,750
Esperance	55	4	10.8	197,100
Geraldton	12	3	13.2	240,900
Joondalup	52	3	13.2	240,900
Kalgoorlie	44	3	13.2	240,900
Kununurra	30	2	15	273,750
Laverton	41	2	15	273,750
Mandurah	54	3	13.2	240,900
Mount Magnet	42	3	13.2	240,900
Newman	40	2	15	273,750
Yanchep	52	3	13.2	240,900

The main reason for this variation in electricity generation capacity of roof top solar PV for different locations is due to the fact that the average solar radiation for locations under solar radiation zone 2 (Broome, Carnarvon, Kununurra, Laverton, and Newman) is 21-24MJ/m^2/year, which is higher than the average solar radiation of 15-18MJ/m^2/year in climate zone 4 (Albany, Augusta, and Esperance). The average solar radiation at locations under solar radiation zone 3 (Armadale, Bunbury, Busselton, Geraldton, Joondalup, Kalgoorlie, Mandurah, Mount Magnet, and Yanchep) is 18-21MJ/m^2/year (Figure 6.1).

The grid connected $3kW_p$ roof top solar PV has been found to have substantial potential for reducing the fossil fuel dominated electricity demand during the lifespan of the house at 17 locations in regional WA.

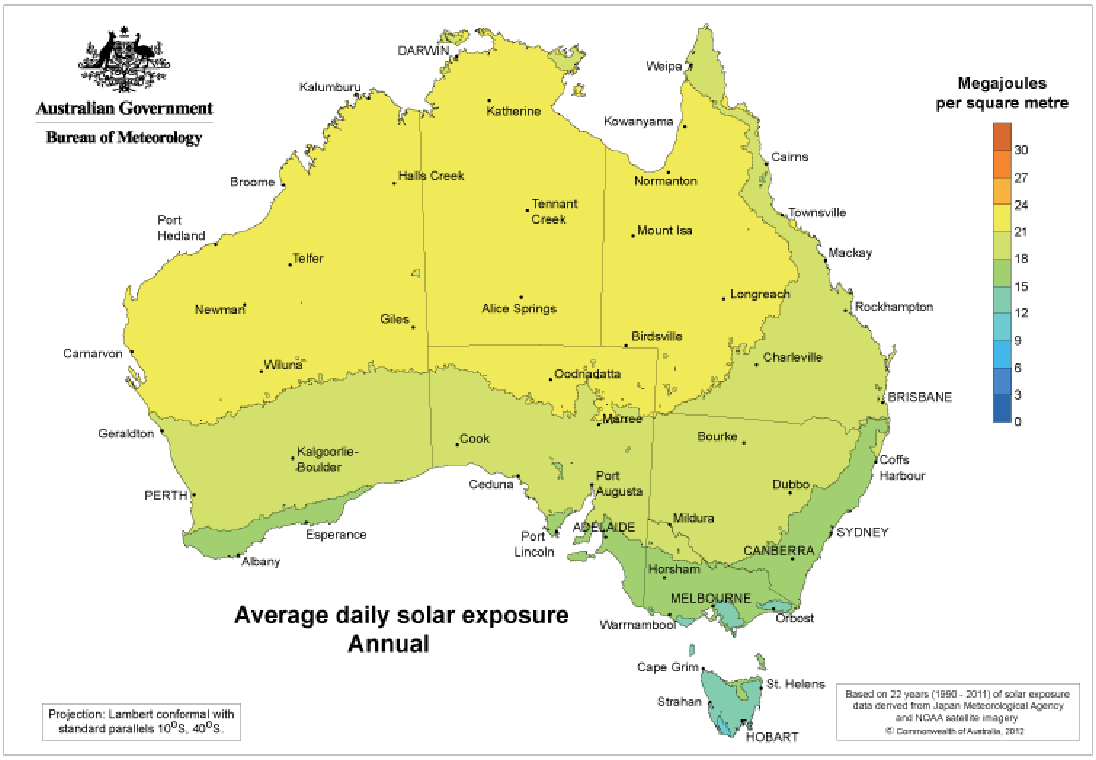


Figure 6.1 Average annual daily solar exposure in regional WA (BOM 2015)

Impacts of locations on integration of gas based water heater with roof top solar water heater (SWH)

As discussed in Section 6.2, Albany, Armadale, Bunbury, Busselton, Geraldton, Joondalup, Kalgoorlie, Mandurah, and Yanchep are connected to ATCO's reticulated natural gas network and the majority of the residents use gas based water heater system (DEWHA 2008a). The residents in Augusta, Broome, Carnarvon, Esperance, Kununurra, Laverton, Mount Magnet and Newman use bottled gas or electric water heaters (based on personal communication with Builders/Contractors listed in Table F.2, Appendix F). The AccuRate software has been used to estimate the revised energy consumption for hot water due to the integration of roof top solar water heater with gas or electricity based hot water system (HWS) for 17 locations as applicable. Similar to the roof top solar PV, the performance of solar water heater is influenced by location specific solar radiation. The results of life cycle energy consumption for hot water with and without SWH for all 17 locations in regional WA are presented in Table 6.2.

It has been found that the life cycle energy consumption for hot water of a typical house could be reduced by 79.7% in Broome, Carnarvon, Kununurra, Laverton, and Newman (hot water region 2) due to the integration of SWH with gas HWS, while this integration could reduce the life cycle energy consumption for hot water in Armadale, Bunbury, Busselton, Geraldton, Joondalup, Kalgoorlie, Mandurah, Mount Magnet, and Yanchep (hot water region 3), and Albany, Augusta, and Esperance(hot water region 4) by 65.2%, and 53.9% respectively.

Table 6.2 Life cycle energy saving potential of SWH in different locations in regional WA

Location *reference	**Life cycle energy consumption for hot water (GJ)**				**Life cycle energy saving potential due to integration of SWH - GJ**	
	Gas	**Electric**	**Solar + Gas**	**Solar + electric**	**Gas**	**Electric**
Perth*	1,130.5	-	393.5	-	737.0	-
Albany	1,214.5	-	560.5	-	654.0	-
Armadale	1,130.5	-	393.5	-	737.0	-
Augusta	1,214.5	703.5	560.5	268.5	654.0	435.0
Broome	1,066.0	577.0	216.0	82.5	850.0	494.5
Bunbury	1,130.5	-	393.5	-	737.0	-
Busselton	1,130.5	-	393.5	-	737.0	-
Carnarvon	1,066.0	577.0	216.0	82.5	850.0	494.5
Esperance	1,214.5	703.5	560.5	268.5	654.0	435.0
Geraldton	1,130.5	-	393.5	-	737.0	-
Joondalup	1,130.5	-	393.5	-	737.0	-
Kalgoorlie	1,130.5	-	393.5	-	737.0	-
Kununurra	1,066.0	577.0	216.0	82.5	850.0	494.5
Laverton	1,066.0	577.0	216.0	82.5	850.0	494.5
Mandurah	1,130.5	-	393.5	-	737.0	-
Mount Magnet	1,130.5	632.0	393.5	161.0	737.0	471.0
Newman	1,066.0	577.0	216.0	82.5	850.0	494.5
Yanchep	1,130.5	-	393.5	-	737.0	-

In the case of integration of SWH with electric HWS (Augusta, Broome, Carnarvon, Esperance, Kununurra, Laverton, Mount Magnet, and Newman), the life cycle energy consumption for hot water could be reduced by 85.7% in Broome, Carnarvon, Kununurra, Laverton, and Newman, while a reduction of 74.5% in Mount Magnet, and 61.8% in Augusta, and Esperance could be achieved.

There are two reasons for this variation in the life cycle energy saving potential of SWH integrated with gas or electric HWS for different locations in regional WA.

Firstly, these locations receive different solar radiations. Secondly, the electric HWS is more energy efficient than the gas HWS because the heating element in electric HWS remains in contact with water thus providing nearly 100% heat transfer efficiency, while only up to 75% of the combustion heat from gas burner is transferred to water thus having lower efficiency (Tsilingiridis, Martinopoulos and Kyriakis 2004; Mutch 1974).

The integration of roof top SWH with gas HWS or electric HWS has been found to have substantial potential for reducing the natural gas or electricity consumption for hot water during the lifespan of the house in 17 locations in regional WA.

Impacts of locations on life cycle operational energy due to changes in building envelope elements (window, roof, and wall)

As discussed in Section 4.4.4, the changes in envelope elements of a house not only affects the impacts during mining to material production, transportation, construction, and the end of life demolition and disposal stages but greatly influence the life cycle operational energy demand for heating and cooling due to the thermal performance of the envelope elements. As the solar radiation across the 17 locations in regional WA is different, the various envelope elements are expected to perform differently due to their thermal performances (Yang, Lam and Tsang 2008; Iwaro and Mwasha 2013; Balaras et al. 2007).

From the analysis of life cycle energy (Table 4.13), environmental impacts (Tables 4.14, and 4.18), and LCC (Section 5.3.1) for different envelope options, it has appeared that the replacement of concrete tiles (CT) to either terracotta tiles (TT), or metal sheet (MS) as roof cover has the least impacts and hence the terracotta roof tiles (TT) and metal roof sheet (MS) have not been considered as variables for assessing their regional implications. The replacement of single glazed windows (SG) with double glazed windows (DG) has been found to have considerable impacts and hence both the window options have been considered for their regional implications. Even though some of the wall elements were found to be environmentally and economically unfeasible in Perth but in order to evaluate their performance under varying climatic conditions in regional WA, all the wall elements (e.g. DB-XX, DB-INS, BV-XX,

RBV-XX, CB-XX, ACC-XX, CSW-POL, PCSW-XX, and TMB-XX) have been considered for their regional implications (Table 6.2).

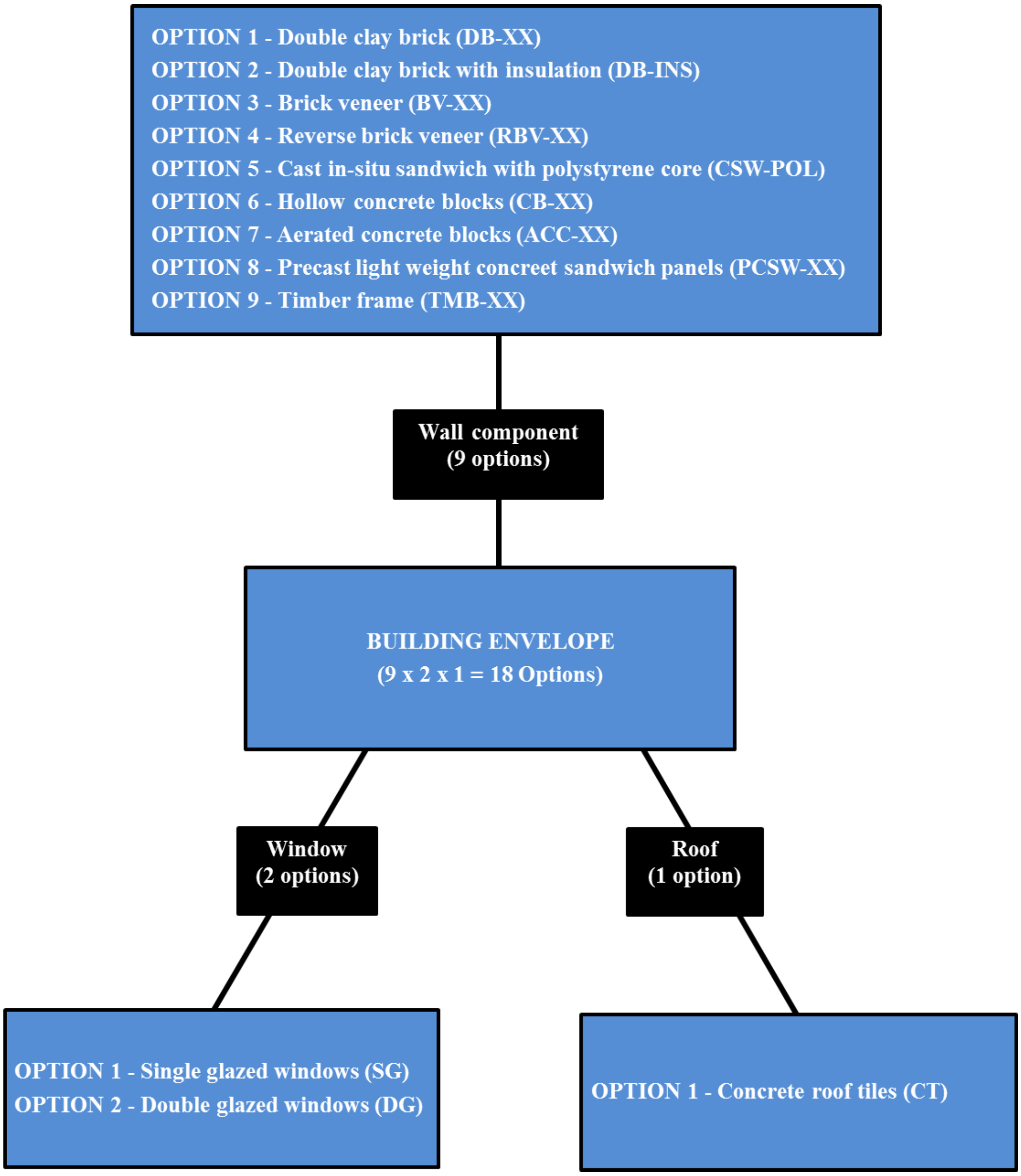


Figure 6.2 Alternative envelope options for 17 locations in regional WA

The life cycle energy demand for heating and cooling of a typical house has been found to be sensitive to the orientation (Section 4.4.3) and hence the AccuRate software has been used to determine the optimum orientations of a typical house in 17 locations in regional WA. Table 6.3 presents the optimum orientations (i.e. the orientation with a minimum amount of heating and cooling energy demand) for a typical house in 17 regional locations in WA.

Table 6.3 Optimum orientations for the house for 17 locations in regional WA

Location	Optimum Orientation
Broome, Geraldton, and Kununurra	East
Armadale, Bunbury, Carnarvon, Kalgoorlie, Laverton, Mandurah, Mount Magnet, and Newman	West
Albany, Augusta, Busselton, Esperance, Joondalup, and Yanchep	North-West

These orientations are considered as ideal orientations in Australia (Southern hemisphere) (Bambrook, Sproul and Jacob 2011; McGee, Reardon and Clarke 2013; Luxmoore 2005). The life cycle operational heating and cooling energy demand of a reference house for 18 alternative envelope options for these optimum orientations in 17 locations in regional WA have been estimated using AccuRate software (Table F.3, Appendix F). As compared to Perth, the life cycle operational energy demand for heating and cooling of the house for all envelope options has been found to be substantially high in Kununurra (i.e. 7 to 15 times), Broome (i.e. 4 to 10 times), and Newman (i.e. 2 to 3 times) (Figure 6.3). Interestingly, out of these three locations, the operational energy requirement for heating in Kununurra and Broome is zero, while in Newman, it is near zero because these are the hottest locations in WA, which falls under climate zone 1 (high humid summer and warm winter), and zone 3 (Hot dry summer and warm winter). As per Australian Bureau of Meteorology, the average annual daily maximum temperature in Kununurra and Broome is more than 33ºC, while it is between 30ºC and 33ºC in Newman (BOM 2016).

The life cycle operational energy demand for heating and cooling of a typical house in Busselton, Albany, and Augusta for all envelope options has been found to be up to three times higher than that of the Perth. Interestingly, the operational energy demand for cooling in these locations is substantially low because these are the coldest locations in WA, which falls under climate zone 5 (Warm temperate), and zone 6 (Mild temperate). As per Australian Bureau of Meteorology, the average annual daily maximum temperature in these locations is less than 21ºC (BOM 2016). As compared to Perth, the variation in the life cycle energy demand for heating and cooling in remaining locations is moderate. The average percentage share of life cycle operational energy demand for heating and cooling for a typical house for alternative envelopes in 17 locations in the regional WA have been presented in Figure 6.4.

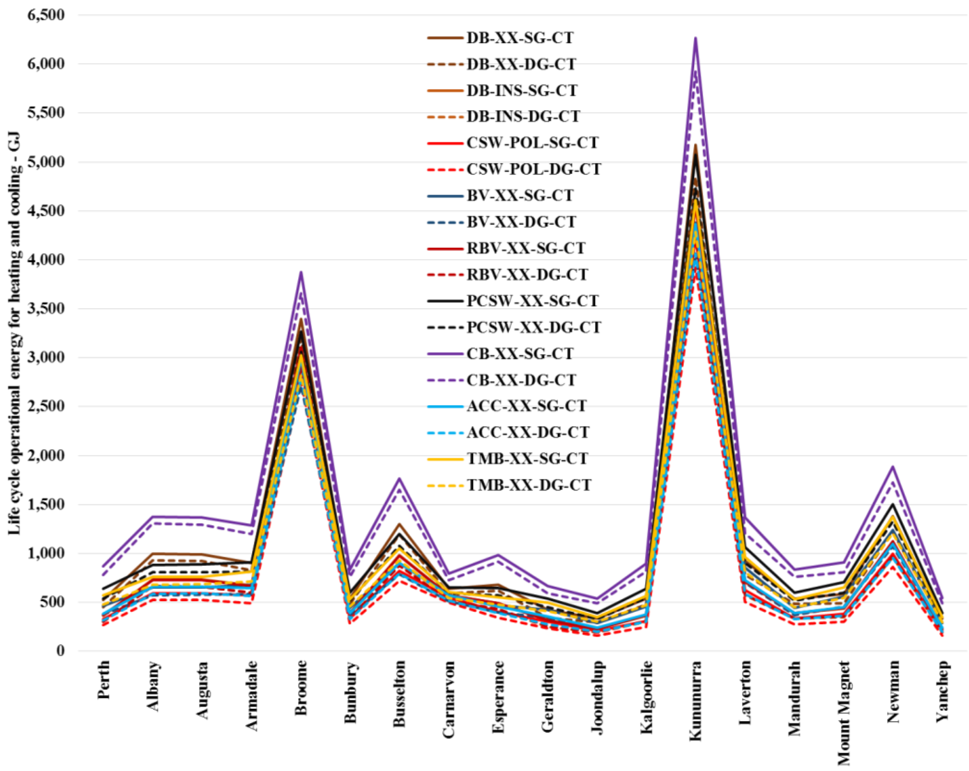


Figure 6.3 Life cycle operational energy demand for heating and cooling of a typical house for alternative envelope options in 17 locations in regional WA

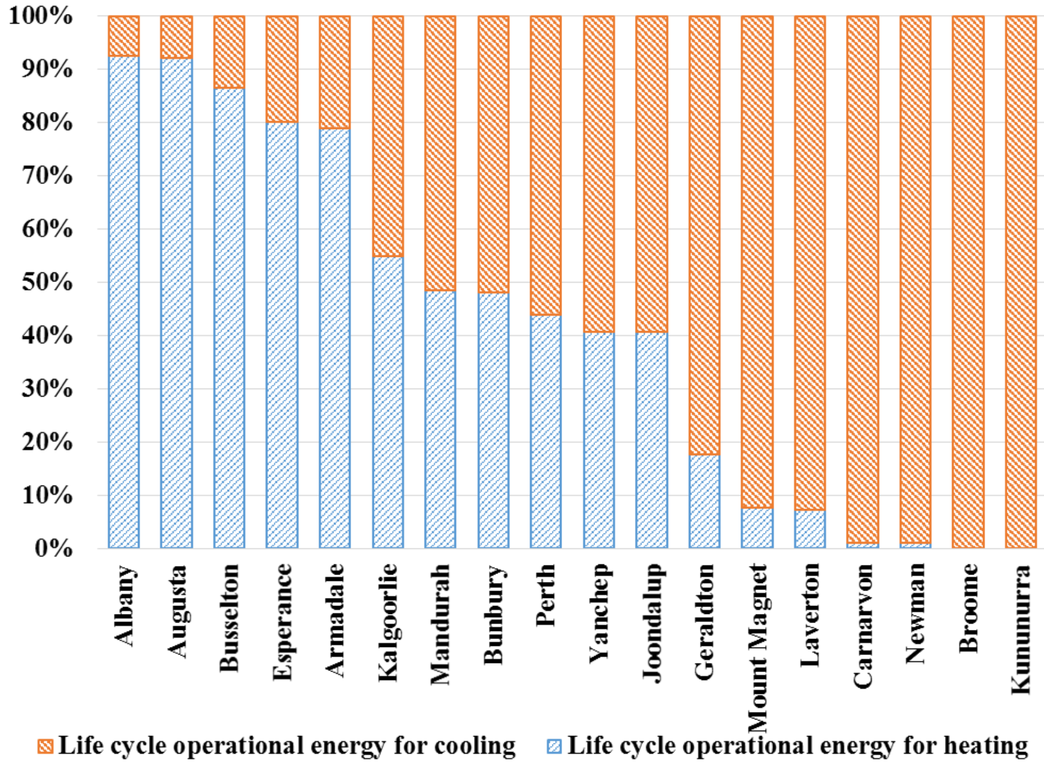


Figure 6.4 Average share of life cycle heating and cooling energy demands of a typical house for alternative envelope options in 17 locations in regional WA

For alternative envelope options, the difference between the lowest and the highest life cycle operational energy demand for heating and cooling of the house varies with location, which is around 1.5 times in Broome, Carnarvon, Kununurra, and Newman, 2.5 times in Albany, Armadale, Augusta, Busselton, and Laverton, and 3 times in Bunbury, Esperance, Geraldton, Joondalup, Kalgoorlie, Mandurah, Mount Magnet, and Yanchep. The reason for the similar performance of all envelopes (i.e. low difference between the lowest and highest) in Broome, Carnarvon, Kununurra and Newman is due to the unique climatic conditions of these locations (hot summer and warm winter). Reardon and Downton (2013b) confirmed that the houses in these locations require substantially high energy to achieve thermal comfort compared to other zones. Studies by Aktacir, Büyükalaca, and Yılmaz (2010), and Yang and Li (2008) reported that the insulation and thermal mass of a house located in the hot summer and warm winters regions has a lower performance than in the other regions.

For each location, the alternative envelope options have been assigned the ranking based on the life cycle operational energy for heating and cooling of the house (lowest to highest) (Table F.4, Appendix F). It has been observed that the rankings of the envelope options CSW-POL-DG-CT (except in Broome), and CB-XX-SG/DG-CT remain unchanged across all locations in regional WA, while a minor change has been observed in the rankings of envelope options PCSW-XX-SG/DG-CT, and ACC-XX-SG/DG-CT. In the case of Broome, the envelope option BV-XX-DG-CT has outperformed in terms of operational energy for heating and cooling. A moderate change has been observed in the rankings of remaining envelope options across all locations in regional WA.

As discussed in Chapter 4, the main reason for this variation in ranking is due to the fact that each envelope (combination of thermal mass, insulation, window system, and roof) reacts in a different manner under different climate conditions (i.e. location and incident solar radiation) as confirmed by other studies (Eskin and Türkmen 2008; Yang, Lam and Tsang 2008; Lam et al. 2008; Yılmaz 2007; Ramesh, Prakash and Shukla 2012; Aste, Angelotti and Buzzetti 2009).

In order to identify the envelope options having the optimum ranking of the life cycle operational energy demand for heating and cooling in all locations, their values have been normalized for each location (Figure 6.5).

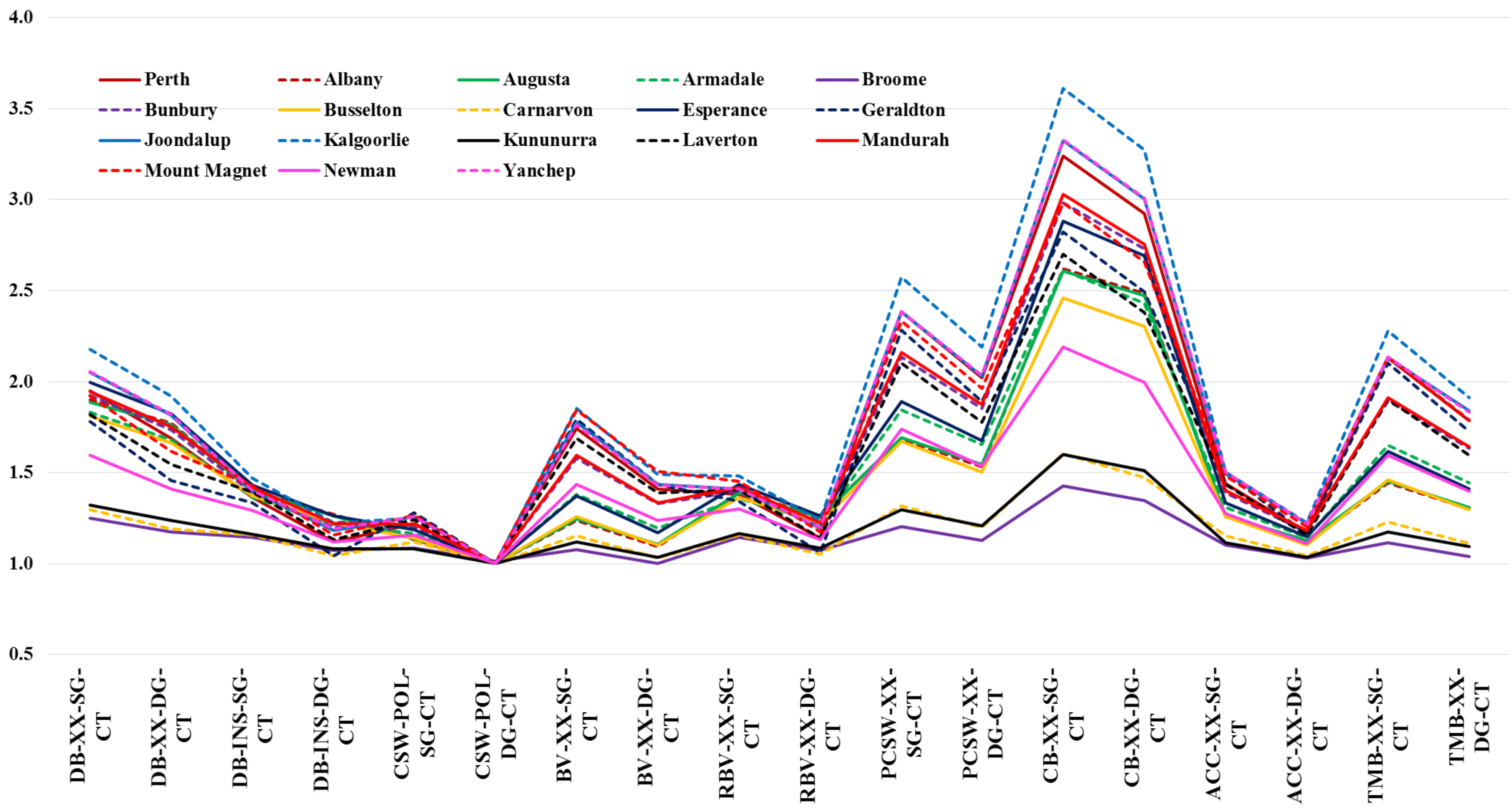


Figure 6.5 Normalized life cycle operational energy values for heating and cooling of a typical house for alternative envelope options in all locations in regional WA

It has been observed that the normalized life cycle operational energy values for envelope option CSW-POL-DG-CT in all locations are at unity (i.e. 1) with no spread; the envelope options DB-INS-DG-CT, CSW-POL-SG-CT, RBV-XX-DG-CT, and ACC-XX-DG-CT have been found to have their normalized values close to unity with low spread. The normalized life cycle operational energy values for remaining envelope options have been found to be widely deviated from unity, which shows the inconsistency in their performance in different locations in regional WA.

The operational energy demand for heating and cooling of a house is a complex function of building envelope's material characteristics such as thermal mass and its relative location, thermal transmittance, thermal admittance, thermal lag, and the climatic conditions. The performance of the envelope gets enhanced due to the combination of the optimum values of above stated characteristics, even if individually these values are not the best as also confirmed by other studies (Aste, Angelotti and Buzzetti 2009; Mohammad and Shea 2013).

The envelope options CSW-POL-DG-CT, DB-INS-DG-CT, CSW-POL-SG-CT, RBV-XX-DG-CT, and ACC-XX-DG-CT have been found to be more energy efficient at all locations but they may not have similar environmental performance, thus requires a further investigation. This is because the source of energy is different for heating and cooling (e.g. electricity and/or natural gas) in different locations.

The life cycle operational energy demand for lighting and home appliances of a typical house in 17 locations in regional WA has been considered to be similar to the house in Perth. The envelope wise breakdown of the life cycle operational energy demand for heating, cooling, lighting, hot water, and home appliances for each location in regional WA has been presented in Table F.5 to Table F.14 (Appendix F)

Impacts of locations on construction of a house due to changes in building envelope elements (window, roof, and wall)

As discussed in Section 4.4.4.1, The construction of a house comprising of mining to material production, transportation of material to construction site, use of plant and equipment including disposal of construction waste during assembly (construction), and use of plant and equipment for the end of life demolition and disposal stages for different envelope options has been found to contribute to 8% to 16% of the total life cycle environmental impacts. It has been assumed that there is no change in material and or energy consumption during mining to material production, use of plant and equipment including disposal of construction waste during assembly (construction), and use of plant and equipment for the end of life demolition and disposal stages for 17 locations in regional WA, while the transportation of material to construction site vary according to the sources of materials at a particular location. For example, there are no brick manufacturing facilities in Broome, Carnarvon, Kununurra and Newman and also Kununurra and Newman do not have an adequate supply of materials such as ceramic tiles, roof tiles, insulation, roof timber, and doors.

It is thus assumed that these materials have to be transported from the suppliers in the nearest large commercial locations. The available published commercial data (Hotfrog 2014; Masters 2014; Bunnings 2014; Yellow-Pages 2014; Hanson 2014; Boral 2014; BGC 2014; Holcim 2014; Midland-Brick 2014; Austral-Bricks 2014) have been reviewed to determine the sources of materials in 17 locations in regional WA to estimate the distance travelled to bring inputs to these locations. Table F.14 and Table F.15 (Appendix F) shows the breakdown of tkm (transportation of materials) for each envelope option in 17 locations in regional WA.

The environmental impacts associated with the construction, use, and the end of life demolition and disposal stages of a typical house for each cleaner production option in 17 locations in regional WA have been discussed in the following section.

6.4 Environmental feasibility of alternative CPS options in regional WA

The GHG emissions and EE consumption associated with the life cycle operational energy for heating, cooling, lighting, hot water, and home appliances and tkm for different envelope options in 17 locations in regional WA have been estimated using SimaPro software. As discussed in Section 6.2, 8 locations out of 17 locations do not have reticulated natural gas supply and the residents use either bottled gas or electricity for hot water. Similarly, in these locations either electric heaters or reverse cycle air-conditioners or portable unflued bottled gas heaters are used for heating (Harrington, Foster and Wilkenfeld 2008). Though some of the heritage housing stock in colder places such as Albany, Augusta, Esperance, Busselton use wooden fireplaces for heating but due to concerns over their environmental impacts and health hazards, their use has either been restricted or declining (Robinson 2011; Yusaf, Goh and Borserio 2011). There is no published data to suggest the percentage share of electricity and bottled gas utilization for heating purpose in these locations, hence both the scenarios have been considered for estimation of environmental impacts. The location wise electricity generation mix, availability of reticulated natural gas, and bottled liquefied petroleum gas (LPG) including their emission factors are presented in Table F.16 (Appendix F).

In addition to the revised operational energy and tkm data for alternative envelope options in 17 locations in regional WA, the life cycle operational energy savings data due to the grid connected 3kW$_P$ roof top solar PV (SPV), and integration of gas based water heater with roof top solar water heater (SWH) is also entered into SimaPro software to estimate their impact on life cycle GHG emissions and EE consumption. It is assumed that the GHG emissions reduction and EE consumption saving due to the use of by-products and recycled material in concrete (GC) are same in all locations.

6.4.1 Location wise life cycle GHG emissions and EE consumption impacts

The location wise breakdown of life cycle GHG emissions and EE consumption associated with the construction, use and the end of life demolition and disposal stages for alternative cleaner production options (envelope, SPV, SWH, and GC) including their rankings (based on the lowest to highest values) is presented in Table F.17 to Table F.41 (Appendix F). Since the operational energy for heating and cooling in 17 locations in regional WA vary significantly from the reference case in Perth, the life cycle GHG emissions and EE consumption results have been individually compared with the results of Perth as following:

Albany

Albany is one of the coldest places (climate zone 6) in WA and as compared to Perth, while there is a significant increase in operational energy requirement for heating, the reduction in operational energy requirement for cooling is also significant (Table F.5, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (235.2tonnes CO_2 e- and 3.2TJ respectively), while the options PCSW-XX-SG-SPV-SWH-GC, and CB-XX-SG-SPV-SWH-GC have the highest life cycle GHG emissions (300.8tonnes CO_2 e-), and EE consumption (4.1TJ) respectively. As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-DG-CT-SPV-SWH-GC, RBV-XX-DG-CT-SPV-SWH-GC, CSW-POL-DG-CT-SPV-SWH-GC, and DB-XX-DG-SPV-SWH-GC have increased significantly by up to 19%, and 25% respectively. This is because of the fact that in winters, the insulation becomes counterproductive. However, there is a slight increase in impacts for less energy efficient options such as PCSW-XX-SG-SPV-SWH-GC, TMB-XX-SG-CT-SPV-SWH-GC, and CB-XX-SG-SPV-SWH-GC (Figure 6.6).

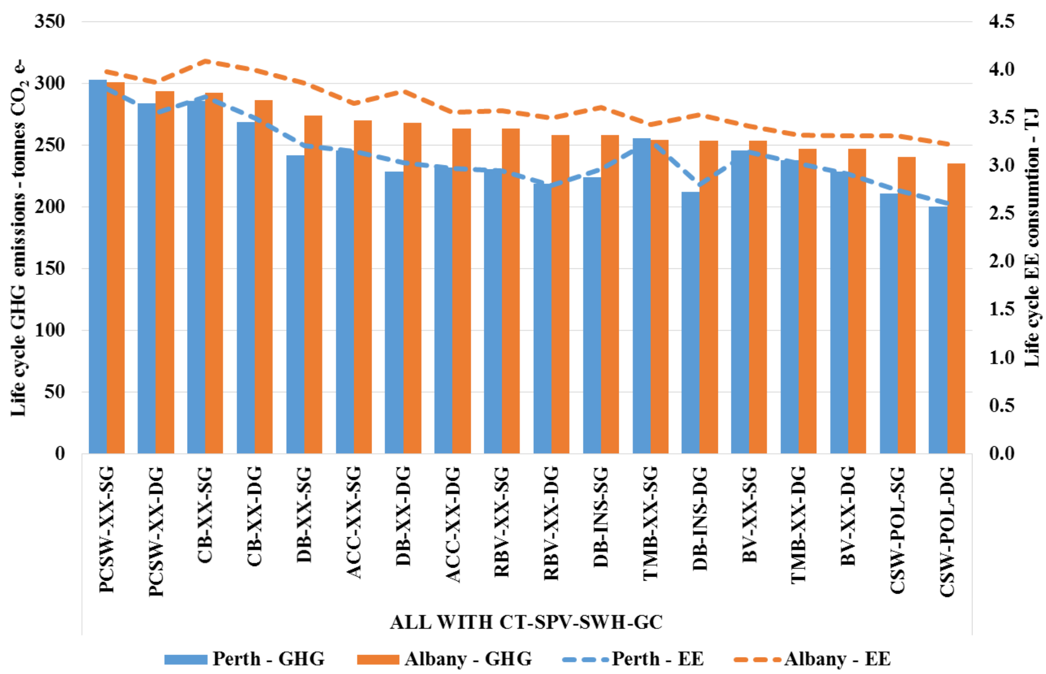


Figure 6.6 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Albany and Perth

The rankings of the CPS options CSW-POL-SG/DG-SPV-SWH-GC in Albany have been found to be same as Perth (i.e. ranked as first and second), while the rankings of CPS options BV-XX-DG-SPV-SWH-GC, and TMB-XX-DG-CT-SPV-SWH-GC have significantly improved to third and fourth positions respectively (Table F.17, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Albany for all CPS options have been found to be slightly more than the Perth mainly due to an increased operational energy demand for heating, which is much more than the reduction in operational demand for cooling.

Augusta

Augusta is in the same climate zone 5 as Perth but these locations fall under two different NatHERS zones. There is a significant increase in the operational energy requirement for heating, while the operational energy requirement for cooling also has reduced significantly (Table F.5, Appendix F).

There is no reticulated natural gas network in Augusta and hence the GHG emissions and EE consumption impacts have been estimated for two scenarios:

- Use of bottled gas for heating and hot water
- Use of electricity for heating and hot water

In the case of use of LPG for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (239.4tonnes CO_2 e- and 3.3TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (306.2tonnes CO_2 e- and 4.1TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-SG/DG-CT-SPV-SWH-GC, RBV-XX-SG/DG-CT-SPV-SWH-GC, DB-XX-SG/DG-SPV-SWH-GC, and CSW-POL-DG-CT-SPV-SWH-GC have increased significantly by up to 20%, and 30% respectively. This is because of the fact that in winters, the insulation becomes counterproductive. There is a slight increase of GHG emissions and EE consumption impacts for less energy efficient options such as PCSW-XX-SG-SPV-SWH-GC, and TMB-XX-SG-CT-SPV-SWH-GC (Figure 6.7).

Similarly, in the case of use of electricity for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions as well as the EE consumption (492.7tonnes CO_2 e- and 6.3TJ respectively). On the other hand, the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (707.5tonnes CO_2 e- and 9.0TJ respectively). This shows an increase of impacts by more than 100% of that associated with the use of LPG because the emission factor of grid electricity is more than four times higher than that of bottled gas. As compared to Perth, the GHG emissions and EE consumption impacts for CPS options such as DB-XX-SG/DG-SPV-SWH-GC, DB-INS-DG-CT-SPV-SWH-GC, and CB-XX-SG/DG-CT-SPV-SWH-GC have increased by up to 150% each, while the GHG emissions and EE consumption impacts for options such as PCSW-XX-SG-SPV-SWH-GC, and TMB-XX-SG-CT-SPV-SWH-GC have increased by up to 100% each (Figure 6.8).

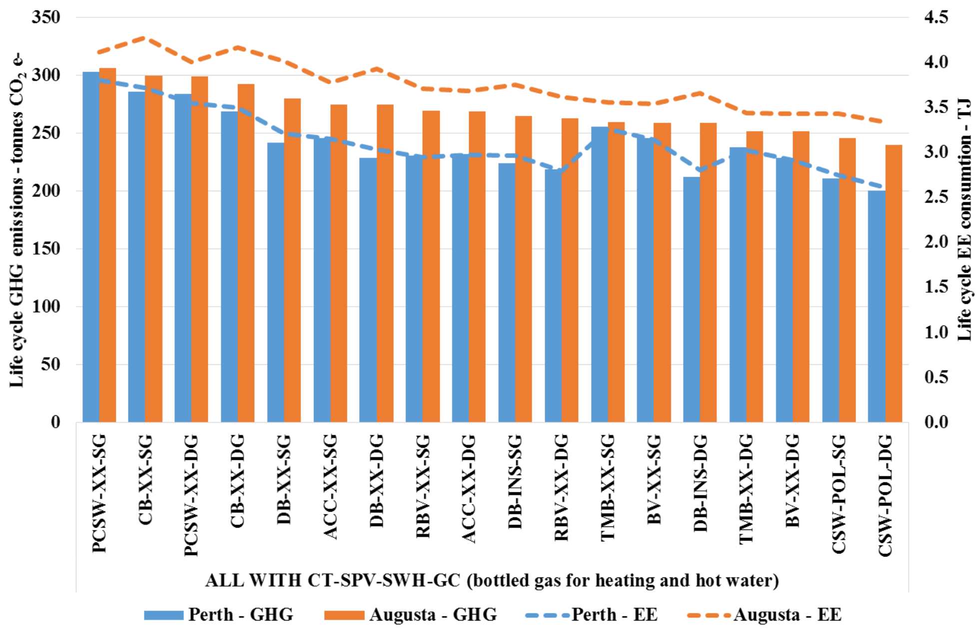


Figure 6.7 Comparison of life cycle GHG emissions and EE consumption of all CPS options between Augusta and Perth (use of bottled gas for heating and hot water)

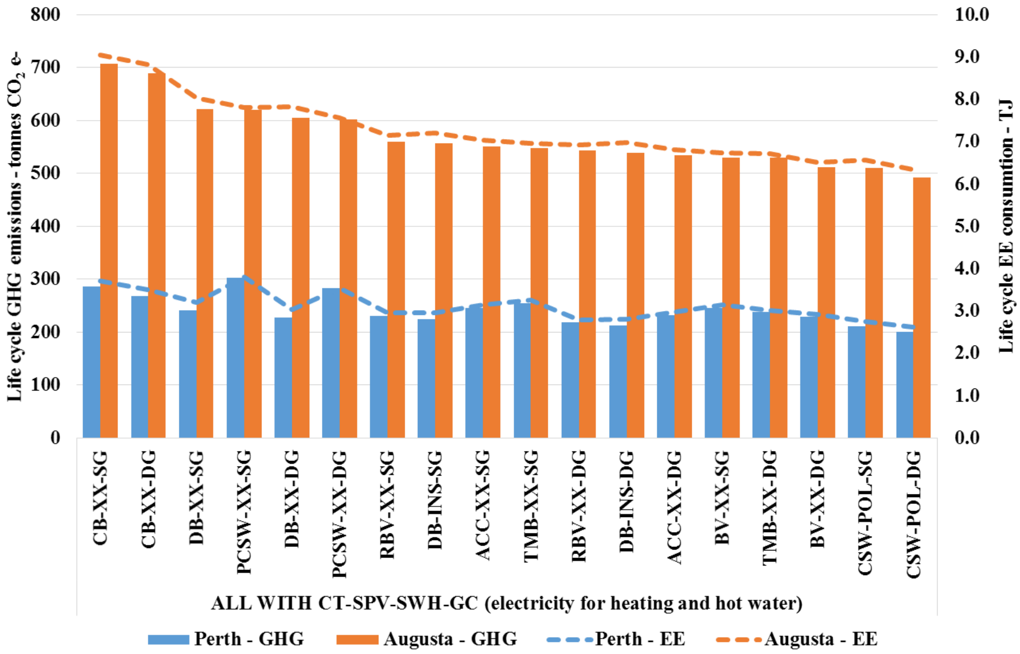


Figure 6.8 Comparison of life cycle GHG emissions and EE consumption of all CPS options between Augusta and Perth (use of electricity for heating and hot water)

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC in Augusta have been found to be same as Perth (i.e. ranked as first and second) for both scenarios, the rankings of the middle order CPS options have slightly changed (up or down by one position) (Table F.18, and Table F.19, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Augusta for all CPS options have been found to be more than the Perth due to an increased operational energy demand for heating, which is much more than the reduction in operational energy demand for cooling.

Armadale

Both Armadale and Perth are in the same climate zone (i.e. 5) but they fall under two different NatHERS zones, which might be the reason for a slight variation in the operational energy demand for heating and cooling in Armadale (Table F.6, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption impacts (200.7tonnes CO_2 e- and 2.7TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (288.9tonnes CO_2 e- and 3.7TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-DG-CT-SPV-SWH-GC, RBV-XX-DG-CT-SPV-SWH-GC, and DB-XX-DG-SPV-SWH-GC have increased slightly by up to 2%, and 5% respectively, while there is a slight reduction of GHG emissions and EE consumption impacts for less energy efficient options such as PCSW-XX-SG/DG-SPV-SWH-GC, TMB-XX-SG/DG-CT-SPV-SWH-GC, and CB-XX-SG/DG-SPV-SWH-GC (Figure 6.9). As discussed earlier, the emission factor of the natural gas (i.e. 0.06tonnes CO_2 e-/GJ), which is used for heating is less than one fourth of the emission factor of grid electricity (i.e. 0.26tonnes CO_2 e-/GJ) used for cooling. Due to this reason, a slight variation in operational energy demand for heating and cooling does not necessarily mean a proportional variation in GHG emissions and EE consumption impacts, thus the impacts due to an increase in operational energy for heating gets compensated easily with the slight decrease in cooling energy demand.

The rankings of the CPS options CSW-POL-SG/DG-SPV-SWH-GC in Armadale have been found to be same as Perth (i.e. ranked as first and second), while the rankings of some of the remaining CPS options have slightly changed by one position up or down

(Table F.20, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Armadale for all CPS options have been found to be similar to Perth.

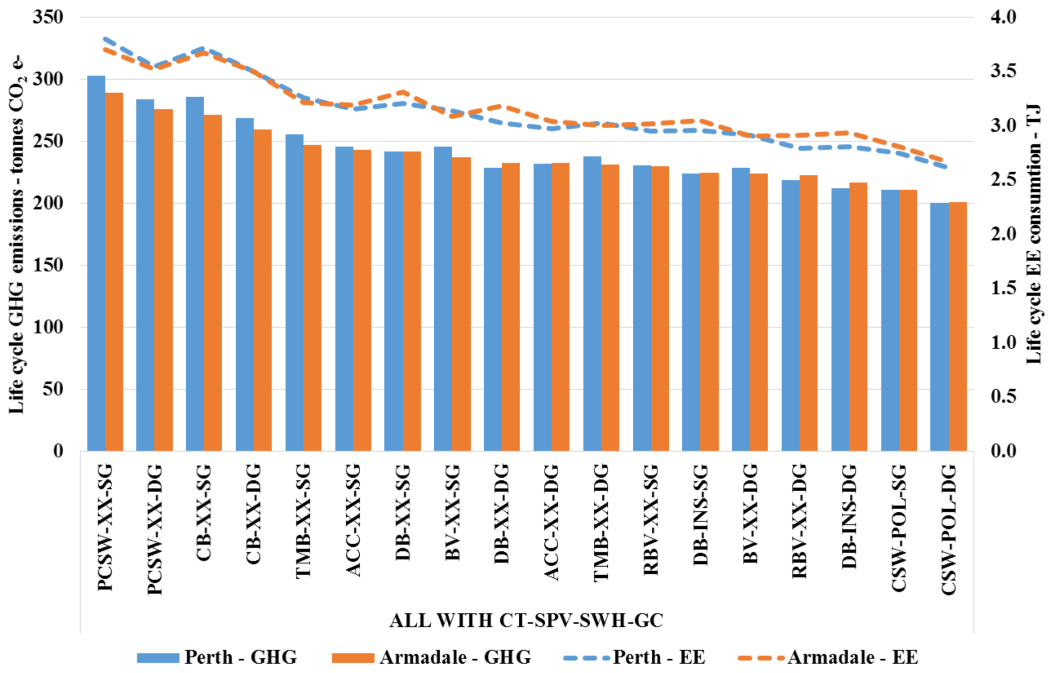


Figure 6.9 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Armadale and Perth

Broome

Broome and Perth are under distinctively different climate and NatHERS zones, which is the reason for a more than tenfold increase in the operational energy requirement for cooling in Broome, while the operational energy requirement for heating is nil (Table F.6, Appendix F). There is no reticulated natural gas network in Broome and hence similar to Augusta, the GHG emissions and EE consumption impacts have been estimated for two scenarios (i.e. the use of bottled gas or electricity for hot water).

In the case of use of bottled gas for hot water, the CPS option BV-XX-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (626.7tonnes CO_2 e- and 10.3TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (838.9tonnes CO_2 e- and 14TJ respectively). As compared to Perth, it has been found that the GHG emissions and EE consumption impacts for all CPS options have increased by up to 200%, and 300% respectively (Figure 6.10).

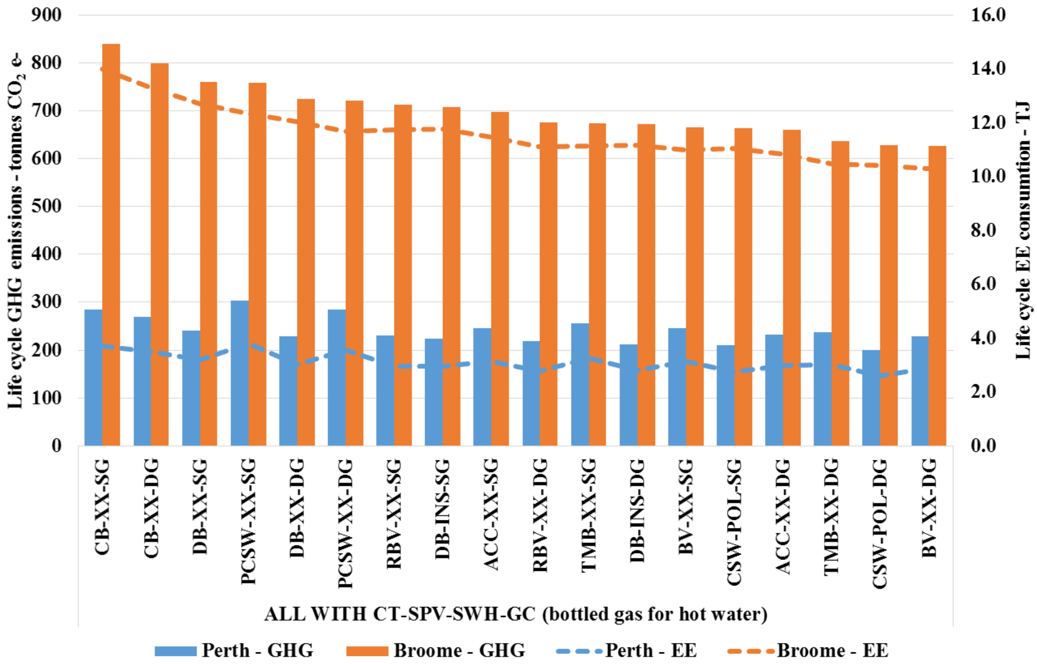


Figure 6.10 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Broome and Perth (bottled gas for hot water)

Similarly, in the case of use of electricity for hot water, the CPS option BV-XX-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (710tonnes CO_2 e- and 11.8TJ respectively). On the other hand, the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (922.2tonnes CO_2 e- and 15.5TJ respectively). This shows an increase of impacts by more than 10% of that associated with the use of bottled gas. Unlike Augusta, where the increase of the impacts was by more than 100% due to the change in use of bottled gas to grid electricity, the electricity generation in Broome is gas based and therefore the difference in impacts is quite low. As compared to Perth, GHG emissions and EE consumption impacts for all CPS options have been increased by up to 250%, and 350% respectively (Figure 6.11).

The rankings of almost all the CPS options in Broome have changed. The CPS option BV-XX-DG-CT-SPV-SWH-GC has moved to the first position by moving the CPS option CSW-POL-DG-SPV-SWH-GC to the second position for both scenarios (i.e. the use of bottled gas or electricity for hot water) in Broome (Table F.21 and Table

F.22, Appendix F). The reason for this change in the rankings of various CPS options is due to the fact that the Broome falls under minimal diurnal temperature range and the influence of the insulation on the energy consumption of a building is very low (Guan 2012), and so a house layout having high energy performance in another climate zone may not perform in the same manner in this climate zone. Other studies also have confirmed that a house layout which may be highly energy efficient in other climate zones may not be equally effective in hot humid summer and warm winter climate and other design approaches such as night-time ventilation, and the change in floor plan should also be considered for the reduction of operational energy for cooling (Kubota, Chyee and Ahmad 2009; Horne and Hayles 2008; Li, Yang and Lam 2013; Reardon and Clarke 2013).

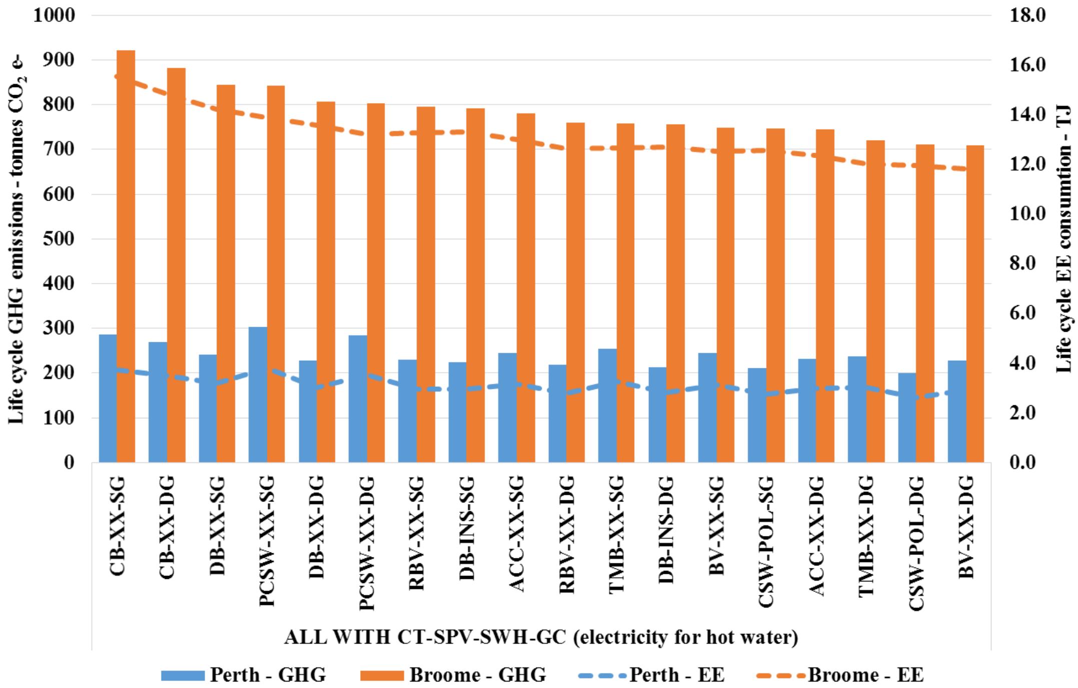


Figure 6.11 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Broome and Perth (electricity for hot water)

Generally, the overall GHG emissions and EE consumption impacts of a typical house in Broome for all CPS options have been found to be more than the Perth.

Bunbury

Both Bunbury and Perth belong to same climate zone 5 but they are in different NatHERS zones. As compared to Perth, there is a minor variation in operational energy requirement for heating and cooling in Bunbury (Table F.7, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (201.1tonnes CO_2 e- and 2.6TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (288tonnes CO_2 e- and 3.6TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-DG-CT-SPV-SWH-GC, RBV-XX-DG-CT-SPV-SWH-GC, DB-XX-DG-SPV-SWH-GC, and CSW-POL-DG-CT-SPV-SWH-GC are almost same, while these impacts have slightly reduced for less energy efficient options such as PCSW-XX-SG/DG-SPV-SWH-GC, TMB-XX-SG/DG-CT-SPV-SWH-GC, and CB-XX-SG/DG-SPV-SWH-GC (Figure 6.12).

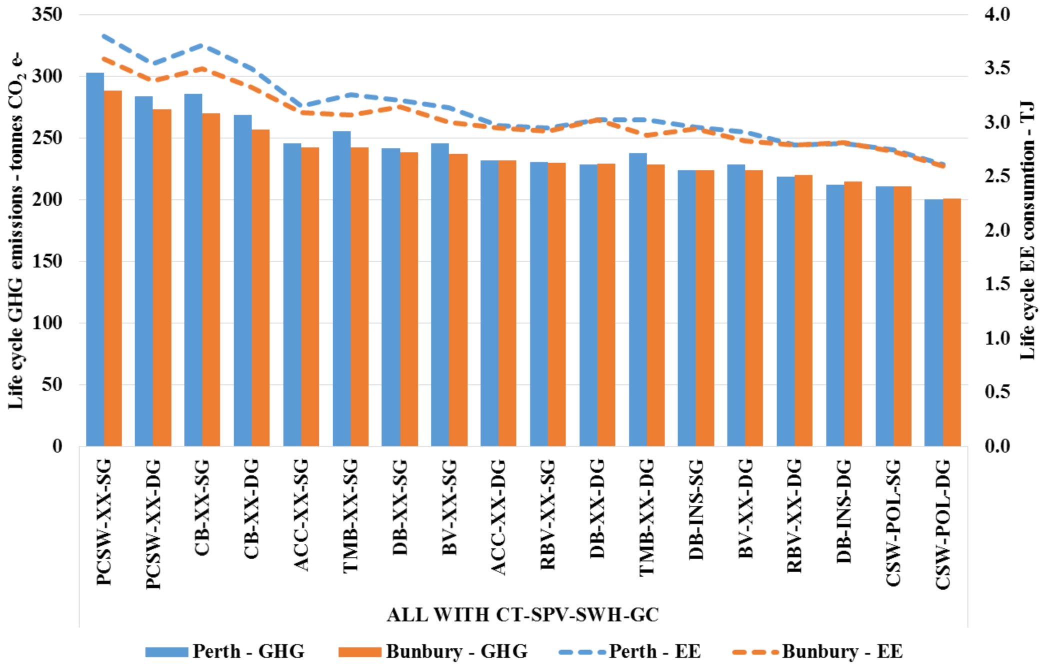


Figure 6.12 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Bunbury and Perth

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC in Bunbury have been found to be the same as Perth (i.e. ranked first and second), while the rankings of some of the remaining options have changed slightly (Table F.23, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Bunbury for all cleaner production options (CPS) have been found to be similar to Perth.

Busselton

Busselton and Perth both are in the same climate zone 5 but they are in different NatHERS zones. As compared to Perth, there is a significant increase in operational energy requirement for heating, while the cooling energy demand has moderately reduced in Busselton (Table F.7, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (211.8tonnes CO_2 e- and 2.9TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (301.2tonnes CO_2 e- and 3.9TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-SG/DG-CT-SPV-SWH-GC, RBV-XX-SG/DG-CT-SPV-SWH-GC, and DB-XX-SG/DG-SPV-SWH-GC have increased by up to 9%, and 15% respectively, these impacts for less energy efficient options such as PCSW-XX-SG/DG-SPV-SWH-GC, TMB-XX-SG/DG-CT-SPV-SWH-GC, and CB-XX-SG/DG-SPV-SWH-GC are same as in Perth (Figure 6.13). Although the increase in operational energy requirement for heating is much more than the reduction in operational energy for cooling, the use of natural gas for heating has conserved the overall GHG emissions and EE consumption impacts.

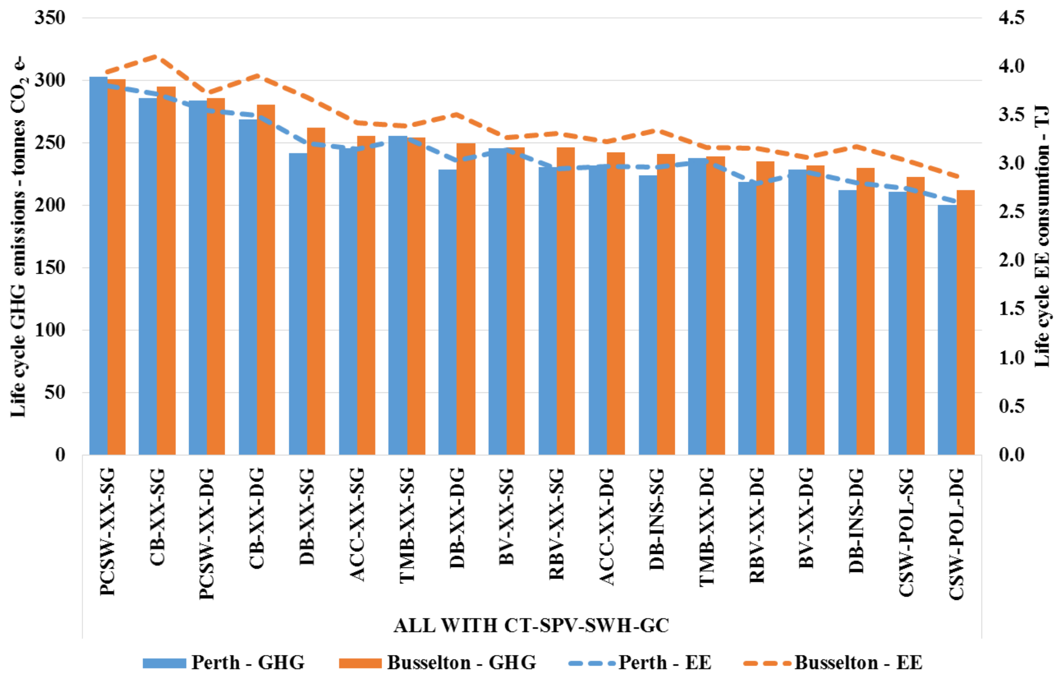


Figure 6.13 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Busselton and Perth

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC in Busselton are same as in Perth (i.e. ranked as first and second), while the rankings of the remaining options have slightly changed (Table F.24, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Busselton for CPS options have been found to be slightly higher than that in Perth.

Carnarvon

Carnarvon and Perth are under two different climate and NatHERS zones. In comparison with Perth, there is an increase in the operational energy requirement for cooling by more than double, but the operational energy requirement for heating is almost nil (Table F.8, Appendix F). There is no reticulated natural gas network in Carnarvon and hence the GHG emissions and EE consumption impacts have been estimated for two scenarios (i.e. the use of bottled gas or electricity for heating and hot water).

In the case of use of bottled gas for heating and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (209.7tonnes CO_2 e- and 3.1TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (272.6tonnes CO_2 e- and 3.3TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for CPS options such as DB-INS-SG/DG-CT-SPV-SWH-GC, and RBV-XX-DG-CT-SPV-SWH-GC have increased by up to 6%, and 20% respectively, these impacts for less energy efficient options such as PCSW-XX-SG-SPV-SWH-GC, and TMB-XX-SG/DG-CT-SPV-SWH-GC have reduced by up to 12%, and 2.5% respectively) (Figure 6.14). Although there is a two fold increase of the operational energy requirement for cooling in Carnarvon, the GHG emissions and EE consumption results are not proportional to increase of cooling energy. This is because the electricity generation in Carnarvon is gas based.

Similarly, in the case of use of electricity for heating and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (293tonnes CO_2 e- and 4.7TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (357.7tonnes CO_2 e- and 5.5TJ respectively).

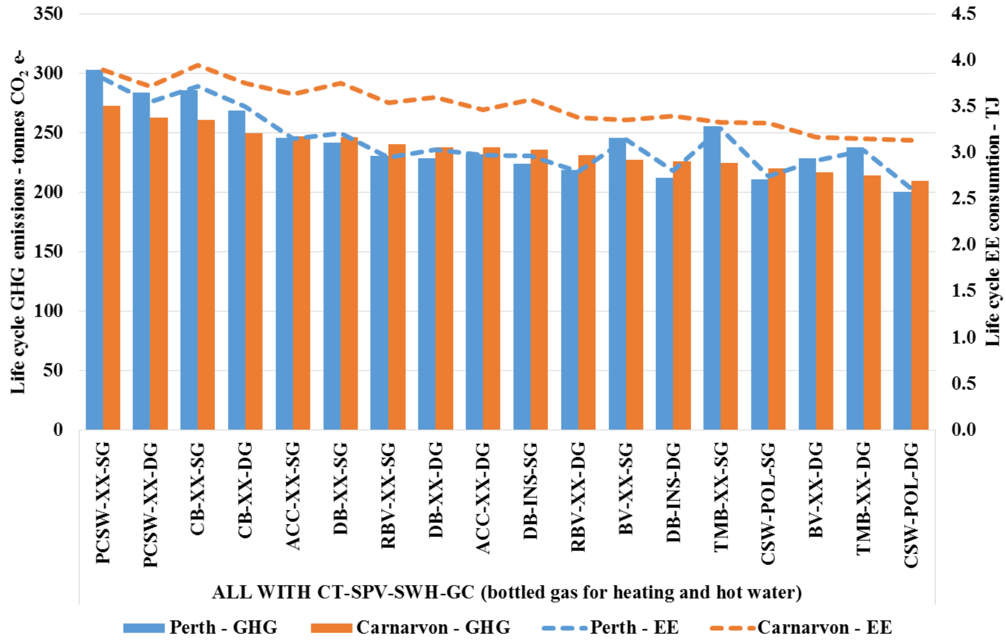


Figure 6.14 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Carnarvon and Perth (bottled gas for heating and hot water)

This shows an increase of GHG emissions and EE consumption impacts by more than 30% of that associated with the use of LPG. As compared to Perth, GHG emissions and EE consumption impacts for all CPS options have increased significantly by up to 40%, and 80% respectively (Figure 6.15).

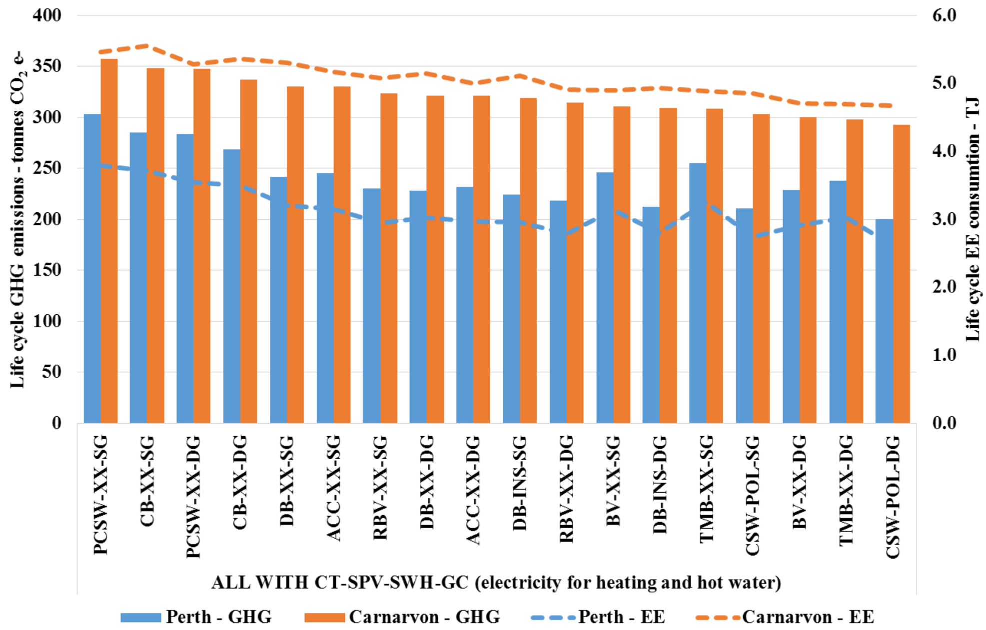


Figure 6.15 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Carnarvon and Perth (electricity for heating and hot water)

In comparison to Perth, the rankings of almost all CPS options except CSW-POL-DG-SPV-SWH-GC (i.e. ranked first) have changed in Carnarvon. The CPS option TMB-XX-DG-CT-SPV-SWH-GC has moved from the tenth position to the second position, while rankings of all the remaining options have slightly changed (Table F.25 and Table F.26, Appendix F).

The reason for this change in the rankings of various CPS option is due to the fact that Carnarvon falls under significant diurnal temperature range and a house with well insulated thermal mass provides an optimum performance. Generally, the overall GHG emissions and EE consumption impacts of a typical house in Carnarvon for all CPS options have been found to be similar to Perth for the use of bottled gas for heating and hot water. In the case of the use of electricity for heating and hot water, the GHG emissions and EE consumption impacts for all CPS options have been found to be more than that of the Perth.

Esperance

Both Esperance and Perth are under same climate zone 5 but they are in different NatHERS zones. As compared to Perth, the operational energy demand for heating has almost doubled in Esperance, the operational energy requirement for cooling has reduced to almost half (Table F.8, Appendix F). There is no reticulated natural gas network in Esperance and hence the GHG emissions and EE consumption impacts have been estimated for two scenarios (i.e. the use of bottled gas or electricity for heating and hot water).

In the case of use of bottled gas for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (232.9tonnes CO_2 e- and 3.2TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (302.6tonnes CO_2 e- and 4.0TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-DG-CT-SPV-SWH-GC, RBV-XX-DG-CT-SPV-SWH-GC, and CSW-POL-DG-CT-SPV-SWH-GC have increased by up to 16%, and 20% respectively. This is because, in winters, the insulation becomes counterproductive. On the other hand these impacts for less energy efficient options such as PCSW-XX-SG-SPV-SWH-GC, TMB-XX-SG-CT-

SPV-SWH-GC and CB-XX-SG-CT-SPV-SWH-GC have been found to be quite similar as Perth (Figure 6.16).

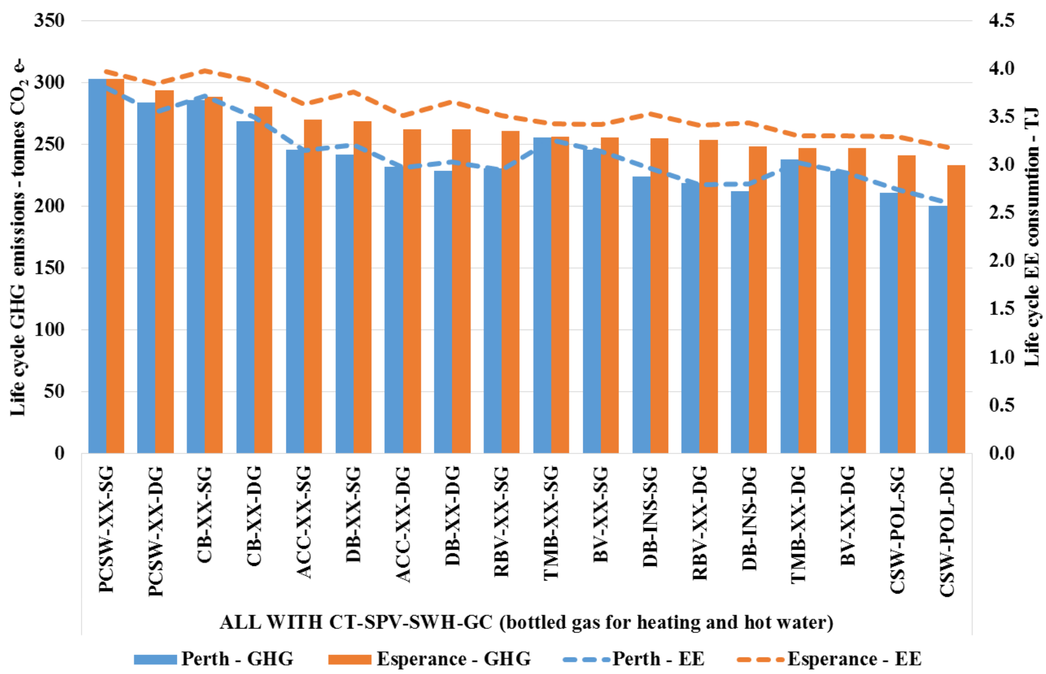


Figure 6.16 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Esperance and Perth (bottled gas for heating and hot water)

In the case of use of electricity for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (445.2tonnes CO_2 e- and 5.8TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (607.8tonnes CO_2 e- and 7.8TJ respectively). This shows an increase of impacts by more than 90% of that associated with the use of bottled gas. As compared to Perth, the GHG emissions and EE consumption impacts for CPS options such as DB-XX-SG/DG-SPV-SWH-GC, DB-INS-DG-CT-SPV-SWH-GC, and CSW-POL-DG-CT-SPV-SWH-GC have increased by more than 120% each. On the other hand, the GHG emissions and EE consumption impacts for options such as PCSW-XX-SG/DG-SPV-SWH-GC, TMB-XX-SG-CT-SPV-SWH-GC, and BV-XX-SG-CT-SPV-SWH-GC also have increased by up to 90% each (Figure 6.17).

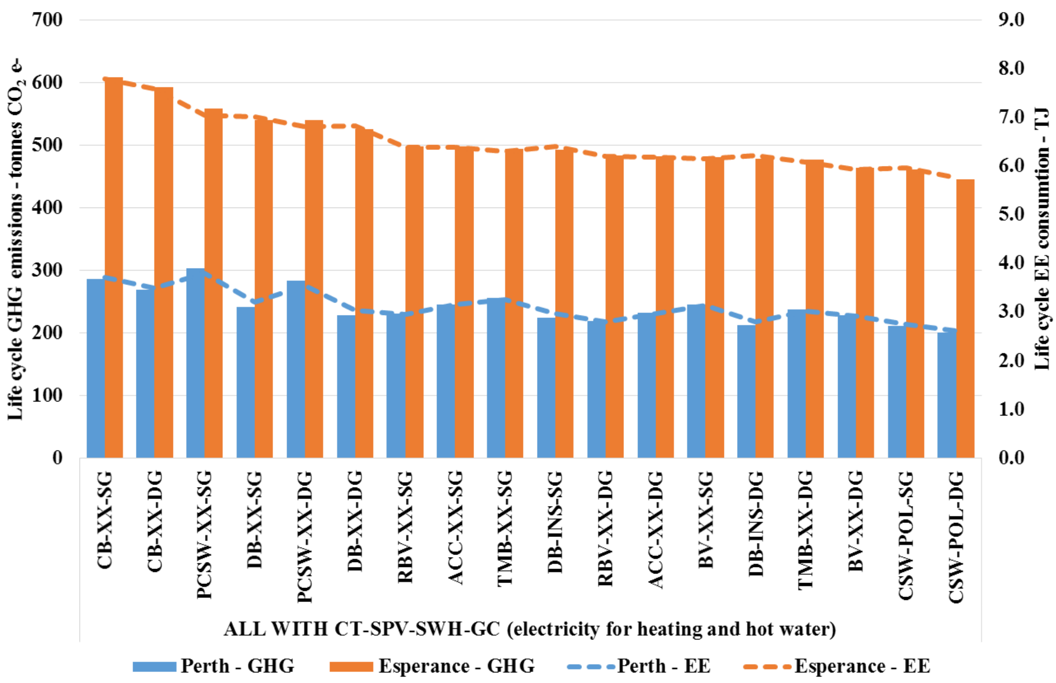


Figure 6.17 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Esperance and Perth (electricity for heating and hot water)

The ranking of CPS options CSW-POL-SG/DG-SPV-SWH-GC in Esperance for both scenarios (i.e. the use of bottled gas or electricity for heating and hot water) remain unchanged (i.e. first and second), while the rankings of other options have changed (Table F.27 and Table F.28, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Esperance for all CPS options have been found to be slightly more than the Perth for the use of bottled gas for heating and hot water. In the case of the use of electricity for heating and hot water, the GHG emissions and EE consumption impacts for all CPS options have been found to be much more than that of the Perth.

Geraldton

Geraldton and Perth both are under same climate zone 5 but they are in different NatHERS zones. As compared to Perth, there is a moderate increase in operational energy demand for cooling and a significant reduction in operational energy demand for heating in Geraldton (Table F.9, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has been found to have the lowest life cycle GHG emissions and EE consumption (208.9tonnes CO_2 e- and 2.7TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption

(306.6tonnes CO_2 e- and 3.8TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for CPS options such as CSW-POL-SG-CT-SPV-SWH-GC, DB-INS-SG-CT-SPV-SWH-GC, RBV-XX-SG-CT-SPV-SWH-GC, and ACC-XX-SG-SPV-SWH-GC have been found to increase by up to 6%, and 4% respectively, while these impacts have slightly reduced for low energy efficient options such as CB-XX-SG/DG-SPV-SWH-GC (Figure 6.18). There is a minor increase in the GHG emissions and EE consumption impacts for remaining CPS options. Whilst the reduction in operational energy demand for heating is more than the increase in operational energy demand for cooling, but because the electricity for cooling has higher GHG emissions than the natural gas for heating, the overall increase in GHG emissions and EE consumption impacts is low.

The ranking of CPS option CSW-POL-DG-SPV-SWH-GC in Geraldton has been found to be same as Perth (i.e. the first), while the rankings of some of the remaining options have changed slightly by position up or down (Table F.29, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Geraldton for CPS options have been found to be slightly more than the Perth.

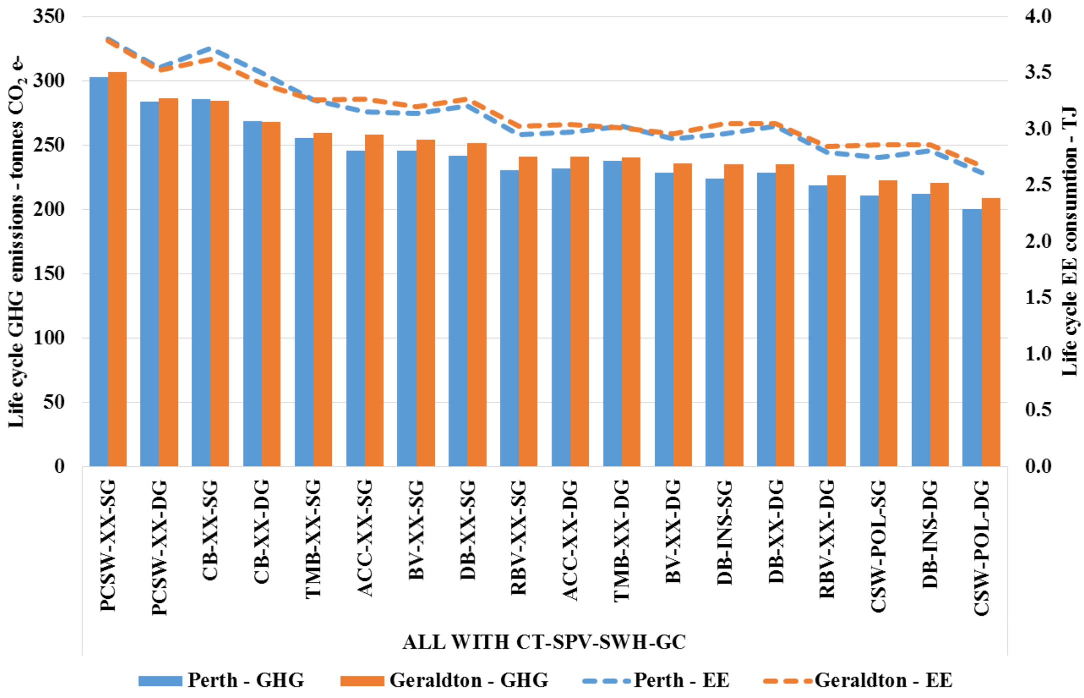


Figure 6.18 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Geraldton and Perth

Joondalup

Joondalup and Perth both are in same climate zone 5 but they are in different NatHERS zones. As compared to Perth, there is a slight reduction in operational energy demand for both heating and cooling in Joondalup (Table F.9, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (185.9tonnes CO_2 e- and 2.4TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (255.7tonnes CO_2 e- and 3.1TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-DG-CT-SPV-SWH-GC, RBV-XX-DG-CT-SPV-SWH-GC, CSW-POL-DG-CT-SPV-SWH-GC, and ACC-XX-DG-SPV-SWH-GC have reduced moderately. On the other hand, there is a significant reduction in these impacts by up to 19%, and 20% respectively for less energy efficient options such as CB-XX-SG/DG-SPV-SWH-GC, PCSW-XX-SG/DG-SPV-SWH-GC, and TMB-XX-SG/DG-CT-SPV-SWH-GC. This is because of the fact that the composite thermal mass of these envelope options allows the quicker dissipation of heat (Figure 6.19) (Reardon, McGee and Milne 2013; Zhu et al. 2009).

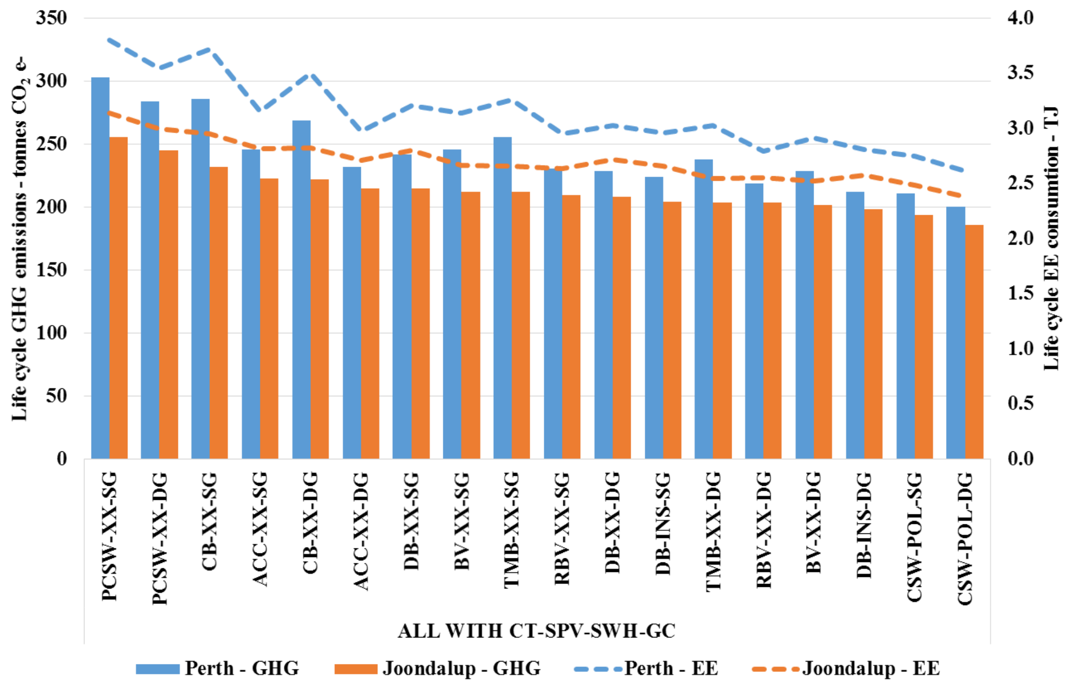


Figure 6.19 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Joondalup and Perth

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC in Joondalup have been found to be same as in Perth (i.e. first and second), while there is a minor change in the rankings of few of the remaining options (Table F.30, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Joondalup for CPS options have been found to be slightly less than the Perth due to the less operational energy demand for heating and cooling in Joondalup.

Kalgoorlie

Kalgoorlie and Perth are in climate zone 4, and 5 respectively and also they have different NatHERS zones. The climate zone 4 has hot dry summer with cool winters. As compared to Perth, there is a slight reduction in operational energy demand for cooling, while there is a moderate increase in operational energy for heating in Kalgoorlie (Table F.10, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has been found to have the lowest life cycle GHG emissions and EE consumption (190.1tonnes CO_2 e- and 2.5TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has been found to have the highest life cycle GHG emissions and EE consumption (289.5tonnes CO_2 e- and 3.6TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for energy efficient CPS option CSW-POL-DG-CT-SPV-SWH-GC have reduced moderately by 5%, and 6% respectively (Figure 6.20). There is a consistency in the reduction of GHG emissions and EE consumption impacts across the remaining CPS options.

The rankings of CPS options in Kalgoorlie have been found to be the same as Perth (Table F.31, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Kalgoorlie for all CPS options have been found to be slightly less than the Perth due to less operational energy demand for heating and cooling.

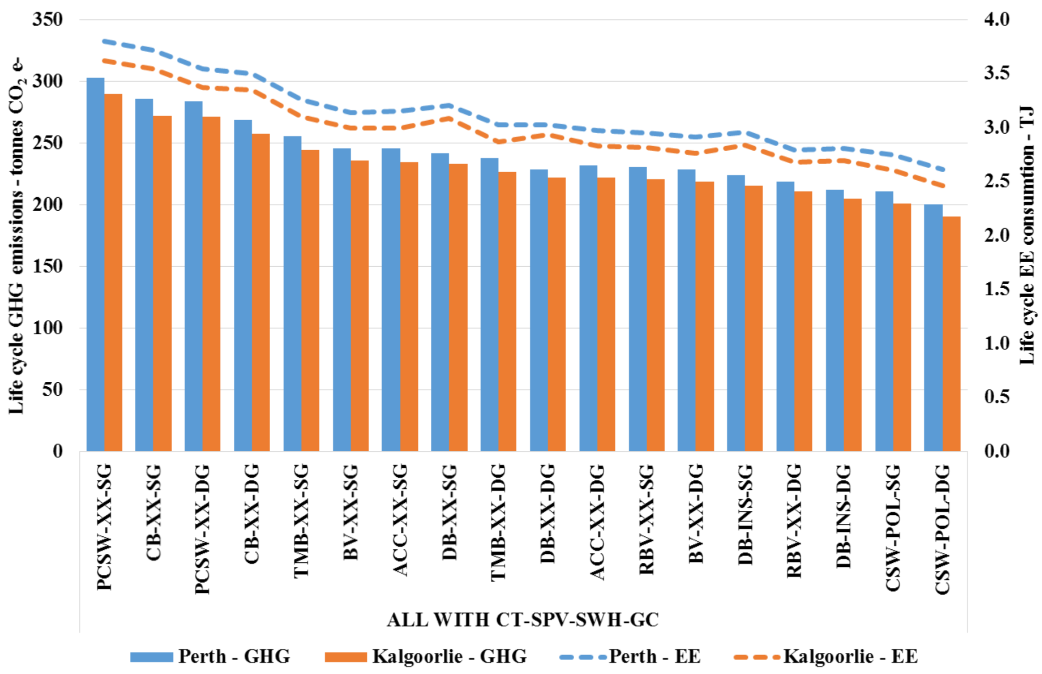


Figure 6.20 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Kalgoorlie and Perth

Kununurra

Kununurra and Perth are in two distinctively different climate and NatHERS zones. As compared to Perth, there is up to fifteen fold increase in the operational energy demand for cooling in Kununurra, while the operational energy demand for heating is nil (Table F.6, Appendix F). There is no reticulated natural gas network in Kununurra and hence the GHG emissions and EE consumption impacts have been estimated for two scenarios (i.e. the use of bottled gas or electricity for hot water).

In the case of use of bottled gas for hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (1412.6tonnes CO_2 e- and 20.7TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (2184tonnes CO_2 e- and 32.0TJ respectively).

The GHG emissions and EE consumption impacts for all CPS options in Kununurra have been found to be up to 670%, and 770% more than that in Perth respectively (Figure 6.21).

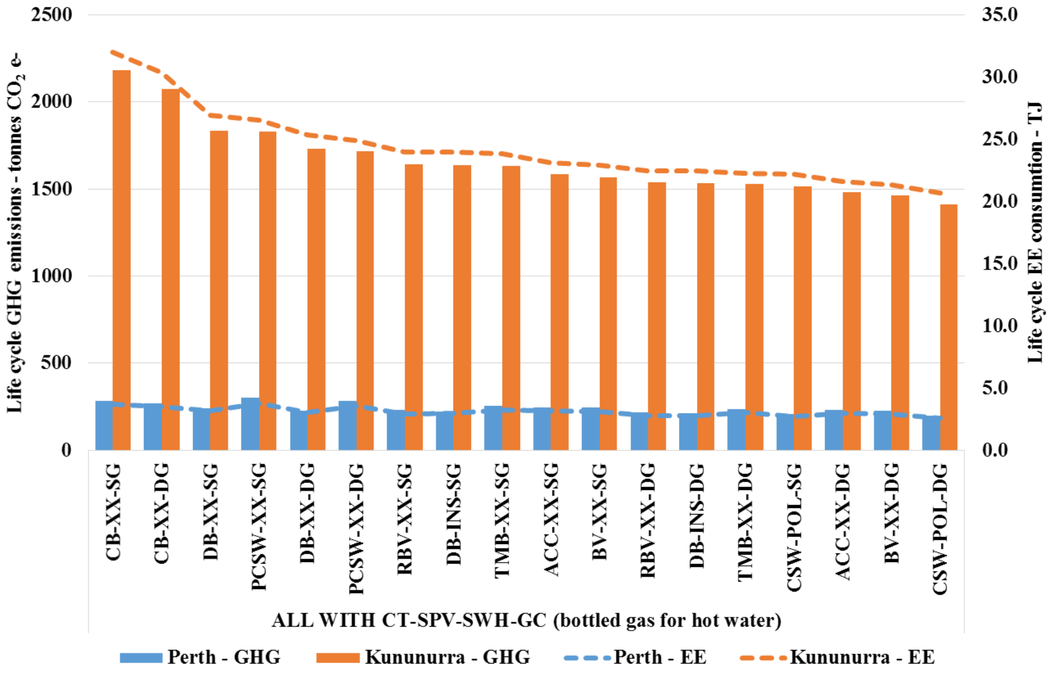


Figure 6.21 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Kununurra and Perth (bottled gas for hot water)

In the case of use of electricity for hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (1567.5tonnes CO_2 e- and 23.0TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (2338.8tonnes CO_2 e- and 34.3TJ respectively). This shows an increase of impacts by more than 10% of that associated with the use of bottled gas. The operational energy demand in Kununurra is already the highest amongst all locations in regional WA, and on top of this factor, the electricity generation is also diesel based, which has the highest GHG emissions intensity as compared to other electricity mix, thus resulting in more GHG emissions and EE consumption.

The GHG emissions and EE consumption impacts for all CPS options have been found to be up to 730%, and 830% more than that in Perth respectively (Figure 6.22).

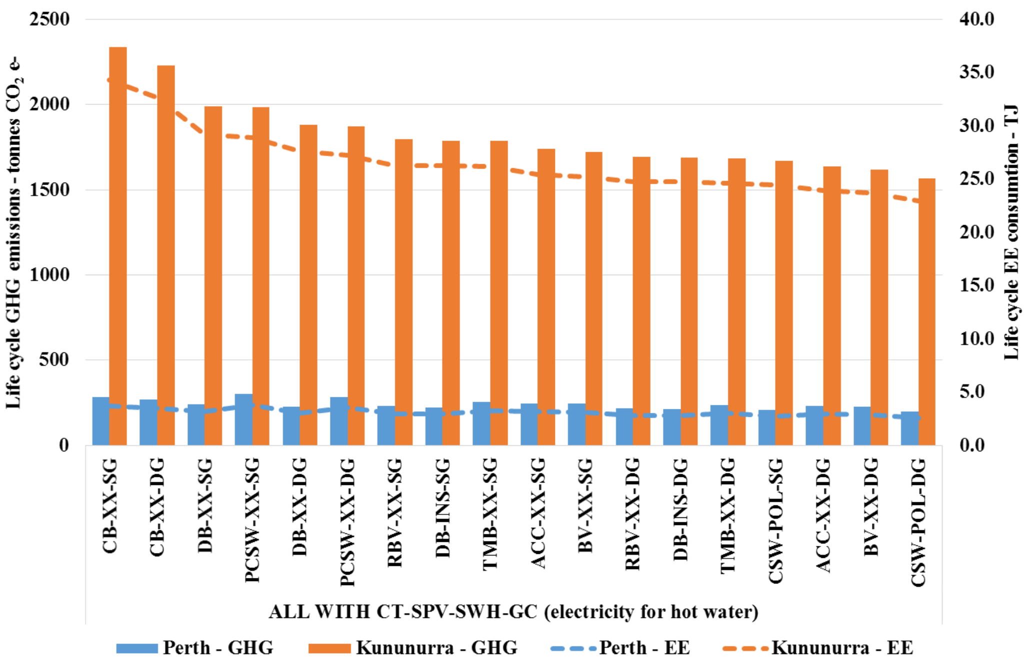


Figure 6.22 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Kununurra and Perth (electricity for hot water)

The rankings of almost all CPS options except CSW-POL-DG-CT-SPV-SWH-GC have changed for both scenarios (i.e. the use of bottled gas or electricity for hot water) in Kununurra (Table F.32 and Table F.33, Appendix F). The CPS options BV-XX-DG-CT-SPV-SWH-GC, and ACC-XX-DG-CT-SPV-SWH-GC have moved from middle order to second and third positions respectively. The reason for this change in the rankings of various CPS option is mainly due to the fact that Kununurra falls under minimal diurnal temperature range and the floor layout, insulation, thermal mass, glazing, and eave projection of a house behaves in a completely different manner than that in the other climate zones (Martel and Horne 2011; Kane et al. 2009; Reardon and Clarke 2013). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Kununurra for CPS options have been found to be substantially more than that in Perth.

Laverton

Laverton and Perth are under different climate and NatHERS zones. As compared to Perth, there is more than threefold increase in the operational energy demand for cooling, while having a threefold reduction in the operational energy demand for heating (Table F.11, Appendix F). There is no reticulated natural gas network in

Laverton and hence the GHG emissions and EE consumption impacts have been estimated for two scenarios (i.e. the use of bottled gas or electricity for heating and hot water).

In the case of use of bottled gas for heating and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (294.8tonnes CO_2 e- and 4.1TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (534.3tonnes CO_2 e- and 7.6TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for all cleaner production options have increased by up to 90%, and 100% respectively (Figure 6.23).

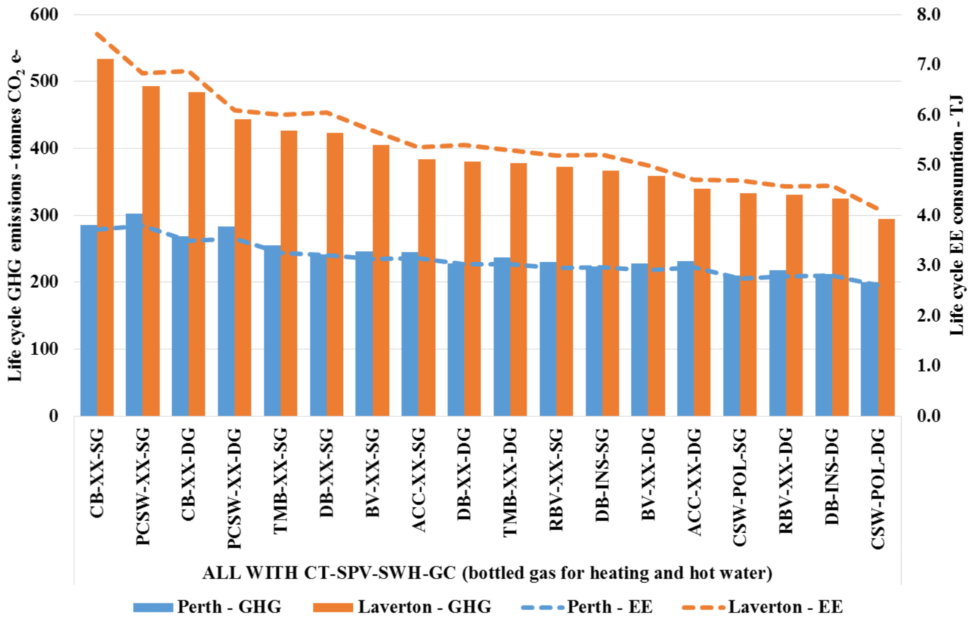


Figure 6.23 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Laverton and Perth (bottled gas for heating and hot water)

Similarly, in the case of use of electricity for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has been found to have the lowest life cycle GHG emissions and EE consumption (465.7tonnes CO_2 e- and 6.7TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (747.2tonnes CO_2 e- and 10.8TJ respectively). This shows an increase of impacts by more than 40% of that associated with the use of bottled gas. Also, the electricity generation in Laverton is diesel based with a high GHG emissions intensity.

As compared to Perth, the GHG emissions and EE consumption impacts for all CPS options have increased by up to 160%, and 190% respectively (Figure 6.24).

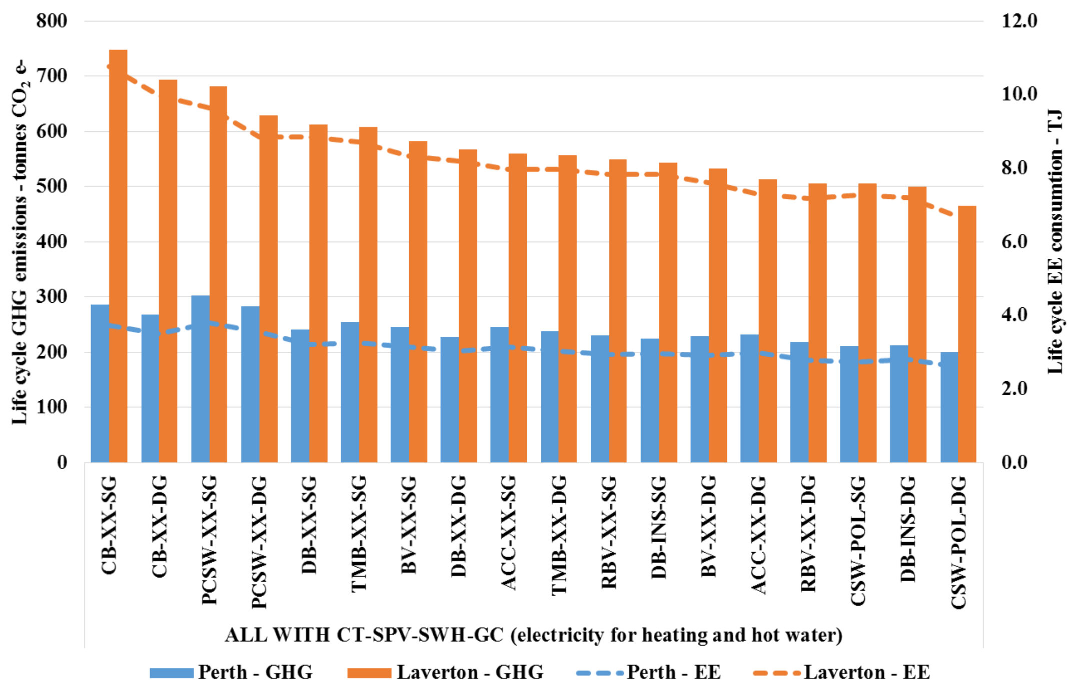


Figure 6.24 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Laverton and Perth (electricity for heating and hot water)

As compared to Perth, there is no change in the ranking of CPS option CSW-POL-DG-SPV-SWH-GC (i.e. first) in Laverton, while the rankings of few of the options have slightly changed (Table F.34 and Table F.35, Appendix F).

Generally, the overall GHG emissions and EE consumption impacts of a typical house in Laverton for CPS options have been found to be much more than the Perth.

Mandurah

Although both Mandurah and Perth are under same climate zone 5 but they are from two different NatHERS zones. As compared to Perth, there is a minor increase in the operational energy demand for heating in Mandurah, while the operational energy demand for cooling is same (Table F.11, Appendix F).

The CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (200.4tonnes CO_2 e- and 2.6TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and

EE consumption (288tonnes CO_2 e- and 3.6TJ respectively). As compared to Perth, there is a minor increase in GHG emissions and EE consumption impacts for CPS options such as DB-INS-DG-CT-SPV-SWH-GC, and RBV-XX-DG-CT-SPV-SWH-GC by up to 1%, and 0.7% respectively. On the other hand, these impacts for less energy efficient options such as PCSW-XX-SG/DG-SPV-SWH-GC, TMB-XX-SG/DG-CT-SPV-SWH-GC, and CB-XX-SG/DG-SPV-SWH-GC have reduced slightly (Figure 6.25).

Due to the use of natural gas for heating, an increase in operational energy for heating does not necessarily mean a sizable increase in GHG emissions and EE consumption impacts.

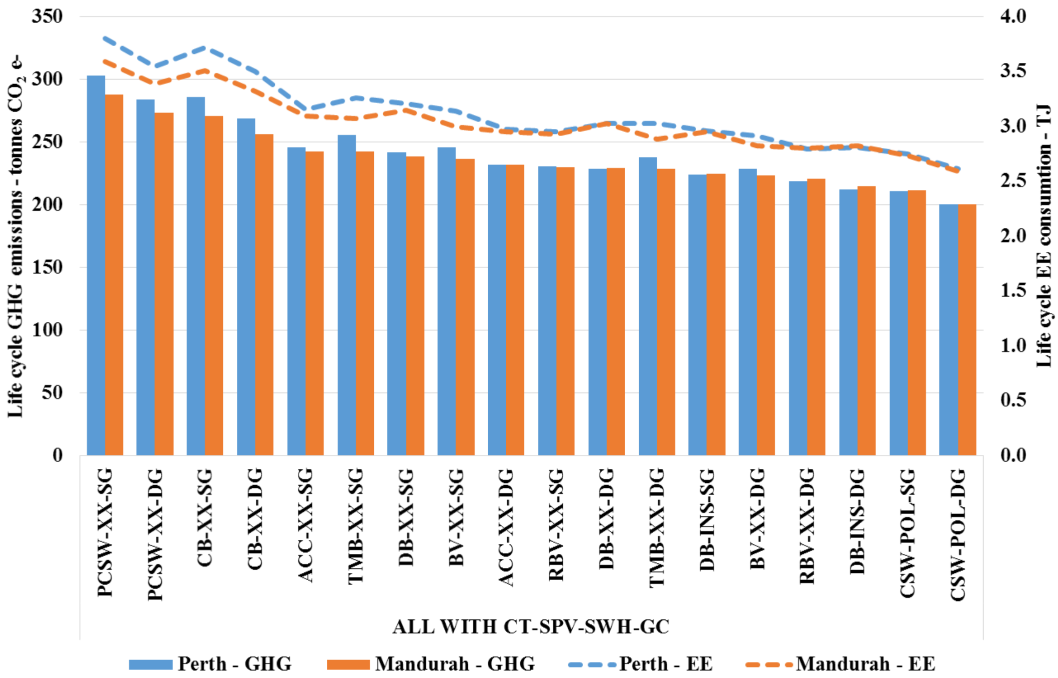


Figure 6.25 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Mandurah and Perth

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC, DB-INS-DG-CT-SPV-SWH-GC, and RBV-XX-DG-CT-SPV-SWH-GC in Mandurah have been found to be same as Perth (i.e. first to fourth), while the rankings of some of the remaining options have changed slightly by one position up or down (Table F.36, Appendix F).

Generally, the overall GHG emissions and EE consumption impacts of a typical house in Mandurah for CPS options have been found to be slightly lower than those in Perth.

Mount Magnet

Mount Magnet and Perth are under distinctively different climate and NatHERS zones. As compared to Perth, there is around twofold increase in the operational energy demand for cooling, while there is up to a sixfold reduction in the operational energy demand for heating (Table F.12, Appendix F). There is no reticulated natural gas network in Mount Magnet and hence the GHG emissions and EE consumption impacts have been estimated for two scenarios (i.e. the use of bottled gas or electricity for heating and hot water).

In the case of use of bottled gas for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (200.3tonnes CO_2 e- and 3.0TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (306.2tonnes CO_2 e- and 4.5TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for all CPS options have increased by up to 7%, and 24% respectively (Figure 6.26).

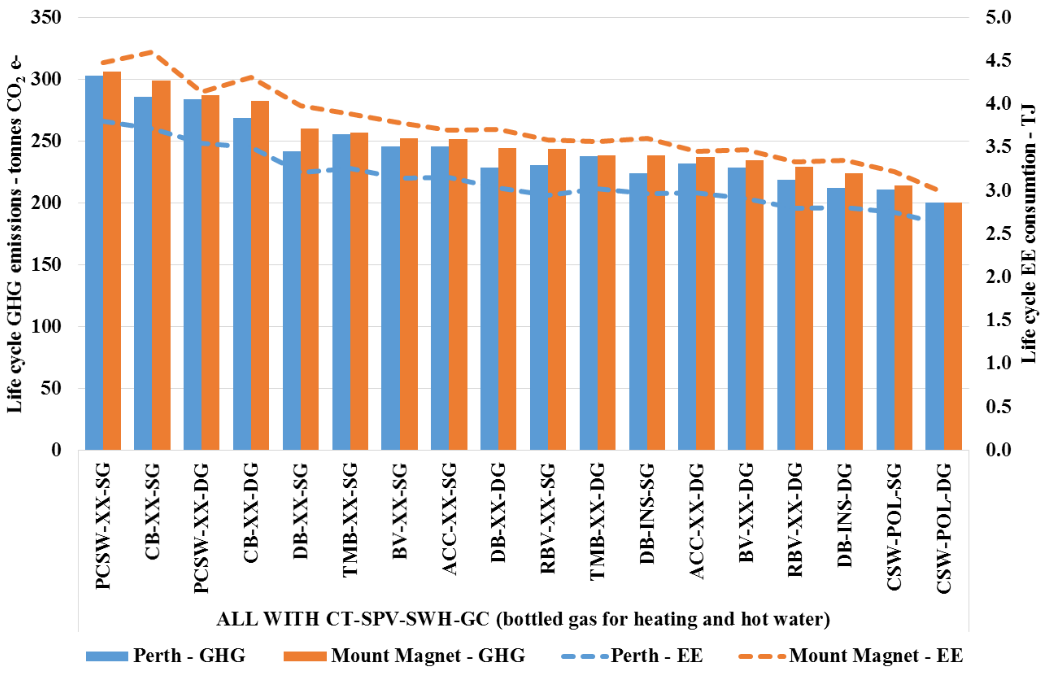


Figure 6.26 Comparison of life cycle GHG emissions and EE consumption of all CPS options between Mount Magnet and Perth (LPG for heating and hot water)

Similarly, in the case of use of electricity for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (407.9tonnes CO_2 e- and 6.5TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (407.9tonnes CO_2 e- and 6.5TJ respectively). This shows an increase of impacts by more than 40% of that associated with the use of bottled gas. As compared to Perth, the GHG emissions and EE consumption impacts for all CPS options have increased by up to 50%, and 80% respectively (Figure 6.27).

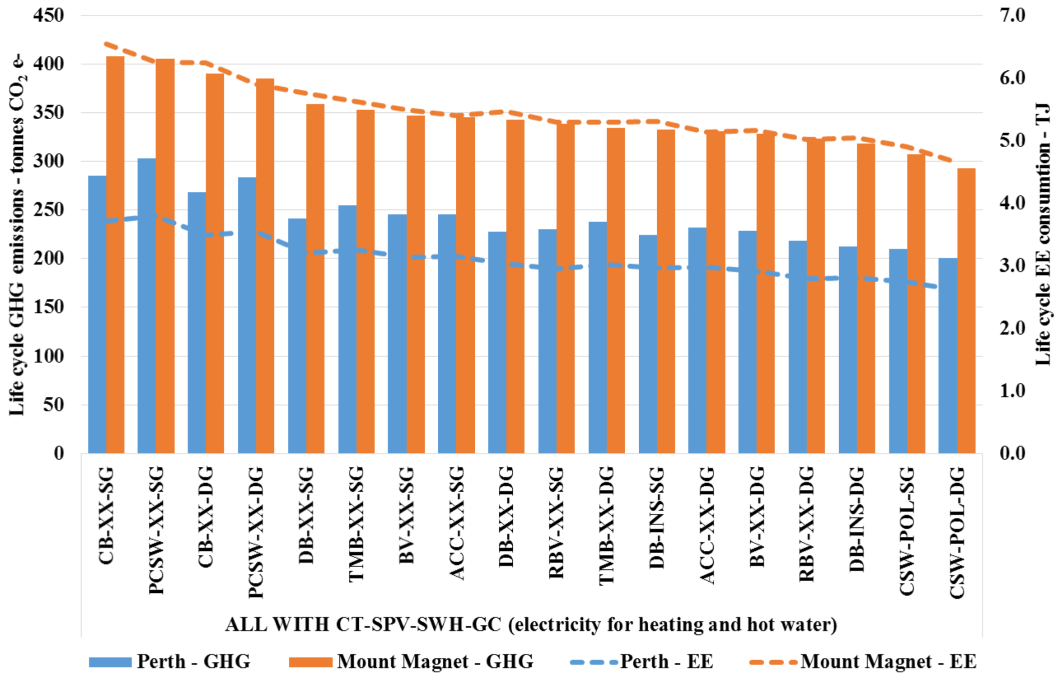


Figure 6.27 Comparison of life cycle GHG emissions and EE consumption of all CPS options between Mount Magnet and Perth (electricity for heating and hot water)

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC, DB-INS-DG-CT-SPV-SWH-GC, and RBV-XX-DG-CT-SPV-SWH-GC in Mount Magnet have been found to be same as Perth (i.e. first to fourth), while the rankings of some middle order options have slightly changed (Table F.34 and Table F.35, Appendix F).

Generally, the overall life cycle GHG emissions and EE consumption impacts of a typical house in Mount Magnet for CPS options have been found to be more than the Perth due to more than twofold increase in the life cycle operational energy demand for cooling.

Newman

Both Newman and Perth are under different climate and NatHERS zones. As compared to Perth, there is more than fivefold increase in the operational energy demand for cooling, while the operational energy demand for heating has drastically reduced to as good as nil for most of the options (Table F.12, Appendix F). There is no reticulated natural gas network in Newman and hence the GHG emissions and EE consumption impacts have been estimated for two scenarios (i.e. the use of bottled gas or electricity for heating and hot water).

In the case of use of bottled gas for heating and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (281.1tonnes CO_2 e- and 4.4TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (471.6tonnes CO_2 e- and 7.6TJ respectively). As compared to Perth, the GHG emissions and EE consumption impacts for all CPS options have increased by up to 65%, and 100% respectively (Figure 6.28).

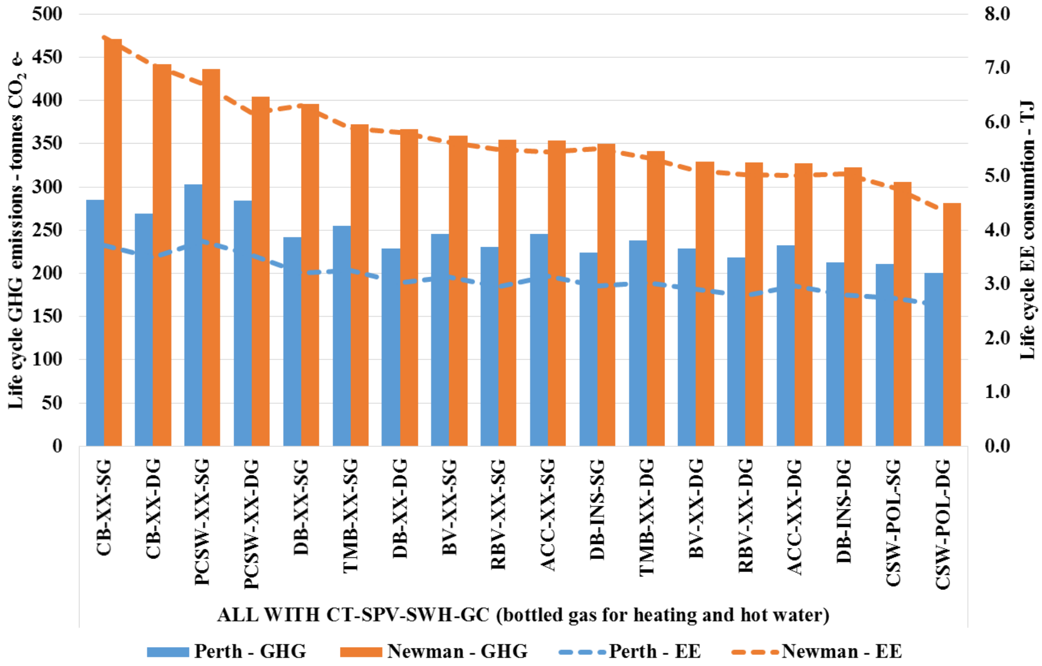


Figure 6.28 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Newman and Perth (bottled gas for heating and hot water)

Similarly, in the case of use of electricity for heating, and hot water, the CPS option CSW-POL-DG-SPV-SWH-GC has the lowest life cycle GHG emissions and EE consumption (364.5tonnes CO_2 e- and 5.9TJ respectively), while the option CB-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (562.5tonnes CO_2 e- and 9.2TJ respectively). This shows an increase of GHG emissions and EE consumption impacts by more than 40% of that associated with the use of bottled gas. As compared to Perth, the GHG emissions and EE consumption impacts for all CPS options have increased by up to 100%, and 145% respectively (Figure 6.29).

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC in Newman have been found to be the same as Perth (i.e. first and second), while the rankings of some of the middle order options have slightly changed (Table F.39 and Table F.40, Appendix F).

Generally, the overall GHG emissions and EE consumption impacts of a typical house in Newman for all CPS options have been found to be much more than the Perth due to more than fivefold demand for operational energy for cooling.

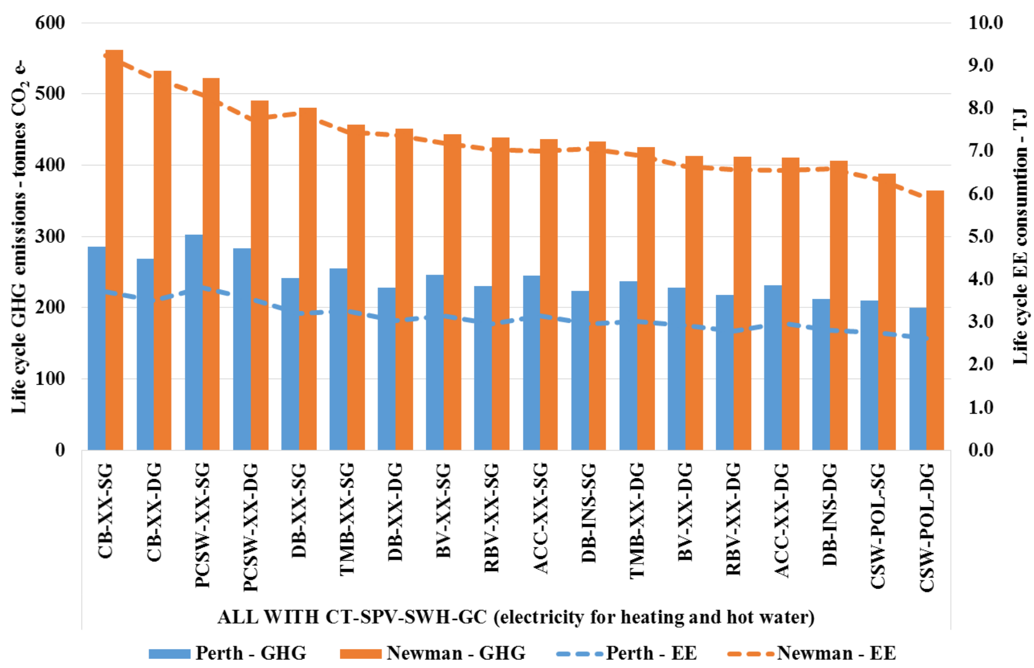


Figure 6.29 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Newman and Perth (electricity for heating and hot water)

Yanchep

Both Yanchep and Perth are under same climate zone 5 but they are in different NatHERS zones. As compared to Perth, there is a moderate reduction in the operational energy demand for both heating and cooling in Yanchep (Table F.13, Appendix F). The CPS option CSW-POL-DG-SPV-SWH-GC has been found to have the lowest life cycle GHG emissions and EE consumption (185.9tonnes CO_2 e- and 2.4TJ respectively), while the option PCSW-XX-SG-SPV-SWH-GC has the highest life cycle GHG emissions and EE consumption (255.7tonnes CO_2 e- and 3.1TJ respectively). As compared to Perth, The GHG emissions and EE consumption impacts for energy efficient CPS options such as DB-INS-DG-CT-SPV-SWH-GC, RBV-XX-DG-CT-SPV-SWH-GC, CSW-POL-DG-CT-SPV-SWH-GC, and ACC-XX-DG-SPV-SWH-GC have reduced moderately. On the other hand, these impacts for less energy efficient options such as CB-XX-SG/DG-SPV-SWH-GC, PCSW-XX-SG/DG-SPV-SWH-GC, and TMB-XX-SG/DG-CT-SPV-SWH-GC have reduced by up to 19%, and 20% respectively because of their relatively lower thermal mass, which allows quicker dissipation of heat (Figure 6.30) (Zhu et al. 2009; Reardon, McGee and Milne 2013).

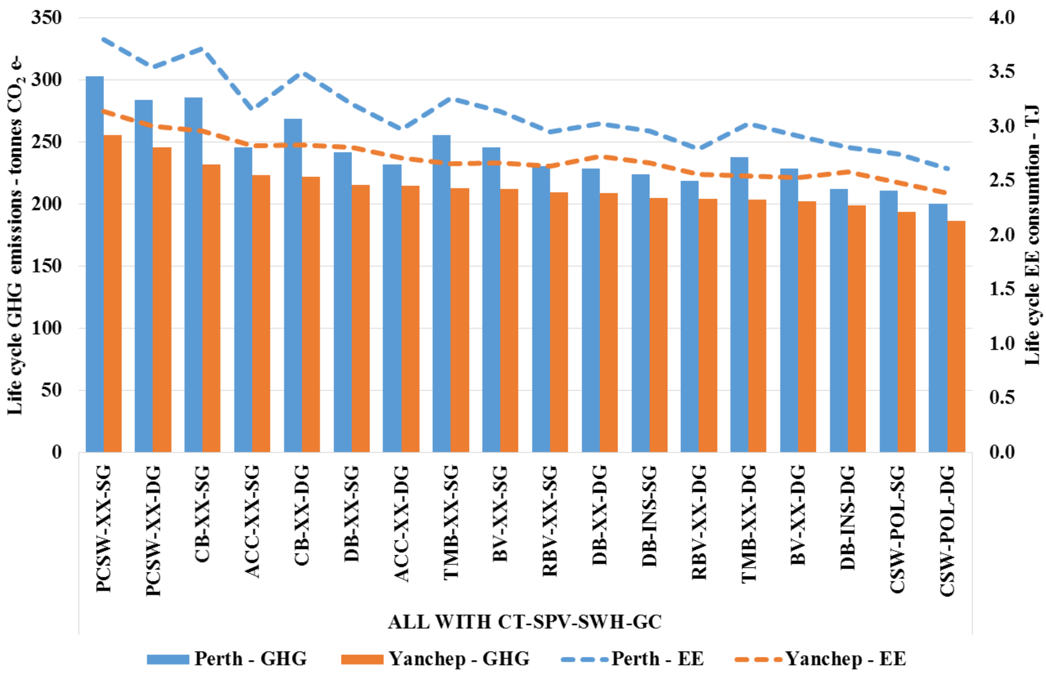


Figure 6.30 Comparison of life cycle GHG emissions and EE consumption results of all CPS options between Yanchep and Perth

The rankings of CPS options CSW-POL-SG/DG-SPV-SWH-GC in Yanchep have been found to be same as Perth (i.e. first and second), while the rankings of most of the remaining options have slightly changed (Table F.41, Appendix F). Generally, the overall GHG emissions and EE consumption impacts of a typical house in Yanchep for all CPS options have been found to be less than the Perth.

6.4.2 Summary of Life cycle GHG emissions and EE consumption impacts

The location wise GHG emissions and EE consumption results of alternative CPS options have been summarized to identify the options with consistent performance across 17 locations in regional WA.

GHG emissions results

The results of life cycle GHG emissions of a reference house for alternative CPS options in 17 locations in regional WA have been summarized and presented in Table F.42 (Appendix F). The life cycle GHG emissions results of alternative CPS options in 17 locations in regional WA have been grouped based on their respective climate zones (Figure 6.31) and it has been found that the life cycle GHG emissions of a reference house for alternative CPS options are the highest in climate zone 1 (hot humid summer, warm winter) (i.e. Kununurra and Broome) with a high degree of variation, which is not the case in other zones and this shows that each option behaves entirely in a different manner.

In the case of climate zone 3 (Hot dry summer, warm winter), the life cycle GHG emissions for alternative CPS options are high in Newman with a medium degree of variation, while the life cycle GHG emissions in Carnarvon are similar to Perth with a low degree of variation.

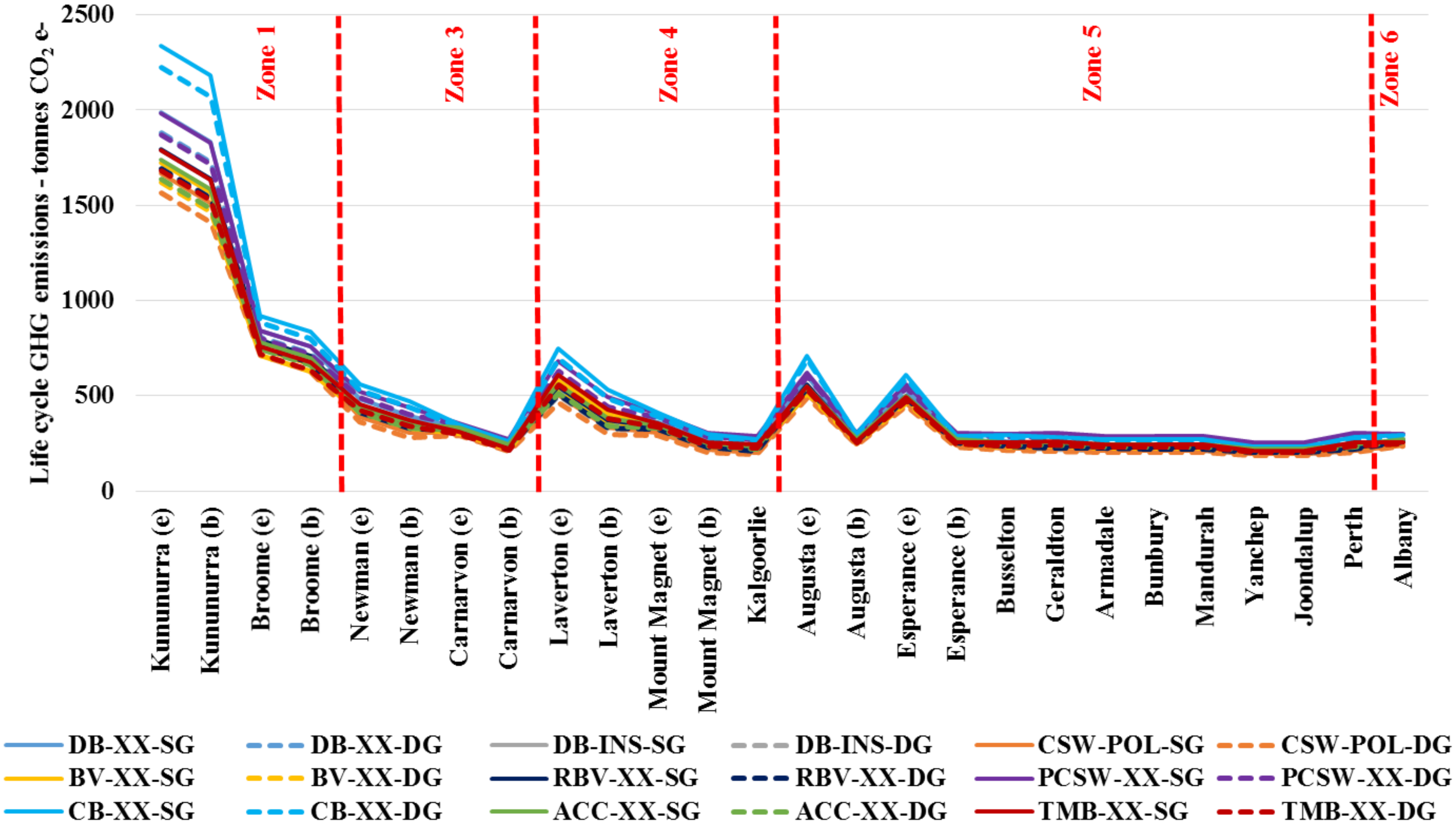
For climate zone 4 (Hot dry summer, cool winter), the life cycle GHG emissions for alternative CPS options are high in Laverton with a medium degree of variation, while the life cycle GHG emissions in Mount Magnet and Kalgoorlie are quite similar to Perth.

For climate zone 5 (Warm temperate), the life cycle GHG emissions for alternative CPS options are high in Augusta and Esperance with a moderate degree of variation, while the life cycle GHG emissions in Busselton, Geraldton, Armadale, Bunbury, Mandurah, Yanchep, and Joondalup are similar to Perth with a very low degree of variation. The low variation shows that the absolute values of life cycle GHG emissions are different but there is a consistency in the overall performance of all CPS options across these locations.

For climate zone 6 (Mild temperate), the life cycle GHG emissions for alternative CPS options in Albany are similar to Perth with a low degree of variation.

As compared to Perth, the main reason for this variation in life cycle GHG emissions for alternative CPS options across these locations is due to the variation in GHG emissions associated with the operational energy for heating, cooling, and hot water for the house for alternative cleaner production options (Figure 6.32).

The location specific solar radiation plays an important role in operational energy demand for heating and cooling as well as in electricity or heat generation by solar PV and solar water heater. The source of electricity (SWIS network, gas based, diesel based) and gas (natural gas, bottled liquefied petroleum gas) are another factors responsible for this variation as they have different emission intensities (Table F.16, Appendix F). A significant change in GHG emissions has been observed when the use of grid electricity is considered for heating and hot water instead of bottled gas in Augusta, Broome, Carnarvon, Esperance, Kununurra, Laverton, Mount Magnet, and Newman.



Note: (b) - use of bottled gas for heating and hot water, (e) - use of electricity for heating and hot water, All options are with CT-SPV-SWH-GC

Figure 6.31 Life cycle GHG emissions of a reference house for alternative CPS options in all climate zones in WA

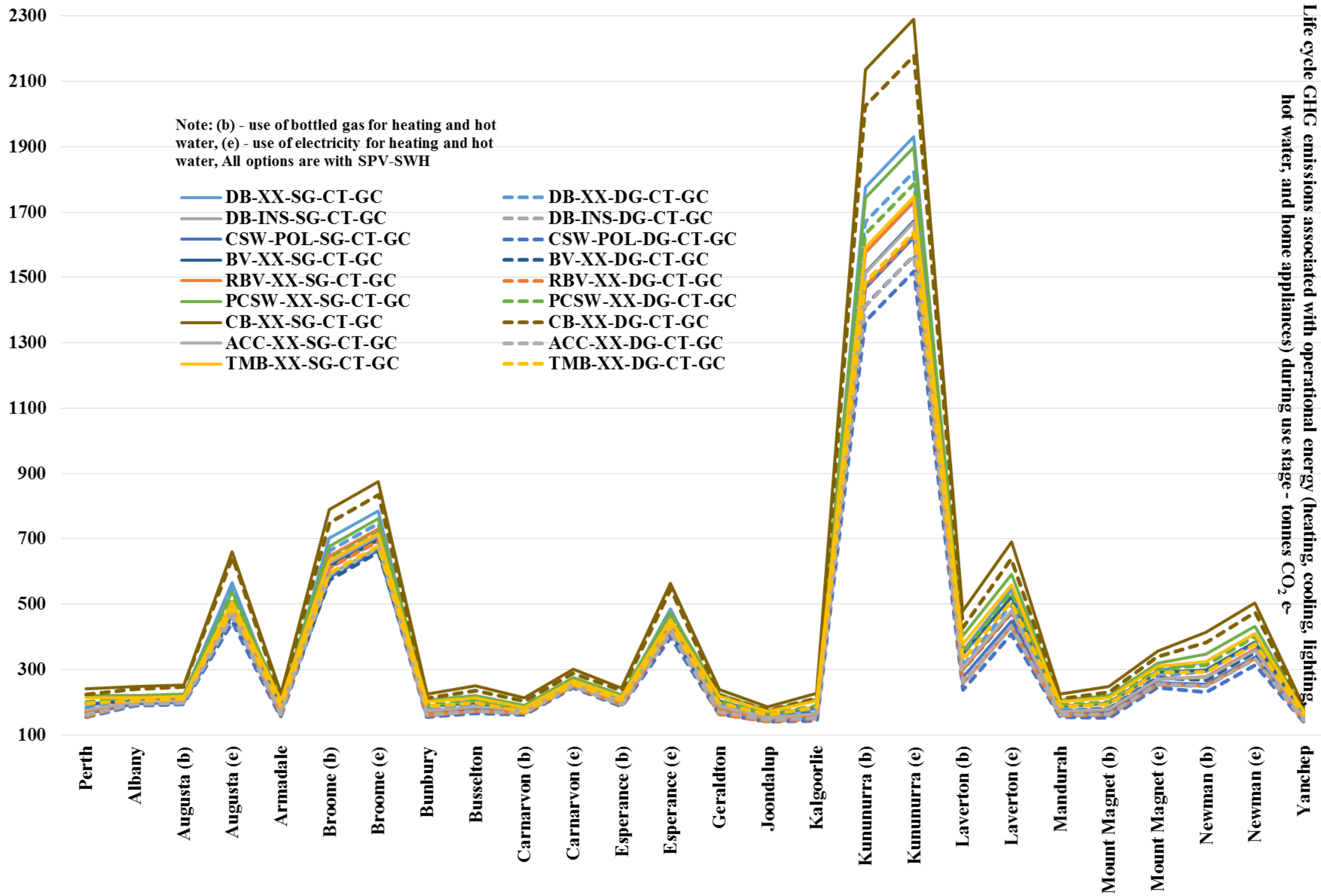


Figure 6.32 Life cycle GHG emissions of a reference house during use stage for alternative CPS options in all locations in regional WA

The GHG emissions associated with the mining to material production, transportation, construction, and the end of life demolition and disposal stages of a reference house for all CPS options in 17 locations in regional WA have been found to vary (Section 6.3, Table F.14, and Table F.15) mainly due to the additional transportation requirement for some of the materials which are not available in remote locations (Figure 6.35).

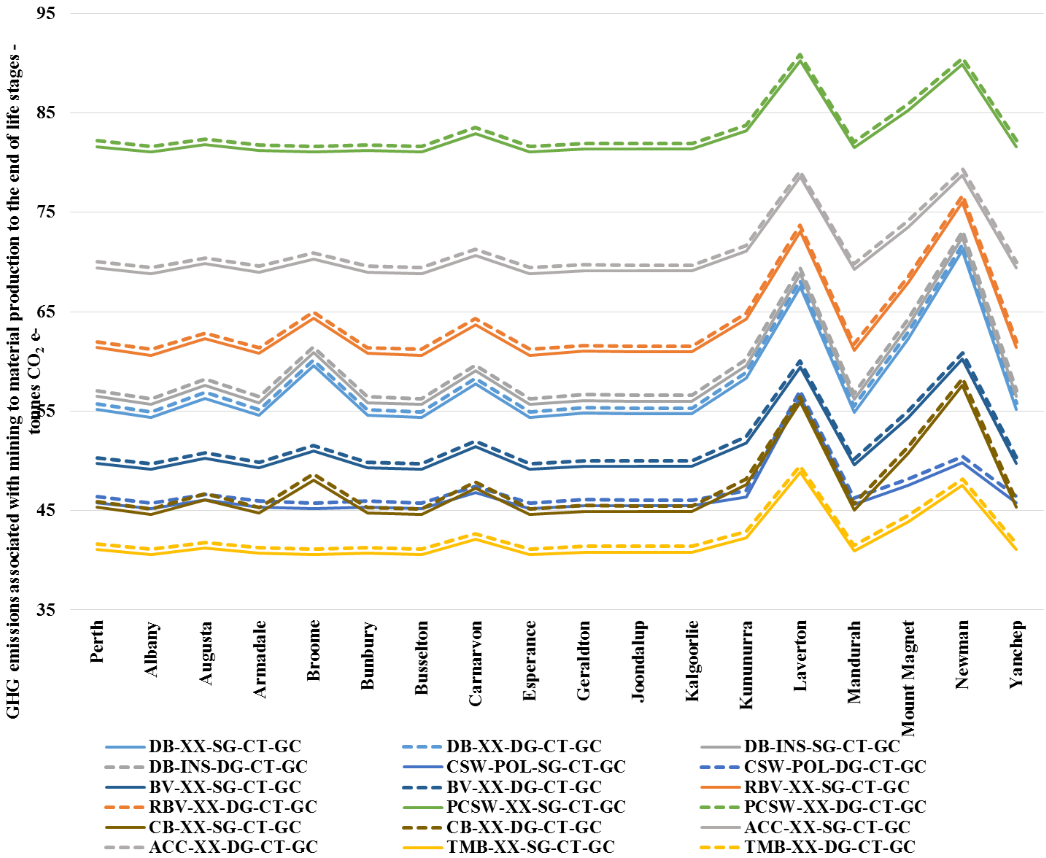


Figure 6.33 GHG emissions of a reference house for alternative CPS options for mining to material production to the end of life stages in 17 locations in regional WA

In order to investigate the influence of the locations on the environmental effectiveness of the alternative CPS options for a reference house, the life cycle GHG emissions values for alternative CPS options have been normalized after dividing by the optimum values of the corresponding location and are arranged in ascending order (Figure 6.34).

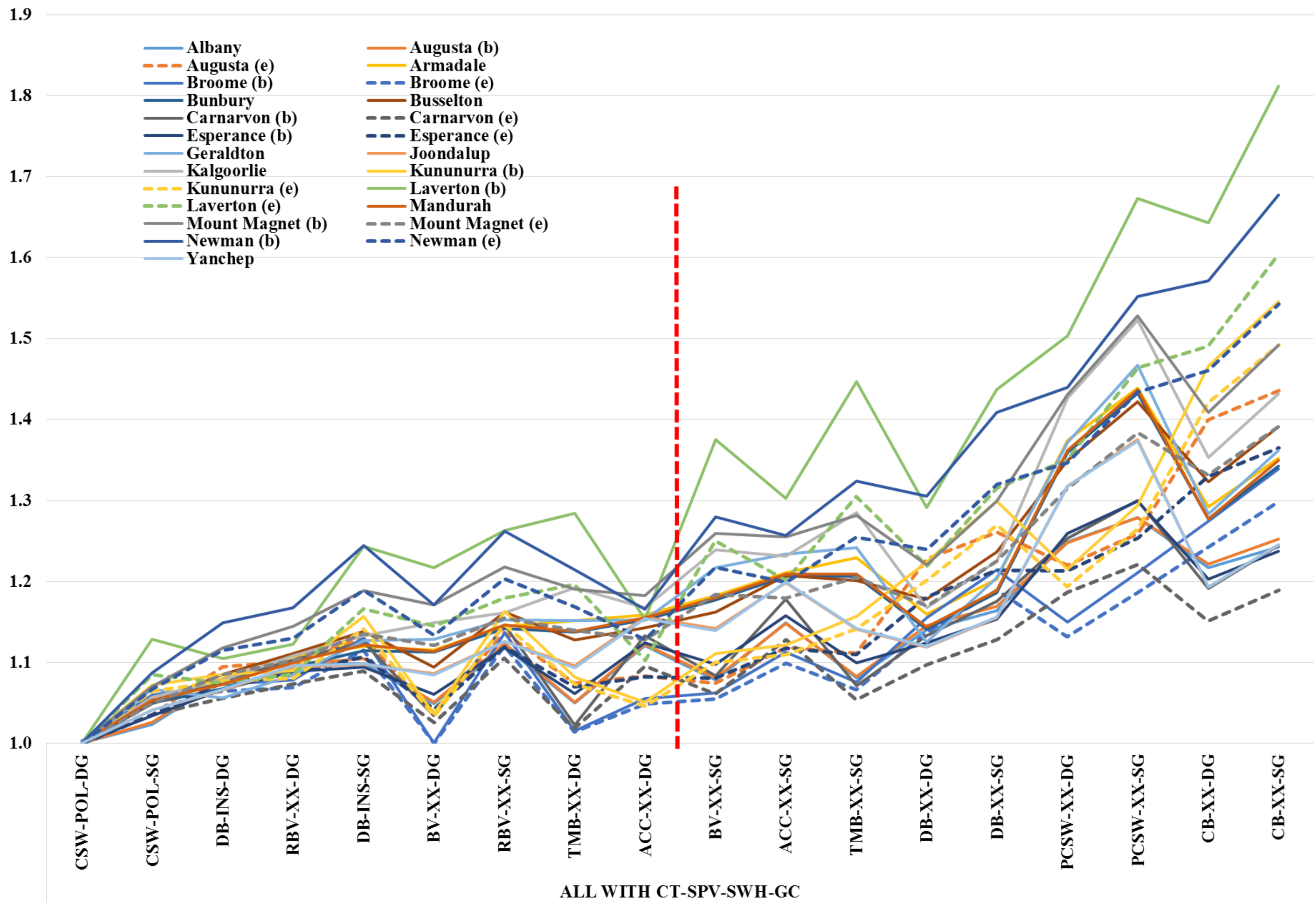


Figure 6.34 Normalized results of life cycle GHG emissions of the reference house for alternative CPS options in 17 locations in regional WA

The interesting finding of this research is that the CPS option CSW-POL-DG-CT-SPV-SWH-GC offers the same normalized life cycle GHG emission values in all locations (at unity with no spread i.e. 1), while the CPS options DB-INS-DG-CT-SPV-SWH-GC, and CSW-POL-SG-CT-SPV-SWH-GC show a small variation in the environmental performance in terms of their normalized life cycle GHG emissions values, which are close to unity with low spread. The normalized life cycle GHG emissions values for CPS options PCSW-XX-SG/DG-CT-SPV-SWH-GC, and CB-XX-SG/DG-CT-SPV-SWH-GC have been found to be substantially away from the unity with a very wide spread, while the normalized values for CPS options DB-XX-SG/DG-CT-SPV-SWH-GC, BV-XX-SG-CT-SPV-SWH-GC, ACC-XX-SG-CT-SPV-SWH-GC, and TMB-XX-SG-CT-SPV-SWH-GC are moderately away from unity but with a wide spread, which shows the inconsistency in their life cycle GHG emissions impacts in different locations in regional WA. The normalized life cycle GHG emissions values for remaining six CPS options have been found to be little away from unity with the medium spread, which shows that the environmental performance of some of these CPS options is reasonably better than others.

EE consumption results

The results of life cycle EE consumption of a reference house for alternative CPS options in 17 locations in regional WA have been summarized and presented in Table F.43 (Appendix F). Similar to life cycle GHG emissions, the EE consumption results of alternative CPS options in 17 locations in regional WA have been grouped based on their respective climate zones (Figure 6.35) and it has been found that the EE consumption of a reference house for alternative CPS options is the highest in climate zone 1 (hot humid summer, warm winter) (i.e. Kununurra and Broome) with a high degree of variation.

For climate zone 3 (Hot dry summer, warm winter), the EE consumption for alternative CPS options is high in Newman with a medium degree of variation, while the life cycle EE consumption in Carnarvon are similar to Perth with a low degree of variation.

For climate zone 4 (Hot dry summer, cool winter), the EE consumption for alternative CPS options is high in Laverton with a medium degree of variation, on the other hand, the EE consumption in Mount Magnet and Kalgoorlie is quite similar to Perth.

For climate zone 5 (Warm temperate), the EE consumption for alternative CPS options is high in Augusta and Esperance with a moderate degree of variation, while the life cycle EE consumption in Busselton, Geraldton, Armadale, Bunbury, Mandurah, Yanchep, and Joondalup is similar to Perth with a very low degree of variation.

For climate zone 6 (Mild temperate), the EE consumption for alternative CPS options in Albany is similar to Perth with a low degree of variation.

Similar to the life cycle GHG emissions, the main reason for this variation in life cycle EE consumption for alternative CPS options across these locations is due to the variation in the EE consumption associated with the operational energy during use stage. The location specific solar radiation and the source of electricity and gas are also the reasons for this variation.

In order to investigate the influence of the locations on the environmental effectiveness of the alternative CPS options for a reference house, the life cycle EE consumption values for alternative CPS options have been normalized for each location and are arranged in ascending order (Figure 6.36).

Similar to GHG emissions, the normalized life cycle EE consumption values for CPS option CSW-POL-DG-CT-SPV-SWH-GC are at unity with no spread (i.e. 1) in all locations, while the CPS options DB-INS-DG-CT-SPV-SWH-GC, and CSW-POL-SG-CT-SPV-SWH-GC show a small spread in their normalized life cycle EE consumption values which are close to unity. The normalized life cycle EE consumption values for CPS options PCSW-XX-SG/DG-CT-SPV-SWH-GC, and CB-XX-SG/DG-CT-SPV-SWH-GC have been found to be substantially away from unity with a very wide spread, while the normalized values for options DB-XX-SG/DG-CT-SPV-SWH-GC, BV-XX-SG-CT-SPV-SWH-GC, ACC-XX-SG-CT-SPV-SWH-GC, and TMB-XX-SG-CT-SPV-SWH-GC are moderately away from unity but with a wide spread, which shows the inconsistency in their life cycle EE consumption impacts in different locations in regional WA. The normalized life cycle EE consumption values for remaining 6 CPS options have been found to be little away from the unity and with the medium spread, which demonstrate that the EE consumption of some of these CPS options is reasonably lower than others.

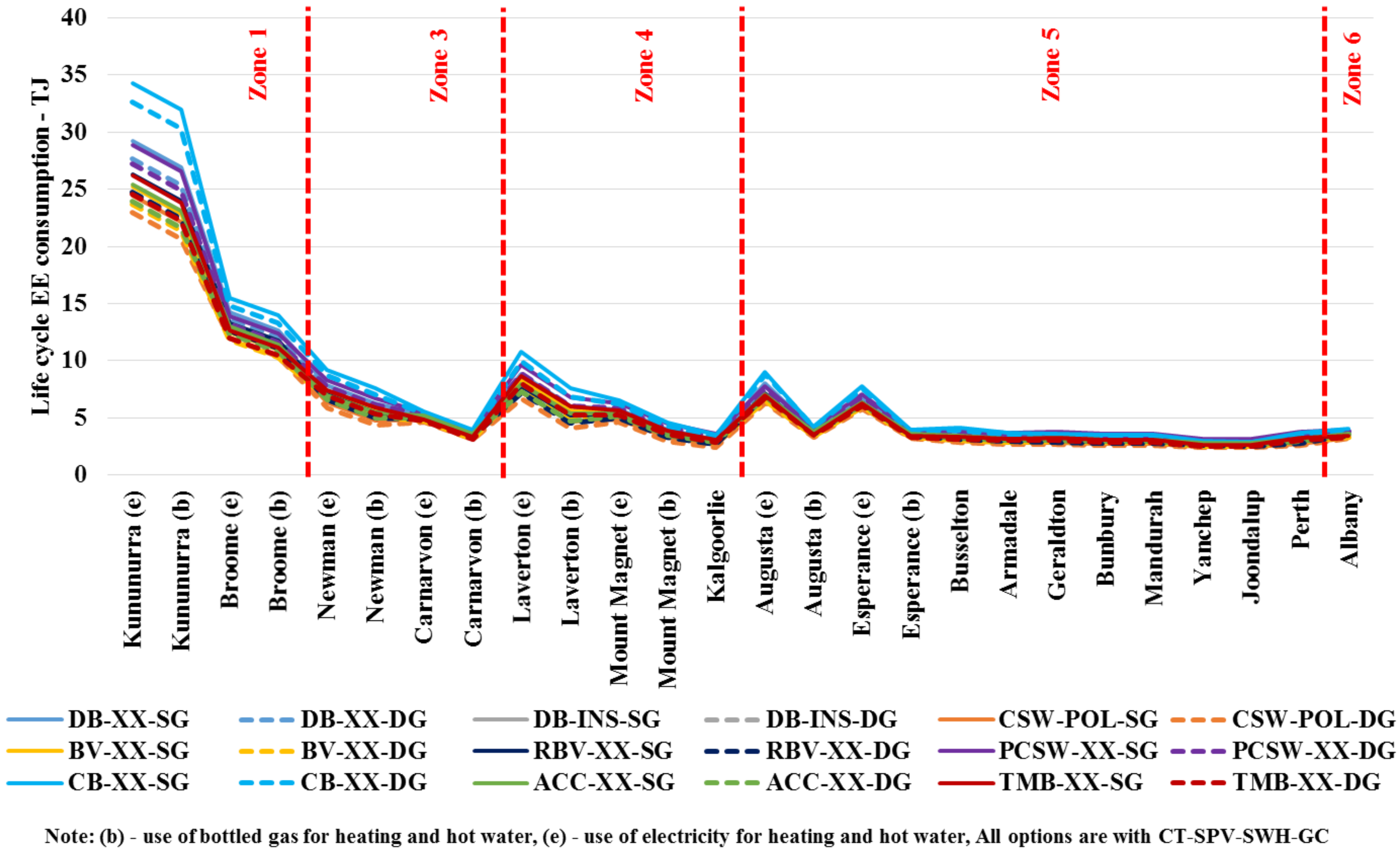


Figure 6.35 Life cycle EE consumption of the reference house for alternative cleaner production options in all locations in regional WA

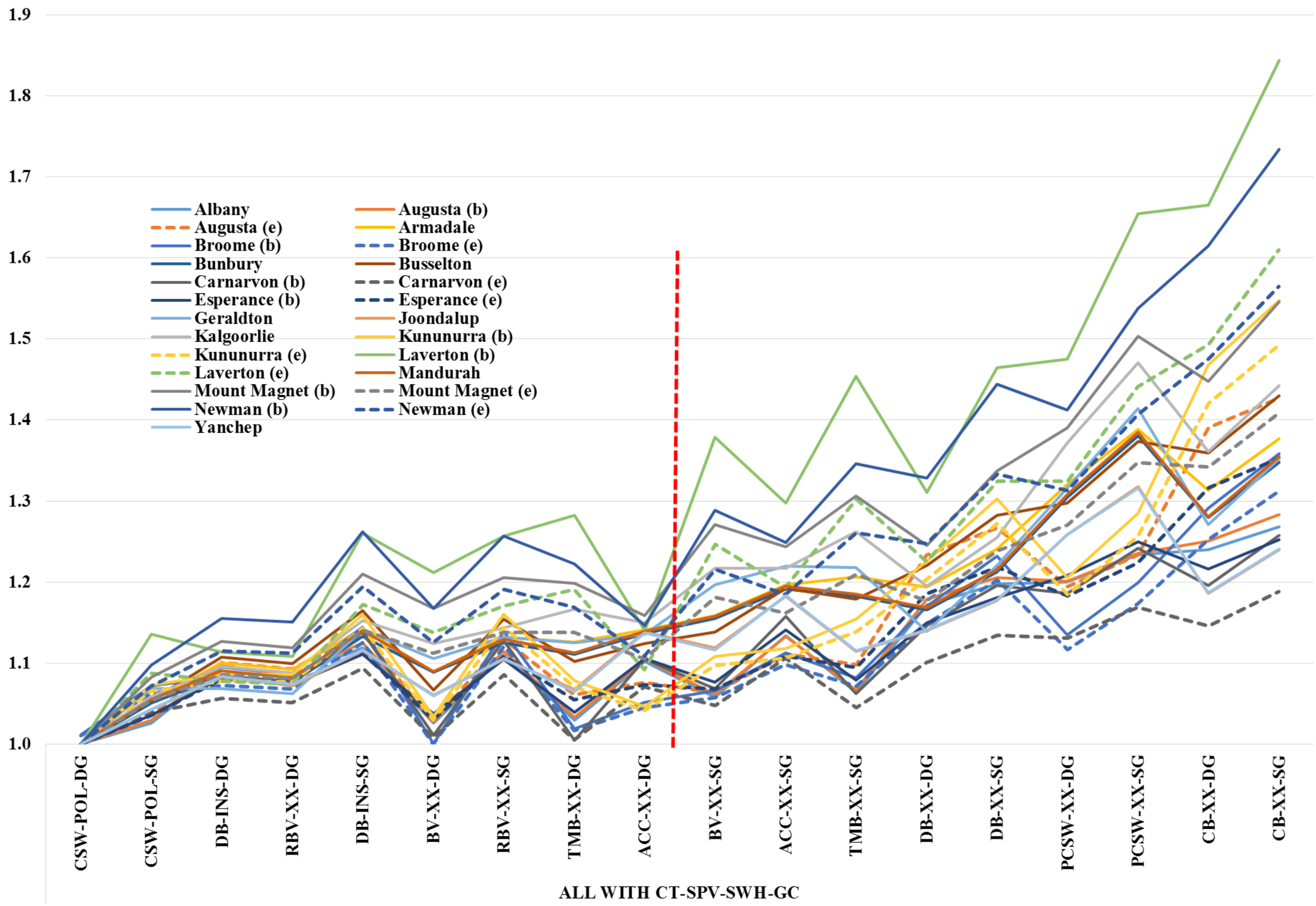


Figure 6.36 Normalized results of life cycle EE consumption of a reference house for alternative CPS options in 17 locations in regional WA

Summary GHG Emissions and EE consumption results

The above life cycle GHG emissions and EE consumption results of alternative CPS options for a typical house in 17 locations in regional WA show that the option CSW-POL-DG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) has the lowest impacts across these locations, thus making it an optimum option. On the other hand, some other CPS options such as CSW-POL-SG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – single glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete), DB-INS-SG/DG-CT-SPV-SWH-GC (double brick walls – wall cavity insulation – single/double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete), RBV-XX-SG/DG-CT-SPV-SWH-GC (reverse brick veneer walls with infill insulation – no wall cavity insulation – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), BV-XX-DG-CT-SPV-SWW-GC (brick veneer walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete), TMB-XX-DG-CT-SPV-SWH-GC (timber frame walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete), and ACC-XX-DG-CT-SPV-SWH-GC (aerated concrete block walls – no wall cavity insulation – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) also have relatively low impacts and may also be considered as environmentally feasible options for majority of these locations in regional WA. The remaining CPS options have relatively high environmental impacts. The similar trend has been observed in the case of Perth. In order to support the decision making, it is now important to evaluate the cost effectiveness of these environmentally feasible CPS options in 17 locations in WA.

6.5 Economic feasibility of alternative CPS options in regional WA

The economic feasibility of alternative CPS options such as grid connected $3kW_p$ roof top solar PV, integration of gas based water heater with roof top solar water heater, alternative envelope options, and replacement of conventional concrete with green concrete for a typical house in Perth has been discussed in Section 5.3.

Based on the detailed economic analysis, the CPS options CSW-POL-SG/DG-CT-SPV-SWH-GC, DB-INS-SG-CT-SPV-SWH-GC, RBV-XX-SG-CT-SPV-SWH-GC, BV-XX-DG-CT-SPV-SWW-GC, and TMB-XX-DG-CT-SPV-SWH-GC were found to be environmentally and economically feasible options in Perth. These CPS options have also been found to be the environmentally feasible in 17 locations in regional WA (Figure 6.34 and Figure 6.36) and hence they have been considered for economic feasibility assessment.

Some CPS options such as DB-INS-DG-CT-SPV-SWH-GC, and RBV-XX-DG-CT-SPV-SWH-GC were found to have relatively low environmental impacts in Perth but their LCCs were slightly more than the reference option. Since this research is more ecologically focused research and environmental performance comes before the economy and society, these two CPS options for a typical house in 17 locations in WA have also been considered for economic analysis.

Similarly, the CPS option ACC-XX-DG-CT-SPV-SWH-GC was found to have low environmental impacts in Perth but had very high LCC as compared to the reference case. In the case of regional implications of this CPS option, the environmental impacts have been found to be comparable with other environmentally feasible CPS options and hence it has also been considered for economic assessment as this option may turn out to be an economically feasible option. The economic assessment of total nine CPS options in 17 locations in regional WA has been conducted. Moreover, these CPS options represent the most commonly used materials and construction systems in regional WA.

The building price indices from construction cost guide (Rawlinsons 2015), have been utilized for estimation of capital costs of the house for all CPS options in 17 locations in regional WA (Table F.44, Appendix F). Similar to Section 5.3, all the present values of capital and replacement costs of grid connected 3kW$_p$ roof top solar PV and roof top solar water heater have been estimated. The present values of operational cost for electricity and natural gas have been estimated using current utility tariffs (DOF 2015d; Alintaenergy 2015). The electricity charges have been found to be same for entire WA, the natural gas tariff has been found to be location specific (Table F.45, Appendix F).The price data for bottled gas in regional WA has been collected through personal communication with Gas suppliers (Table F.46, Appendix F). The end of life demolition and disposal costs have also been estimated using building price indices.

Life cycle cost of environmentally viable CPS options in regional WA

The location wise breakdown of life cycle cost (LCC) of a reference house for environmentally feasible CPS options has been presented in Table F.47 (Appendix F). The results show that the LCC of the house for all environmentally CPS options is the lowest in Joondalup, while the Kununurra is found to have the highest LCC in both cases (i.e. use of bottled gas or electricity for hot water). The LCC of different environmentally viable CPS options in Kununurra is between 100% and 109.3% (i.e. use of electricity for hot water) and between 95.6% and 105% (i.e. use of bottled gas for hot water) more than the LCC of these CPS options in Joondalup. The large difference of LCC has been observed for the CPS options having single glazed windows. The LCC of CPS option CSW-POL-SG-CT-SPV-SWH-GC has been found to be the lowest in all locations except Broome, while the LCC of CPS option ACC-XX-DG-CT-SPV-SWH-GC is the highest in all locations. The LCC of CPS option BV-XX-DG-CT-SPV-SWH-GC has been found to be the lowest in Broome in both cases (i.e. use of bottled gas or electricity for hot water). The LCC of CPS option CSW-POL-SG-CT-SPV-SWH-GC, which is the lowest in all other locations has been found to be only 0.53% (US$1,686.53) more than the LCC of CPS option BV-XX-DG-CT-SPV-SWH-GC (i.e. the lowest) (Figure 6.37). The main reasons for the variation in LCC of different CPS options in regional WA are due to the variations in associated operational energy demand for heating, cooling, and hot water (Table F.3, Appendix F), price indices (Table F.44, Appendix F), natural gas tariff (Table F.45, Appendix F), and the cost of bottled gas (Table F.46, Appendix F).

Capital costs of environmentally feasible CPS options in regional WA

Further analysis shows that the capital cost of a reference house for environmentally viable CPS options, is the lowest in Armadale, Joondalup, and Mandurah, while the capital cost is the highest in Newman (Figure 6.38). The capital cost consists of the construction cost including materials, the present value of the end of life demolition and disposal cost, the capital cost of SPV and SWH including present values of their replacement costs, and cost saving due to GC. The main reason for the variation in capital costs is not only the difference in material inputs and their unit prices as discussed in Chapter 5, the transportation and construction costs in some of these locations are high because of resource scarcity and shortage of skilled labour. This is evident from the building price indices, wherein the building price indices for construction in Broome, Carnarvon, Laverton, Mount Magnet and Newman are 50%-65% more than the building price indices in major population centres such as Perth, Armadale, and Joondalup. However, the pattern of the capital cost of the house for different environmentally viable CPS options is consistent across the regional WA.

Operational costs of environmentally feasible CPS options in regional WA

The operational cost of a reference house has been found to be the lowest in Joondalup for most of the environmentally feasible CPS options, while the operational cost for CPS options is the highest in Kununurra for both cases (i.e. use of bottled gas or electricity for hot water) (Figure 6.39). The operational cost consists of the cost of electricity and natural gas or bottled gas as well as the cost savings due to the integration of roof top SPV and SWH during use stage over a lifespan of 50 years.

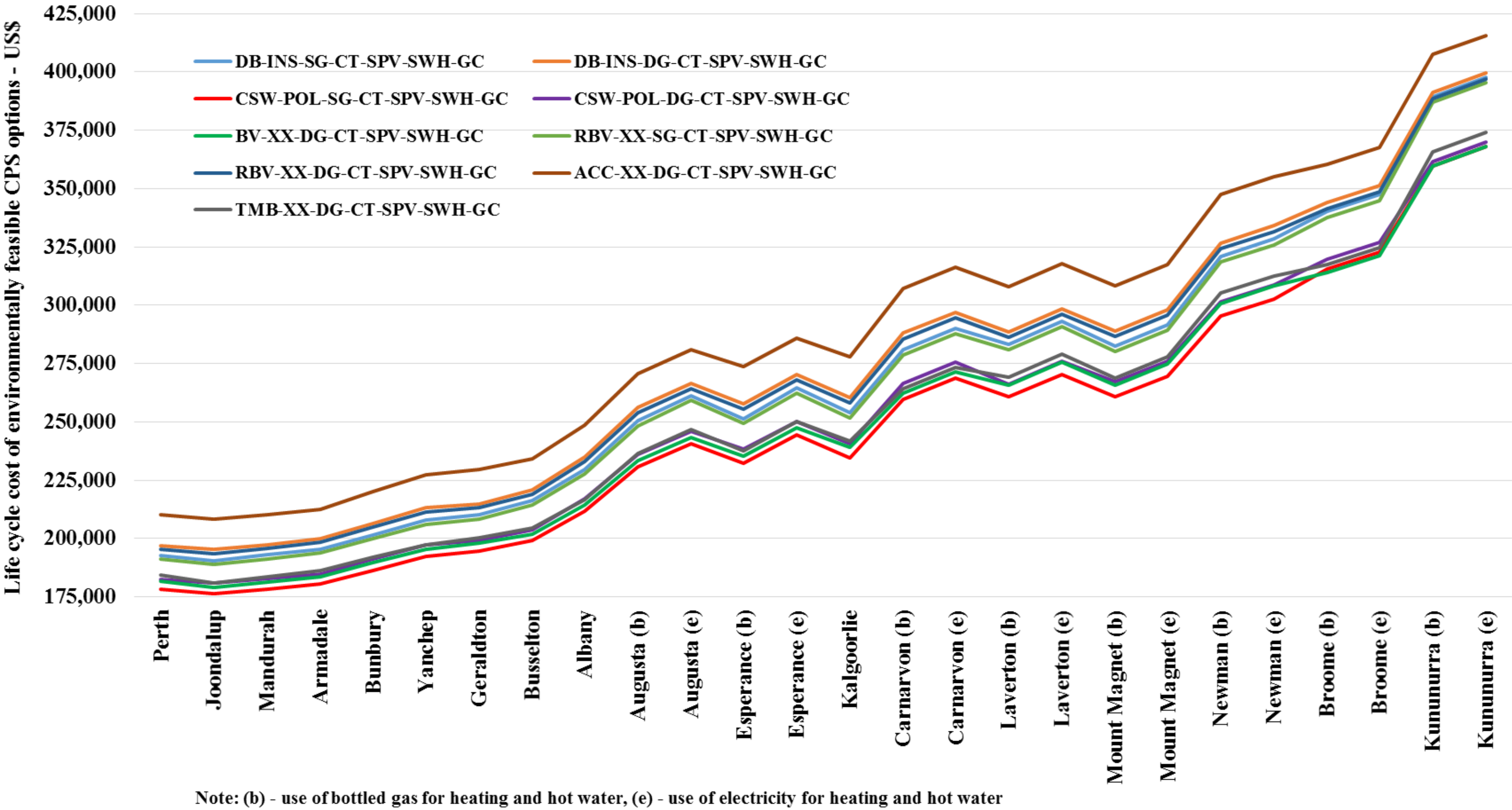


Figure 6.37 LCC of a reference house for environmentally feasible CPS options in 17 locations in regional WA

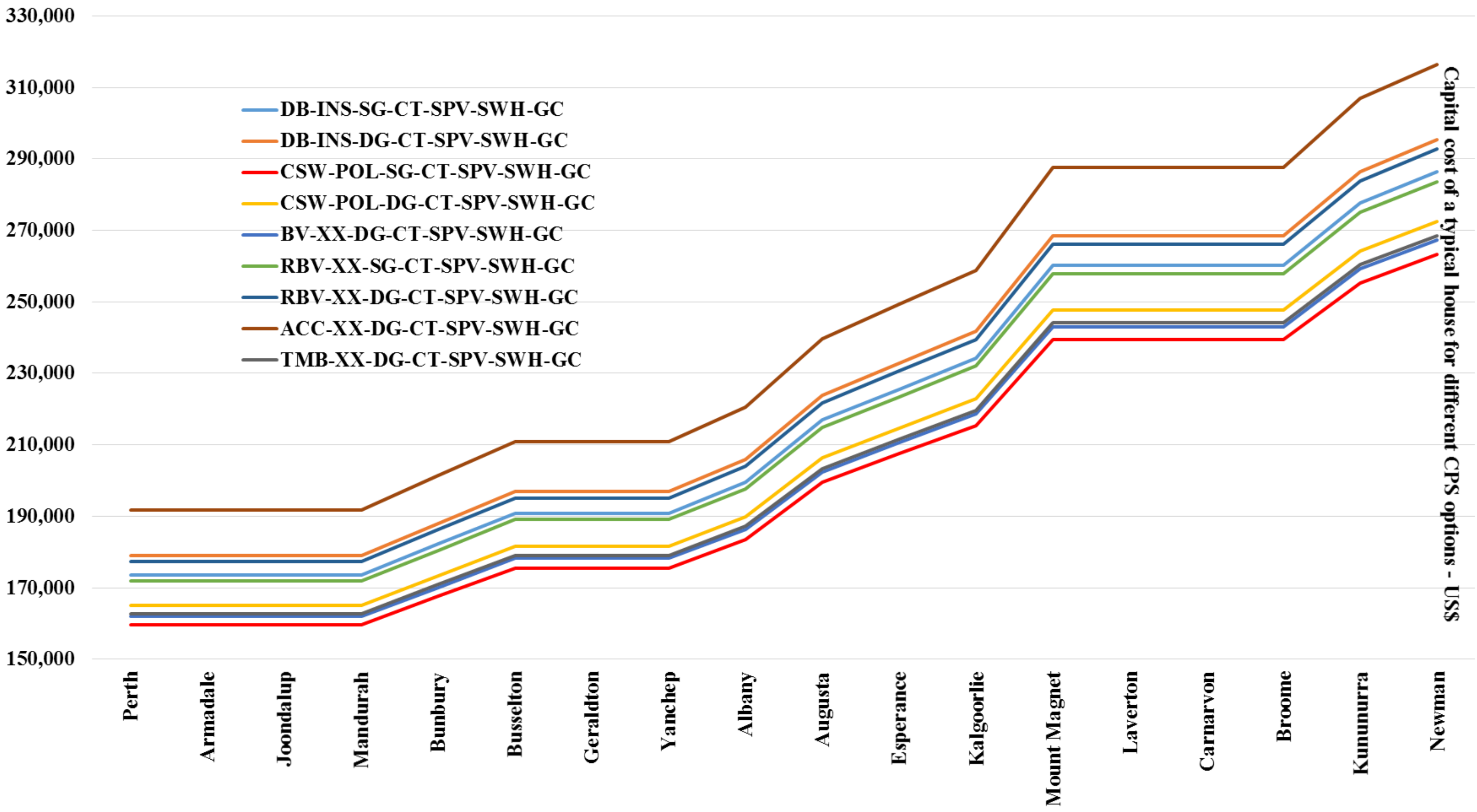


Figure 6.38 Capital cost of a reference house for alternative CPS options in 17 locations in regional WA

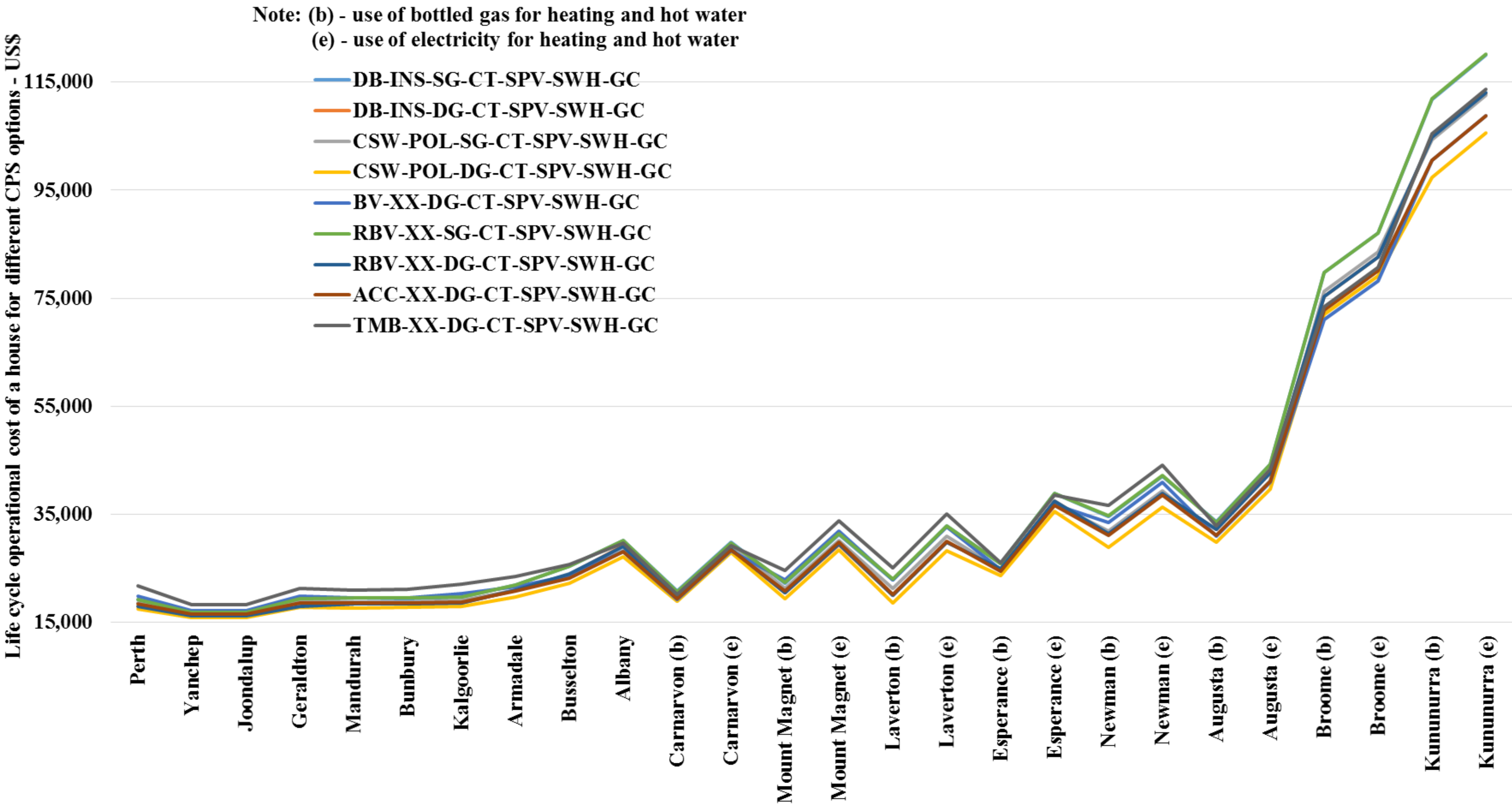


Figure 6.39 Life cycle operational cost of a reference house for alternative CPS options in 17 locations in regional WA

The operational cost of a reference house for different environmentally feasible CPS options in Kununurra has been found to be up to 7 times more than the operational cost in Joondalup (i.e. the lowest) for these options. The operational cost of a reference house for CPS option CSW-POL-DG-CT-SPV-SWH-GC has been found to be the lowest in all 17 locations in regional WA except in Broome, where the operational cost of CPS option BV-XX-DG-CT-SPV-SWH-GC has been found to be the lowest. However, there is an insignificant difference in operational cost between these two options in Broome (i.e. only 1%). Similarly, the operational cost for CPS option TMB-XX-DG-CT-SPV-SWH-GC has been found to be the highest in most of the locations.

The main reasons for the huge variation in the operational cost of different CPS options in regional WA are due to the variations in the operational energy demand for heating, cooling, and hot water, natural gas tariff, and the cost of bottled gas. For example, the operational energy demands for a reference house for environmentally feasible CPS options in Broome and Kununurra are around 6 to 10 times, and 9 to 15 times more than the operational energy demand in Perth respectively. Another reason for the very high operational cost in Broome and Kununurra is because the operational energy demand for cooling is the highest which requires relatively expensive grid electricity.

The cost of bottled gas also has been found to vary with location with up to 84% difference between the lowest and highest costs. However, the roof top solar PV (SPV) and solar water heater (SWH) have been found to offer the savings to investment ratios of greater than 2 in 17 locations in regional WA.

In order to investigate the influence of the locations on the economic effectiveness of the alternative CPS options for a reference house, the LCC values for alternative CPS options have been normalized by dividing by the optimum values of the corresponding location and are arranged in ascending order (Figure 6.40). It appears that the normalized LCC values for CPS option CSW-POL-SG-CT-SPV-SWH-GC are at unity (i.e. 1) for all locations except Broome, where CPS option BV-XX-DG-CT-SPV-SWH-GC is the most economic option. The normalized LCC values for CPS options CSW-POL-DG-CT-SPV-SWH-GC and TMB-XX-DG-CT-SPV-SWH-GC are close to unity but with an inconsistent variation. This shows that their LCC values are low but their relative rankings are not same in all locations. The normalized LCC values of CPS options DB-INS-SG/DG-CT-SPV-SWH-GC, RBV-XX-SG/DG-CT-SPV-SWH-

GC, and ACC-XX-DG-CT-SPV-SWH-GC have been found to be far away from the unity.

6.6 Economic versus environmental performance of alternative CPS options in regional WA

In order to make the optimal decision, the LCC, GHG emissions, and EE consumption values of a typical house for alternative CPS options in 17 locations in regional WA have been normalized by dividing them by their respective location wise optimum values and results have been presented in Table F.49 (Appendix F).

From these normalized data, it has been observed that the CPS option CSW-POL-DG-CT-SPV-SWH-GC has the LCC, GHG emissions, and EE consumption values at unity (i.e. 1) or close to unity with a minimum variation, which makes it the optimum CPS option. Although the normalized LCC values for CPS options BV-XX-DG-CT-SPV-SWH-GC, CSW-POL-DG-CT-SPV-SWH-GC, and TMB-XX-DG-CT-SPV-SWH-GC are also close to the unity but their normalized GHG emissions and EE consumption values are far away from the unity (Figure 6.41). The second best CPS option in regional WA has been found to be CSW-POL-SG-CT-SPV-SWH-GC as it has the optimum combination of thermal mass, insulation and its location, material contents, and material inventory, which results in the minimum possible environmental and economic impacts during various life cycle stages.

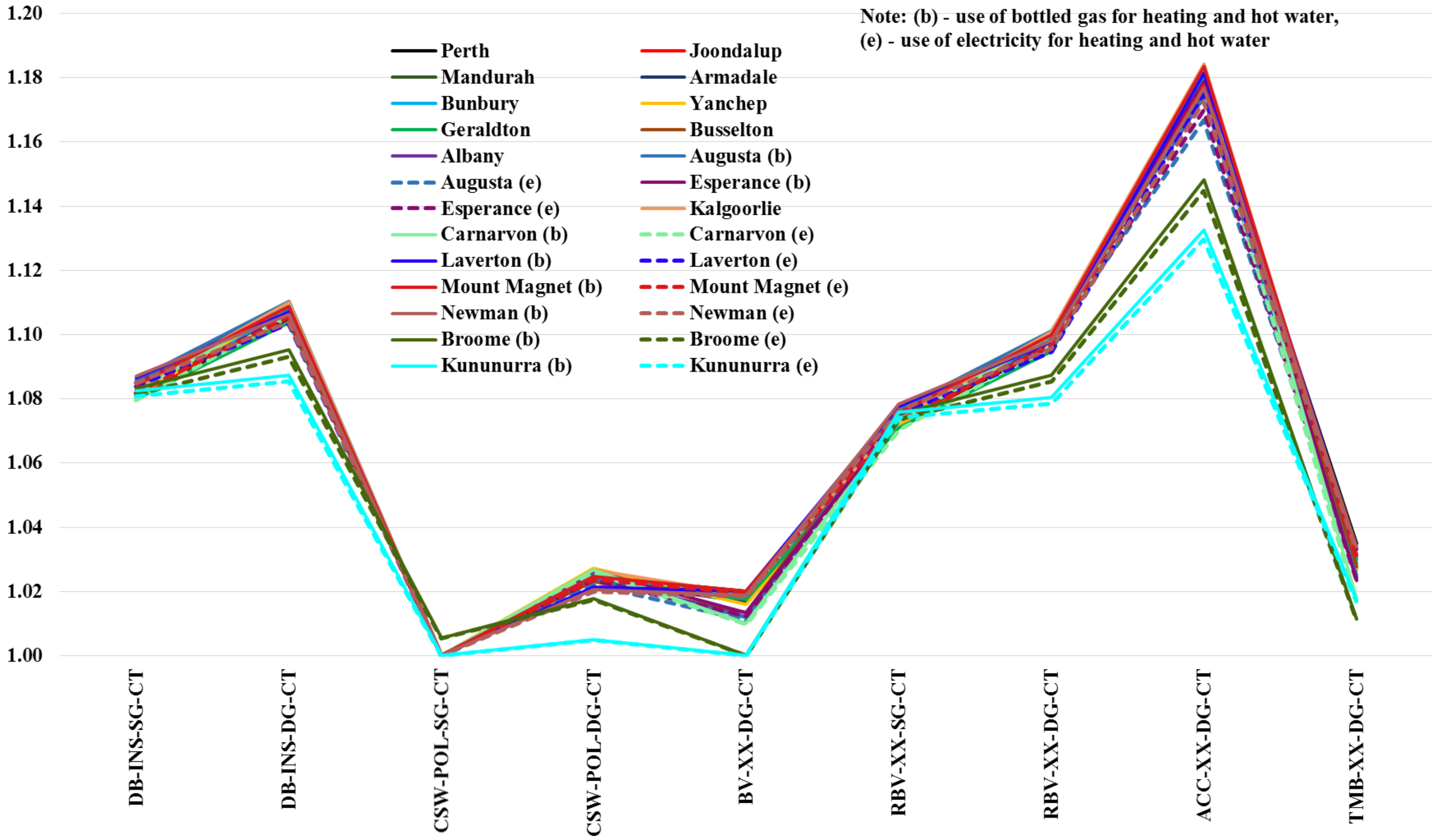


Figure 6.40 Normalized values of LCC of a reference house for alternative CPS options in 17 locations in regional WA

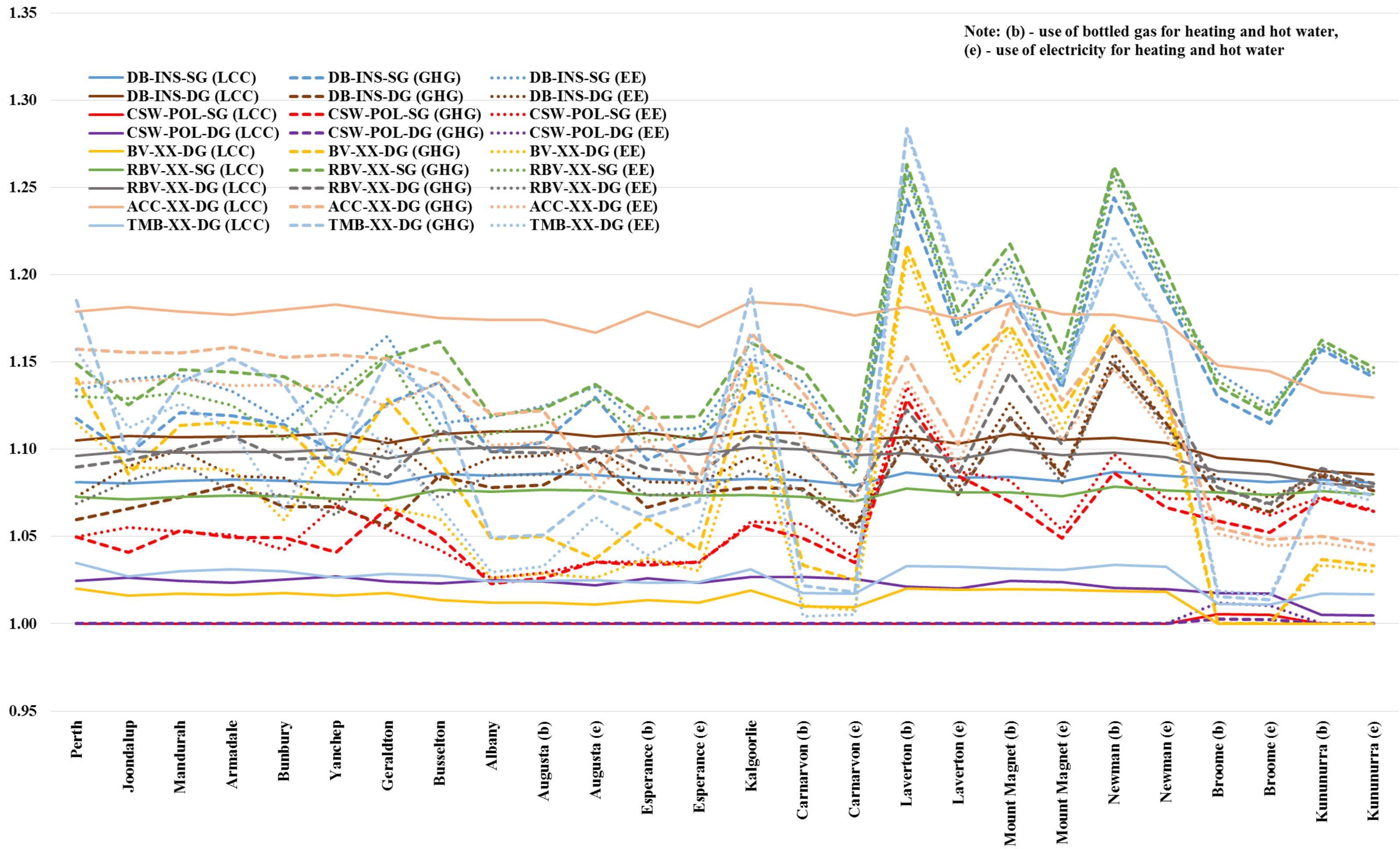


Figure 6.41 Normalized values of LCC, GHG emissions, and EE consumption of a reference house for alternative CPS options in all locations in regional WA

6.7 Conclusion

This chapter has presented the life cycle cost results of a reference house for environmentally viable cleaner production strategy (CPS) options in 17 locations in regional WA and the results have been compared with the life cycle cost results of the reference house in Perth. The CPS options CSW-POL-SG/DG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – single/double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) have been found to be most cost-effective options with the lowest GHG emissions and EE consumption in all 17 locations in regional WA. This is how this cleaner production option has complied with the eco-efficiency objective by doing more with less. Though some other CPS options also have low economic impacts but these options may not be feasible options due to their high GHG emissions and EE consumption because this research is more ecologically focused, and the environmental performance comes before the economy and the society.

The next chapter is the final chapter wherein the conclusions and recommendations of this research study have been presented.

Chapter 7

Conclusion

7.1 Introduction

The aim of this research, as stated in Chapter 1, was to develop a comprehensive life cycle management framework which integrates the NatHERS energy rating tool, a life cycle assessment (LCA) approach, cleaner production strategies (CPS), life cycle costing (LCC) approach, and policy instrument for sustainability assessment of different building materials and methods for houses in Western Australia. In order to address the aim of this research, it was necessary to understand the theory and practice of sustainability and sustainable development with a particular attention to the existing body of knowledge on sustainable house construction. The objectives as stated in Chapter 1, were addressed through the application of LCM framework and intensive data collection.

7.2 Outcome of research objectives

Five research objectives as stated in Chapter 1, were addressed and the outcomes of these objectives are presented:

7.2.1 Objective 1: To develop a framework for improving the sustainability performance of houses in Western Australia

The objective to develop a comprehensive sustainability assessment framework was achieved. This framework focuses on all aspects of the buildings including construction materials and methods, thermal performance due to climatic variations, operational energy demand, environmental impacts, cost-effectiveness of energy efficiency improvement measures, use of by-products and recyclates, integration of renewable technologies, and address policy barriers to implement sustainability for Western Australia's housing sector.

Nationally and internationally published peer reviewed journal articles, conference proceedings, books, Australian Federal and State government reports, Intergovernmental Panel on Climate Change (IPCC) reports, and the reports from United Nations and its allied Institutions helped establish knowledge of the state of the art research tools for sustainability assessment of buildings. None of these tools have considered life cycle assessment (LCA), life cycle costing (LCC), social and policy instruments together to address WA's building sector as mentioned above.

A holistic life cycle management (LCM) framework comprising of Australian Nationwide House Energy Rating Scheme (NatHERS) tool, life cycle energy assessment (LCEA), LCA, and LCC with a focus on different materials and methods of construction, climatic conditions, energy consumption (for heating, cooling, lighting, hot water, and home appliances), solar energy, environmental impacts, socio-economic implications, and resource availability for addressing WA's sustainability requirements in different locations under different climatic zones was developed as discussed in Chapter 3.

7.2.2 Objective 2: To estimate the life cycle environmental impacts of construction, use, and disposal of a typical house in Perth using LCA tool

The life cycle greenhouse gas (GHG) emissions and embodied energy (EE) consumption impacts associated with the construction, use, and the end of life demolition and disposal of a typical 4x2x2 conventional double clay brick wall house in Perth were estimated using an LCA approach, which employed the four steps as defined by ISO 14040-44: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation.

The life cycle energy analysis, a predecessor to LCA, was conducted using AccuRate software to estimate the operational energy for heating, cooling, lighting, and hot water. The operational energy for home appliances was estimated using MS Excel software. The energy modelling was conducted for 8 house orientations, and the East facing house was found to have minimum life cycle operational energy (2689GJ). The operational energy for cooling of a typical house could increase by 6% to 24% as a result of temperature rise due to climate change impacts over a lifespan of 50 years.

The material data that is obtained from building specification and drawings and the energy data from LCEA were used for the development of a life cycle inventory (LCI) for LCA. The life cycle GHG emissions and EE consumptions were estimated using SimaPro software and were found to be 467tonnes CO_2 e-, and 6.5TJ respectively. The mining to material production, transportation, construction, use, and the end of life demolition and disposal stages are found to contribute to 11.36%, 0.35%, 0.52%, 87.61%, and 0.16% of the life cycle GHG emissions, and 10.97%, 0.35%, 0.62%, 87.59%, and 0.46% of the life cycle EE consumption respectively as discussed in Chapter 4. The change in orientation and an increase in temperature due to climate change impacts could cause variations of up to 10%, and 5% of the life cycle GHG emissions and EE consumption of a typical conventional house in Perth.

7.2.3 Objective 3: To identify hotspots and apply appropriate cleaner production strategies (CPS) to mitigate the life cycle environmental impacts associated with identified hotspots for a typical house in Perth

The stage wise breakdown of GHG emissions and EE consumption results was used to identify the materials and activities causing the highest impacts (hotspots). The use stage and mining to material production stage were found to cause 87%, and 11% of the life cycle impacts respectively and thus were identified as the hotspots. The other stages combined were responsible for up to 2% of the life cycle impacts.

Five cleaner production strategies including good housekeeping, technology modification, product modification, input substitution, and recycling and reuse were implemented to reduce GHG emissions and EE consumption impacts as discussed in Chapter 4. Grid connected roof top solar PV (1kW$_p$, 1.5kW$_p$, and 3kW$_p$), integration of solar water heater with conventional water heating system, 53 building envelope components, and 72 combinations of by-products and recyclates for concrete mix were considered as potential alternatives to treat the hotspots by mitigating the GHG emissions and EE consumptions of a typical house in Perth.

The life cycle energy analysis was conducted to estimate the impacts of all potential cleaner production options. The revised material and energy inputs were utilized to modify the LCI, and the GHG emissions and EE consumption impacts of a typical house for each potential cleaner production were then estimated. The grid connected 3kWp roof top solar PV and roof top solar water heater were found to be the most effective cleaner production options, which could reduce up to 50% of the life cycle GHG emissions and EE consumption of a typical house in Perth. The life cycle GHG emissions and EE consumption impacts of a typical house in Perth could change from -8% to +13.5%, and -9% to +10% respectively due to the change in envelope components. A typical house in Perth with cast in-situ sandwich walls, polystyrene insulation core, double glazed windows, concrete roof tiles, 3kWp grid connected roof top solar PV, solar water heater, and partial replacement of cement by fly ash and virgin aggregates by recycled aggregates in the concrete mixture (CSW-POL-DG-CT-SPV-SWH-GC) was found to have the lowest life cycle GHG emissions (200tonnes CO2 e-) and EE consumption (2.6TJ). The cleaner production strategies are found to have the potential to reduce the GHG emissions by 57% and EE consumption by 60% of a typical conventional double clay brick wall house in Perth as discussed in Chapter 4.

Due to high environmental impacts, 23 envelope and cleaner production options such as DB-XX-SG-TT/MS-SPV-SWH-GC (double brick walls – no wall cavity insulation – single glazed windows – terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), BV-XX-SG-CT/TT/MS-SPV-SWH-GC (brick veneer walls with infill insulation – no wall cavity insulation – single glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), CB-XX-SG/DG-CT/TT/MS-SPV-SWH-GC (concrete block walls – no wall cavity insulation – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), ACC-XX-SG-CT/TT/MS-SPV-SWH-GC (aerated concrete block walls – no wall cavity insulation – single glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), PCSW-XX-SG/DG-CT/TT/MS-SPV-SWH-GC (pre-cast sandwich walls – no wall cavity insulation – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), and TMB-XX-SG-CT/TT/MS (timber frame walls with infill insulation – no wall cavity insulation – single glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete) were not feasible options.

The 30 envelope and cleaner production options DB-XX-DG-CT/TT/MS-SPV-SWH-GC (double brick walls – no wall cavity insulation – double glazed windows – terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), DB-INS-SG/DG-CT/TT/MS-SPV-SWH-GC (double brick walls –

wall cavity insulation – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), BV-XX-DG-CT/TT/MS-SPV-SWH-GC (brick veneer walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), RBV-XX-SG/DG-CT/TT/MS-SPV-SWH-GC (reverse brick veneer walls with infill insulation – no wall cavity insulation – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), ACC-XX-DG-CT/TT/MS-SPV-SWH-GC (aerated concrete block walls – no wall cavity insulation – double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), CSW-POL-SG/DG-CT/TT/MS-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – single/double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete), and TMB-XX-DG-CT/TT/MS (timber frame walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles/terracotta roof tiles/metal roof sheet – roof top solar PV – roof top solar water heater – green concrete) have been found to be environmentally viable options.

7.2.4 Objective 4: To estimate the socio-economic implications of environmentally viable cleaner production options for mitigation of life cycle impacts of a typical house in Perth

The economic implications of the environmentally viable cleaner production options to mitigate the life cycle impacts associated with a typical house in Perth were determined using the life cycle costing (LCC) approach, which is an effective technique for forecasting and evaluating the cost performance of buildings to find an optimum design option. The Net Present Value (NPV) method for estimation of LCC was used, which converts the future costs into present values. The cost-effectiveness of alternative options was evaluated by comparing their LCCs with the LCC of a conventional house. Originally, the costs have been estimated in Australian Dollar which were then converted to American Dollar or US$ (1AUD = 0.7229US$)

With an annual inflation rate of 3% and discount rates of 7%, the life cycle cost of a typical conventional double clay brick wall house in Perth was found to be US$211,439. While the capital cost of a typical house was US$ 160,007 (75.5% of LCC), the operational cost over the lifespan of 50 years was US$49,735 (23.5% of LCC) followed by the end of life demolition and disposal cost of US$1,697 (1%) as discussed in Chapter 5.

The initial capital cost including replacement cost (after every 25 years) of a grid connected 3kW$_p$ roof top solar PV of US$3,807 was found to be easily recovered from the cost savings of US$19,621 from the grid electricity over the lifespan of 50 years and thus resulting in a net saving of US$15,814. The initial capital cost including replacement cost (after every 13 years) of the solar water heater of US$6,063 was found to be recovered from the cost savings of US$8,452 from the natural gas over the lifespan of 50 years and thus resulting in a net saving of US$2,389.

The capital cost of the house for environmentally viable alternative envelope options vary between US$148,303 and US$183,419, and with respect to the capital cost of the conventional house, 12 alternative envelope options offered a cost saving of up to US$11,703, whilst the remaining 18 options were significantly costlier by up to US$23,412.

The operational cost of the house over a lifespan of 50 years was varying between US$45,771 and US$50,043, and with respect to the operational cost of conventional house, 27 envelope options offered a cost saving of up to US$3,964, while the remaining 3 options had negligibly higher operational costs of up to US$308. It is interesting to note that almost all alternative envelope options offered operational energy cost saving due to improved thermal performance.

The end of life demolition and disposal cost of the house was varying between US$1,309 and US$1,738. The partial replacement of cement and aggregates in the concrete mix by fly ash and recycled aggregates offered a saving between US$169 and US$327 depend on the quantity of concrete required for different building envelope options.

The LCC estimation helped in developing a matrix of economically and environmentally viable cleaner production options including their rankings based on life cycle GHG emissions reduction, life cycle EE consumption saving, and LCC cost saving potential. LCC of a typical house in Perth using cast in-situ sandwich walls – polystyrene insulation core - double glazed windows - concrete roof tiles – roof top solar PV – solar water heater – green concrete (CSW-POL-DG-CT-SPV-SWH-GC) option that had the lowest GHG emissions and EE consumption was 14% lower than the LCC of conventional house (US$182,674.52).

Out of 30 environmentally viable envelopes and cleaner production options, the LCC of only one option (ACC-XX-DG-TT-SPV-SWH-GC) was slightly higher (<1%) than the LCC of a conventional house due to very high capital cost of ACC blocks. All other options were cost-effective options for mitigating the impacts of environmental hotspots.

The sensitivity analysis was performed for discount rates of 4% and 10% and as expected, the absolute values of LCC changed with a change in discount rates but did not change their order in terms of cost saving or incremental cost as compared to the conventional house as discussed in Chapter 5.

The impacts of the probable carbon tax on LCC of a typical house for alternative cleaner production options were investigated and LCC results were found to be least sensitive to the carbon tax. The environmentally and economically viable options for the construction of the house in Perth were found to enhance the affordability of the house with the additional benefits of reduction of resource consumption and increased recovery of construction and demolition (C&D) waste.

7.2.5 Objective 5: To investigate the implication of environmentally, and economically viable options for 17 locations in regional Western Australia to capture the location specific climatic, economic, energy, and policy variations

Western Australia is the largest state of Australia with a unique geographical, demographical, and climatic landscape. The seventeen analysed locations (Albany, Armadale, Augusta, Broome, Bunbury, Busselton, Carnarvon, Esperance, Geraldton, Joondalup, Kalgoorlie, Kununurra, Laverton, Mandurah, Mount Magnet, Newman, and Yanchep) fall under 5 climate zones and were selected based on the growth potential of population and housing.

The majority of these locations receive the electricity supply from South West interconnected system (SWIS) grid, but in a few locations, the electricity is generated using diesel or natural gas. Similarly, half of these locations have reticulated natural gas supply, while the other half depend on bottled LPG gas. Also, as compared to Perth, the costs of materials, labour, and utilities in these locations varies due to logistics and availability of resources.

The variation in climatic conditions in these locations would affect the thermal performance of the building's envelope because it is not only a function of the individual performance of each envelope component and their combinations (e.g. walls, roof, and floor) but is highly influenced by the climate conditions. Therefore the environmental performance of the building options in Perth was not expected to be the same in all 17 locations.

The influence of terracotta roof tiles and metal roof sheets on operational energy, GHG emissions and EE consumption of the house in Perth was found to be significantly low and hence they were not included for the investigation in regional WA.

The AccuRate software was used for energy modelling of the house for 8 orientations and for all building envelope options to identify the optimum orientation for each location, which helped in the estimation of the life cycle operational energy. The life cycle operational energy of the house for all envelope options was the highest in Kununurra (6TJ to 8.3TJ), and the lowest in Joondalup (2.3TJ to 2.7TJ). For all locations except Broome, the life cycle operational energy of the house for envelope option CSW-POL-DG-CT (cast in-situ sandwich walls – polystyrene insulation core - double glazed windows - concrete roof tiles) was the lowest (2.3TJ to 6TJ), whereas in the case of Broome, the envelope option BV-XX-DG-CT (brick veneer walls - double glazed windows - concrete roof tiles) had 0.8% lower life cycle operational energy than the former envelope option. For all locations, the envelope option CB-XX-SG-CT (hollow concrete block walls - single glazed windows - concrete roof tiles) had the highest life cycle operational energy (2.7TJ to 8.3TJ). As compared to the life cycle operational energy of the house for all envelope options in Perth (2.4TJ to 3TJ), the house in Albany, Augusta, Armadale, Broome, Busselton, Carnarvon, Esperance, Kununurra, Laverton, and Newman had higher life cycle operational energy (2.6TJ to 8.4TJ), but the house in Bunbury, Geraldton, Joondalup, Kalgoorlie, Mandurah, Mount

Magnet, and Yanchep had equal or lower life cycle operational energy (2.3TJ to 3TJ). This justifies the incorporation of AccuRate software into the LCM framework as the software captures operational energy variation associated with climatic differences in these locations.

The material, transport, and energy inputs for all envelope options for all locations were utilized for preparation of a life cycle inventory (LCI) to conduct the LCA. The GHG emissions and EE consumption associated with the construction, use, and the end of life demolition and disposal of a typical house for all cleaner production options (e.g. solar energy, different envelope options, and use of by-products and recyclates) were estimated for all locations in regional WA as discussed Chapter 6.

The locations where reticulated natural gas network is not available, residents use either grid electricity or bottled LPG for heating, and hot water. In the absence of any published data on their share, both the options were considered for estimation of life cycle GHG emissions and EE consumption. Similar to life cycle operational energy, the life cycle GHG emissions and EE consumption of the house for all cleaner production options were the highest in Kununurra (1,567tonnes CO_2 e- to 2,339tonnes CO_2 e-, and 23TJ to 34TJ respectively), and the lowest in Joondalup (186tonnes CO_2 e- to 256tonnes CO_2 e-, and 2.4TJ to 3.1TJ respectively). For all locations except the Broome, the life cycle GHG emissions and EE consumption of the house for option CSW-POL-DG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) were the lowest (186tonnes CO_2 e- to 1,567tonnes CO_2 e-, and 2.4TJ to 23TJ respectively), whereas in the case of Broome, the option BV-XX-DG-CT-SPV-SWH-GC (brick veneer walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) had 0.25%, and 1.2% lower life cycle GHG emissions and EE consumption respectively than the former option. For all locations, the cleaner production option CB-XX-SG-CT-SPV-SWH-GC (concrete block walls – no wall cavity insulation – single glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) had the highest life cycle GHG emissions and EE consumptions (222tonnes CO_2 e- to 1,739tonnes CO_2 e- and 2.8TJ to 32.6TJ respectively).

As compared to the life cycle GHG emissions and EE consumption of the house for all cleaner production options in Perth (200tonnes CO_2 e- to 303tonnes CO_2 e-, and 2.6TJ to 3.8TJ respectively), the house in Albany, Augusta, Broome, Busselton, Carnarvon, Esperance, Geraldton, Kununurra, Laverton, Mount Magnet, and Newman had higher life cycle GHG emissions and EE consumption (200tonnes CO_2 e- to 2,339tonnes CO_2 e-, and 2.7TJ to 34TJ respectively), but the house in Armadale, Bunbury, Joondalup, Kalgoorlie, Mandurah, and Yanchep had almost equal or lower life cycle GHG emissions and EE consumption (186tonnes CO_2 e- to 289tonnes CO_2 e-, and 2.4TJ to 3.7TJ respectively).

The life cycle cost (LCC) for construction, use, and the end of life demolition and disposal of a typical house for all environmentally viable cleaner production options for 17 locations in regional WA was estimated to capture the regional economic variations.

The LCC of the house for all environmentally viable options was the highest in Kununurra (between US$367,923 and US$415,604), and the lowest in Joondalup (between US$176,278 and US$208,259). For all locations except Broome, the LCC of the house for option CSW-POL-DG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) with the lowest GHG emissions and EE consumption was found between US$180,965 and US$369,719, whereas in the case of Broome, the option BV-XX-DG-CT-SPV-SWH-GC (brick veneer walls with infill insulation – no wall cavity insulation – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) had 1.7% lower LCC than the former option. For all locations, the option ACC-XX-DG-CT-SPV-SWH-GC (autoclaved aerated concrete block walls – double glazed windows – concrete roof tiles - 3kWp grid connected roof top solar PV - solar water heater – green concrete) had the highest LCC (between US$208,259 and US$415,604). As compared to LCC (between US$178,270 and US$210,193) of the house for these options in Perth, the house in Joondalup only had lower LCC (between US$176,278 and US$208,259), while the house in all remaining locations had higher LCC (between US$178,416 and US$415,604).

The life cycle GHG emissions, EE consumption and LCC values of a typical house for alternative cleaner production options in all 18 locations in WA were normalized by dividing them by their respective location wise optimum values to identify the best suited options for the construction of the sustainable house.

The option CSW-POL-DG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – double glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete) had the life cycle GHG emissions, and EE consumption and LCC values at unity or close to unity with minimum spread thus making this a sustainable option. The second best sustainable option was found to be CSW-POL-SG-CT-SPV-SWH-GC (cast in-situ sandwich walls – polystyrene insulation core – single glazed windows – concrete roof tiles – roof top solar PV – roof top solar water heater – green concrete). The main reasons for these options to be sustainable are the optimum combination of their thermal mass, insulation and placement, material contents, material inventory resulting into minimum environmental and economic impacts during various life cycle stages.

The life cycle management (LCM) framework was able to identify the sustainable cleaner production strategies (CPS) for 17 locations in regional Western Australia.

7.2.6 Summary of outcomes of research objectives

The aim of this research was to develop a comprehensive life cycle management framework which integrates NatHERS energy rating tool, life cycle assessment (LCA) approach, cleaner production strategies (CPS), life cycle costing (LCC) approach, and policy barriers to sustainability assessment of different building materials and methods for the construction of sustainable houses in Western Australia.

As all five objectives were successfully and comprehensively addressed, it can thus be concluded that the aim of the research was met.

Limitations of the research may include factors such as home-owner and builder tendency to maintain traditional practices, traditional trade domination in the construction sector, subsidised cost of energy, and absence of carbon tax which may affect the sustainability of the houses.

7.3 Recommendations

During the development and application of a comprehensive life cycle management framework which integrated various tools and concepts from a life cycle perspective for sustainability assessment of different building materials and methods for the construction of sustainable houses in Western Australia, some limitations and improvement opportunities were identified. However, they are beyond the scope of this research and did not affect the development of life cycle management framework and outcome of the research. The recommendations for industry and future research are as follows:

- Although the cast in-situ concrete sandwich wall system for the construction of a house offers a wide range of technical, environmental, economic, and social advantages, the use of this method of house construction as a mainstream product is relatively new to Western Australia and so further research should be undertaken for actual implementation, and field assessment of the performance in Western Australia.

- There are further opportunities to mitigate environmental impacts by replacement of the polystyrene core of cast in-situ concrete sandwich wall system by polyethylene terephthalate (PET) foam core manufactured from post consumed PET bottles, and the replacement of metal columns and lintels by pultruded fibre reinforced polymer sections. A further research should be undertaken to investigate their appropriateness, and structural capacity and compliance to building codes.

- In addition to wall applications, the cast in-situ concrete sandwich system has been proven as a technically viable alternative to conventional roof systems and is being used in different countries. However the same has not been investigated for Australian climatic conditions. Further research should be undertaken to investigate the sustainability assessment of the cast in-situ concrete sandwich roof for the construction of houses in Western Australia.

- This research considered only one rectangular shaped floor layout of a typical 4x2x2 house in Western Australia for sustainability assessment. It was found that the shape of the house has some influence on the operational energy for heating and cooling of the house and hence the investigation to be undertaken for different floor layouts.

- Further research should be undertaken to investigate the impacts of the lot size on operational energy for heating and cooling of the house as the houses in narrow lots or infill construction tends to obstruct the access of solar energy to maintain the thermal comfort of the occupants.

- This research investigated the climate change impacts on cooling energy demand of the house due to anticipated temperature rise. The further research should be conducted to investigate the impacts of anticipated temperature rise on heating energy demand of a house.

- In spite of the successful implementation of Australian minimum energy efficiency standards for the houses, the desired results are not achieved due to the absence of any guidelines for energy audits and monitoring of actual performance. Hence, policy change is needed to develop performance based regulations for improving energy efficiency.

- Further research should be undertaken to investigate the impacts of colours of building envelope components (e.g. internal and external walls, roof, window frame and glazing, flooring, and ceiling) on operational energy demand for heating and cooling of a house.

- The system boundary has a major impact on the outcome of sustainability assessment studies of buildings using LCEA, LCA, and LCC approaches and is found to vary due to the absence of any stringent regulations and building sector specific guidelines. For example, some studies have included maintenance activities during use stage, while others have excluded maintenance activities. There is an urgent need to develop a uniform policy and guidelines for residential building sector to achieve the common goal of sustainable development.

- The inflation rate and discount rate are found to influence the life cycle costing and thus the decision making. There is a need to develop a building sector specific approach for selection of inflation rate and discount rate.

- A drastic policy change is needed so that the integration of renewable energy technologies such as roof top solar PV and solar water heaters are included as a mandatory component in new housing construction. This research has found that the slight increase in the overall capital cost of energy efficient options could attain significant operational cost savings from the reduction of electricity and natural gas consumption.

7.4 Conclusion

Considering the growing demand for houses in Western Australia, this integrated life cycle management framework for sustainability assessment of building materials and methods of construction of houses could not only help in reducing the associated GHG emissions and embodied energy consumption but will also offer social and economic sustainability. The outcome of this research will provide useful information for Architects, designers, developers, and policy makers to choose from sustainable options for construction of a house at a regional level.

The thesis has thus described the successful development and application of the comprehensive life cycle management (LCM) framework for improving the sustainability performance of a house construction in Western Australian.

References

Aashish Sharma, Abhishek Saxena, Muneesh Sethi, Venu Shree, Varun. 2011. "Life Cycle Assessment of Buildings: A Review." *Renewable and Sustainable Energy Reviews* 15: 871-875. www.elsevier.com/locate/rser.

ABBTF. 2016. Australian Brick & Blocklaying Training Foundation Ltd - Purpose and Levy. Accessed 19.01.2016, http://www.abbtf.com.au.

ABCB. 2014. *Climate Zone Maps*. Australian Building Codes Board (ABCB) http://www.abcb.gov.au/work-program/energy-efficiency/climate-zone-maps.aspx.

———. 2015a. *National Construction Code Series 2015 Volume Two*. Australian Building Codes Board (ABCB)

———. 2015b. *Ncc Volume Two - Energy Efficiency Provisions - Second Edition*. Australian Building Codes Board (ABCB)

ABS. 2006. "4153.0 - How Australians Use Their Time, 2006 (Released on 21.02.2008) " edited by Australian Bureau of Statistics, Canberra.

———. 2012. *Year Book Australia - Industry Structure and Performance*. http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/1301.0~2012~Main%20Features~Value%20of%20goods%20and%20services%20produced%20by%20Australian%20Industry~240.

———. 2013. *2011 Census of Population and Housing - Quickstats*. http://www.censusdata.abs.gov.au/census_services/getproduct/census/2011/quickstat/5004?opendocument&navpos=220.

———. 2014. "4602.0.55.001 - Environmental Issues: Energy Use and Conservation, March 2014 (Released on 03.12.2014)." edited by Australian Bureau of Statistics, Canberra.

ACCC. 2014. Accc Reauthorises Brick Levy to Help with Bricklayer Shortage. (MR 174/14) Accessed 19.01.2016, https://www.accc.gov.au/media-release/accc-reauthorises-brick-levy-to-help-with-bricklayer-shortage.

AccuRate. 2015. *Accurate Sustainability Tool Help Version 2.3.3.13sp2* Victoria, Australia: CSIRO Land & Water Flagship and distributed by Energy Inspection Pty Ltd.

ADAA. 2014. *Annual Membership Survey Results - January - December 2013*. http://www.adaa.asn.au/uploads/default/files/adaa_mship_report_2013.pdf.

Adalberth, Karin, Anders Almgren, and E Holleris Petersen. 2001. "Life-Cycle Assessment of Four Multi-Family Buildings." *International Journal of Low Energy and Sustainable Buildings*.

AER. 2014. Energy Made Easy - Choosing the Most Energy Efficient Appliances. Australian Energy Regulator, . Accessed 17.09.2014, https://www.energymadeeasy.gov.au/energy-efficiency/choosing-between-electricity-gas-and-solar.

Ahmed, Shaikh Faiz Uddin. 2012. "Properties of Concrete Containing Construction and Demolition Wastes and Fly Ash." *Journal of Materials in Civil Engineering* 25 (12): 1864-1870.

Aktacir, Mehmet Azmi, Orhan Büyükalaca, and Tuncay Yılmaz. 2010. "A Case Study for Influence of Building Thermal Insulation on Cooling Load and Air-Conditioning System in the Hot and Humid Regions." *Applied Energy* 87 (2): 599-607. doi: http://dx.doi.org/10.1016/j.apenergy.2009.05.008.

Al-Homoud, Dr Mohammad S. 2005. "Performance Characteristics and Practical Applications of Common Building Thermal Insulation Materials." *Building* *and Environment* 40 (3): 353-366. doi: http://dx.doi.org/10.1016/j.buildenv.2004.05.013.

Alam, Firoz, MGolam Rasul, Wasim Saman, Tranon Theos, and Aliakbar Akbarzadeh. 2009. "Residential House Energy Rating in Australia" *Regional Sustainability: Local Solutions to Global Issues: Proceedings of Central Region Engineering Conference 2009, 14-15 August, 2009, Rockhampton, Queensland*: College of Engineering and Built Environment, Faculty of Sciences, Engineering and Health, CQUniversity.

Aldawi, Fayez, Abhijit, Alam, Firoz Khan, Iftekhar Alghamdi and Mohammed. 2013. "Energy Efficient Residential House Wall System." *Applied Thermal Engineering* 58 (1): 400-410.

Aldawi, Fayez, Firoz Alam, Abhijit Date, Mohammed Alghamdi, and Fahad Aldhawi. 2013. "A New House Wall System for Residential Buildings." *Energy and Buildings* 67: 403-418.

Aldawi, Fayez, Firoz Alam, Iftekhar Khan, and Mohamed Alghamdi. 2013. "Effect of Climates and Building Materials on House Wall Thermal Performance." *Procedia Engineering* 56: 661-666.

Alexandre Kossoy, Grzegorz Peszko, Klaus Oppermann, Nicolai Prytz, Noémie Klein, Kornelis Blok, Long Lam, Lindee Wong, and Bram Borkent. 2015. *State and Trends of Carbon Pricing 2015*. Washington DC. doi: 10.1596/ 978-1-4648-0725-1.

Alintaenergy. 2015. Natural Gas Pricing and Fee, Western Australia. Accessed 17.11.2015, https://alintaenergy.com.au/wa/natural-gas/natural-gas-pricing-fees.

Alwi, Sugiharto, and Keith D Hampson. 2003. "Identifying the Important Causes of Delays in Bulding Construction Projects."

Ambrose, Michael, and P Newton. 2008. *Energy Efficient Housing and Subdivision Design*: CSIRO: Melbourne, Australia.

Amstalden, Roger W., Michael Kost, Carsten Nathani, and Dieter M. Imboden. 2007. "Economic Potential of Energy-Efficient Retrofitting in the Swiss Residential Building Sector: The Effects of Policy Instruments and Energy Price Expectations." *Energy Policy* 35 (3): 1819-1829. doi: http://dx.doi.org/10.1016/j.enpol.2006.05.018.

Anda, Martin, and Justin Temmen. 2014. "Smart Metering for Residential Energy Efficiency: The Use of Community Based Social Marketing for Behavioural Change and Smart Grid Introduction." *Renewable Energy* 67: 119-127.

Andersson, Brandt, Wayne Place, Ronald Kammerud, and M. Peter Scofield. 1985. "The Impact of Building Orientation on Residential Heating and Cooling." *Energy and Buildings* 8 (3): 205-224. doi: http://dx.doi.org/10.1016/0378-7788(85)90005-2.

Andrew, Jane, Mary A Kaidonis, and Brian Andrew. 2010. "Carbon Tax: Challenging Neoliberal Solutions to Climate Change." *Critical Perspectives on Accounting* 21 (7): 611-618.

APC. 2014. *2012-13 National Plastics Recycling Survey - Final Report*. http://www.packagingcovenant.org.au/data/Publications/R03-03-A11013_NPRS_2013-14_Report.pdf.

APVI. 2015. *National Survey Report of Pv Power Applications in Australia 2014*. Australian PV Institute. http://apvi.org.au/wp-content/uploads/2015/09/PV-in-Australia-2014.pdf.

Ardente, Fulvio, Giorgio Beccali, Maurizio Cellura, and Valerio Lo Brano. 2005. "Life Cycle Assessment of a Solar Thermal Collector." *Renewable Energy* 30 (7): 1031-1054. doi: http://dx.doi.org/10.1016/j.renene.2004.09.009.

Arif, Mohammad Taufiqul, Amanullah MT Oo, and ABM Ali. 2013. "Investigation of Energy Storage Systems, Its Advantage and Requirement in Various Locations in Australia." *Journal of Renewable Energy* 2013.

Arivalagan, S. 2014. "Sustainable Studies on Concrete with Ggbs as a Replacement Material in Cement." *Jordan Journal of Civil Engineering* 8 (3).

ASA. 2011. *Reference Data Sheet 1 - 2011 Blast Furnace Slag Aggregate & Cementitious Products*. http://www.asa-inc.org.au/uploads/default/files/asa_rds_1.pdf.

ASBEC. 2007. *Capitalising on the Building Sector's Potential to Lessen the Costs of a Broad Based Ghg Emissions Cut*.

Aste, Niccolò, Adriana Angelotti, and Michela Buzzetti. 2009. "The Influence of the External Walls Thermal Inertia on the Energy Performance of Well Insulated Buildings." *Energy and Buildings* 41 (11): 1181-1187. doi: http://dx.doi.org/10.1016/j.enbuild.2009.06.005.

ATCO. 2012. Atco Gas Australia - Gas Distribution. ATCO Gas Australia. Accessed 20.07.2013, http://www.atcogas.com.au.

Atmaca, Adem. 2016. "Life Cycle Assessment and Cost Analysis of Residential Buildings in South East of Turkey: Part 1—Review and Methodology." *The International Journal of Life Cycle Assessment*: 1-16. doi: 10.1007/s11367-016-1050-8.

Austral-Bricks. 2014. Clay Bricks across Western Australia - Locations and Availability. Accessed 24.09.2014, http://australbricks.com.au/wa/bricks/.

Avi-Yonah, Reuven S, and David M Uhlmann. 2009. "Combating Global Climate Change: Why a Carbon Tax Is a Better Response to Global Warming Than Cap and Trade." *Stanford Environmental Law Journal* 28 (3).

AWA. 2014. *Windows in New Dwellings*. Sydney, Australia. http://www.awa.org.au/documents/item/706.

Awaja, Firas, and Dumitru Pavel. 2005. "Recycling of Pet." *European Polymer Journal* 41 (7): 1453-1477. doi: http://dx.doi.org/10.1016/j.eurpolymj.2005.02.005.

Aye, Lu, and Dominique Hes. 2012. "Green Building Rating System Scores for Building Reuse." *College Publishing* 7 (2): 105-112.

Azapagic, Adisa, and R Clift. 1999. "Life Cycle Assessment and Multiobjective Optimisation." *Journal of Cleaner Production* 7 (2): 135-143.

Baggs, David, and Neal Mortensen. 2006. "Thermal Mass in Building Design." *Environmental Design Guide*.

Bahadori, Alireza, and Chikezie Nwaoha. 2013. "A Review on Solar Energy Utilisation in Australia." *Renewable and Sustainable Energy Reviews* 18: 1-5. doi: http://dx.doi.org/10.1016/j.rser.2012.10.003.

Bajracharya, R.M, W.P Lokuge, W Karunasena, K.T Lau, and A.S Mosallam. 2010. Structural Evaluation of Concrete Expanded Polystyrene Sandwich Panels for Slab Application. University of Southern Queensland. eprints.usq.edu.au/22601/5/Bajracharya_Lokuge_Karnasena_Lau_ACMSM.

Balaras, Constantinos A., Athina G. Gaglia, Elena Georgopoulou, Sevastianos Mirasgedis, Yiannis Sarafidis, and Dimitris P. Lalas. 2007. "European Residential Buildings and Empirical Assessment of the Hellenic Building Stock, Energy Consumption, Emissions and Potential Energy Savings."

Building and Environment 42 (3): 1298-1314. doi: http://dx.doi.org/10.1016/j.buildenv.2005.11.001.

Bambrick, Hilary Jane, Anthony Guy Capon, Guy Bruce Barnett, R Matthew Beaty, and Anthony John Burton. 2011. "Climate Change and Health in the Urban Environment: Adaptation Opportunities in Australian Cities." *Asia-Pacific Journal of Public Health* 23 (2 suppl): 67S-79S.

Bambrook, S. M., A. B. Sproul, and D. Jacob. 2011. "Design Optimisation for a Low Energy Home in Sydney." *Energy and Buildings* 43 (7): 1702-1711. doi: http://dx.doi.org/10.1016/j.enbuild.2011.03.013.

Bayer, Charlene, Michael Gamble, Russell Gentry, and Surabhi Joshi. 2010. "Aia Guide to Building Life Cycle Assessment in Practice." *Georgia Institute of Technology*.

Bazilian, Morgan, Ijeoma Onyeji, Michael Liebreich, Ian MacGill, Jennifer Chase, Jigar Shah, Dolf Gielen, Doug Arent, Doug Landfear, and Shi Zhengrong. 2013. "Re-Considering the Economics of Photovoltaic Power." *Renewable Energy* 53: 329-338. doi: http://dx.doi.org/10.1016/j.renene.2012.11.029.

BCEC. 2014. *Housing Affordability - the Real Costs of Housing in Wa*. Perth, Western Australia. http://business.curtin.edu.au/wp-content/uploads/sites/5/2015/09/066808_Bankwest_Curtin_Economics_Centre_Housing_Affordability_Report_WEB_V2.pdf.

Beattie, Colin, Jessica Bunning, Joanne Stewart, Peter Newman, and Martin Anda. 2012. "Measuring Carbon for Urban Development Planning." *The International Journal of Climate Change: Impacts and Responses* 3 (4): 35-52.

Beer, Andrew, Bridget Kearins, and Hans Pieters. 2007. "Housing Affordability and Planning in Australia: The Challenge of Policy under Neo-Liberalism." *Housing Studies* 22 (1): 11-24. doi: 10.1080/02673030601024572.

Bellamy, Larry. 2014. "Towards the Development of New Energy Performance Indicators for the External Walls of Residential Buildings." *Energy and Buildings* 68, Part B: 696-702. doi: http://dx.doi.org/10.1016/j.enbuild.2013.08.057.

Belusko, M., F. Bruno, and W. Saman. 2011. "Investigation of the Thermal Resistance of Timber Attic Spaces with Reflective Foil and Bulk Insulation, Heat Flow Up." *Applied Energy* 88 (1): 127-137. doi: http://dx.doi.org/10.1016/j.apenergy.2010.07.017.

Bender, Lloyd, and Thomas F. Stinson. 1984. "Mitigating Impacts of Rapid Growth on Local Government." *Journal of the Community Development Society* 15 (1): 59-73. doi: 10.1080/15575338409490074.

Bengtsson, Jonas, Clint Craggs, and Josh Dowse. 2014. *Energy-Efficient Dwellings - Can Embodied Energy Spoil the Story?* Australia. http://edgeenvironment.com.au/wordpress/wp-content/uploads/Lifecycle-emissions-of-energy-efficient-homes.pdf.

Berardi, Umberto. 2012. "Sustainability Assessment in the Construction Sector: Rating Systems and Rated Buildings." *Sustainable Development* 20 (6): 411-424. doi: 10.1002/sd.532.

Berndt, M. L. 2009. "Properties of Sustainable Concrete Containing Fly Ash, Slag and Recycled Concrete Aggregate." *Construction and Building Materials* 23 (7): 2606-2613. doi: http://dx.doi.org/10.1016/j.conbuildmat.2009.02.011.

Berry, Mike, and Tony Dalton. 2004. "Housing Prices and Policy Dilemmas: A Peculiarly Australian Problem?" *Urban Policy and Research* 22 (1): 69-91. doi: 10.1080/0811114042000185509.

Berry, Stephen, and Tony Marker. 2015a. "Australia's Nationwide House Energy Rating Scheme: The Scientific Basis for the Next Generation of Tools." *International Journal of Sustainable Building Technology and Urban Development* 6 (2): 90-102. doi: 10.1080/2093761X.2015.1025451.

———. 2015b. "Residential Energy Efficiency Standards in Australia: Where to Next?" *Energy Efficiency* 8 (5): 963-974.

Betts, Mike, Global Construction Perspectives, and Oxford Economics. 2009. *Global Construction 2020: A Global Forecast for the Construction Industry over the Next Decade to 2020*: Global Construction Perspectives and Oxford economics.

BGC. 2014. Construction Material and Concrete Products across Western Australia - Locations and Availability. Accessed 23.09.2014, http://www.bgc.com.au/.

Bienge, Katrin, Justus von Geibler, Michael Lettenmeier, B Biermann, O Adria, M Kuhndt, I Darnhofer, and M Grötzer. 2010. "Sustainability Hot Spot Analysis: A Streamlined Life Cycle Assessment Towards Sustainable Food Chains" *Conference proceedings of the 9th European International Farming System Association Symposium, Vienna Austria*.

Biswas, Wahidul K. 2014. "Carbon Footprint and Embodied Energy Consumption Assessment of Building Construction Works in Western Australia." *International Journal of Sustainable Built Environment* 3 (2): 179-186.

Biswas, Wahidul K, and David Cooling. 2013. "Sustainability Assessment of Red Sand as a Substitute for Virgin Sand and Crushed Limestone." *Journal of Industrial Ecology* 17 (5): 756-762.

Biswas, Wahidul K., and Gary Naude. 2016. "A Life Cycle Assessment of Processed Meat Products Supplied to Barrow Island: A Western Australian Case Study." *Journal of Food Engineering* 180: 48-59. doi: http://dx.doi.org/10.1016/j.jfoodeng.2016.02.008.

Björklund, Anna E. 2002. "Survey of Approaches to Improve Reliability in Lca." *The International Journal of Life Cycle Assessment* 7 (2): 64-72. doi: 10.1007/bf02978849.

Blackwell, P., E. Krull, G. Butler, A. Herbert, and Z. Solaiman. 2010. "Effect of Banded Biochar on Dryland Wheat Production and Fertiliser Use in South-Western Australia: An Agronomic and Economic Perspective." *Soil Research* 48 (7): 531-545. doi: http://dx.doi.org/10.1071/SR10014.

Blair, J., D. Prasad, B. Judd, R. Zehner, V. Soebarto, and R. Hyde. 2004. *Affordability and Sustainability Outcomes: A Triple Bottom Line Assessment of Traditional Development and Master Planned Communities—Volume 1, Ahuri Final Report No. 63*. Australian Housing and Urban Research Institute Limited. http://www.ahuri.edu.au/research/final-reports/63.

Blanchard, Benjamin S. 2014. "Life-Cycle Costing: An Effective Tool for Total Asset Management." *The Journal of Reliability, Maintainability & Supportability in Systems Engineering*: 6.

Blismas, Nick, and Ron Wakefield. 2009. "Drivers, Constraints and the Future of Offsite Manufacture in Australia." *Construction Innovation* 9 (1): 72-83. doi: doi:10.1108/14714170910931552.

Bloom, E, and C Wheelock. 2010. "Green Building Certification Programs." *Global Certification Programs for New and Existing Buildings in the Commercial and Residential Sectors: Market Analysis and Forecasts*.

Bluyssen, Philomena M. 2010. "Towards New Methods and Ways to Create Healthy and Comfortable Buildings." *Building and Environment* 45 (4): 808-818. doi: http://dx.doi.org/10.1016/j.buildenv.2009.08.020.

Bojić, Milorad, and Francis Yik. 2007. "Application of Advanced Glazing to High-Rise Residential Buildings in Hong Kong." *Building and Environment* 42 (2): 820-828. doi: http://dx.doi.org/10.1016/j.buildenv.2005.09.021.

BOM. 2015. Average Annual Daily Solar Exposure over Australia (1990-2011). Australian Government, Bureau of Meteorology. Accessed 10.01.2015, http://www.bom.gov.au/jsp/ncc/climate_averages/solar-exposure/index.jsp?period=an.

———. 2016. Average Daily Maximum Temperature Annual Based on S Standard 30 Year Climatology (1961-1990). Australian Government, Bureau of Meteorology. Accessed 01.06.2016, http://www.bom.gov.au/jsp/ncc/climate_averages/temperature/index.jsp.

Bond, Sandy. 2011. "Barriers and Drivers to Green Buildings in Australia and New Zealand." *Journal of Property Investment & Finance* 29 (4/5): 494-509. doi: doi:10.1108/14635781111150367.

Boral. 2014. Construction Material and Clay Bricks across Western Australia - Locations and Availability. Accessed 27.09.2014, http://www.boral.com.au/home.asp.

Bostancioğlu, E. 2010. "Effect of Building Shape on a Residential Building's Construction, Energy and Life Cycle Costs." *Architectural Science Review* 53 (4): 441-467. doi: 10.3763/asre.2009.0040.

BP. 2016. Calling for a Price on Carbon. Accessed 20.03.2016, http://www.bp.com/en/global/corporate/sustainability/the-energy-challenge-and-climate-change/calling-for-a-price-on-carbon.html.

Bragança, L, and Ricardo Mateus. 2012. *Life-Cycle Analysis of Buildings: Envirnonmental Impact of Building Elements*. Portugal: iiSBE Portugal.

Brännlund, Runar, Tarek Ghalwash, and Jonas Nordström. 2007. "Increased Energy Efficiency and the Rebound Effect: Effects on Consumption and Emissions." *Energy Economics* 29 (1): 1-17. doi: http://dx.doi.org/10.1016/j.eneco.2005.09.003.

BRANZ. 2011. *Technical Assessments of Products for Building and Construction - Evg3d Building System*. New Zealand. http://www.branz.co.nz/Appraisal/750.

BREE. 2014. *Energy in Australia 2014*. Canberra. http://www.industry.gov.au/industry/Office-of-the-Chief-Economist/Publications/Documents/energy-in-aust/bree-energyinaustralia-2014.pdf.

Breheny, N., E. Geelhoed, J. Goldblatt, H. Ee, and P. O'Leary. 2006. "Economic Evaluation of the Familial Cancer Programme in Western Australia: Predictive Genetic Testing for Familial Adenomatous Polyposis and Hereditary Non-Polyposis Colorectal Carcinoma." *Public Health Genomics* 9 (2): 98-106. http://www.karger.com/DOI/10.1159/000091487.

Brereton, S, and Rene van Berkel. 2001. "Cleaner Production in Residential Building." *Centre for Excellence in Cleaner Production, Curtin University, WA.*

Bunnings. 2014. Building Material, Hardware and Accessories across Western Australia - Locations and Availability. Accessed 23.09.2015, http://l.bunnings.com.au/trade/our-nearest-trade-store.aspx?state=WA.

Burchart-Korol, Dorota. 2013. "Life Cycle Assessment of Steel Production in Poland: A Case Study." *Journal of Cleaner Production* 54: 235-243. doi: http://dx.doi.org/10.1016/j.jclepro.2013.04.031.

Burgan, Bassam A, and Michael R Sansom. 2006. "Sustainable Steel Construction." *Journal of constructional steel research* 62 (11): 1178-1183.

Burgess, Jacquelin, and Michael Nye. 2008. "Re-Materialising Energy Use through Transparent Monitoring Systems." *Energy Policy* 36 (12): 4454-4459. doi: http://dx.doi.org/10.1016/j.enpol.2008.09.039.

Burinskienė, Marija, and Vitalija Rudzkienė. 2007. "Assessment of Sustainable Development in Transition." *Ekologija* 53 (Supplement): 27-33.

Burton, Elizabeth. 2003. "Housing for an Urban Renaissance: Implications for Social Equity." *Housing Studies* 18 (4): 537-562.

Buyle, MATTHIAS, JOHAN Braet, and AMARYLLIS Audenaert. 2012. "Review on Lca in the Construction Industry: Case Studies" *Proceedings of the 3rd INEEE conference: energy, environment, devices, systems, communications, computers (INEEE'12). Rovaniemi, Finland*.

Buys, Laurie, Karen R Barnett, Evonne Miller, and Chanel Bailey. 2005. "Smart Housing and Social Sustainability: Learning from the Residents of Queensland's Research House." *Australian Journal of Emerging Technologies and Society* 3 (1): 43-57.

Byrnes, Liam, Colin Brown, John Foster, and Liam D. Wagner. 2013. "Australian Renewable Energy Policy: Barriers and Challenges." *Renewable Energy* 60: 711-721. doi: http://dx.doi.org/10.1016/j.renene.2013.06.024.

Cabeza, Luisa F, Lídia Rincón, Virginia Vilariño, Gabriel Pérez, and Albert Castell. 2014. "Life Cycle Assessment (Lca) and Life Cycle Energy Analysis (Lcea) of Buildings and the Building Sector: A Review." *Renewable and Sustainable Energy Reviews* 29: 394-416.

Cabeza, Luisa F., Camila Barreneche, Laia Miró, Josep M. Morera, Esther Bartolí, and A. Inés Fernández. 2013. "Low Carbon and Low Embodied Energy Materials in Buildings: A Review." *Renewable and Sustainable Energy Reviews* 23: 536-542. doi: http://dx.doi.org/10.1016/j.rser.2013.03.017.

Campbell, Peter K., Tom Beer, and David Batten. 2011. "Life Cycle Assessment of Biodiesel Production from Microalgae in Ponds." *Bioresource Technology* 102 (1): 50-56. doi: http://dx.doi.org/10.1016/j.biortech.2010.06.048.

Carbonari, G., Cavalaro, S.H.P, Cansario, M.M., Aguado, A. 2012. "Flexural Behaviour of Light-Weight Sandwich Panels Composed by Concrete and Eps." *Elsevier - Construction and Building Materials* 35 (2012): 792-799. http://www.elsevier.com/locate/conbuildmat.

Carre, A, Enda Crossin, and Stephen Clune. 2013. "Lca of Kerbside Recycling in Victoria." *Report for Sustainability Victoria. Melbourne: RMIT University*.

Carre, A. 2011a. *A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design for Forest & Wood Products Australia*. Melbourne, Australia. http://www.fwpa.com.au/images/marketaccess/PNA147-0809-Australand.pdf.

Carre, A., and E. Crossin. 2015. *A Comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings Prepared for Forest & Wood Products Australia*. Melbourne, Australia. http://www.fwpa.com.au/images/marketaccess/PRA344-1415-Australand.pdf.

Carre, Andrew. 2011b. "Lca of Construction Materials in an Australian House Design." In *7th Australian Conference on Life Cycle Assessment. Life Cycle Assessment: Revealing the secrates of a green market, 9-10th March, 2011, Melbourne, Australia*. Australian Life Cycle Assessment Society (ALCAS). http://www.conference.alcas.asn.au/2011/Carre_Session1A_01032011.pdf.

Cavalline, Tara L., and David C. Weggel. 2013. "Recycled Brick Masonry Aggregate Concrete." *Structural Survey* 31 (3): 160-180. doi: doi:10.1108/SS-09-2012-0029.

CCAA. 2007. *Guide to Concrete for Housing*. Cement Concrete and Agregates Australia http://www.ccaa.com.au/imis_prod/documents/Library%20Documents/CCAA%20Technical%20Publications/CCAA%20Guides/CCAAGUIDE2007-T53-HousingWEB.pdf.

———. 2008. Guide to the Specification and Use of Manufactured Sand in Concrete.

———. 2012. *Sustainable Concrete Materials, Briefing 11*. http://www.ccaa.com.au/imis_prod/documents/Library%20Documents/CCAA%20Technical%20Publications/CCAA%20Briefings/Breifing%2011%20Materials_WEB.pdf.

———. 2013. *Sustainable Use of Aggregates, Briefing 19*. http://59.167.233.142/publications/pdf/Briefing%2019_2013_FINAL.pdf.

CEC. 2011. "Consumer Guide to Buying Household Solar Panels (Photovoltaic Panels)." Volume 14: 26 August 2011. http://www.cleanenergycouncil.org.au/dam/cec-solar-accreditation-shared/guides/Guide-to-installing-solar-PV-for-households.pdf.

———. 2013. *Clean Energy Australia 2013*. file:///C:/Users/257451H/Downloads/Clean-Energy-Australia-Report-2013.pdf.

———. 2014. *Clean Energy Australia Report 2014*. http://www.cleanenergycouncil.org.au/dam/cec/policy-and-advocacy/reports/2015/Clean-Energy-Australia-Report-2014.pdf.

Cetiner, Ikbal, and Ertan Özkan. 2005. "An Approach for the Evaluation of Energy and Cost Efficiency of Glass Façades." *Energy and Buildings* 37 (6): 673-684. doi: http://dx.doi.org/10.1016/j.enbuild.2004.10.007.

Chan, A. L. S. 2011. "Developing Future Hourly Weather Files for Studying the Impact of Climate Change on Building Energy Performance in Hong Kong." *Energy and Buildings* 43 (10): 2860-2868. doi: http://dx.doi.org/10.1016/j.enbuild.2011.07.003.

Chen, Dong, Michael Syme, Seongwon Seo, Wan Yee Chan, Mingwei Zhou, and Stephen Meddings. 2010. "Development of an Embodied Co2 Emissions Module for Accurate." *Forest & Wood Products Australia (FWPA), Melbourne, Australia. http://www. fwpa. com. au*.

Cheung, C. K., R. J. Fuller, and M. B. Luther. 2005. "Energy-Efficient Envelope Design for High-Rise Apartments." *Energy and Buildings* 37 (1): 37-48. doi: http://dx.doi.org/10.1016/j.enbuild.2004.05.002.

Chidambaram, Ramanathan, SP Narayanan, and Arazi B Idrus. 2012. "Construction Delays Causing Risks on Time and Cost-a Critical Review."

Chow, W. K., and Philip C. H. Yu. 2000. "Controlling Building Energy Use by Overall Thermal Transfer Value (Ottv)." *Energy* 25 (5): 463-478. doi: http://dx.doi.org/10.1016/S0360-5442(99)00079-1.

Chwieduk, Dorota. 2003. "Towards Sustainable-Energy Buildings." *Applied energy* 76 (1): 211-217.

CIF. 2014. *Industry Report 2013*. http://www.cement.org.au/Portals/0/Documents/CIF%20Publications/2013%20CIF%20Industry%20Report%20(Med%20Res).pdf.

Ciroth, Andreas, Günter Fleischer, and Jörg Steinbach. 2004. "Uncertainty Calculation in Life Cycle Assessments." *The International Journal of Life Cycle Assessment* 9 (4): 216-226. doi: 10.1007/BF02978597.

Clarkson, Scott, and Jonas Bengtsson. 2010. "Cradle to Grave Assessment and Benchmark of the Csr House."

Clune, Stephen, John Morrissey, and Trivess Moore. 2012. "Size Matters: House Size and Thermal Efficiency as Policy Strategies to Reduce Net Emissions of New Developments." *Energy policy* 48: 657-667.

Coates-Hire. 2014. Construction Plants and Machinery across Western Australia - Locations, Availability and Energy Consumption. Accessed 23.09.2014, http://www.coateshire.com.au/?gclid=CjwKEAjwotmoBRCc6LWd2ZnkuBYSJACyt2quV5eapH8T8YC_hmmqy8b-q2A-wD1h_ZeeTsfeLvMO5xoCriHw_wcB.

Codes, National Conference of States on Building, and Standards. 1980. *Ashrae Standard 90a-1980 Model Code for Energy Conservation in New Building Construction, December 1977: Comparison Paper*: National Conference of States on Building Codes and Standard.

Cole, Raymond J. 1998. "Energy and Greenhouse Gas Emissions Associated with the Construction of Alternative Structural Systems." *Building and Environment* 34 (3): 335-348.

Collins, Frank. 2013. "2nd Generation Concrete Construction: Carbon Footprint Accounting." *Engineering, Construction and Architectural Management* 20 (4): 330-344. doi: doi:10.1108/ECAM-09-2010-0072.

Consoli, F, D Allen, I Boustead, J Fava, W Franklin, and AA Jensen. 1993. "A Code of Practice." *Guidelines for life-cycle assessment, Pensacola, USA: SETAC*.

Crabtree, Louise, and Dominique Hes. 2009. "Sustainability Uptake in Housing in Metropolitan Australia: An Institutional Problem, Not a Technological One." *Housing Studies* 24 (2): 203-224. doi: 10.1080/02673030802704337.

Crawford, Emily. 2003. "Equity and the City: The Case of the East Perth Redevelopment." *Urban Policy and Research* 21 (1): 81-92.

Crawford, R. H., G. J. Treloar, B. D. Ilozor, and P. E. D. Love. 2003. "Comparative Greenhouse Emissions Analysis of Domestic Solar Hot Water Systems." *Building Research & Information* 31 (1): 34-47. doi: 10.1080/09613210210160800.

Crawford, Robert, and Robert Fuller. 2011. "Energy and Greenhouse Gas Emissions Implications of Alternative Housing Types for Australia" *Proceedings of the State of Australian Cities National Conference*: [Australian Sustainable Cities and Regions Network (ASCRN)].

Crawford, Robert H, and Graham J Treloar. 2004a. "Net Energy Analysis of Solar and Conventional Domestic Hot Water Systems in Melbourne, Australia." *Solar Energy* 76 (1): 159-163.

Crawford, Robert H. 2014. "Post-Occupancy Life Cycle Energy Assessment of a Residential Building in Australia." *Architectural Science Review* 57 (2): 114-124. doi: 10.1080/00038628.2013.819556.

Crawford, Robert H., Isabella Czerniakowski, and Robert J. Fuller. 2010. "A Comprehensive Framework for Assessing the Life-Cycle Energy of Building Construction Assemblies." *Architectural Science Review* 53 (3): 288-296. doi: 10.3763/asre.2010.0020.

———. 2011. "A Comprehensive Model for Streamlining Low-Energy Building Design." *Energy and Buildings* 43 (7): 1748-1756. doi: http://dx.doi.org/10.1016/j.enbuild.2011.03.020.

Crawford, Robert H., and Graham J. Treloar. 2004b. "Net Energy Analysis of Solar and Conventional Domestic Hot Water Systems in Melbourne, Australia." *Solar Energy* 76 (1–3): 159-163. doi: http://dx.doi.org/10.1016/j.solener.2003.07.030.

Crawley, Drury B. 2008. "Estimating the Impacts of Climate Change and Urbanization on Building Performance." *Journal of Building Performance Simulation* 1 (2): 91-115. doi: 10.1080/19401490802182079.

Crossin, E. 2015. "The Greenhouse Gas Implications of Using Ground Granulated Blast Furnace Slag as a Cement Substitute." *Journal of Cleaner Production* 95: 101-108. doi: http://dx.doi.org/10.1016/j.jclepro.2015.02.082.

Crossin, Enda, Mehdi Hedayati, and Stephen Clune. 2014. *Waste Avoidance and Reuse Strategies for Residential Buildings in Australia*. RMIT University, Melbourne. http://mams.rmit.edu.au/y1wjxknbixsu.pdf.

CSIRO. 2001. *Climate Change Projections for Australia*. Melbourne, Australia. http://www.cmar.csiro.au/e-print/open/projections2001.pdf.

———. 2012. *Area Correction Factors in Accurate V1.1.4.1 from Accurate Chenath Repository*. Melbourne, Australia.

CTC. 2015. "Pricing Carbon Efficiently and Equitably - Where Carbon Is Taxed." http://www.carbontax.org/where-carbon-is-taxed/.

Cucchiella, Federica, and Idiano D'Adamo. 2012. "Estimation of the Energetic and Environmental Impacts of a Roof-Mounted Building-Integrated Photovoltaic Systems." *Renewable and Sustainable Energy Reviews* 16 (7): 5245-5259. doi: http://dx.doi.org/10.1016/j.rser.2012.04.034.

Cuéllar-Franca, Rosa M., and Adisa Azapagic. 2012. "Environmental Impacts of the Uk Residential Sector: Life Cycle Assessment of Houses." *Building and Environment* 54: 86-99. doi: http://dx.doi.org/10.1016/j.buildenv.2012.02.005.

DCCEE. 2010. "Your Home, Technical Manual, Fourth Edition." edited by Department of Climate Change and Energy Efficiency.

De Boeck, L., S. Verbeke, A. Audenaert, and L. De Mesmaeker. 2015. "Improving the Energy Performance of Residential Buildings: A Literature Review." *Renewable and Sustainable Energy Reviews* 52: 960-975. doi: http://dx.doi.org/10.1016/j.rser.2015.07.037.

De Laborderie, Alexis, Clément Puech, Nadine Adra, Isabelle Blanc, Didier Beloin-Saint-Pierre, Pierryves Padey, Jérôme Payet, Marion Sie, and Philippe Jacquin. 2011. "Environmental Impacts of Solar Thermal Systems with Life Cycle Assessment" *World Renewable Energy Congress-Sweden*: Linköping University Electronic Press, Linköpings universitet.

de Meester, Tatiana, Anne-Françoise Marique, André De Herde, and Sigrid Reiter. 2013. "Impacts of Occupant Behaviours on Residential Heating Consumption for Detached Houses in a Temperate Climate in the Northern Part of Europe." *Energy and Buildings* 57 (0): 313-323. doi: http://dx.doi.org/10.1016/j.enbuild.2012.11.005.

Del Borghi, Adriana. 2013. "Lca and Communication: Environmental Product Declaration." *The International Journal of Life Cycle Assessment* 18 (2): 293-295. doi: 10.1007/s11367-012-0513-9.

Delsante, Angelo. 2005. "Is the New Generation of Building Energy Rating Software up to the Task?-a Review of Accurate" *ABCB Conference,"Building Australia's Future, Gold Coast, Queensland, Australia.*

DER. 2015. Landfill Levy Rates to Rise from January 2015. Department of Environment Regulation, Government of Western Australia. https://www.der.wa.gov.au/about-us/media-statements/112-landfill-levy-rates-to-rise-from-january-2015.

DEWHA, "Energy Use in the Australian Residentail Sector 1986-2020," 2008a, http://www.industry.gov.au/Energy/Energy-information/Documents/energyuseaustralianresidentialsector19862020part1.pdf.

———. 2008b. *Energy Use in the Australian Residential Sector 1986-2020*: Department of the Environment, Water, Heritage and the Arts.

Dewsbury, Mark, Florence Soriano, and Roger Fay. 2011. "An Empirical Validation of The'accurate'software Envelope Model Using a Concrete Slab-on-Ground Test Building" *Proceedings of the 12th Conference of International Building Performance Simulation Association, Sydney*, Australia.

Dick Clarke, Bernard Hockings, Caitlin McGee. 2013. *Materials, Concrete Slab Floors - Your Home Australia's Guide to Environmentally Sustainable Homes, 5th Editionhttp*. Canberra, Australia. http://www.yourhome.gov.au/materials/concrete-slab-floors.

Dincer, Ibrahim, and Marc A Rosen. 2012. *Exergy: Energy, Environment and Sustainable Development*: Newnes.

Ding, Grace K. C. 2008. "Sustainable Construction—the Role of Environmental Assessment Tools." *Journal of environmental management* 86 (3): 451-464. doi: http://dx.doi.org/10.1016/j.jenvman.2006.12.025.

DIS. 2015. *Residential Baseline Study for Australia 2000-2030*. Victoria, Australia: Energy Consult pty ltd. http://www.energyrating.gov.au/document/report-residential-baseline-study-australia-2000-2030.

Dixit, Manish K, Jose L Fernández-Solís, Sarel Lavy, and Charles H Culp. 2012. "Need for an Embodied Energy Measurement Protocol for Buildings: A Review Paper." *Renewable and Sustainable Energy Reviews* 16 (6): 3730-3743.

DOE. 2013. *National Waste Reporting 2013* http://www.environment.gov.au/topics/environment-protection/nwp/reporting/national-waste-stream#a1.

———. 2014a. *Australian National Greenhouse Accounts - Quarterly Update of Australia's National Greenhouse Gas Inventory - September Quarter 2013*. http://www.environment.gov.au/system/files/resources/e18788bd-2a8a-49d1-b797-307a9763c93f/files/quartlery-update-september-2013_1.pdf.

———. 2014b. *Australian National Greenhouse Accounts Factors - Australian National Greenhouse Accounts - July 2014*. http://www.environment.gov.au/system/files/resources/b24f8db4-e55a-4deb-a0b3-32cf763a5dab/files/national-greenhouse-accounts-factors-2014.pdf.

———. 2015a. *Australia's 2030 Emissions Reduction Target*. Canberra, Australia. http://www.environment.gov.au/system/files/resources/f52d7587-8103-49a3-

aeb6-651885fa6095/files/summary-australias-2030-emissions-reduction-target.pdf.

———. 2015b. *Australian National Greenhouse Accounts - Quarterly Update of Australia's National Greenhouse Gas Inventory - March 2015*. http://www.environment.gov.au/system/files/resources/5e5fafe9-15be-4eb9-a8cf-a92db6814ea6/files/nggi-quarterly-update-mar-2015.pdf.

DOF. 2015a. Electricity in Western Australia. Department of Finance, Government of Western Australia. Accessed 23.09.2015, http://www.finance.wa.gov.au/cms/Public_Utilities_Office/Energy_in_Western_Australia/Electricity/Electricity_in_Western_Australia.aspx.

———. 2015b. Electricity Pricing in Western Australia. Department of Finance, Government of Western Australia. Accessed 17.11.2015, http://www.finance.wa.gov.au/cms/Public_Utilities_Office/Energy_in_Western_Australia/Electricity/Electricity_pricing.aspx.

———. 2015c. Gas in Western Australia. Department of Finance, Government of Western Australia. Accessed 16.12.2015, http://www.finance.wa.gov.au/cms/Public_Utilities_Office/Energy_in_Western_Australia/Gas/Gas_in_WA.aspx.

———. 2015d. Residential Net Feed-in Tariff Scheme. Department of Finance, Government of Western Australia. Accessed 15.10.2015, http://www.finance.wa.gov.au/cms/Public_Utilities_Office/Energy_Initiatives/Residential_net_feed-in_tariff_scheme.aspx.

DOH&DOP. 2013. *The Housing We'd Choose: A Study for Perth and Peel*. Western Australia.http://www.housing.wa.gov.au/HousingDocuments/HWC_FullReport.pdf.

Donald Marron, Eric Toder, Lydia Austin. 2015. *Taxing Carbon: What, Why, and How*. USA. http://www.taxpolicycenter.org/UploadedPDF/2000274-Taxing-Carbon-What-Why-and-How.pdf.

DOP. 2015. Regional Planning. Department of Planning, Western Australian Planning Commission, Government of Western Australia. Accessed 23.07.2013, http://www.planning.wa.gov.au/regional-planning.asp.

DOSD. 2015. Western Australia - Economic Profile, November 2015. Government of Western Australia - Department of State Development. Accessed 16.12.2015, http://www.dsd.wa.gov.au/docs/default-source/default-document-library/wa-economic-profile---november-2015?sfvrsn=4.

Dowdell, David C. 2014. *New Zealand Whole Building Whole of Life Framework: Life Cycle Assessment Based Indicators; Branz Study Report Sr 293[2014] Judgeford*. http://www.branz.co.nz/cms_show_download.php?id=11af33c627ad42a02e5c6e62b5d4a9cfb280efca.

DRDL. 2012. "Business Case Proposal for Manjimup, Developing an Age-Friendly Town." edited by Government of Western Australia Department of Regional Development and Lands, Western Australia.

DRET. 2013. *Solar Water Heater Guide for Households*. Canberra, Australia. http://www.industry.gov.au/Energy/EnergyEfficiency/Documents/08_2013/Solar-water-heater-guide-for-households.pdf.

EcoHub-Perth. 2014. The City of Perth Sustainable Living Guide. City of Perth in conjunction with The Natural Strategies Group. Accessed 25.09.2014, http://www.ecohub.perth.wa.gov.au/.

Engelbrecht, Deborah, Wahidul K Biswas, and Waqar Ahmad. 2013. "An Evaluation of Integrated Spatial Technology Framework for Greenhouse Gas Mitigation in Grain Production in Western Australia." *Journal of Cleaner Production* 57: 69-78.

Eskin, Nurdil, and Hamdi Türkmen. 2008. "Analysis of Annual Heating and Cooling Energy Requirements for Office Buildings in Different Climates in Turkey." *Energy and Buildings* 40 (5): 763-773. doi: http://dx.doi.org/10.1016/j.enbuild.2007.05.008.

Farmery, A., C. Gardner, B. S. Green, S. Jennings, and R. Watson. 2015. "Life Cycle Assessment of Wild Capture Prawns: Expanding Sustainability Considerations in the Australian Northern Prawn Fishery." *Journal of Cleaner Production* 87: 96-104. doi: http://dx.doi.org/10.1016/j.jclepro.2014.10.063.

Fate, Swapnil S. 2014. "Concrete with Smart Material (Manufactured Crushed Sand)-a Review." *IOSR Journal of Mechanical and Civil Engineering*: 27-29.

Fay, Roger, Graham Treloar, and Usha Iyer-Raniga. 2000. "Life-Cycle Energy Analysis of Buildings: A Case Study." *Building Research & Information* 28 (1): 31-41.

Ferreira, Adelino, and João Santos. 2013. "Life-Cycle Cost Analysis System for Pavement Management at Project Level: Sensitivity Analysis to the Discount Rate." *International Journal of Pavement Engineering* 14 (7): 655-673. doi: 10.1080/10298436.2012.719618.

Finnveden, Göran, Michael Z Hauschild, Tomas Ekvall, Jeroen Guinée, Reinout Heijungs, Stefanie Hellweg, Annette Koehler, David Pennington, and Sangwon Suh. 2009. "Recent Developments in Life Cycle Assessment." *Journal of environmental management* 91 (1): 1-21.

Florides, G. A., S. A. Tassou, S. A. Kalogirou, and L. C. Wrobel. 2002. "Measures Used to Lower Building Energy Consumption and Their Cost Effectiveness." *Applied Energy* 73 (3–4): 299-328. doi: http://dx.doi.org/10.1016/S0306-2619(02)00119-8.

Flower, David JM, and Jay G Sanjayan. 2007. "Green House Gas Emissions Due to Concrete Manufacture." *The International Journal of Life Cycle Assessment* 12 (5): 282-288.

Flugge, Felicity, and Amir Abadi. 2006. "Farming Carbon: An Economic Analysis of Agroforestry for Carbon Sequestration and Dryland Salinity Reduction in Western Australia." *Agroforestry Systems* 68 (3): 181-192. doi: 10.1007/s10457-006-9008-7.

Forsythe, Perry, and Kirsty Máté. 2007. "Assessing Brick Waste on Domestic Construction Sites for Future Avoidance." In *41st Annual Conference of the Architectural Science Association ANZAScA 2007 at Deakin University*. http://anzasca.net/wp-content/uploads/2014/08/ANZAScA2007_Perry-Forsythe_Kirsty-Mate.pdf.

Foti, Dora. 2011. "Preliminary Analysis of Concrete Reinforced with Waste Bottles Pet Fibers." *Construction and Building Materials* 25 (4): 1906-1915.

Frischknecht, R, N Jungbluth, HJ Althaus, C Bauer, G Doka, R Dones, R Hischier, S Hellweg, S Humbert, and T Köllner. 2007. "Implementation of Life Cycle Impact Assessment Methods." *Ecoinvent report*.

Frischknecht, Rolf, Franziska Wyss, Sybille Büsser Knöpfel, Thomas Lützkendorf, and Maria Balouktsi. 2015. "Cumulative Energy Demand in Lca: The Energy Harvested Approach." *The International Journal of Life Cycle Assessment* 20 (7): 957-969. doi: 10.1007/s11367-015-0897-4.

Gara, F, L Ragni, D Roia, and L Dezi. 2012. "Experimental Tests and Numerical Modelling of Wall Sandwich Panels." *Elsevier - Engineering Structures* 37 (2012): 193-204. http://www.elsevier.com/locate/engstruct.

Geard, Detlev. 2011. "An Empirical Validation of the House Energy Rating Software Accurate for Residential Buildings in Cool Temperate Climates of Australia." University of Tasmania.

Geoscience-Australia, and BREE. 2010. *Australian Energy Resource Assessment*. http://data.daff.gov.au/brs/data/warehouse/pe_abarebrs99014434/energy_proj.pdf.

———. 2014. *Australian Energy Resource Assessment 2nd Ed.* Canberra, Australia. https://d28rz98at9flks.cloudfront.net/79675/79675_AERA.pdf.

Ghattas, Randa, Jeremy Gregory, Elsa Olivetti, Suzanne Greene, and Concrete Sustainability Hub. 2013. "Life Cycle Assessment for Residential Buildings: A Literature Review and Gap Analysis."

Gheewala, Shabbir H. 2003. "Application of Life Cycle Assessment to Cleaner Production." *International Energy Journal* 4 (1): 5e15.

Giannetti, BF, SH Bonilla, IR Silva, and CMVB Almeida. 2008. "Cleaner Production Practices in a Medium Size Gold-Plated Jewelry Company in Brazil: When Little Changes Make the Difference." *Journal of Cleaner Production* 16 (10): 1106-1117.

Gibson, Robert B. 2006. "Sustainability Assessment: Basic Components of a Practical Approach." *Impact Assessment and Project Appraisal* 24 (3): 170-182.

Gillingham, Kenneth, Matthew J. Kotchen, David S. Rapson, and Gernot Wagner. 2013. "Energy Policy: The Rebound Effect Is Overplayed." *Nature* 493 (7433): 475-476. http://dx.doi.org/10.1038/493475a.

Gluch, Pernilla, and Henrikke Baumann. 2004. "The Life Cycle Costing (LCC) Approach: A Conceptual Discussion of Its Usefulness for Environmental Decision-Making." *Building and Environment* 39 (5): 571-580. doi: http://dx.doi.org/10.1016/j.buildenv.2003.10.008.

GOWA. 2003. *Hope for the Future: The Western Australian State Sustainability Strategy*. Perth, WA. http://www.nrm.wa.gov.au/media/19609/state_sustainability_strategy_2003.pdf.

Grant, Tim. 2009. "Inclusion of Uncertainty in Lca." *Centre for Design at RMIT University, Melbourne*.

Greening, Lorna A., David L. Greene, and Carmen Difiglio. 2000. "Energy Efficiency and Consumption — the Rebound Effect — a Survey." *Energy Policy* 28 (6–7): 389-401. doi: http://dx.doi.org/10.1016/S0301-4215(00)00021-5.

Gregory, Katherine, Behdad Moghtaderi, Heber Sugo, and Adrian Page. 2008. "Effect of Thermal Mass on the Thermal Performance of Various Australian Residential Constructions Systems." *Energy and Buildings* 40 (4): 459-465. doi: http://dx.doi.org/10.1016/j.enbuild.2007.04.001.

Guan, Lisa. 2009. "Implication of Global Warming on Air-Conditioned Office Buildings in Australia." *Building Research & Information* 37 (1): 43-54.

———. 2012. "Energy Use, Indoor Temperature and Possible Adaptation Strategies for Air-Conditioned Office Buildings in Face of Global Warming." *Building and Environment* 55: 8-19.

Guggemos, A., and A. Horvath. 2005. "Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings." *Journal of Infrastructure Systems* 11 (2): 93-101. doi: doi:10.1061/(ASCE)1076-0342(2005)11:2(93).

Guo, M, and RJ Murphy. 2012. "Lca Data Quality: Sensitivity and Uncertainty Analysis." *Science of the total environment* 435: 230-243.

Gurran, Nicole. 2008. "Affordable Housing: A Dilemma for Metropolitan Planning?".

Gurung, Netra, and Mahen Mahendran. 2002. "Comparative Life Cycle Costs for New Steel Portal Frame Building Systems." *Building Research & Information* 30 (1): 35-46. doi: 10.1080/09613210110054999.

Gustavsson, Leif, and Anna Joelsson. 2010. "Life Cycle Primary Energy Analysis of Residential Buildings." *Energy and Buildings* 42 (2): 210-220.

Häkkinen, Tarja, and Kaisa Belloni. 2011. "Barriers and Drivers for Sustainable Building." *Building Research & Information* 39 (3): 239-255. doi: 10.1080/09613218.2011.561948.

Hall, Mark, and David Purchase. 2006. "Building or Bodging? Attitudes to Sustainability in Uk Public Sector Housing Construction Development." *Sustainable Development* 14 (3): 205-218.

Hanson. 2014. Concrete and Concrete Products across Western Australia - Locations and Availability. Accessed 23.09.2014, http://www.hanson.com.au/Productsandservices.aspx.

Harrington, Lloyd, Robert Foster, and George Wilkenfeld. 2008. *Energy Use in the Australian Residential Sector 1986-2020*.

Harrison, M. 2010. "*Valuing the Future: The Social Discount Rate in Cost-Benefit Anlysis*, Visiting Researcher Paper " edited by Productivity Commission, Canberra, Australia.

Hauschild, Michael Z, Mark Goedkoop, Jeroen Guinée, Reinout Heijungs, Mark Huijbregts, Olivier Jolliet, Manuele Margni, An De Schryver, Sebastien Humbert, and Alexis Laurent. 2013. "Identifying Best Existing Practice for Characterization Modeling in Life Cycle Impact Assessment." *The International Journal of Life Cycle Assessment* 18 (3): 683-697.

HE, Sheng-Dong, Hua WANG, and Lei LI. 2015. "Experimental Study on Compressive Strength of Manufactured Sand Concrete."

Hedayati, Mehdi, Usha Iyer-Raniga, and Enda Crossin. 2014. "A Greenhouse Gas Assessment of a Stadium in Australia." *Building Research & Information* 42 (5): 602-615.

Heijungs, Reinout, Jeroen Bartholomeus Guinée, Gjalt Huppes, Raymond M Lankreijer, Helias A Udo de Haes, Anneke Wegener Sleeswijk, AMM Ansems, PG Eggels, R van Duin, and HP De Goede. 1992. "Environmental Life Cycle Assessment of Products: Guide and Backgrounds (Part 1)."

Henry, Michael, and Yoshitaka Kato. 2012. "Understanding the Regional Context of Sustainable Concrete in Asia: Case Studies in Thailand and Korea." *Resources, Conservation and Recycling* 69: 122-129. doi: http://dx.doi.org/10.1016/j.resconrec.2012.09.016.

Hernandez, Patxi, and Paul Kenny. 2012. "Net Energy Analysis of Domestic Solar Water Heating Installations in Operation." *Renewable and Sustainable Energy Reviews* 16 (1): 170-177. doi: http://dx.doi.org/10.1016/j.rser.2011.07.144.

Herring, Horace. 2006. "Energy Efficiency—a Critical View." *Energy* 31 (1): 10-20. doi: http://dx.doi.org/10.1016/j.energy.2004.04.055.

Herring, Horace, and Robin Roy. 2007. "Technological Innovation, Energy Efficient Design and the Rebound Effect." *Technovation* 27 (4): 194-203. doi: http://dx.doi.org/10.1016/j.technovation.2006.11.004.

Holcim. 2014. Concrete and Concrete Products across Western Australia - Locations and Availability. Accessed 27.09.2014, http://www.holcim.com.au/products-and-services.html.

Hollaway, LC. 2010. "A Review of the Present and Future Utilisation of FRP Composites in the Civil Infrastructure with Reference to Their Important in-Service Properties." *Construction and Building Materials* 24 (12): 2419-2445.

Holmes, Michael J., and Jacob N. Hacker. 2007. "Climate Change, Thermal Comfort and Energy: Meeting the Design Challenges of the 21st Century." *Energy and Buildings* 39 (7): 802-814. doi: http://dx.doi.org/10.1016/j.enbuild.2007.02.009.

Horizon. 2015a. Horizon Power Service Areas. Horizon Power. http://horizonpower.com.au/documents/service-areas.pdf.

———. 2015b. Mungullah Power Station, Carnarvon. Horizon Power. http://horizonpower.com.au/about-us/our-assets/mungullah-power-station-carnarvon/.

Horne, Ralph, and Carolyn Hayles. 2008. "Towards Global Benchmarking for Sustainable Homes: An International Comparison of the Energy Performance of Housing." *Journal of Housing and the Built Environment* 23 (2): 119-130.

Horne, Ralph, Lisa Opray, and Tim Grant. 2006. "Integrating Life Cycle Assessment into Housing Environmental Performance Assessment" *5th Australian Conference on Life Cycle Assessment" Achieving business benefits from managing life cycle impacts*, *Melbourne, Australia* .

Horner, M, C Hardcastle, and A Price. 2007. "Examining the Role of Building Envelopes Towards Achieving Sustainable Buildings."

Hotfrog. 2014. Building Materials in Western Australia - Free Online Business Directory. Accessed 23.09.2014, http://www.hotfrog.com.au/Products/Building-Materials/WA.

Huijbregts, Mark AJ, Wim Gilijamse, Ad MJ Ragas, and Lucas Reijnders. 2003. "Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling." *Environmental science & technology* 37 (11): 2600-2608.

Hung, Ming-Lung, and Hwong-wen Ma. 2009. "Quantifying System Uncertainty of Life Cycle Assessment Based on Monte Carlo Simulation." *The International Journal of Life Cycle Assessment* 14 (1): 19-27. doi: 10.1007/s11367-008-0034-8.

Hunkeler, DAVID, KONRAD Saur, HEIDI Stranddorf, GERALD Rebitzer, WP Schmidt, Allan A Jensen, and K Christiansen. 2003. "Life Cycle Management." *SETAC, in review (to be published in 2003).*

Hunt, Greg. 2015. "Labor Party Has Put Carbon Tax Back on the Agenda." *THE AUSTRALIAN*, 30.01.2015. http://www.theaustralian.com.au/opinion/labor-party-has-put-carbon-tax-back-on-the-agenda/news-story/7a3c7df0815299d1880f69fee03b5a7b.

Huppes, Gjalt, and Masanobu Ishikawa. 2005. "A Framework for Quantified Eco-Efficiency Analysis." *Journal of Industrial Ecology* 9 (4): 25-41. doi: 10.1162/108819805775247882.

Huy, Nguyen Huu. 2002. "Risk Assessment and Management for a Sustained Shelter Delivery System in Vietnam." *the International Federation of Red Cross and Red Crescent Societies Disaster Management Center*: 59.

IA. 2016. *Infrastructure Australia Assessment Framework - Detailed Technical Guidance*. Sydney, Australia.

http://infrastructureaustralia.gov.au/projects/files/Assessment_Framework_Detailed_Technical_Guidance.pdf.

Ibn-Mohammed, T., R. Greenough, S. Taylor, L. Ozawa-Meida, and A. Acquaye. 2013. "Operational Vs. Embodied Emissions in Buildings—a Review of Current Trends." *Energy and Buildings* 66: 232-245. doi: http://dx.doi.org/10.1016/j.enbuild.2013.07.026.

IMO. 2014. *2014 Swis Electricity Demand Outlook*. http://www.imowa.com.au/docs/default-source/Reserve-Capacity/soo/imo_2014-swis-electricity-demand-outlook.pdf?sfvrsn=0.

Ingwersen, Wesley W., Ahjond S. Garmestani, Michael A. Gonzalez, and Joshua J. Templeton. 2013. "A Systems Perspective on Responses to Climate Change." *Clean Technologies and Environmental Policy* 16 (4): 719-730. doi: 10.1007/s10098-012-0577-z.

Intini, Francesca, and Silvana Kühtz. 2011. "Recycling in Buildings: An Lca Case Study of a Thermal Insulation Panel Made of Polyester Fiber, Recycled from Post-Consumer Pet Bottles." *The International Journal of Life Cycle Assessment* 16 (4): 306-315.

IPCC. 2014. *Glimate Change 2014: Synthesis Report. Contribution of Working Groups I, Ii and Iii to the Fifth Assessment Report (Ar5) of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer(Eds.)]*. Geneva, Switzerland. http://ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf.

Islam, H, M Jollands, and S Setunge. 2010. "Life Cycle Assessment of Residential Buildings: Sustainable Material Options in Wall Assemblies." In *Chemeca 2010: Engineering at the Edge; 26-29 September 2010. Barton, A.C.T.: Engineers Australia, 2010: [3443]-[3452], Hilton Adelaide, Australia*.

Islam, Hamidul, Margaret Jollands, and Sujeeva Setunge. 2015. "Life Cycle Assessment and Life Cycle Cost Implication of Residential Buildings—a Review." *Renewable and Sustainable Energy Reviews* 42: 129-140.

Islam, Hamidul, Margaret Jollands, Sujeeva Setunge, Iftekhar Ahmed, and Nawshad Haque. 2014. "Life Cycle Assessment and Life Cycle Cost Implications of Wall Assemblages Designs." *Energy and Buildings* 84: 33-45.

Islam, Hamidul, Margaret Jollands, Sujeeva Setunge, Nawshad Haque, and Muhammed A. Bhuiyan. 2015. "Life Cycle Assessment and Life Cycle Cost Implications for Roofing and Floor Designs in Residential Buildings." *Energy and Buildings* 104: 250-263. doi: http://dx.doi.org/10.1016/j.enbuild.2015.07.017.

Islam, M. Raisul, K. Sumathy, and Samee Ullah Khan. 2013. "Solar Water Heating Systems and Their Market Trends." *Renewable and Sustainable Energy Reviews* 17: 1-25. doi: http://dx.doi.org/10.1016/j.rser.2012.09.011.

ISO14040. 2006. "Iso 14040:2006 - Environmental Management -- Life Cycle Assessment -- Principles and Framework." International Organization for Standardization, Geneva.

ISO14044. 2006. "Iso 14044:2006 - Environmental Management -- Life Cycle Assessment -- Requirements and Guidelines." International Organization for Standardization, Geneva.

ISO15686-5. 2008(en). *Iso 15686-5:2008(En) - Buildings and Constructed Assets - Service-Life Planning - Part5: Life-Cycle Costing*. International Organization

for Standardization, Geneva https://www.iso.org/obp/ui/#iso:std:iso:15686:-5:ed-1:v1:en.
Iwaro, Joseph, and Abrahams Mwasha. 2013. "The Impact of Sustainable Building Envelope Design on Building Sustainability Using Integrated Performance Model." *International Journal of Sustainable Built Environment* 2 (2): 153-171.
Iyer-Raniga, Usha, and James Pow Chew Wong. 2012. "Evaluation of Whole Life Cycle Assessment for Heritage Buildings in Australia." *Building and Environment* 47: 138-149.
Jaber, Samar, and Salman Ajib. 2011. "Optimum, Technical and Energy Efficiency Design of Residential Building in Mediterranean Region." *Energy and Buildings* 43 (8): 1829-1834. doi: http://dx.doi.org/10.1016/j.enbuild.2011.03.024.
Jadhav, Priyanka A, and Dilip K Kulkarni. 2012. "An Experimental Investigation on the Properties of Concrete Containing Manufactured Sand." *International Journal of Advanced Engineering Technology* 3 (2): 101-104.
Japon, Sonia, Yves Leterrier, and Jan-Anders E Månson. 2000. "Recycling of Poly (Ethylene Terephthalate) into Closed-Cell Foams." *Polymer Engineering & Science* 40 (8): 1942-1952.
Jensen, Allan Astrup. 1996. "Lca on the Right Track!" *The International Journal of Life Cycle Assessment* 1 (3): 121-122.
Jensen, Allan Astrup, Leif Hoffman, Birgitte T. Moller, and Anders Schmidt. 1997. *Life Cycle Assessment (Lca): A Guide to Approaches, Experiences and Information Sources*: European Communities.
Jensen, Christopher. 2013. *Independent Review of the Thermal Performance of Roofing Material Proposal for Australian Building Codes Board (Abcb)*. Melbourne, Australia.
Ji, Tao, Cai-Yi Chen, Yi-Zhou Zhuang, and Jian-Feng Chen. 2013. "A Mix Proportion Design Method of Manufactured Sand Concrete Based on Minimum Paste Theory." *Construction and Building Materials* 44: 422-426. doi: http://dx.doi.org/10.1016/j.conbuildmat.2013.02.074.
Jin, Sang-Hyeon. 2007. "The Effectiveness of Energy Efficiency Improvement in a Developing Country: Rebound Effect of Residential Electricity Use in South Korea." *Energy Policy* 35 (11): 5622-5629. doi: http://dx.doi.org/10.1016/j.enpol.2007.05.028.
Jørgensen, Tine Herreborg. 2008. "Towards More Sustainable Management Systems: Through Life Cycle Management and Integration." *Journal of Cleaner Production* 16 (10): 1071-1080. doi: http://dx.doi.org/10.1016/j.jclepro.2007.06.006.
Joseph, Paul, and Svetlana Tretsiakova-McNally. 2010. "Sustainable Non-Metallic Building Materials." *Sustainability* 2 (2): 400-427.
Kabir, M.Z., Rezaifar, O., Rahbar, M.R. 2004. "Non-Linear Dynamic Behavior of Combined System on Rc Frame Precast 3d Wall Panels with Irregularities in Vertical Stiffness." In *13th World Conference On Earthquake Engineering Vancouver, B.C., Canada, August 1-6, 2004*. http://www.iitk.ac.in/nicee/wcee/article/13_3134.pdf.
Kalogirou, Soteris. 2009. "Thermal Performance, Economic and Environmental Life Cycle Analysis of Thermosiphon Solar Water Heaters." *Solar Energy* 83 (1): 39-48. doi: http://dx.doi.org/10.1016/j.solener.2008.06.005.

Kane, A, RJ Fuller, MB Luther, and R Boldys. 2009. "Improving Comfort Levels in Darwin Houses through Passive Design" *ANZSES 2009: Proceedings of the Solar 2009 the 47th ANZSES Annual Conference*: ANZSES.

Kannan, R., K. C. Leong, R. Osman, H. K. Ho, and C. P. Tso. 2006. "Life Cycle Assessment Study of Solar Pv Systems: An Example of a 2.7 Kwp Distributed Solar Pv System in Singapore." *Solar Energy* 80 (5): 555-563. doi: http://dx.doi.org/10.1016/j.solener.2005.04.008.

Karimpour, Mahsa, Martin Belusko, Ke Xing, and Frank Bruno. 2014. "Minimising the Life Cycle Energy of Buildings: Review and Analysis." *Building and Environment* 73: 106-114. doi: http://dx.doi.org/10.1016/j.buildenv.2013.11.019.

Karuppannan, Sadasivam, and Sun Sheng Han. 2013. "Assessing Household Energy Consumption in Adelaide and Melbourne" *Proceedings of the 2013 State of Australian Cities Conference, 26-29th November, Sydney, Australia*.

Kayrbekova, Dina, Tore Markeset, and Behzad Ghodrati. 2011. "Activity-Based Life Cycle Cost Analysis as an Alternative to Conventional Lcc in Engineering Design." *International Journal of System Assurance Engineering and Management* 2 (3): 218-225. doi: 10.1007/s13198-011-0064-7.

Kelly, Anthony. 2015. *Ibis World Industry Report E3011 House Construction in Australia*. http://clients1.ibisworld.com.au/reports/au/industry/default.aspx?entid=309.

Kelly, Jane-Frances, P Breadon, and J Reichl. 2011. *Getting the Housing We Want*: Grattan Institute Melbourne.

Kendall, David. 2007. "Building the Future with Frp Composites." *Reinforced Plastics* 51 (5): 26-33.

Kennards. 2014. Construction Plan and Machinery across Western Australia - Locations, Availability and Energy Consumption. Accessed 24.09.2014, http://www.kennards.com.au/index.php#X0FUy7ITiUyRXiIC.97.

Keoleian, Gregory A, Steven Blanchard, and Peter Reppe. 2000. "Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House." *Journal of Industrial Ecology* 4 (2): 135-156.

Khan, Zahiruddin. 2008. "Cleaner Production: An Economical Option for ISO Certification in Developing Countries." *Journal of Cleaner Production* 16 (1): 22-27. doi: http://dx.doi.org/10.1016/j.jclepro.2006.06.007.

Khasreen, Mohamad, Phillip F. Banfill, and Gillian Menzies. 2009. "Life-Cycle Assessment and the Environmental Impact of Buildings: A Review." *Sustainability* 1 (3): 674. http://www.mdpi.com/2071-1050/1/3/674.

Kibert, Charles J. 2008. *Sustainable Construction: Green Building Design and Delivery*: John Wiley & Sons.

Kibert, Charles J., Jan Sendzimir, and Brad Guy. 2000. "Construction Ecology and Metabolism: Natural System Analogues for a Sustainable Built Environment." *Construction Management and Economics* 18 (8): 903-916. doi: 10.1080/014461900446867.

Klöpffer, Walter, and Andreas Ciroth. 2011. "Is Lcc Relevant in a Sustainability Assessment?" *The International Journal of Life Cycle Assessment* 16 (2): 99-101.

Kneifel, Joshua. 2010. "Life-Cycle Carbon and Cost Analysis of Energy Efficiency Measures in New Commercial Buildings." *Energy and Buildings* 42 (3): 333-340. doi: http://dx.doi.org/10.1016/j.enbuild.2009.09.011.

Kordjamshidi, Maria. 2011. "Modelling Efficient Building Design: Efficiency for Low Energy or No Energy?" In *House Rating Schemes*, 53-115. Springer.

Koroneos, Christopher J, and Evanthia A Nanaki. 2012. "Life Cycle Environmental Impact Assessment of a Solar Water Heater." *Journal of Cleaner Production* 37: 154-161.

Korpi, Eric, and Timo Ala-Risku. 2008. "Life Cycle Costing: A Review of Published Case Studies." *Managerial Auditing Journal* 23 (3): 240-261. doi: doi:10.1108/02686900810857703.

Kou, Shi-cong, Chi-sun Poon, and Francisco Agrela. 2011. "Comparisons of Natural and Recycled Aggregate Concretes Prepared with the Addition of Different Mineral Admixtures." *Cement and Concrete Composites* 33 (8): 788-795.

Kshirsagar, Anurag Shankar, Mohamed A. El-Gafy, and Tariq Sami Abdelhamid. 2010. "Suitability of Life Cycle Cost Analysis (LCCA) as Asset Management Tools for Institutional Buildings." *Journal of Facilities Management* 8 (3): 162-178. doi: doi:10.1108/14725961011058811.

Kubota, Tetsu, Doris Toe Hooi Chyee, and Supian Ahmad. 2009. "The Effects of Night Ventilation Technique on Indoor Thermal Environment for Residential Buildings in Hot-Humid Climate of Malaysia." *Energy and Buildings* 41 (8): 829-839. doi: http://dx.doi.org/10.1016/j.enbuild.2009.03.008.

Kulczycka, Joanna, and Marzena Smol. 2015. "Environmentally Friendly Pathways for the Evaluation of Investment Projects Using Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA)." *Clean Technologies and Environmental Policy*: 1-14.

Kumar Sahu, Bikash. 2015. "A Study on Global Solar Pv Energy Developments and Policies with Special Focus on the Top Ten Solar Pv Power Producing Countries." *Renewable and Sustainable Energy Reviews* 43: 621-634. doi: http://dx.doi.org/10.1016/j.rser.2014.11.058.

Kurnitski, Jarek, Arto Saari, Targo Kalamees, Mika Vuolle, Jouko Niemelä, and Teet Tark. 2011. "Cost Optimal and Nearly Zero (Nzeb) Energy Performance Calculations for Residential Buildings with Rehva Definition for Nzeb National Implementation." *Energy and Buildings* 43 (11): 3279-3288. doi: http://dx.doi.org/10.1016/j.enbuild.2011.08.033.

Kverndokk, Snorre, Eric Nævdal, and Linda Nøstbakken. 2014. "The Trade-Off between Intra- and Intergenerational Equity in Climate Policy." *European Economic Review* 69: 40-58. doi: http://dx.doi.org/10.1016/j.euroecorev.2014.01.007.

Lai, Chi-Ming, and Yao-Hong Wang. 2011. "Energy-Saving Potential of Building Envelope Designs in Residential Houses in Taiwan." *Energies* 4 (11): 2061-2076. http://www.mdpi.com/1996-1073/4/11/2061.

Lam, Joseph C., C. L. Tsang, Danny H. W. Li, and S. O. Cheung. 2005. "Residential Building Envelope Heat Gain and Cooling Energy Requirements." *Energy* 30 (7): 933-951. doi: http://dx.doi.org/10.1016/j.energy.2004.07.001.

Lam, Joseph C., Kevin K. W. Wan, C. L. Tsang, and Liu Yang. 2008. "Building Energy Efficiency in Different Climates." *Energy Conversion and Management* 49 (8): 2354-2366. doi: http://dx.doi.org/10.1016/j.enconman.2008.01.013.

Lam, Joseph C., Kevin K. W. Wan, S. L. Wong, and Tony N. T. Lam. 2010. "Long-Term Trends of Heat Stress and Energy Use Implications in Subtropical Climates." *Applied Energy* 87 (2): 608-612. doi: http://dx.doi.org/10.1016/j.apenergy.2009.05.014.

Lawania, Krishna Kumar, and Wahidul K. Biswas. 2016. "Achieving Environmentally Friendly Building Envelope for Western Australia's Housing Sector: A Life Cycle Assessment Approach." *International Journal of Sustainable Built Environment*. doi: http://dx.doi.org/10.1016/j.ijsbe.2016.04.005.

Lawania, Krishna, Natalie Lloyd, and Wahidul Biswas. 2014. "Sustainability Assessment of the Replacement of Clay Brick Walls with in-Situ Composite Sandwich Walls." In *The Second Australasia and South-East Asia Structural Engineering and Construction Conference, Bangkok, Thailand, ,* November 3–7, 2014 edited by W. Suanpaga, Yazdani, S., Vimonsatit, V., Singh, A., and Chantawarangul, K.

Lawania, Krishna, Prabir Sarker, and Wahidul Biswas. 2015. "Global Warming Implications of the Use of by-Products and Recycled Materials in Western Australia's Housing Sector." *Materials* 8 (10): 5347. http://www.mdpi.com/1996-1944/8/10/5347.

Leckner, Mitchell, and Radu Zmeureanu. 2011. "Life Cycle Cost and Energy Analysis of a Net Zero Energy House with Solar Combisystem." *Applied Energy* 88 (1): 232-241. doi: http://dx.doi.org/10.1016/j.apenergy.2010.07.031.

Lee, AJ, H Kelly, R Jagoda, A Rosenfeld, E Stubee, J Colaco, A Gadgil, H Akbari, L Norford, and H van Burik. 2006. "Affordable, Safe Housing Based on Expanded Polystyrene (EPS) Foam and a Cementitious Coating." *Journal of materials science* 41 (21): 6908-6916.

Lee, W. L., and F. W. H. Yik. 2004. "Regulatory and Voluntary Approaches for Enhancing Building Energy Efficiency." *Progress in Energy and Combustion Science* 30 (5): 477-499. doi: http://dx.doi.org/10.1016/j.pecs.2004.03.002.

Leung, TM, CK Chau, WL Lee, and FWH Yik. 2005. "Willingness to Pay for Improved Environmental Performance of the Building Envelope of Office Buildings in Hong Kong." *Indoor and Built Environment* 14 (2): 147-156.

Li, Danny H. W., Liu Yang, and Joseph C. Lam. 2012. "Impact of Climate Change on Energy Use in the Built Environment in Different Climate Zones – a Review." *Energy* 42 (1): 103-112. doi: http://dx.doi.org/10.1016/j.energy.2012.03.044.

———. 2013. "Zero Energy Buildings and Sustainable Development Implications – a Review." *Energy* 54: 1-10. doi: http://dx.doi.org/10.1016/j.energy.2013.01.070.

Li, DZ, HX Chen, Eddie CM Hui, JB Zhang, and QM Li. 2013. "A Methodology for Estimating the Life-Cycle Carbon Efficiency of a Residential Building." *Building and Environment* 59: 448-455.

Li, Jun, and Michel Colombier. 2009. "Managing Carbon Emissions in China through Building Energy Efficiency." *Journal of Environmental Management* 90 (8): 2436-2447. doi: http://dx.doi.org/10.1016/j.jenvman.2008.12.015.

Li, Tao, Hongchao Zhang, Zhichao Liu, Qingdi Ke, and Leo Alting. 2014. "A System Boundary Identification Method for Life Cycle Assessment." *The International Journal of Life Cycle Assessment* 19 (3): 646-660.

Lin, Boqiang, and Xuehui Li. 2011. "The Effect of Carbon Tax on Per Capita Co 2 Emissions." *Energy policy* 39 (9): 5137-5146.

Lindfors, LG, K Christiansen, L Hoffman, Y Virtanen, V Juntilla, OJ Hanssen, A Rønning, T Ekvall, and G Finnveden. 1995. *Lca-Nordic*.

Lloyd, Shannon M., and Robert Ries. 2007. "Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches." *Journal of Industrial Ecology* 11 (1): 161-179. doi: 10.1162/jiec.2007.1136.

Lo, Shih-Chi, Hwong-wen Ma, and Shang-Lien Lo. 2005. "Quantifying and Reducing Uncertainty in Life Cycle Assessment Using the Bayesian Monte Carlo Method." *Science of The Total Environment* 340 (1–3): 23-33. doi: http://dx.doi.org/10.1016/j.scitotenv.2004.08.020.

Lockrey, Simon, Hung Nguyen, Enda Crossin, and Karli Verghese. 2016. "Recycling the Construction and Demolition Waste in Vietnam: Opportunities and Challenges in Practice." *Journal of Cleaner Production*.

Lopes Silva, D. A., I. Delai, M. A. S. De Castro, and A. R. Ometto. 2013. "Quality Tools Applied to Cleaner Production Programs: A First Approach toward a New Methodology." *Journal of Cleaner Production* 47: 174-187. doi: 10.1016/j.jclepro.2012.10.026.

Lovegrove, Keith, and Mike Dennis. 2006. "Solar Thermal Energy Systems in Australia." *International Journal of Environmental Studies* 63 (6): 791-802. doi: 10.1080/00207230601047156.

Luxmoore, D. A., M. T. R. Jayasinghe, and M. Mahendran. 2005. "Mitigating Temperature Increases in High Lot Density Sub-Tropical Residential Developments." *Energy and Buildings* 37 (12): 1212-1224. doi: http://dx.doi.org/10.1016/j.enbuild.2004.12.017.

Luxmoore, David Alexander. 2005. "Evaluation of Three Greensmart Houses: A Comparison with Current Mainstream Housing and Sustainable Housing." Queensland University of Technology.

Ma, Tao, Hongxing Yang, and Lin Lu. 2014. "Feasibility Study and Economic Analysis of Pumped Hydro Storage and Battery Storage for a Renewable Energy Powered Island." *Energy Conversion and Management* 79: 387-397. doi: http://dx.doi.org/10.1016/j.enconman.2013.12.047.

Macintosh, Andrew, and Deb Wilkinson. 2011. "Searching for Public Benefits in Solar Subsidies: A Case Study on the Australian Government's Residential Photovoltaic Rebate Program." *Energy Policy* 39 (6): 3199-3209. doi: http://dx.doi.org/10.1016/j.enpol.2011.03.007.

Málovics, György, Noémi Nagypál Csigéné, and Sascha Kraus. 2008. "The Role of Corporate Social Responsibility in Strong Sustainability." *The Journal of Socio-Economics* 37 (3): 907-918. doi: http://dx.doi.org/10.1016/j.socec.2006.12.061.

Mangan, Suzi Dilara, and Gül Koçlar Oral. 2016. "Assessment of Residential Building Performances for the Different Climate Zones of Turkey in Terms of Life Cycle Energy and Cost Efficiency." *Energy and Buildings* 110: 362-376. doi: http://dx.doi.org/10.1016/j.enbuild.2015.11.002.

Manioğlu, Gülten, and Zerrin Yılmaz. 2006. "Economic Evaluation of the Building Envelope and Operation Period of Heating System in Terms of Thermal Comfort." *Energy and Buildings* 38 (3): 266-272. doi: http://dx.doi.org/10.1016/j.enbuild.2005.06.009.

Marinković, S., V. Radonjanin, M. Malešev, and I. Ignjatović. 2010. "Comparative Environmental Assessment of Natural and Recycled Aggregate Concrete." *Waste management* 30 (11): 2255-2264. doi: http://dx.doi.org/10.1016/j.wasman.2010.04.012.

Martel, Andrew, and Ralph Horne. 2011. "Thermal Comfort Modelling of Top End Remote Indigenous Housing in the Northern Territory." *MTRO (More Than a Roof Overhead) Working Paper* (2).

Martin, Nigel, and John Rice. 2013. "The Solar Photovoltaic Feed-in Tariff Scheme in New South Wales, Australia." *Energy Policy* 61: 697-706. doi: http://dx.doi.org/10.1016/j.enpol.2013.06.038.

Mashal, M, Filiatrault, A. 2012. "Quantification of Seismic Performance Factors for Buildings Incorporating Three-Dimensional Construction System" *World Conference on Earthquake Engineering*, Lisbon, Portugal.

Masoso, O. T., and L. J. Grobler. 2008. "A New and Innovative Look at Anti-Insulation Behaviour in Building Energy Consumption." *Energy and Buildings* 40 (10): 1889-1894. doi: http://dx.doi.org/10.1016/j.enbuild.2008.04.013.

Masters. 2014. Building Material, Hardware and Accessories across Western Australia - Locations and Availability. Accessed 23.09.2014, https://www.masters.com.au/building-timber.

Maurice, B, R Frischknecht, V Coelho-Schwirtz, and K Hungerbühler. 2000. "Uncertainty Analysis in Life Cycle Inventory. Application to the Production of Electricity with French Coal Power Plants." *Journal of Cleaner Production* 8 (2): 95-108.

McCleese, David L, and Peter T LaPuma. 2002. "Using Monte Carlo Simulation in Life Cycle Assessment for Electric and Internal Combustion Vehicles." *The International Journal of Life Cycle Assessment* 7 (4): 230-236.

McGee, Caitlin, Chris Reardon, and Dick Clarke. 2013. *Passive Design, Orientation - Your Home: Australia's Guide to Environmentally Sustainable Homes, 5th Edition*. Canberra, Australia. http://www.yourhome.gov.au/passive-design/orientation.

McLeod, Phil, and Roger Fay. 2011. "The Cost Effectiveness of Housing Thermal Performance Improvements in Saving Co2-E." *Architectural Science Review* 54 (2): 117-123. doi: 10.1080/00038628.2011.582370.

Mebratu, Desta. 1998. "Sustainability and Sustainable Development: Historical and Conceptual Review." *Environmental Impact Assessment Review* 18 (6): 493-520. doi: http://dx.doi.org/10.1016/S0195-9255(98)00019-5.

Memon, Aftab Hameed, Ismail Abdul Rahman, and Tuan Nurul Shahida Tuan Yacob. 2014. "Application of Life Cycle Management (Lcm) in Infrastructure Projects of Malaysia." *Australian Journal of Basic and Applied Sciences* 8 (6): 496-502.

Midland-Brick. 2014. Clay Bricks across Western Australia - Locations and Availability. Accessed 24.09.2014, https://www.midlandbrick.com.au/Shop/Default.

Miller, Wendy, and Laurie Buys. 2012. "Anatomy of a Sub-Tropical Positive Energy Home (Peh)." *Solar Energy* 86 (1): 231-241. doi: http://dx.doi.org/10.1016/j.solener.2011.09.028.

Milne, Geoff, and Chris Reardon. 2013. *Materials, Embodied Energy - Your Home Australia's Guide to Environmentally Sustainable Homes, 5th Edition*. http://yourhome.gov.au/materials/embodied-energy.

Minne, Elizabeth, and John C. Crittenden. 2014. "Impact of Maintenance on Life Cycle Impact and Cost Assessment for Residential Flooring Options." *The International Journal of Life Cycle Assessment* 20 (1): 36-45. doi: 10.1007/s11367-014-0809-z.

Mitscher, Martin, and Ricardo Rüther. 2012. "Economic Performance and Policies for Grid-Connected Residential Solar Photovoltaic Systems in Brazil." *Energy Policy* 49: 688-694. doi: http://dx.doi.org/10.1016/j.enpol.2012.07.009.

Mogre, Rajendra P, Dhananjay K Parbat, and Shirish D Dhobe. 2015. "Modeling of Compressive and Flexural Strength for Incremental Replacement of Natural Sand with Artificial Sand in Concrete." *Indian Concrete Journal*: 44.

Mohammad, Shaghayegh, and Andrew Shea. 2013. "Performance Evaluation of Modern Building Thermal Envelope Designs in the Semi-Arid Continental Climate of Tehran." *Buildings* 3 (4): 674-688.

Mohammed, Feisal, Wahidul K Biswas, Hongmei Yao, and Moses Tadé. 2016. "Identification of an Environmentally Friendly Symbiotic Process for the Reuse of Industrial Byproduct–an Lca Perspective." *Journal of Cleaner Production* 112: 3376-3387.

Monahan, J, and JC Powell. 2011. "An Embodied Carbon and Energy Analysis of Modern Methods of Construction in Housing: A Case Study Using a Lifecycle Assessment Framework." *Energy and Buildings* 43 (1): 179-188.

Monteiro, Helena, and Fausto Freire. 2012. "Life-Cycle Assessment of a House with Alternative Exterior Walls: Comparison of Three Impact Assessment Methods." *Energy and Buildings* 47: 572-583. doi: http://dx.doi.org/10.1016/j.enbuild.2011.12.032.

Moore, Trivess. 2014. "Modelling the through-Life Costs and Benefits of Detached Zero (Net) Energy Housing in Melbourne, Australia." *Energy and Buildings* 70: 463-471. doi: http://dx.doi.org/10.1016/j.enbuild.2013.11.084.

Moore, Trivess, Ralph Horne, and John Morrissey. 2014. "Zero Emission Housing: Policy Development in Australia and Comparisons with the Eu, Uk, USA and California." *Environmental Innovation and Societal Transitions* 11: 25-45. doi: http://dx.doi.org/10.1016/j.eist.2013.12.003.

Moore, Trivess, and John Morrissey. 2014. "Lifecycle Costing Sensitivities for Zero Energy Housing in Melbourne, Australia." *Energy and Buildings* 79: 1-11. doi: http://dx.doi.org/10.1016/j.enbuild.2014.04.050.

Moore, Trivess, John Morrissey, and Ralph Horne. 2014. "Cost Efficient Low-Emission Housing: Implications for Household Cash-Flows in Melbourne." *International Journal of Sustainable Development 4* 17 (4): 374-386.

Moosavian, S. M., N. A. Rahim, J. Selvaraj, and K. H. Solangi. 2013. "Energy Policy to Promote Photovoltaic Generation." *Renewable and Sustainable Energy Reviews* 25: 44-58. doi: http://dx.doi.org/10.1016/j.rser.2013.03.030.

Morrissey, J, and RE Horne. 2011a. "Life Cycle Cost Implications of Energy Efficiency Measures in New Residential Buildings." *Energy and Buildings* 43 (4): 915-924.

Morrissey, J., and R. E. Horne. 2011b. "Life Cycle Cost Implications of Energy Efficiency Measures in New Residential Buildings." *Energy and Buildings* 43 (4): 915-924. doi: http://dx.doi.org/10.1016/j.enbuild.2010.12.013.

Morrissey, J., B. Meyrick, D. Sivaraman, R. E. Horne, and M. Berry. 2013. "Cost-Benefit Assessment of Energy Efficiency Investments: Accounting for Future Resources, Savings and Risks in the Australian Residential Sector." *Energy Policy* 54: 148-159. doi: http://dx.doi.org/10.1016/j.enpol.2012.11.005.

Morrissey, J., T. Moore, and R. E. Horne. 2011. "Affordable Passive Solar Design in a Temperate Climate: An Experiment In residential Building Orientation." *Renewable Energy* 36 (2): 568-577. doi: http://dx.doi.org/10.1016/j.renene.2010.08.013.

Mousa A.M., Nasim Uddin. 2012. "Structural Behavior and Modeling of Full-Scale Composite Structural Insulated Wall Panels." *Elsevier - Engineering Structures* 41(2012): 320-334. http://www.elsevier.com/locate/engstruct.

Mousa, Ahmad, and Ahmed Zidan. 2014. "3-D Panel System: A Sustainable Building Solution for Egypt" *International Conference on Industry Academia Collaboration-IAC 2014*,

Mutch, James J. 1974. *Residential Water Heating: Fuel Conservation, Economics, and Public Policy*: Rand.

Nath, Pradip, and Prabir Kumar Sarker. 2013. "Effect of Mixture Proportions on the Drying Shrinkage and Permeation Properties of High Strength Concrete Containing Class F Fly Ash." *KSCE Journal of Civil Engineering* 17 (6): 1437-1445.

NatHERS. 2012. Nationwide House Energy Rating Scheme - Software Accreditation Protocol. NatHERS National Administrator, Department of Industry, Innovation and Science. Accessed 17.12.2015, http://www.nathers.gov.au/accredited-software/how-nathers-software-works/area-correction-factor.

———. 2015. Nationwide House Energy Rating Scheme - Administrative and Governance Arrangements. NatHERS National Administrator, Department of Industry, Innovation and Science. Accessed 17.12.2015, http://www.nathers.gov.au/sites/prod.nathers.gov.au/files/files/Admin-governance-arrangements-August%202015.pdf.

Nejat, Payam, Fatemeh Jomehzadeh, Mohammad Mahdi Taheri, Mohammad Gohari, and Muhd Zaimi Abd Majid. 2015. "A Global Review of Energy Consumption, Co 2 Emissions and Policy in the Residential Sector (with an Overview of the Top Ten Co 2 Emitting Countries)." *Renewable and sustainable energy reviews* 43: 843-862.

Nelson, Richard R, Alexander Peterhansl, and Bhaven Sampat. 2004. "Why and How Innovations Get Adopted: A Tale of Four Models." *Industrial and Corporate Change* 13 (5): 679-699. doi: 10.1093/icc/dth027.

Nepal, Binod, Robert Tanton, and Ann Harding. 2010. "Measuring Housing Stress: How Much Do Definitions Matter?" *Urban Policy and Research* 28 (2): 211-224. doi: 10.1080/08111141003797454.

Newton, Peter, Selwyn Tucker, and Michael Ambrose. 2000. "Housing Form, Energy Use and Greenhouse Gas Emissions." *Achieving sustainable urban form*: 74-83.

NHSC. 2011. *The Key Findings of 2011, the State of Supply Report, the Australian Government*. http://www.afr.com/rw/2009-2014/AFR/2011/12/21/Photos/34648d1a-2b7a-11e1-8d63-cda11eaed121_housing%20report.pdf.

Niero, Monia, Massimo Pizzol, Henrik Gundorph Bruun, and Marianne Thomsen. 2014. "Comparative Life Cycle Assessment of Wastewater Treatment in Denmark Including Sensitivity and Uncertainty Analysis." *Journal of Cleaner Production* 68: 25-35. doi: http://dx.doi.org/10.1016/j.jclepro.2013.12.051.

Nikolaidis, Yiannis, Petros A Pilavachi, and Alexandros Chletsis. 2009. "Economic Evaluation of Energy Saving Measures in a Common Type of Greek Building." *Applied Energy* 86 (12): 2550-2559.

Nilsson, Lennart. 2007. *Cleaner Production: Technologies and Tools for Resource Efficient Production*. Vol. 2: Baltic University Press.

Ny, Henrik, Jamie P MacDonald, Göran Broman, Ryoichi Yamamoto, and Karl-Henrik Robért. 2006. "Sustainability Constraints as System Boundaries: An Approach to Making Life-Cycle Management Strategic." *Journal of Industrial Ecology* 10 (1-2): 61-77.

O'Flynn, ML. 2000. "Manufactured Sands from Hardrock Quarries: Environmental Solution or Dilemma for Southeast Queensland?" *Australian Journal of Earth Sciences* 47 (1): 65-73.

Olivier, JGJ, G Janssens-Maenhout, M Muntean, and JAHW Peters. 2014. *Trends in Global Co2 Emissions; 2014 Report*. PBL Publishers. http://edgar.jrc.ec.europa.eu/news_docs/jrc-2014-trends-in-global-co2-emissions-2014-report-93171.pdf.

Omid Rezaifar, Majid Gholhaki. 2008. "Nonlinear Dynamic Behavior of Structural Frames Constructed with 3d Wall Panels with Vertical Irregular Arrangement." In *1st international conference on seismic retrofitting, Tabriz-Iran, 20-22 October 2008, Iran*.

OneSteel. 2014. "Life Cycle Analysis Information Sheet."

Oral, Gül Koçlar, Alpin Köknel Yener, and Nurgün Tamer Bayazit. 2004. "Building Envelope Design with the Objective to Ensure Thermal, Visual and Acoustic Comfort Conditions." *Building and Environment* 39 (3): 281-287. doi: http://dx.doi.org/10.1016/S0360-1323(03)00141-0.

Ortiz-Rodríguez, Oscar, Francesc Castells, and Guido Sonnemann. 2010. "Life Cycle Assessment of Two Dwellings: One in Spain, a Developed Country, and One in Colombia, a Country under Development." *Science of the total environment* 408 (12): 2435-2443.

Ortiz, Oscar, Cécile Bonnet, Joan Carles Bruno, and Francesc Castells. 2009. "Sustainability Based on Lcm of Residential Dwellings: A Case Study in Catalonia, Spain." *Building and Environment* 44 (3): 584-594. doi: http://dx.doi.org/10.1016/j.buildenv.2008.05.004.

Ortiz, Oscar, Francesc Castells, and Guido Sonnemann. 2009. "Sustainability in the Construction Industry: A Review of Recent Developments Based on Lca." *Construction and Building Materials* 23 (1): 28-39.

Osmani, Mohamed, and Alistair O'Reilly. 2009. "Feasibility of Zero Carbon Homes in England by 2016: A House Builder's Perspective." *Building and Environment* 44 (9): 1917-1924. doi: http://dx.doi.org/10.1016/j.buildenv.2009.01.005.

Otanicar, Todd P, and Jay S Golden. 2009. "Comparative Environmental and Economic Analysis of Conventional and Nanofluid Solar Hot Water Technologies." *Environmental science & technology* 43 (15): 6082-6087.

Pacheco, R., J. Ordóñez, and G. Martínez. 2012. "Energy Efficient Design of Building: A Review." *Renewable and Sustainable Energy Reviews* 16 (6): 3559-3573. doi: http://dx.doi.org/10.1016/j.rser.2012.03.045.

Pargana, Nuno, Manuel Duarte Pinheiro, Jose Dinis Silvestre, and Jorge de Brito. 2014. "Comparative Environmental Life Cycle Assessment of Thermal Insulation Materials of Buildings." *Energy and Buildings* 82: 466-481.

Passer, Alexander, Johannes Wall, Helmuth Kreiner, Peter Maydl, and Karl Höfler. 2015. "Sustainable Buildings, Construction Products and Technologies: Linking Research and Construction Practice." *The International Journal of Life Cycle Assessment* 20 (1): 1-8.

Pelzeter, Andrea. 2007. "Building Optimisation with Life Cycle Costs – the Influence of Calculation Methods." *Journal of Facilities Management* 5 (2): 115-128. doi: doi:10.1108/14725960710751861.

Peng, Jinqing, Lin Lu, and Hongxing Yang. 2013. "Review on Life Cycle Assessment of Energy Payback and Greenhouse Gas Emission of Solar Photovoltaic Systems." *Renewable and Sustainable Energy Reviews* 19: 255-274. doi: http://dx.doi.org/10.1016/j.rser.2012.11.035.

Peter Lyons, Bernard Hockings, Chris Reidy Chris Reardon, and Richard Hamber Tracey Gramlick. 2013. *Passive Design, Glazing - Your Home: Australia's Guide to Environmentally Sustainable Homes, 5th Edition*. Canberra, Australia. http://www.yourhome.gov.au/passive-design/glazing.

Peterkin, Neville. 2009. "Rewards for Passive Solar Design in the Building Code of Australia." *Renewable Energy* 34 (2): 440-443. doi: http://dx.doi.org/10.1016/j.renene.2008.05.017.

Poluraju, P, and G Appa Rao. 2014. "Behaviour of 3d-Panels for Structural Applications under General Loading: A State-of-the-Art." *International Journal of Research in Engineering and Technology* 3 (16): 173-181.

Pope, Jenny, David Annandale, and Angus Morrison-Saunders. 2004. "Conceptualising Sustainability Assessment." *Environmental Impact Assessment Review* 24 (6): 595-616. doi: http://dx.doi.org/10.1016/j.eiar.2004.03.001.

Poullikkas, Andreas. 2013. "A Comparative Assessment of Net Metering and Feed in Tariff Schemes for Residential Pv Systems." *Sustainable Energy Technologies and Assessments* 3: 1-8. doi: http://dx.doi.org/10.1016/j.seta.2013.04.001.

Praseeda, KI, BV Venkatarama Reddy, and Monto Mani. 2015. "Embodied Energy Assessment of Building Materials in India Using Process and Input–Output Analysis." *Energy and Buildings* 86: 677-686.

PRé-Consultants. 2015. *Simapro 8.0.5.13 Lca Software*. Stationsplein 121, 3818 LE Amersfoort - The Netherlands: PRé Consultants bv.

Pryshlakivsky, Jonathan, and Cory Searcy. 2013. "Fifteen Years of Iso 14040: A Review." *Journal of Cleaner Production* 57: 115-123. doi: http://dx.doi.org/10.1016/j.jclepro.2013.05.038.

QBE. 2015. *Australian Housing Outlook 205-2018*. Sydney, Australia: QBE Insurance (Australia) Limited. http://www.qbelmi.com/Uploads/Documents/7bb2836c-f872-4c1b-8722-f94dbc7861fb.pdf.

Qureshi, ME, and Steve R Harrison. 2001. "A Decision Support Process to Compare Riparian Revegetation Options in Scheu Creek Catchment in North Queensland." *Journal of Environmental Management* 62 (1): 101-112.

Ramadhan, Mohammad, and Adel Naseeb. 2011. "The Cost Benefit Analysis of Implementing Photovoltaic Solar System in the State of Kuwait." *Renewable Energy* 36 (4): 1272-1276. doi: http://dx.doi.org/10.1016/j.renene.2010.10.004.

Ramesh, T, Ravi Prakash, and KK Shukla. 2010. "Life Cycle Energy Analysis of Buildings: An Overview." *Energy and Buildings* 42 (10): 1592-1600.

———. 2012. "Life Cycle Energy Analysis of a Residential Building with Different Envelopes and Climates in Indian Context." *Applied Energy* 89 (1): 193-202.

Ramesh, Talakonukula, Ravi Prakash, and Karunesh Kumar Shukla. 2013. "Life Cycle Energy Analysis of a Multifamily Residential House: A Case Study in Indian Context." *Open Journal of Energy Efficiency* Vol.02No.01: 8. doi: 10.4236/ojee.2013.21006.

Randolph, W, and Patrick Nicol Troy. 2007. *Energy Consumption and the Built Environment: A Social and Behavioural Analysis*: City Futures Research Centre, University of New South Wales Sydney.

Rawlinsons. 2015. *Construction Cost Guide*. Rawlinsons Publishing

Ray, AS, H Connan, B Liu, and P Thomas. 2009. "Alumina-Silica Rich Clay Brick Waste in Hydrothermally Treated Cement-Based Construction Products"

Conference On Our World In Concrete & Structures: CI-Premier Conference Organisation, Singapore.

RBA. 2015. Reserve Bank of Australia - Inflation Target. Accessed 07.11.2015, http://www.rba.gov.au/monetary-policy/inflation-target.html.

Real, S, and M Pinheiro. 2010. "Life Cycle Cost as Base to Define Low Cost Sustainable Building Solutions." *proceedings of Portugal SB10–Sustainable Building affordable to all–Low cost sustainable solutions*: 313-320.

Real, SF. 2010. "Contribution of Life Cycle Cost Analysis to Design Sustainability in Construction." Masters dissertation in Civil Engineering, Department of Civil Engineering and Architecture-Instituto Superior Técnico-Technical University of Lisbon, Lisbon, Portugal. 153 p.

Reardon, Chris, and Dick Clarke. 2013. *Passive Design, Passive Cooling - Your Home Australia's Guide to Environmentally Sustainable Homes, 5th Edition*. http://www.yourhome.gov.au/passive-design/passive-cooling.

Reardon, Chris, and Paul Downton. 2013a. *Materials, Construction Systems - Your Home Australia's Guide to Environmentally Sustainable Homes, 5th Edition*. http://www.yourhome.gov.au/materials/construction-systems.

———. 2013b. *Passive Design, Design for Climate - Your Home Australia's Guide to Environmentally Sustainable Homes, 5th Edition*. http://www.yourhome.gov.au/passive-design/design-climate.

Reardon, Chris, Caitlin McGee, and Geoff Milne. 2013. *Passive Design, Thermal Mass - Your Home: Australia's Guide to Environmentally Sustainable Homes, 5th Edition*. Canberra, Australia. http://www.yourhome.gov.au/passive-design/thermal-mass.

Rebitzer, G., T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W. P. Schmidt, S. Suh, B. P. Weidema, and D. W. Pennington. 2004. "Life Cycle Assessment: Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications." *Environment International* 30 (5): 701-720. doi: http://dx.doi.org/10.1016/j.envint.2003.11.005.

Rebitzer, Gerald, and David Hunkeler. 2003. "Life Cycle Costing in Lcm: Ambitions, Opportunities, and Limitations." *The International Journal of Life Cycle Assessment* 8 (5): 253-256. doi: 10.1007/BF02978913.

Rebitzer, Gerald, David Hunkeler, and Olivier Jolliet. 2003. "Lcc—the Economic Pillar of Sustainability: Methodology and Application to Wastewater Treatment." *Environmental progress* 22 (4): 241-249.

Reiner, Mark, and Kevin Rens. 2006. "High-Volume Fly Ash Concrete: Analysis and Application." *Practice Periodical on Structural Design and Construction* 11 (1): 58-64.

REMCo. 2014. "Electricity Full Retail Contestability in Western Australia - Detailed Report." edited by Retail Energy Market Company, Western Australia.

Ren, Zhengen, and Zhengdong Chen. 2010. "Enhanced Air Flow Modelling for Accurate–a Nationwide House Energy Rating Tool in Australia." *Building and Environment* 45 (5): 1276-1286.

Ren, Zhengen, Zhengdong Chen, and Xiaoming Wang. 2011. "Climate Change Adaptation Pathways for Australian Residential Buildings." *Building and Environment* 46 (11): 2398-2412. doi: http://dx.doi.org/10.1016/j.buildenv.2011.05.022.

Ren, Zhengen, Greg Foliente, Wan-Yee Chan, Dong Chen, Michael Ambrose, and Phillip Paevere. 2013. "A Model for Predicting Household End-Use Energy Consumption and Greenhouse Gas Emissions in Australia." *International*

Journal of Sustainable Building Technology and Urban Development 4 (3): 210-228. doi: 10.1080/2093761x.2013.801801.

Ren, Zhengen, Phillip Paevere, and Cheryl McNamara. 2012. "A Local-Community-Level, Physically-Based Model of End-Use Energy Consumption by Australian Housing Stock." *Energy Policy* 49: 586-596. doi: http://dx.doi.org/10.1016/j.enpol.2012.06.065.

Renouf, M.A., Grant, T., Sevenster, M., Logie, J., Ridoutt, B., Ximenes, F., Bengtsson, J., Cowie, A., Lane, J. 2015. *Best Practice Guide for Life Cycle Impact Assessment (Lcia) in Australia. Australian Life Cycle Assessment Society*. Melbourne, Australia. www.alcas.asn.au.

Rezaifar, O, and M. Gholhaki. 2008. "Nonlinear Dynamic Behavior of Structural Frames Constructed with 3d Wall Panels with Vertical Irregular Arrangement." In *1st international conference on seismic retrofitting, Tabriz-Iran, 20-22 October 2008*. profs.semnan.ac.ir/mgholhaki/upload_file/conf.28.pdf

Rezaifar, O., Kabir, M.Z., Taribakhsh, M., Tehranian, A. 2008. "Dynamic Behaviour of 3d-Panel Single-Storey System Using Shaking Table Testing." *Elsevier - Engineering Structures* 30 (2008) 318–337. www.sciencedirect.com.

Ricci, I, G Gasparini, S Silvestri, T Trombetti, D Foti, S Ivorra Chooro, and S Ivorra Chooro. 2012. "Design of a Shaking Table Test on a 3-Storey Building Composed of Cast-in-Situ Concrete Walls" *Lisbon: Proceedings of the 15th World Conference on Earthquake Engineering (15WCEE),*

Ricci, I., G. Gasparini, G., Silvestri, S., Trombetti, T., Foti, D., Ivorra-Chorro, S. 2012. "Design of a Shaking Table Test on a 3-Storey Building Composed of Cast-in-Situ Concrete Walls." In *15th World Conference on Earthquake Engineering, Lisbon, Portugal from September 24-28, 2012*. http://www.iitk.ac.in/nicee/wcee/article/WCEE2012_0884.pdf.

Ricci, I., Palermo, M., Gasparini, G., Silvestri, S., Trombetti, T. 2013. "Results of Pseudo-Static Tests with Cyclic Horizontal Load on Cast in Situ Sandwich Squat Concrete Walls." *Elsevier - Engineering Structures* 54(2013): 131-149. http://www.elsevier.com/locate/engstruct.

Riedy, Chris, Geoff Milne, and Robert Foster. 2013. *Energy - Appliances - Your Home Australia's Guide to Environmentally Sustainable Homes, 5th Editionhttp://Www.Yourhome.Gov.Au/Energy/Appliances*. http://www.yourhome.gov.au/energy/appliances.

Riedy, Chris, Geoff Milne, and Paul Ryan. 2013. *Energy - Hot Water Service - Your Home Australia's Guide to Environmentally Sustainable Homes, 5th Editionhttp://Www.Yourhome.Gov.Au/Energy/Appliances*. http://www.yourhome.gov.au/energy/hot-water-service.

Ristimäki, Miro, Antti Säynäjoki, Jukka Heinonen, and Seppo Junnila. 2013. "Combining Life Cycle Costing and Life Cycle Assessment for an Analysis of a New Residential District Energy System Design." *Energy* 63: 168-179. doi: http://dx.doi.org/10.1016/j.energy.2013.10.030.

Roberts, Simon. 2008. "Effects of Climate Change on the Built Environment." *Energy Policy* 36 (12): 4552-4557. doi: http://dx.doi.org/10.1016/j.enpol.2008.09.012.

Robinson, Dorothy L. 2011. "Australian Wood Heaters Currently Increase Global Warming and Health Costs." *Atmospheric Pollution Research* 2 (3): 267-274. doi: http://dx.doi.org/10.5094/APR.2011.033.

Ross Maher, Rob Rouwette, Mary Stewart. 2011. "Greenhouse Gas Assessment of Selected Australian Residential Buildings" *7th Australian Conference on Life Cycle Assessment*

Life Cycle Assessment: Revealing the secrets of a green market, Melbourne, Australia,2011. Australian Life Cycle Assessment Society. http://www.conference.alcas.asn.au/2011/Index.htm.
Rossi, Barbara, Anne-Françoise Marique, Mauritz Glaumann, and Sigrid Reiter. 2012. "Life-Cycle Assessment of Residential Buildings in Three Different European Locations, Basic Tool." *Building and Environment* 51: 395-401.
Rossi, Giuseppe, Antonino Cancelliere, and Giuseppe Giuliano. 2005. "Case Study: Multicriteria Assessment of Drought Mitigation Measures." *Journal of Water Resources Planning and Management* 131 (6): 449-457.
Rouwette, R. 2010. *Lca of Brick Products, Life Cycle Assessment(Lca) Report by Energetics for Think Brick Australia*. Melbourne, Australia. http://blog.thinkbrick.com.au/wp-content/uploads/2010/03/Industry-LCA-Report-final.pdf.
RTAA. 2013. *Roof Tile Fact Sheet & the Properties of Roof Tiles*. NSW, Australia. http://www.rtaa.com.au/factsheet.html.
Russo, Salvatore, Behzad Ghadimi, Krishna Lawania, and Michele Rosano. 2015. "Residual Strength Testing in Pultruded Frp Material under a Variety of Temperature Cycles and Values." *Composite Structures* 133: 458-475. doi: http://dx.doi.org/10.1016/j.compstruct.2015.07.034.
———. 2016. "Failure Analysis Using Acoustic and Energy Emission Assessment of Fibre Reinforced Polymer Material Performance under Severe Conditions." *Journal of Reinforced Plastics and Composites*. doi: 10.1177/0731684416638552.
Rwelamila, PD, AA Talukhaba, and AB Ngowi. 2000. "Project Procurement Systems in the Attainment of Sustainable Construction." *Sustainable Development* 8 (1): 39.
Sadineni, Suresh B., Srikanth Madala, and Robert F. Boehm. 2011. "Passive Building Energy Savings: A Review of Building Envelope Components." *Renewable and Sustainable Energy Reviews* 15 (8): 3617-3631. doi: http://dx.doi.org/10.1016/j.rser.2011.07.014.
Safiuddin, Md, Mohd Zamin Jumaat, MA Salam, MS Islam, and R Hashim. 2010. "Utilization of Solid Wastes in Construction Materials." *International Journal of the Physical Sciences* 5 (13): 1952-1963.
Saghafi, Mohammad Djavad, and Zahra Sadat Hosseini Teshnizi. 2011. "Recycling Value of Building Materials in Building Assessment Systems." *Energy and Buildings* 43 (11): 3181-3188. doi: http://dx.doi.org/10.1016/j.enbuild.2011.08.016.
Saikia, Nabajyoti, and Jorge de Brito. 2012. "Use of Plastic Waste as Aggregate in Cement Mortar and Concrete Preparation: A Review." *Construction and Building Materials* 34: 385-401.
Saman, Wasim Y. 2013. "Towards Zero Energy Homes Down Under." *Renewable Energy* 49: 211-215.
Sanders, C. H., and M. C. Phillipson. 2003. "Uk Adaptation Strategy and Technical Measures: The Impacts of Climate Change on Buildings." *Building Research & Information* 31 (3-4): 210-221. doi: 10.1080/0961321032000097638.
Sarcia, Sam Rhea. 2004. "Design and Analysis of a Concrete Modular Housing System Constructed with 3d Panels." Massachusetts Institute of Technology.
Sartori, I., and A. G. Hestnes. 2007. "Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article." *Energy and Buildings* 39 (3): 249-257. doi: http://dx.doi.org/10.1016/j.enbuild.2006.07.001.

SASA. 2010. *Recycled Aggregates Bring Carbon Reduction Benefits - Info Sheet*. http://www.sustainableaggregates.com.au/docs/SASA_Env_Info_Sheet.pdf.

Schade, Jutta. 2007. "Life Cycle Cost Calculation Models for Buildings." *InPro Project Avaialbe at http://www. inpro-project. eu/media/lcc_juttaschade. pdf [Accessed at 21 September 2011]*.

Scheuer, Chris, Gregory A. Keoleian, and Peter Reppe. 2003. "Life Cycle Energy and Environmental Performance of a New University Building: Modeling Challenges and Design Implications." *Energy and Buildings* 35 (10): 1049-1064. doi: http://dx.doi.org/10.1016/S0378-7788(03)00066-5.

Schwartfeger, Luke, and Allan Miller. 2015. "Environmental Aspects of Photovoltaic Solar Power: The New Zealand Context."

Seo, Seongwon, Chi-Hsiang Wang, and George Grozev. 2013. "Cooling Energy Consumption and Reduction Effect for Residential Buildings in South East Queensland, Australia." *Building and Environment* 59: 408-416. doi: http://dx.doi.org/10.1016/j.buildenv.2012.09.006.

SEP. 2015. Solar Energy Products - Multi Crystalline Solar Modules. Accessed 15.10.2015, http://www.solarenergyproducts.com.au/.

Serghides, Despina K, and Chrissa G Georgakis. 2012. "The Building Envelope of Mediterranean Houses: Optimization of Mass and Insulation." *Journal of Building Physics* 36 (1): 83-98. doi: 10.1177/1744259112448369.

Sev, Aysin. 2009. "How Can the Construction Industry Contribute to Sustainable Development? A Conceptual Framework." *Sustainable Development* 17 (3): 161-173. doi: 10.1002/sd.373.

Shahabi, Maedeh P, Adam McHugh, Martin Anda, and Goen Ho. 2015. "Comparative Economic and Environmental Assessments of Centralised and Decentralised Seawater Desalination Options." *Desalination* 376: 25-34.

Shen, Li-yin, Vivian W. Y. Tam, Leona Tam, and Ying-bo Ji. 2010. "Project Feasibility Study: The Key to Successful Implementation of Sustainable and Socially Responsible Construction Management Practice." *Journal of Cleaner Production* 18 (3): 254-259. doi: http://dx.doi.org/10.1016/j.jclepro.2009.10.014.

Silva, RV, J de Brito, and RK Dhir. 2014. "The Influence of the Use of Recycled Aggregates on the Compressive Strength of Concrete: A Review."

Singh, Amanjeet, George Berghorn, Satish Joshi, and Matt Syal. 2010. "Review of Life-Cycle Assessment Applications in Building Construction." *Journal of Architectural Engineering* 17 (1): 15-23.

Singh, M. C., and S. N. Garg. 2009. "Energy Rating of Different Glazings for Indian Climates." *Energy* 34 (11): 1986-1992. doi: http://dx.doi.org/10.1016/j.energy.2009.08.013.

SOE. 2011. *State of the Environment 2011 Committee. Australia State of the Environment 2011. Independent Report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities.* Canberra. www.environment.gov.au/.../state-environment-reporting/soe-2011.

Sonnemann, Guido, and Bas de Leeuw. 2006. "Life Cycle Management in Developing Countries: State of the Art and Outlook." *The International Journal of Life Cycle Assessment* 11 (1): 123-126. doi: 10.1065/lca2006.04.020.

Sorrell, Steve. 2003. "Making the Link: Climate Policy and the Reform of the Uk Construction Industry." *Energy Policy* 31 (9): 865-878.

Sorrell, Steve, John Dimitropoulos, and Matt Sommerville. 2009. "Empirical Estimates of the Direct Rebound Effect: A Review." *Energy Policy* 37 (4): 1356-1371. doi: http://dx.doi.org/10.1016/j.enpol.2008.11.026.

Sozer, Hatice. 2010. "Improving Energy Efficiency through the Design of the Building Envelope." *Building and Environment* 45 (12): 2581-2593. doi: http://dx.doi.org/10.1016/j.buildenv.2010.05.004.

Standard, Australian. 1982. *As 1181-1982 - Method of Measurement of Civil Engineering Works and Associated Building Works*. Standards Australia

———. 2008. *As/Nzs 4234:2008 (Reissued Incorporating Amendment No. 3 (November 2014) - Heated Water Systems-Calculation of Energy Consumption*. Standards Australia and Standards New Zealand

———. 2014. *As/Nzs 4536:1999 (Reconfirmed 2014) - Life Cycle Costing - an Application Guide*. Standards Australia and Standards New Zealand

Stephan, André, Robert H. Crawford, and Kristel de Myttenaere. 2013. "A Comprehensive Assessment of the Life Cycle Energy Demand of Passive Houses." *Applied Energy* 112: 23-34. doi: http://dx.doi.org/10.1016/j.apenergy.2013.05.076.

Stewart, J, M Anda, and RJ Harper. 2016. "Carbon Profiles of Remote Australian Indigenous Communities: A Base for Opportunities." *Energy Policy* 94: 77-88.

Strengers, Yolande, and Cecily Maller. 2011. "Integrating Health, Housing and Energy Policies: Social Practices of Cooling." *Building Research & Information* 39 (2): 154-168. doi: 10.1080/09613218.2011.562720.

Strezov, Les, and Joe Herbertson. 2006. *A Life Cycle Perspective on Steel Building Materials*. http://www.onesteel.com/images/db_images/pages/page20_Life_Cycle_Perspective_on_Steel_Building_Materials.pdf.

Sumner, Jenny, Lori Bird, and Hillary Dobos. 2011. "Carbon Taxes: A Review of Experience and Policy Design Considerations." *Climate Policy* 11 (2): 922-943. doi: 10.3763/cpol.2010.0093.

Swan, Lukas G., and V. Ismet Ugursal. 2009. "Modeling of End-Use Energy Consumption in the Residential Sector: A Review of Modeling Techniques." *Renewable and Sustainable Energy Reviews* 13 (8): 1819-1835. doi: http://dx.doi.org/10.1016/j.rser.2008.09.033.

Swarr, ThomasE, David Hunkeler, Walter Klöpffer, Hanna-Leena Pesonen, Andreas Ciroth, AlanC Brent, and Robert Pagan. 2011. "Environmental Life-Cycle Costing: A Code of Practice." *The International Journal of Life Cycle Assessment* 16 (5): 389-391. doi: 10.1007/s11367-011-0287-5.

Tharumarajah, Ambalavanar, and Tim Grant. 2006. "Australian National Life Cycle Inventory Database: Moving Forward" *Proceedings of the fifth ALCAS conference. Melbourne, Australia*.

Todd, Joel Ann, Mary Ann Curran, Keith Weitz, Aarti Sharma, Bruce Vigon, Ed Price, Greg Norris, Pat Eagan, Willie Owens, and Agis Veroutis. 1999. "Streamlined Life-Cycle Assessment: A Final Report from the Setac North America Streamlined Lca Workgroup." *Society of Environmental Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education*.

Treloar, Graham, Roger Fay, Benedict Ilozor, and Peter Love. 2001. "Building Materials Selection: Greenhouse Strategies for Built Facilities." *Facilities* 19 (3/4): 139-150. doi: doi:10.1108/02632770110381694.

Tsilingiridis, G., G. Martinopoulos, and N. Kyriakis. 2004. "Life Cycle Environmental Impact of a Thermosyphonic Domestic Solar Hot Water System in Comparison with Electrical and Gas Water Heating." *Renewable Energy* 29 (8): 1277-1288. doi: http://dx.doi.org/10.1016/j.renene.2003.12.007.

Turk, Janez, Zvonko Cotič, Ana Mladenovič, and Aljoša Šajna. 2015. "Environmental Evaluation of Green Concretes Versus Conventional Concrete by Means of Lca." *Waste Management* 45: 194-205.

UNCED. 1992. *United Nations Conference on Environment & Development, Rio De Janerio, Brazil, 3 to 14 June 1992, Agenda 21*. https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf.

UNCSD. 2012. *United Nations Conference on Sustainable Development, Rio De Janerio, Brazil, 20 to 22 June 2012, Agenda 21*. http://uncsd2012.org/content/documents/814UNCSD%20REPORT%20final%20revs.pdf.

UNEP. 1994. *Government Strategies & Policies for Cleaner Production* http://www.unep.org/publications/search/pub_details_s.asp?ID=2148.

———. 1996. *Life Cycle Assessment: What It Is and How to Do It*. Belgium: United Nations Environment Programme.

———. 2007. *Life Cycle Management: A Business Guide to Sustainability*. France: United Nations Environment Programme - Division of Technology, Industry, and Economics, Sustainable Consumption & Production Branch

———. 2009. *Guidelines for Social Life Cycle Assessment of Products*. Belgium: United Nations Environment Programme, UNEP/SETAC Life Cycle Initiative at UNEP, CIRAIG, FAQDD and the Belgium Federal Public Planning Service Sustainable Development.

———. 2011a. *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*. Nairobi, Kenya. http://www.unep.org/greeneconomy/Portals/88/documents/ger/ger_final_dec_2011/Green%20EconomyReport_Final_Dec2011.pdf.

———. 2011b. *Towards a Life Cycle Sustainability Assessment - Making Informed Choices on Products*. France: UNEP/SETAC Life Cycle Initiative.

———. 2012. *Geo-5 for Local Government: Solving Global Problems Locally*. http://www.unep.org/geo/pdfs/geo5/UNEP-ICLEI-GEO-5.pdf.

———. 2015. "Introduction to Cleaner Production (CP) Concepts and Practices." For UNEP, Division of Technology, Industry, and Economics.

UNIDO. 2002. *Manual on the Development of Cleaner Production Policies - Approaches and Instruments*. Vienna.

Val, Dimitri V., and Mark G. Stewart. 2003. "Life-Cycle Cost Analysis of Reinforced Concrete Structures in Marine Environments." *Structural Safety* 25 (4): 343-362. doi: http://dx.doi.org/10.1016/S0167-4730(03)00014-6.

Van Berkel, Rene. 2007. "Cleaner Production and Eco-Efficiency Initiatives in Western Australia 1996–2004." *Journal of Cleaner Production* 15 (8–9): 741-755. doi: http://dx.doi.org/10.1016/j.jclepro.2006.06.012.

Van Den Bergh, Jeroen C. J. M. 2010. "Externality or Sustainability Economics?" *Ecological Economics* 69 (11): 2047-2052. doi: http://dx.doi.org/10.1016/j.ecolecon.2010.02.009.

Verbeeck, G., and H. Hens. 2010. "Life Cycle Inventory of Buildings: A Contribution Analysis." *Building and Environment* 45 (4): 964-967. doi: http://dx.doi.org/10.1016/j.buildenv.2009.10.003.

Vijayalaxmi, J. 2010. "Concept of Overall Thermal Transfer Value (OTTV) in Design of Building Envelope to Achieve Energy Efficiency." *Int. J. of Thermal & Environmental Engineering* 1 (2): 75-80.

wa.gov.au. 2015. Helping You Find Information & Services in Western Australia - All About Regions. Accessed 16.12.2015, https://www.wa.gov.au/information-about/regions/all-about-regions.

Wafa, Latifa Mohamed. 2011. "Low Cost Housing Can Be Technically Sophisticated and Architecturally Attractive." *Journal of Engineering Research (University of Tripoli) Issue* 15: 115.

Wan, Kevin K. W., Danny H. W. Li, Wenyan Pan, and Joseph C. Lam. 2012. "Impact of Climate Change on Building Energy Use in Different Climate Zones and Mitigation and Adaptation Implications." *Applied Energy* 97: 274-282. doi: http://dx.doi.org/10.1016/j.apenergy.2011.11.048.

Wang, Liping, Julie Gwilliam, and Phil Jones. 2009. "Case Study of Zero Energy House Design in Uk." *Energy and Buildings* 41 (11): 1215-1222. doi: http://dx.doi.org/10.1016/j.enbuild.2009.07.001.

Wang, Xiaoming, Dong Chen, and Zhengen Ren. 2010. "Assessment of Climate Change Impact on Residential Building Heating and Cooling Energy Requirement in Australia." *Building and Environment* 45 (7): 1663-1682. doi: http://dx.doi.org/10.1016/j.buildenv.2010.01.022.

WAWA. 2015. *Recycling Activity in Western Australia 2013-14*. Perth, Australia: Western Australia West Authority. http://www.wasteauthority.wa.gov.au/media/files/documents/WA_Recycling_Activity_13_14.pdf.

———. 2016. *Waste Authority Position Statement - Construction and Demolition (C&D) Waste*. Perth, Australia: Western Australia West Authority. http://www.wasteauthority.wa.gov.au/media/files/documents/CD_Position_statement.pdf.

WCED, UN. 1987. "Our Common Future." *World Commission on Environment and DevelopmentOxford University Press*.

Weisz, Helga, and Julia K. Steinberger. 2010. "Reducing Energy and Material Flows in Cities." *Current Opinion in Environmental Sustainability* 2 (3): 185-192. doi: http://dx.doi.org/10.1016/j.cosust.2010.05.010.

Westkämper, E., Alting, and Arndt. 2000. "Life Cycle Management and Assessment: Approaches and Visions Towards Sustainable Manufacturing (Keynote Paper)." *CIRP Annals - Manufacturing Technology* 49 (2): 501-526. doi: http://dx.doi.org/10.1016/S0007-8506(07)63453-2.

Whetton, PH, KL McInnes, RN Jones, KJ Hennessy, R Suppiah, CM Page, J Bathols, and PJ Durack. 2005. *Australian Climate Change Projections for Impact Assessment and Policy Application: A Review*: CSIRO Marine and Atmospheric Research.

Wiedenhofer, Dominik, Manfred Lenzen, and Julia K Steinberger. 2013. "Energy Requirements of Consumption: Urban Form, Climatic and Socio-Economic Factors, Rebounds and Their Policy Implications." *Energy Policy* 63: 696-707.

Wilhite, Harold, and Jorgen S Norgard. 2004. "Equating Efficiency with Reduction: A Self-Deception in Energy Policy." *Energy & Environment* 15 (6): 991-1009.

Williams, J. 2013. "The Role of Planning in Delivering Low-Carbon Urban Infrastructure." *Environment and Planning B: Planning and Design* 40 (4): 683-706. http://www.envplan.com/abstract.cgi?id=b38180.

Williams, Katie, and Carol Dair. 2007. "What Is Stopping Sustainable Building in England? Barriers Experienced by Stakeholders in Delivering Sustainable Developments." *SUSTAINABLE DEVELOPMENT-BRADFORD-* 15 (3): 135.

Williams, Tristan. 2015. *Ibis World Industry Report C2021 Clay Brick Manufacturing in Australia*. http://clients1.ibisworld.com.au/reports/au/industry/default.aspx?indid=208.

Winistorfer, Paul, Zhangjing Chen, Bruce Lippke, and Nicole Stevens. 2005. "Energy Consumption and Greenhouse Gas Emissions Related to the Use, Maintenance, and Disposal of a Residential Structure." *Wood and Fiber Science* 37: 128-139.

WWF. 2014. *Living Planet Report 2014*. http://awsassets.wwf.org.au/downloads/mc096_g_living_planet_report_2014_21oct14.pdf.

Ximenes, FabianoA, and Tim Grant. 2013. "Quantifying the Greenhouse Benefits of the Use of Wood Products in Two Popular House Designs in Sydney, Australia." *The International Journal of Life Cycle Assessment* 18 (4): 891-908. doi: 10.1007/s11367-012-0533-5.

Xing, Yangang, Neil Hewitt, and Philip Griffiths. 2011. "Zero Carbon Buildings Refurbishment—a Hierarchical Pathway." *Renewable and Sustainable Energy Reviews* 15 (6): 3229-3236. doi: http://dx.doi.org/10.1016/j.rser.2011.04.020.

Xu, Peng, Yu Joe Huang, Norman Miller, Nicole Schlegel, and Pengyuan Shen. 2012. "Impacts of Climate Change on Building Heating and Cooling Energy Patterns in California." *Energy* 44 (1): 792-804. doi: http://dx.doi.org/10.1016/j.energy.2012.05.013.

Xu, Xu, and Steven Van Dessel. 2008. "Evaluation of an Active Building Envelope Window-System." *Building and Environment* 43 (11): 1785-1791. doi: http://dx.doi.org/10.1016/j.buildenv.2007.10.013.

Yan, Hui, Qiping Shen, Linda C. H. Fan, Yaowu Wang, and Lei Zhang. 2010. "Greenhouse Gas Emissions in Building Construction: A Case Study of One Peking in Hong Kong." *Building and Environment* 45 (4): 949-955. doi: http://dx.doi.org/10.1016/j.buildenv.2009.09.014.

Yang, Lina, and Yuguo Li. 2008. "Cooling Load Reduction by Using Thermal Mass and Night Ventilation." *Energy and Buildings* 40 (11): 2052-2058. doi: http://dx.doi.org/10.1016/j.enbuild.2008.05.014.

Yang, Liu, Joseph C. Lam, and C. L. Tsang. 2008. "Energy Performance of Building Envelopes in Different Climate Zones in China." *Applied Energy* 85 (9): 800-817. doi: http://dx.doi.org/10.1016/j.apenergy.2007.11.002.

Yellow-Pages. 2014. Business Listings, Maps and Websites for Local Western Australian Businesses - Construction. Accessed 23.09.2014, http://www.yellowpages.com.au/search/listings?clue=Construction&locationClue=wa&lat=&lon=&selectedViewMode=list.

Yik, F. W. H., and K. S. Y. Wan. 2005. "An Evaluation of the Appropriateness of Using Overall Thermal Transfer Value (Ottv) to Regulate Envelope Energy Performance of Air-Conditioned Buildings." *Energy* 30 (1): 41-71. doi: http://dx.doi.org/10.1016/j.energy.2004.03.001.

Yıldız, Yusuf, and Zeynep Durmuş Arsan. 2011. "Identification of the Building Parameters That Influence Heating and Cooling Energy Loads for Apartment Buildings in Hot-Humid Climates." *Energy* 36 (7): 4287-4296. doi: http://dx.doi.org/10.1016/j.energy.2011.04.013.

Yılmaz, Z. 2007. "Evaluation of Energy Efficient Design Strategies for Different Climatic Zones: Comparison of Thermal Performance of Buildings in Temperate-Humid and Hot-Dry Climate." *Energy and Buildings* 39 (3): 306-316.

Yu, Yajuan, Xiang Wang, Dong Wang, Kai Huang, Lijing Wang, Liying Bao, and Feng Wu. 2012. "Environmental Characteristics Comparison of Li-Ion Batteries and Ni–Mh Batteries under the Uncertainty of Cycle Performance." *Journal of Hazardous Materials* 229–230: 455-460. doi: http://dx.doi.org/10.1016/j.jhazmat.2012.06.017.

Yusaf, Talal, Steven Goh, and J. A. Borserio. 2011. "Potential of Renewable Energy Alternatives in Australia." *Renewable and Sustainable Energy Reviews* 15 (5): 2214-2221. doi: http://dx.doi.org/10.1016/j.rser.2011.01.018.

Yusup, M. Z., W. H. Wan Mahmood, M. R. Salleh, and M. R. Muhamad. 2014. "The Sustainability Challenges in the Adoption of Cleaner Production System: A Review." *Jurnal Teknologi (Sciences and Engineering)* 70 (1): 117-123. doi: 10.11113/jt.v70.2388.

Zabalza Bribián, Ignacio, Antonio Valero Capilla, and Alfonso Aranda Usón. 2011. "Life Cycle Assessment of Building Materials: Comparative Analysis of Energy and Environmental Impacts and Evaluation of the Eco-Efficiency Improvement Potential." *Building and Environment* 46 (5): 1133-1140. doi: http://dx.doi.org/10.1016/j.buildenv.2010.12.002.

Zachariah, Jose-Ann Leslie. 2004. *Towards Sustainable Homes through Optimization: An Approach to Balancing Life Cycle Environmental Impacts and Life Cycle Costs in Residential Buildings*.

Zahedi, A. 2010. "A Review on Feed-in Tariff in Australia, What It Is Now and What It Should Be." *Renewable and Sustainable Energy Reviews* 14 (9): 3252-3255. doi: http://dx.doi.org/10.1016/j.rser.2010.07.033.

Zambrana-Vasquez, David, Alfonso Aranda-Usón, Ignacio Zabalza-Bribián, Alberto Janez, Eva Llera-Sastresa, Patxi Hernandez, and Eneko Arrizabalaga. 2015. "Environmental Assessment of Domestic Solar Hot Water Systems: A Case Study in Residential and Hotel Buildings." *Journal of Cleaner Production* 88: 29-42.

Zeng, Ruolang, Xin Wang, Hongfa Di, Feng Jiang, and Yinping Zhang. 2011. "New Concepts and Approach for Developing Energy Efficient Buildings: Ideal Specific Heat for Building Internal Thermal Mass." *Energy and Buildings* 43 (5): 1081-1090. doi: http://dx.doi.org/10.1016/j.enbuild.2010.08.035.

Zhang, Xiaoling, Liyin Shen, and Lei Zhang. 2013. "Life Cycle Assessment of the Air Emissions During Building Construction Process: A Case Study in Hong Kong." *Renewable and Sustainable Energy Reviews* 17: 160-169.

Zhao, Xiao-Ling, and Lei Zhang. 2007. "State-of-the-Art Review on Frp Strengthened Steel Structures." *Engineering Structures* 29 (8): 1808-1823.

Zhu, Li, R Hurt, D Correia, and R Boehm. 2009. "Detailed Energy Saving Performance Analyses on Thermal Mass Walls Demonstrated in a Zero Energy House." *Energy and Buildings* 41 (3): 303-310.

Appendix A

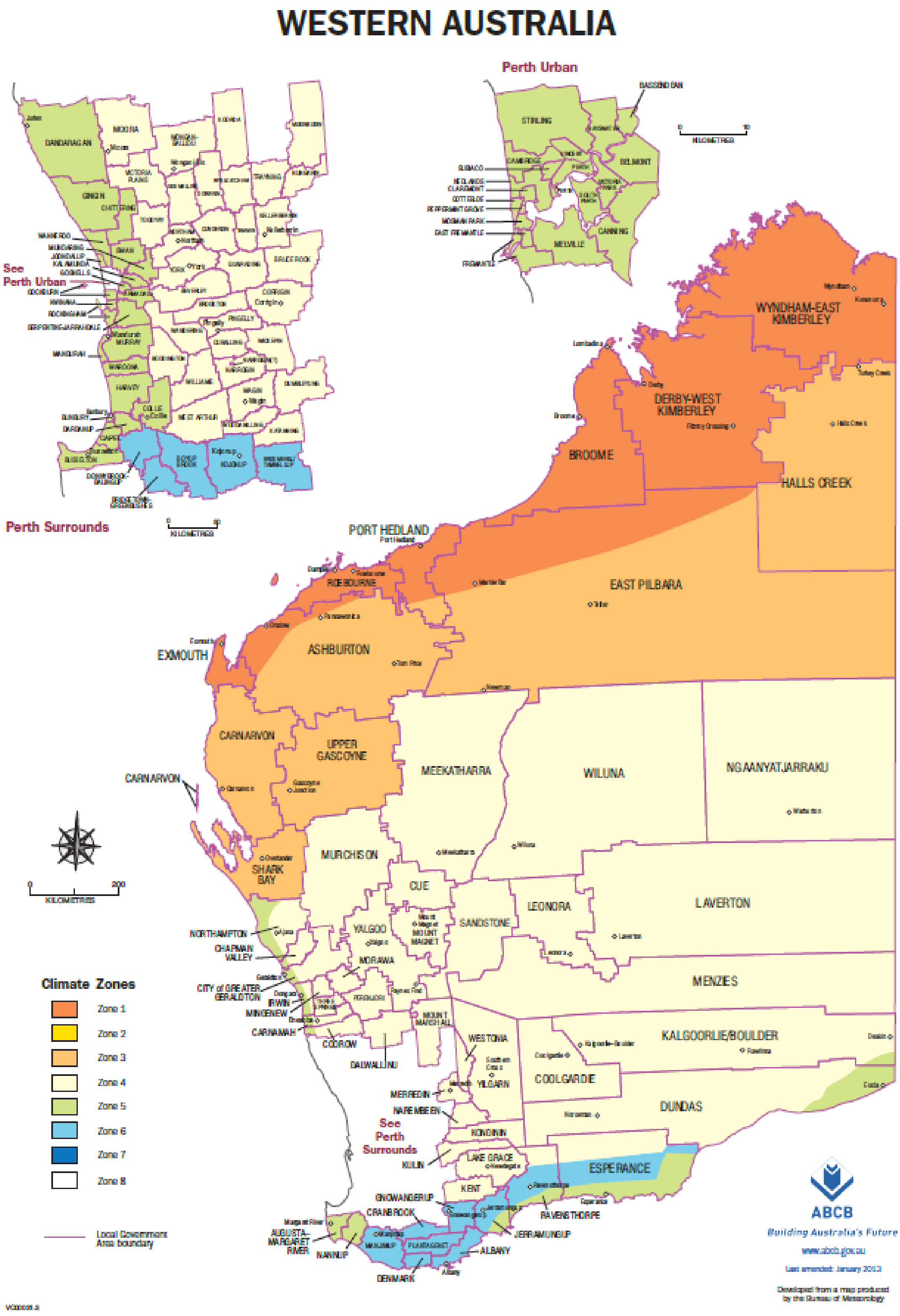


Figure A.1 Western Australian climate zones (ABCB 2014)

Appendix B

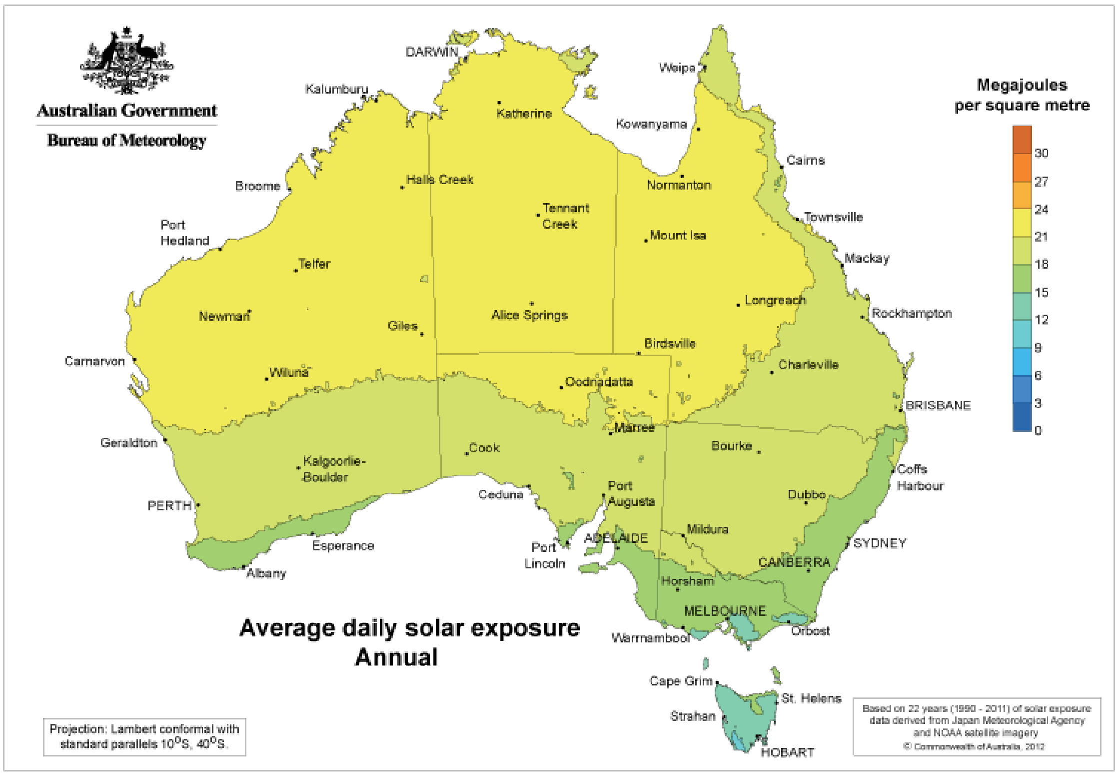


Figure B.1 Average daily solar exposure on Annual basis (BOM 2015)

Appendix C

Table C.1 Population and number of existing house in shortlisted locations

Location	Population	Number of Houses
Albany	55,357	27,245
Armadale	62,297	25,045
Augusta	4,436	3,016
Broome	12,766	6,405
Bunbury	65,608	27,700
Busselton	30,286	15,834
Carnarvon	5,347	2,997
Esperance	15,608	7,838
Geraldton	35,749	15,317
Joondalup	9,197	3,831
Kalgoorlie	30,842	12,433
Kununurra	5,525	2,852
Laverton	1,023	319
Mandurah	83,294	41,679
Mount Magnet	643	345
Newman	9,087	2,320
Perth	1,670,953	704,180
Yanchep	7,443	3,390

Table C.2 Details of walls, windows, and roof elements of various envelopes

Envelope	External Wall	Internal Wall	Window	Roof tile/sheet
DB-XX-SG-CT	110mm thick face brick + 50mm air gap + 90mm thick utility brick + 13mm thick float and white set	13mm thick float and white set + 90mm thick utility brick + 13mm tick float and white set	Single Glazed	Concrete
DB-XX-SG-TT				Terracotta
DB-XX-SG-MS				Metal
DB-XX-DG-CT			Double Glazed	Concrete
DB-XX-DG-TT				Terracotta
DB-XX-DG-MS				Metal
DB-INS-SG-CT	110mm thick face brick + 10mm air gap + 40mm insulation + 10mm air gap + 90mm thick utility brick + 13mm thick float and white set	13mm thick float and white set + 90mm thick utility brick + 13mm tick float and white set	Single Glazed	Concrete
DB-INS-SG-TT				Terracotta
DB-INS-SG-MS				Metal
DB-INS-DG-CT			Double Glazed	Concrete
DB-INS-DG-TT				Terracotta
DB-INS-DG-MS				Metal
BV-XX-SG-CT	110mm thick face brick + 50mm air gap + moisture membrane + 90mm thick timber frame with rockwool batt insulation + 12mm thick gypboard lining	12mm thick gypboard lining + 90mm thick timber frame with rockwool batt insulation + 12mm thick gypboard lining	Single Glazed	Concrete
BV-XX-SG-TT				Terracotta
BV-XX-SG-MS				Metal
BV-XX-DG-CT			Double Glazed	Concrete
BV-XX-DG-TT				Terracotta
BV-XX-DG-MS				Metal
RBV-XX-SG-CT	10mm fibre cement sheet + moisture membrane + 90mm thick timber frame with rockwool batt insulation + moisture	13mm thick float and white set + 90mm thick utility brick + 13mm tick float and white set	Single Glazed	Concrete
RBV-XX-SG-TT				Terracotta
RBV-XX-SG-MS				Metal
RBV-XX-DG-CT				Concrete

Envelope	External Wall	Internal Wall	Window	Roof tile/sheet
RBV-XX-DG-TT	membrane + 110mm thick brick + 13mm thick float and white set		Double Glazed	Terracotta
RBV-XX-DG-MS				Metal
CSW-POL-SG-CT	50mm thick concrete + 100mm polystyrene core sandwiched between diagonally connected welded mesh + 50mm concrete	40mm thick concrete + 50mm polystyrene core sandwiched between diagonally connected welded mesh + 40mm concrete	Single Glazed	Concrete
CSW-POL-SG-TT				Terracotta
CSW-POL-SG-MS				Metal
CSW-POL-DG-CT			Double Glazed	Concrete
CSW-POL-DG-TT				Terracotta
CSW-POL-DG-MS				Metal
CB-XX-SG-CT	13mm thick render + 190mm hollow concrete block + 13mm float and white set	13mm thick float and white set + 90mm hollow concrete block + 13mm float and white set	Single Glazed	Concrete
CB-XX-SG-TT				Terracotta
CB-XX-SG-MS				Metal
CB-XX-DG-CT			Double Glazed	Concrete
CB-XX-DG-TT				Terracotta
CB-XX-DG-MS				Metal
ACC-XX-SG-CT	15mm thick polymer modified render + 100mm ACC block + 50mm air gap + 100mm ACC block + 15mm polymer modified render	15mm thick polymer modified render + 100mm ACC block + 15mm polymer modified render	Single Glazed	Concrete
ACC-XX-SG-TT				Terracotta
ACC-XX-SG-MS				Metal
ACC-XX-DG-CT			Double Glazed	Concrete
ACC-XX-DG-TT				Terracotta
ACC-XX-DG-MS				Metal
PCSW-XX-SG-CT	Skim coat + 75mm thick pre-cast light weight concrete sandwich panel with 6mm fibre cement sheets on either faces +	skim coat + 75mm thick pre-cast light weight concrete sandwich panel with	Single Glazed	Concrete
PCSW-XX-SG-TT				Terracotta
PCSW-XX-SG-MS				Metal

Envelope	External Wall	Internal Wall	Window	Roof tile/sheet
PCSW-XX-DG-CT	50mm air gap + 75mm thick pre-cast light weight concrete sandwich panel with 6mm fibre cement sheets on either faces + skim coat	6mm fibre cement sheets on either faces + skim coat	Double Glazed	Concrete
PCSW-XX-DG-TT				Terracotta
PCSW-XX-DG-MS				Metal
TMB-XX-SG-CT	10mm fibre cement sheet + moisture membrane + 90mm thick timber frame with rockwool batt insulation + moisture membrane + 12mm thick gypboard lining	12mm thick gypboard lining + 90mm thick timber frame with rockwool batt insulation + 12mm thick gypboard lining	Single Glazed	Concrete
TMB-XX-SG-TT				Terracotta
TMB-XX-SG-MS				Metal
TMB-XX-DG-CT			Double Glazed	Concrete
TMB-XX-DG-TT				Terracotta
TMB-XX-DG-MS				Metal

Appendix D

Table D.1 Bill of materials of a reference house (DB-XX-SG-CT) in Perth

Material/Energy	Measured Quantity		Density		Quantity tonnes
	Unit	Value	Unit	Value	
Non Envelope Elements					
Sand to make up levels for footings and ground slab	m^3	21.15	kg/m^3	1,700	35.96
Polythene Sheet	m^2	272.25	g/m^2	160	0.04
Mesh reinforcement	m^2	253.69	kg/m^2	2.5	0.63
Ready mix concrete	m^3	32.65	kg/m^3	2,400	78.35
Metal door frames	nos.	12	kg/frame	15	0.18
Roof Timber	m^3	7.5	kg/m^3	550	4.13
Bat Insulation for Roof	m^2	264	kg/m^2	1.8	0.48
Gyprock boards & cornices	m^2	264	kg/m^2	7.5	1.98
Door shutters	nos.	12	kg/door	31	0.37
Floor tiles	m^2	182.2	kg/m^2	30	5.47
Wall tiles	m^2	26.4	kg/m^2	26	0.69
Envelope Elements					
External wall - Face bricks (DB-XX)	m^3	17.07	kg/m^3	1,950	33.29
External wall - Utility bricks (DB-XX)	m^3	15.03	kg/m^3	1,950	29.32
Internal wall - Utility bricks	m^3	16.42	kg/m^3	1,700	32.01
Aluminium Windows – single glazed (SG)	m^2	40.99	kg/m^2	35	1.43
Roof Tiles – concrete (CT)	m^2	290.4	kg/m^2	50	14.52
Cement, brickie sand and lime for mortar	-	-	-	-	11.48
Metal lintels, columns, bracings, wall ties, and structural fixtures	-	-	-	-	0.58
Cement, plaster sand and lime for rendering	-	-	-	-	10.54

Table D.2 tonnes-km (tkm) travelled information for materials transported to the construction site of a reference house (DB-XX-SG-CT) in Perth

Material/Energy	Quantity tonnes	Distance km	tkm
Non Envelope Elements			
Sand to make up levels for footings and ground slab	35.96	50	1,797.75
Polythene Sheet	0.04	30	1.31
Mesh reinforcement	0.63	30	19.03
Ready mix concrete	78.35	30	2,350.62
Metal door frames	0.18	30	5.4
Roof Timber	4.13	30	123.75
Bat Insulation for Roof	0.48	30	14.26
Gyprock boards & cornices	1.98	30	59.4
Door shutters	0.37	30	11.14
Floor tiles	5.47	30	163.99
Wall tiles	0.69	30	20.59
Envelope Elements			
External wall - Face bricks (DB-XX)	33.29	30	998.76
External wall - Utility bricks (DB-XX)	29.32		879.47
Internal wall - Utility bricks	32.01	30	960.34
Aluminium Windows – single glazed (SG)	1.43	30	43.04
Roof Tiles – concrete (CT)	14.52	30	435.6
Cement, brickie sand, and lime for mortar	11.48	50/30	538.15
Metal lintels, columns, bracings, wall ties, and structural fixtures	0.58	30	17.41
Cement, plaster sand and lime for rendering	10.54	50/30	492.62

Table D.3 Energy consumption and operating hours for plants and tools including tkm travelled for construction waste disposal of a reference house (DB-XX-SG-CT) in Perth

Activity	Duration
Excavator and compactor	9 hours
Front end loader	3 hours
Mortar mixer	60 kWh
Fork life/crane	22 hours
Hand tools	60 kWh
Transportation of excavated soil (15.78m^3 @ 1,700kg/m^3)	1,340.88tkm
Transportation of construction waste (20m^3 @ 1,500kg/m^3)	1500tkm

Table D.4 Energy consumption and operating hours for plants including tkm travelled for demolition waste disposal of a reference house (DB-XX-SG-CT) in Perth

Activity	Duration
Excavator and breaker	30 hours
Front end loader	10 hours
Transportation of C&D waste to recyclers @ 75% of total waste*	3,921.80tkm
Transportation of C&D waste to landfill @ 25% of total waste*	3,268.16tkm
*Western Australian Waste Authority has a target that by the year 2020, up to 75% of the C&D waste will be recycled (WAWA 2015, 2016)	

P R E V I E W

Interim Simulation Result

***NOT FOR RATING

Run: Base

PROJECT DETAILS	
Postcode: 6155	**Climate Zone:** 13

CALCULATED ENERGY REQUIREMENTS*				
Heating	**Cooling (sensible)**	**Cooling (latent)**	**Total Energy**	**Units**
38.9	29.4	4.4	72.7	MJ/m².annum

* These energy requirements have been calculated using a standard set of occupant behaviours and so do not necessarily represent the usage pattern or lifestyle of the intended occupants. They should be used solely for the purposes of rating the building. They should not be used to infer actual energy consumption or running costs. The settings used for the simulation are shown in the building data report.

AREA-ADJUSTED ENERGY REQUIREMENTS				
Heating	**Cooling (sensible)**	**Cooling (latent)**	**Total Energy**	**Units**
36.3	27.5	4.1	67.9	MJ/m².annum
Floor area	**conditioned:** 153.6 m²	**unconditioned:** 61.6 m²	**garage:** 40.0 m²	

BAND RESULT
Building was run in non-rating mode

Area-adjusted band score thresholds									
Band 1	**Band 2**	**Band 3**	**Band 4**	**Band 5**	**Band 6**	**Band 7**	**Band 8**	**Band 9**	**Band 10**
387	251	167	118	89	70	52	34	17	4

Figure D.1 Sample summary report of AccuRate simulation for a reference (DB-XX-SG-CT) house in Perth

Table D.5 Inventory for home appliances during use stage of a reference house (DB-XX-SG-CT) in Perth

Appliance	Energy rating	Use duration	Total energy consumption kWh/year
Digital TV	200W	4h/day	292.00
Computer + chargers	300W	4h/day	438.00
Refrigerator	668kWh/year	-	668.00
Microwave	1600W	20min/day	194.67
Coffee maker	1200W	20min/day	146.00
Toaster	1200W	10min/day	73.00
Oven	2400W	30min/day	438.00
Mixer/food processor	400W	15min/day	36.50
Tea kettle	1800W	10min/day	109.50
Steam iron	600W	1h/week	31.20
Dishwasher	2400W	1h/day	876.00
Vacuum cleaner	1100W	1h/week	57.20
Range hood	140W	2h/day	102.20
Washing machine	300kWh/year	-	300.00
Cloth dryer	222kWh/year	-	222.00

Table D.6 Stage wise GHG emissions of a reference house (DB-XX-SG-CT) in Perth (without climate change impacts)

Orientation	**Life cycle GHG emissions (tonnes CO_2 e-)**							
	North	**South**	**East**	**West**	**North East**	**North West**	**South East**	**South West**
Mining to Material Production - Envelope - Wall	23.71	23.71	23.71	23.71	23.71	23.71	23.71	23.71
Mining to Material Production - Envelope - Window	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92
Mining to Material Production - Envelope - Roof	3.49	3.49	3.49	3.49	3.49	3.49	3.49	3.49
Mining to Material Production - Non Envelope Elements	22.93	22.93	22.93	22.93	22.93	22.93	22.93	22.93
Transportation	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64
Construction	2.43	2.43	2.43	2.43	2.43	2.43	2.43	2.43
Use - Thermal (Heating and cooling)	103.60	117.80	78.30	80.30	90.90	96.10	102.00	109.50
Use - Non Thermal (Hot water, home appliances, and lighting)	330.91	330.91	330.91	330.91	330.91	330.91	330.91	330.91
End of Life Demolition and Disposal	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Total	492.40	506.60	467.10	469.10	479.70	484.90	490.80	498.30

Table D.7 Stage wise GHG emissions of a reference house (DB-XX-SG-CT) in Perth (with low climate change impacts/temperature increase)

Orientation	**Life cycle GHG emissions (tonnes CO_2 e-)**							
	North	**South**	**East**	**West**	**North East**	**North West**	**South East**	**South West**
Mining to Material Production - Envelope - Wall	23.71	23.71	23.71	23.71	23.71	23.71	23.71	23.71
Mining to Material Production - Envelope - Window	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92
Mining to Material Production - Envelope - Roof	3.49	3.49	3.49	3.49	3.49	3.49	3.49	3.49
Mining to Material Production - Non Envelope Elements	22.93	22.93	22.93	22.93	22.93	22.93	22.93	22.93
Transportation	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64
Construction	2.43	2.43	2.43	2.43	2.43	2.43	2.43	2.43
Use - Thermal (Heating and cooling)	109.10	123.64	82.03	84.23	95.50	101.03	106.99	114.81
Use - Non Thermal (Hot water, home appliances, and lighting)	330.91	330.91	330.91	330.91	330.91	330.91	330.91	330.91
End of Life Demolition and Disposal	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Total	497.90	512.44	470.83	473.03	484.30	489.83	495.79	503.61

Table D.8 Stage wise GHG emissions of a reference house (DB-XX-SG-CT) in Perth (with high climate change impacts/temperature increase)

Orientation	**Life cycle GHG emissions (tonnes CO_2 e-)**							
	North	**South**	**East**	**West**	**North East**	**North West**	**South East**	**South West**
Mining to Material Production - Envelope - Wall	23.71	23.71	23.71	23.71	23.71	23.71	23.71	23.71
Mining to Material Production - Envelope - Window	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92
Mining to Material Production - Envelope - Roof	3.49	3.49	3.49	3.49	3.49	3.49	3.49	3.49
Mining to Material Production - Non Envelope Elements	22.93	22.93	22.93	22.93	22.93	22.93	22.93	22.93
Transportation	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64
Construction	2.43	2.43	2.43	2.43	2.43	2.43	2.43	2.43
Use - Thermal (Heating and cooling)	125.15	140.92	93.15	95.73	108.83	115.60	121.66	130.61
Use - Non Thermal (Hot water, home appliances, and lighting)	330.91	330.91	330.91	330.91	330.91	330.91	330.91	330.91
End of Life Demolition and Disposal	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Total	513.95	529.72	481.95	484.53	497.63	504.40	510.46	519.41

Table D.9 Breakdown of GHG emissions during use stage of a reference house (DB-XX-SG-CT) in Perth for all 8 orientations under 3 climate change impact/temperature increase scenarios

Activity	Climate change impact scenario	Life cycle GHG emissions (tonnes CO_2 e-)							
		North	**South**	**East**	**West**	**North East**	**North West**	**South East**	**South West**
Heating	Scenario 1	14.20	21.45	16.26	16.17	16.62	14.87	20.20	21.36
	Scenario 2								
	Scenario 3								
Cooling	Scenario 1	89.44	96.31	61.98	64.14	74.34	81.21	81.79	88.07
	Scenario 2	94.91	102.19	65.77	68.06	78.88	86.17	86.79	93.45
	Scenario 3	110.95	119.47	76.89	79.57	92.22	100.74	101.47	109.25
Home appliances	Scenario 1	183.13	183.13	183.13	183.13	183.13	183.13	183.13	183.13
	Scenario 2								
	Scenario 3								
Hot water	Scenario 1	65.92	65.92	65.92	65.92	65.92	65.92	65.92	65.92
	Scenario 2								
	Scenario 3								
Lighting	Scenario 1	81.82	81.82	81.82	81.82	81.82	81.82	81.82	81.82
	Scenario 2								
	Scenario 3								

Table D.10 Stage wise EE consumption of a reference house (DB-XX-SG-CT) in Perth (without climate change impacts)

Orientation	Life cycle EE consumption (TJ)							
	North	South	East	West	North East	North West	South East	South West
Mining to Material Production - Envelope - Wall	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Mining to Material Production - Envelope - Window	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mining to Material Production - Envelope - Roof	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Mining to Material Production - Non Envelope Elements	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Transportation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Construction	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Use - Thermal (Heating and cooling)	1.41	1.63	1.09	1.12	1.26	1.32	1.42	1.52
Use - Non Thermal (Hot water, home appliances, and lighting)	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60
End of Life Demolition and Disposal	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	6.82	7.04	6.50	6.53	6.67	6.73	6.83	6.93

Table D.11 Stage wise EE consumption of a reference house (DB-XX-SG-CT) in Perth (with low climate change impacts/temperature increase)

Orientation	Life cycle EE consumption (TJ)							
	North	**South**	**East**	**West**	**North East**	**North West**	**South East**	**South West**
Mining to Material Production - Envelope - Wall	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Mining to Material Production - Envelope - Window	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mining to Material Production - Envelope - Roof	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Mining to Material Production - Non Envelope Elements	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Transportation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Construction	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Use - Thermal (Heating and cooling)	1.48	1.71	1.14	1.17	1.32	1.38	1.48	1.59
Use - Non Thermal (Hot water, home appliances, and lighting)	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60
End of Life Demolition and Disposal	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	6.9	7.12	6.55	6.58	6.73	6.79	6.9	7.0

Table D.12 Stage wise EE consumption of a reference house (DB-XX-SG-CT) in Perth (with high climate change impacts/temperature increase)

Orientation	Life cycle EE consumption (TJ)							
	North	South	East	West	North East	North West	South East	South West
Mining to Material Production - Envelope - Wall	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Mining to Material Production - Envelope - Window	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Mining to Material Production - Envelope - Roof	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Mining to Material Production - Non Envelope Elements	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Transportation	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Construction	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Use - Thermal (Heating and cooling)	1.69	1.93	1.29	1.32	1.49	1.57	1.67	1.80
Use - Non Thermal (Hot water, home appliances, and lighting)	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60
End of Life Demolition and Disposal	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	7.10	7.34	6.70	6.73	6.90	6.98	7.09	7.21

Table D.13 Breakdown of EE consumption during use stage of a reference house (DB-XX-SG-CT) in Perth for all 8 orientations under 3 climate change impact scenarios

Activity	**Climate change impact scenario**	**Life cycle EE consumption (TJ)**							
		North	**South**	**East**	**West**	**North East**	**North West**	**South East**	**South West**
Heating	Scenario 1	0.25	0.38	0.28	0.28	0.29	0.26	0.35	0.37
	Scenario 2								
	Scenario 3								
Cooling	Scenario 1	1.16	1.25	0.81	0.84	0.97	1.06	1.06	1.15
	Scenario 2	1.24	1.33	0.86	0.89	1.03	1.12	1.13	1.22
	Scenario 3	1.44	1.56	1.00	1.04	1.20	1.31	1.32	1.42
Home appliances	Scenario 1	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
	Scenario 2								
	Scenario 3								
Hot water	Scenario 1	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
	Scenario 2								
	Scenario 3								
Lighting	Scenario 1	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
	Scenario 2								
	Scenario 3								

Table D.14 Bill of materials of a reference house in Perth for alternative envelope options

Material	DB-XX-SG/DG-CT/TT/MS	DB-INS-SG/DG-CT/TT/MS	BV-XX-SG/DG-CT/TT/MS	RBV-XX-SG/DG-CT/TT/MS	CB-XX-SG/DG-CT/TT/MS	ACC-XX-SG/DG-CT/TT/MS	PCSW-XX-SG/DG-CT/TT/MS	TMB-XX-SG/DG-CT/TT/MS	CSW-POL-SG/DG-CT/TT/MS
	tonnes								
Non Envelope Elements									
Excavation for foundation and cartaway	13.01	13.01	13.01	13.01	13.01	13.01	13.01	13.01	13.01
Excavation and levelling for ground slab and cartaway	13.81	13.81	13.81	13.81	13.81	13.81	13.81	13.81	13.81
Sand to make up levels for footings and ground slab	35.96	35.96	35.96	35.96	35.96	35.96	35.96	35.96	35.96
Polythene Sheet	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Mesh reinforcement	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Ready mix concrete	78.35	78.35	78.35	78.35	78.35	78.35	78.35	78.35	78.35
Metal door frames	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Roof Timber	4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13
Bat Insulation for Roof	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Gyprock boards & cornices	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
Door shutters	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Floor tiles	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47	5.47
Wall tiles	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Envelope Elements									
External Walls									

Material	DB-XX-SG/DG-CT/TT/MS	DB-INS-SG/DG-CT/TT/MS	BV-XX-SG/DG-CT/TT/MS	RBV-XX-SG/DG-CT/TT/MS	CB-XX-SG/DG-CT/TT/MS	ACC-XX-SG/DG-CT/TT/MS	PCSW-XX-SG/DG-CT/TT/MS	TMB-XX-SG/DG-CT/TT/MS	CSW-POL-SG/DG-CT/TT/MS
	tonnes								
Face bricks	33.29	33.29	33.29	-	-	-	-	-	-
Utility bricks	29.32	29.32	-	35.83	-	-	-	-	-
Cast in-situ concrete	-	-	-	-	-	-	-	-	31.01
Concrete blocks	-	-	-	-	36.08	-	-	-	-
ACC blocks	-	-	-	-	-	16.92	-	-	-
Structural Timber frame	-	-	14.54	13.82	-	-	-	13.82	-
Gyprock board lining for internal face	-	-	1.09	-	-	-	-	1.09	-
Fibre cement board/weather board cladding	-	-	-	2.64	-	-	-	2.64	-
Pre-cast concrete sandwich panels	-	-	-	-	-	-	19.33	-	-
Internal Walls									
Utility bricks	32.01	32.01	-	32.01	-	-	-	-	-
Cast in-situ concrete	-	-	-	-	-	-	-	-	35.9
Structural Timber frame	-	-	2.09	-	-	-	-	2.09	-
Concrete blocks	-	-	-	-	27.54	-	-	-	-
ACC blocks	-	-	-	-	-	9.58	-	-	-
Gyprock board lining	-	-	2.37	-	-	-	-	2.37	-
Pre-cast concrete sandwich panels	-	-	-	-	-	-	10.94	-	-
Insulation									
Wall Insulation	-	0.2	0.27	0.12	-	-	-	0.26	-

Material	DB-XX-SG/DG-CT/TT/MS	DB-INS-SG/DG-CT/TT/MS	BV-XX-SG/DG-CT/TT/MS	RBV-XX-SG/DG-CT/TT/MS	CB-XX-SG/DG-CT/TT/MS	ACC-XX-SG/DG-CT/TT/MS	PCSW-XX-SG/DG-CT/TT/MS	TMB-XX-SG/DG-CT/TT/MS	CSW-POL-SG/DG-CT/TT/MS
	tonnes								
Moisture barrier	-	-	0.14	0.13	-	-	-	0.13	-
Polystyrene insulation core for cast in-situ walls	-	-	-	-	-	-	-	-	0.33
Single glazed aluminium windows (**SG**) or	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Double glazed aluminium windows (**DG**)	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Concrete roof tiles (**CT**) or	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52
Terracotta roof tiles (**TT**) or	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62	11.62
Metal roof sheet (**MS**)	1.63	1.63	1.63	1.63	1.63	1.63	1.63	1.63	1.63
Others									
Cement, brickie sand and lime for mortar	11.48	11.48	3.66	7.82	10.33	-	-	-	-
Polymer modified mortar	-	-	-	-	-	1.26	0.5	-	-
Metal lintels, columns, bracings, wall ties, and structural fixtures	0.58	0.58	0.06	0.58	0.58	0.58	0.06	0.17	-
Wire mesh for cast in-situ walls	-	-	-	-	-	-	-	-	2.52
Metal tracks for tilt-up panels	-	-	-	-	-	-	0.56	-	-
Cement, plaster sand and lime for rendering	10.54	10.54	-	10.54	13.86	-	-	-	-
Polymer modified render	-	-	-	-	-	16.77	5.5	-	-

Table D.15 tonnes-km (tkm) travelled information for materials transported to the construction site for a typical house in Perth for alternative envelope options

Material	DB-XX-SG/DG-CT/TT/MS	DB-INS-SG/DG-CT/TT/MS	BV-XX-SG/DG-CT/TT/MS	RBV-XX-SG/DG-CT/TT/MS	CB-XX-SG/DG-CT/TT/MS	ACC-XX-SG/DG-CT/TT/MS	PCSW-XX-SG/DG-CT/TT/MS	TMB-XX-SG/DG-CT/TT/MS	CSW-POL-SG/DG-CT/TT/MS
	tkm								
Non Envelope Elements									
Sand to make up levels for footings and ground slab	1,797.75	1,797.75	1,797.75	1,797.75	1,797.75	1,797.75	1,797.75	1,797.75	1,797.75
Polythene Sheet	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
Mesh reinforcement	19.03	19.03	19.03	19.03	19.03	19.03	19.03	19.03	19.03
Ready mix concrete	2,350.62	2,350.62	2,350.62	2,350.62	2,350.62	2,350.62	2,350.62	2,350.62	2,350.62
Metal door frames	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40
Roof Timber	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75
Bat Insulation for Roof	14.26	14.26	14.26	14.26	14.26	14.26	14.26	14.26	14.26
Gyprock boards & cornices	59.40	59.40	59.40	59.40	59.40	59.40	59.40	59.40	59.40
Door shutters	11.14	11.14	11.14	11.14	11.14	11.14	11.14	11.14	11.14
Floor tiles	163.99	163.99	163.99	163.99	163.99	163.99	163.99	163.99	163.99
Wall tiles	20.59	20.59	20.59	20.59	20.59	20.59	20.59	20.59	20.59
Envelope Elements									
External Walls									
Face bricks	998.76	998.76	998.76	-	-	-	-	-	-
Utility bricks	879.47	879.47	-	1,074.90	-	-	-	-	-

Material	DB-XX-SG/DG-CT/TT/MS	DB-INS-SG/DG-CT/TT/MS	BV-XX-SG/DG-CT/TT/MS	RBV-XX-SG/DG-CT/TT/MS	CB-XX-SG/DG-CT/TT/MS	ACC-XX-SG/DG-CT/TT/MS	PCSW-XX-SG/DG-CT/TT/MS	TMB-XX-SG/DG-CT/TT/MS	CSW-POL-SG/DG-CT/TT/MS
	tkm								
Cast in-situ concrete	-	-	-	-	-	-	-	-	930.25
Concrete blocks	-	-	-	-	1,082.42	-	-	-	-
ACC blocks	-	-	-	-	-	507.54	-	-	-
Structural Timber frame	-	-	436.06	414.50	-	-	-	414.50	-
Gyprock board lining for internal face	-	-	32.57	-	-	-	-	32.57	-
Fibre cement board/weather board cladding	-	-	-	79.16	-	-	-	79.16	-
Pre-cast concrete sandwich panels	-	-	-	-	-	-	580.04	-	-
Internal Walls									
Utility bricks	960.34	960.34	-	960.34	-	-	-	-	-
Cast in-situ concrete	-	-	-	-	-	-	-	-	1,076.89
Structural Timber frame	-	-	62.79	-	-	-	-	62.79	-
Concrete blocks	-	-	-	-	826.27	-	-	-	-
ACC blocks	-	-	-	-	-	287.28	-	-	-
Gyprock board lining	-	-	71.14	-	-	-	-	71.14	-
Pre-cast concrete sandwich panels	-	-	-	-	-	-	328.32	-	-
Insulation									
Wall Insulation	-	6.01	8.07	3.59	-	-	-	7.80	-
Moisture barrier	-	-	4.21	3.91	-	-	-	3.91	-

Material	DB-XX-SG/DG-CT/TT/MS	DB-INS-SG/DG-CT/TT/MS	BV-XX-SG/DG-CT/TT/MS	RBV-XX-SG/DG-CT/TT/MS	CB-XX-SG/DG-CT/TT/MS	ACC-XX-SG/DG-CT/TT/MS	PCSW-XX-SG/DG-CT/TT/MS	TMB-XX-SG/DG-CT/TT/MS	CSW-POL-SG/DG-CT/TT/MS
	tkm								
Polystyrene insulation core for cast in-situ walls	-	-	-	-	-	-	-	-	9.98
Single glazed aluminium windows (**SG**) or	43.04	43.04	43.04	43.04	43.04	43.04	43.04	43.04	43.04
Double glazed aluminium windows (**DG**)	57.80	57.80	57.80	57.80	57.80	57.80	57.80	57.80	57.80
Concrete roof tiles (**CT**) or	435.60	435.60	435.60	435.60	435.60	435.60	435.60	435.60	435.60
Terracotta roof tiles (**TT**) or	348.48	348.48	348.48	348.48	348.48	348.48	348.48	348.48	348.48
Metal roof sheet (**MS**)	48.79	48.79	48.79	48.79	48.79	48.79	48.79	48.79	48.79
Others									
Cement, brickie sand and lime for mortar	538.15	538.15	171.61	366.55	454.50	-	-	-	-
Polymer modified mortar	-	-	-	-	-	51.73	25.00	-	-
Metal lintels, columns, bracings, wall ties, and structural fixtures	17.41	17.41	1.67	17.41	17.41	17.41	1.67	5.01	-
Wire mesh for cast in-situ walls	-	-	-	-	-	-	-	-	75.51
Metal tracks for tilt-up panels	-	-	-	-	-	-	16.79	-	-
Cement, plaster sand and lime for rendering	492.62	492.62	-	492.62	647.34	-	-	-	-
Polymer modified render	-	-	-	-	-	704.47	230.85	-	-

Table D.16 Energy consumption and operating hours for plants and tools including tkm travelled for construction waste for a typical house in Perth for alternative envelope options

Material	DB-XX-SG/DG-CT/TT/MS	DB-INS-SG/DG-CT/TT/MS	BV-XX-SG/DG-CT/TT/MS	RBV-XX-SG/DG-CT/TT/MS	CB-XX-SG/DG-CT/TT/MS	ACC-XX-SG/DG-CT/TT/MS	PCSW-XX-SG/DG-CT/TT/MS	TMB-XX-SG/DG-CT/TT/MS	CSW-POL-SG/DG-CT/TT/MS
Tools and Plants	**Duration/Energy consumption**								
Excavator and compactor (hours)	9	9	9	9	9	9	9	9	9
Front end loader (hours)	3	3	3	3	3	3	3	3	3
Mortar mixer (kWh)	60	60	18	48	70	60	30	-	-
Shotcrete pump (kWh)	-	-	-	-	-	-	-	-	75
Fork life/crane (CT/TT) (hours) or	20	22	37	30	30	20	50	50	10
Fork life/crane (MS) (hours)	18	20	35	28	28	18	48	45	8
Hand tools (CT/TT) (kWh) or	60	60	100	80	60	60	80	130	60
Hand tools (MS) (kWh)	66	66	105	85	66	66	86	135	62.5
tkm for construction waste disposal	**tkm**								
Transportation of unsuitable excavated soil	1,340.88	1,340.88	1,340.88	1,340.88	1,340.88	1,340.88	1,340.88	1,340.88	1,340.88
Transportation of construction waste (CT/TT)	1,500.00	1,500.00	750.00	1,125.00	1,500.00	1,125.00	750.00	750.00	562.50
Transportation of construction waste (MS)	1,425.00	1,425.00	675.00	1,050.00	1,425.00	1,050.00	675.00	675.00	487.50

Note: *Data source: Fozdar Technologies Pty Ltd; Budget Developments Australia Pty Ltd*

Table D.17 Energy consumption and operating hours for plants including tkm travelled for demolition waste for a typical house in Perth for alternative envelope options

Material	**DB-XX-SG/DG-CT/TT/MS**	**DB-INS-SG/DG-CT/TT/MS**	**BV-XX-SG/DG-CT/TT/MS**	**RBV-XX-SG/DG-CT/TT/MS**	**CB-XX-SG/DG-CT/TT/MS**	**ACC-XX-SG/DG-CT/TT/MS**	**PCSW-XX-SG/DG-CT/TT/MS**	**TMB-XX-SG/DG-CT/TT/MS**	**CSW-POL-SG/DG-CT/TT/MS**
Tools and Plants	**Duration/Energy consumption**								
Excavator and breaker (hours)	30	30	30	30	35	25	40	25	50
Front end loader (CT/TT) (hours)	10	10	12	12	12	10	15	15	15
Front end loader (MS) (hours)	9	9	11	11	11	9	14	14	14
tkm for construction waste disposal	**tkm (75% of total waste to recyclers and 25% to landfill)**								
C&D waste to recyclers (SG-CT)	-	3,924.80	3,025.96	3,715.78	3,489.21	2,840.02	2,716.74	2,501.82	3,209.69
C&D waste to recyclers (SG-TT)	3,878.24	3,881.24	2,982.40	3,672.22	3,445.65	2,796.46	2,673.18	2,458.26	3,166.13
C&D waste to recyclers (SG-MS)	3,728.39	3,731.40	2,832.55	3,522.37	3,295.81	2,646.62	2,523.34	2,308.42	3,016.29
C&D waste to recyclers (DG-CT)	3,929.17	3,932.18	3,033.33	3,723.15	3,496.59	2,847.40	2,724.12	2,509.20	3,217.07
C&D waste to recyclers (DG-TT)	3,885.61	3,888.62	2,989.77	3,679.59	3,453.03	2,803.84	2,680.56	2,465.64	3,173.51
C&D waste to recyclers (DG-MS)	3,735.77	3,738.78	2,839.93	3,529.75	3,303.18	2,654.00	2,530.71	2,315.79	3,023.67
C&D waste to landfill (SG-CT)	-	3,270.67	2,521.63	3,096.48	2,907.68	2,366.69	2,263.95	2,084.85	2,674.75
C&D waste to landfill (SG-TT)	3,231.86	3,234.37	2,485.33	3,060.18	2,871.38	2,330.39	2,227.65	2,048.55	2,638.45
C&D waste to landfill (SG-MS)	3,106.99	3,109.50	2,360.46	2,935.31	2,746.50	2,205.51	2,102.78	1,923.68	2,513.57
C&D waste to landfill (DG-CT)	3,274.31	3,276.82	2,527.78	3,102.63	2,913.83	2,372.84	2,270.10	2,091.00	2,680.89
C&D waste to landfill (DG-TT)	3,238.01	3,240.52	2,491.48	3,066.33	2,877.53	2,336.54	2,233.80	2,054.70	2,644.59
C&D waste to landfill (DG-MS)	3,113.14	3,115.65	2,366.61	2,941.46	2,752.65	2,211.66	2,108.93	1,929.83	2,519.72

Note: *Data source: Fozdar Technologies Pty Ltd; Budget Developments Australia Pty Ltd;(WAWA 2015, 2016)*

Table D.18 Stage wise breakdown of life cycle GHG emissions of a typical house in Perth for all alternative envelope options

Envelope option *reference case	Mining to material production stage				Transportation	Use stage		Construction	End of life demolition and disposal	Total GHG tonnes CO_2 e-
	Envelope - wall	Envelope - window	Envelope - roof	Non envelope		Heating and cooling	Hot water, home appliances, and lighting			
DB-XX-SG-CT*	23.70	2.92	3.49	23.00	1.64	78.24	331.00	2.43	0.76	**467.09**
DB-XX-SG-TT	23.70	2.92	4.49	23.00	1.62	77.70	331.00	2.43	0.76	**467.63**
DB-XX-SG-MS	23.70	2.92	5.06	23.00	1.56	77.80	331.00	2.31	0.71	**468.08**
DB-XX-DG-CT	23.70	3.50	3.49	23.00	1.64	64.28	331.00	2.43	0.76	**453.81**
DB-XX-DG-TT	23.70	3.50	4.49	23.00	1.62	64.09	331.00	2.43	0.76	**454.59**
DB-XX-DG-MS	23.70	3.50	5.06	23.00	1.57	64.98	331.00	2.31	0.71	**455.83**
DB-INS-SG-CT	24.90	2.92	3.49	23.00	1.64	59.37	331.00	2.53	0.76	**449.61**
DB-INS-SG-TT	24.90	2.92	4.49	23.00	1.62	58.83	331.00	2.53	0.76	**450.05**
DB-INS-SG-MS	24.90	2.92	5.06	23.00	1.56	59.52	331.00	2.41	0.71	**451.09**
DB-INS-DG-CT	24.90	3.50	3.49	23.00	1.64	47.13	331.00	2.53	0.76	**437.95**
DB-INS-DG-TT	24.90	3.50	4.49	23.00	1.62	47.18	331.00	2.53	0.76	**438.98**
DB-INS-DG-MS	24.90	3.50	5.06	23.00	1.57	47.68	331.00	2.41	0.71	**439.83**
BV-XX-SG-CT	18.10	2.92	3.49	23.00	1.25	87.88	331.00	2.91	0.84	**471.39**
BV-XX-SG-TT	18.10	2.92	4.49	23.00	1.23	87.10	331.00	2.91	0.84	**471.59**
BV-XX-SG-MS	18.10	2.92	5.06	23.00	1.18	88.23	331.00	2.79	0.79	**473.07**
BV-XX-DG-CT	18.10	3.50	3.49	23.00	1.25	70.13	331.00	2.91	0.84	**454.21**
BV-XX-DG-TT	18.10	3.50	4.49	23.00	1.24	69.34	331.00	2.91	0.84	**454.41**
BV-XX-DG-MS	18.10	3.50	5.06	23.00	1.18	71.26	331.00	2.88	0.79	**456.77**
RBV-XX-SG-CT	29.60	2.92	3.49	23.00	1.55	60.75	331.00	2.75	0.85	**455.91**

Envelope option *reference case	Mining to material production stage				Transportation	Use stage		Construction	End of life demolition and disposal	Total GHG tonnes CO_2 e-
	Envelope - wall	Envelope - window	Envelope - roof	Non envelope		Heating and cooling	Hot water, home appliances, and lighting			
RBV-XX-SG-TT	29.60	2.92	4.49	23.00	1.53	59.77	331.00	2.75	0.85	**455.91**
RBV-XX-SG-MS	29.60	2.92	5.06	23.00	1.48	60.70	331.00	2.63	0.80	**457.19**
RBV-XX-DG-CT	29.60	3.50	3.49	23.00	1.55	48.31	331.00	2.75	0.85	**444.05**
RBV-XX-DG-TT	29.60	3.50	4.49	23.00	1.53	47.72	331.00	2.75	0.85	**444.45**
RBV-XX-DG-MS	29.60	3.50	5.06	23.00	1.48	48.66	331.00	2.63	0.80	**445.73**
CB-XX-SG-CT	13.40	2.92	3.49	23.00	1.48	131.95	331.00	2.91	0.88	**511.03**
CB-XX-SG-TT	13.40	2.92	4.49	23.00	1.46	131.41	331.00	2.91	0.88	**511.47**
CB-XX-SG-MS	13.40	2.92	5.06	23.00	1.41	132.26	331.00	2.79	0.83	**512.67**
CB-XX-DG-CT	13.40	3.50	3.49	23.00	1.48	114.72	331.00	2.91	0.88	**494.38**
CB-XX-DG-TT	13.40	3.50	4.49	23.00	1.46	113.79	331.00	2.91	0.88	**494.43**
CB-XX-DG-MS	13.40	3.50	5.06	23.00	1.41	114.44	331.00	2.79	0.83	**495.43**
ACC-XX-SG-CT	38.60	2.92	3.49	23.00	1.21	67.70	331.00	2.28	0.70	**470.90**
ACC-XX-SG-TT	38.60	2.92	4.49	23.00	1.19	67.11	331.00	2.28	0.70	**471.29**
ACC-XX-SG-MS	38.60	2.92	5.06	23.00	1.14	67.85	331.00	2.15	0.65	**472.37**
ACC-XX-DG-CT	38.60	3.50	3.49	23.00	1.21	53.80	331.00	2.28	0.71	**457.58**
ACC-XX-DG-TT	38.60	3.50	4.49	23.00	1.20	53.01	331.00	2.28	0.70	**457.78**
ACC-XX-DG-MS	38.60	3.50	5.06	23.00	1.14	54.15	331.00	2.15	0.65	**459.25**
PCSW-XX-SG-CT	49.30	2.92	3.49	23.00	1.14	113.11	331.00	3.50	1.04	**528.51**
PCSW-XX-SG-TT	49.30	2.92	4.49	23.00	1.12	112.37	331.00	3.50	1.04	**528.75**
PCSW-XX-SG-MS	49.30	2.92	5.06	23.00	1.07	113.27	331.00	3.39	0.99	**529.99**

Envelope option *reference case	Mining to material production stage				Transportation	Use stage		Construction	End of life demolition and disposal	Total GHG tonnes CO_2 e-
	Envelope - wall	Envelope - window	Envelope - roof	Non envelope		Heating and cooling	Hot water, home appliances, and lighting			
PCSW-XX-DG-CT	49.30	3.50	3.49	23.00	1.14	93.55	331.00	3.50	1.04	**509.52**
PCSW-XX-DG-TT	49.30	3.50	4.49	23.00	1.13	92.56	331.00	3.50	1.04	**509.52**
PCSW-XX-DG-MS	49.30	3.50	5.06	23.00	1.07	93.65	331.00	3.39	0.99	**510.96**
TMB-XX-SG-CT	8.91	2.92	3.49	23.00	1.05	105.99	331.00	3.52	0.93	**480.82**
TMB-XX-SG-TT	8.91	2.92	4.49	23.00	1.03	105.41	331.00	3.52	0.93	**481.21**
TMB-XX-SG-MS	8.91	2.92	5.06	23.00	0.98	107.37	331.00	3.26	0.88	**483.38**
TMB-XX-DG-CT	8.91	3.50	3.49	23.00	1.05	87.80	331.00	3.52	0.93	**463.20**
TMB-XX-DG-TT	8.91	3.50	4.49	23.00	1.03	87.80	331.00	3.52	0.93	**464.18**
TMB-XX-DG-MS	8.91	3.50	5.06	23.00	0.98	88.98	331.00	3.26	0.88	**465.57**
CSW-POL-SG-CT	17.50	2.92	3.49	23.00	1.31	56.42	331.00	1.59	1.12	**438.35**
CSW-POL-SG-TT	17.50	2.92	4.49	23.00	1.29	56.23	331.00	1.59	1.12	**439.14**
CSW-POL-SG-MS	17.50	2.92	5.06	23.00	1.24	56.77	331.00	1.47	1.07	**440.02**
CSW-POL-DG-CT	17.50	3.50	3.49	23.00	1.31	45.86	331.00	1.59	1.12	**428.37**
CSW-POL-DG-TT	17.50	3.50	4.49	23.00	1.29	44.88	331.00	1.59	1.12	**428.37**
CSW-POL-DG-MS	17.50	3.50	5.06	23.00	1.24	46.40	331.00	1.47	1.07	**430.24**

Table D.19 Stage wise breakdown of life cycle EE consumption of a typical house in Perth for all alternative envelope options

Envelope options *reference case	Mining to material production stage				Transportation	Use stage		Construction	End of life demolition and disposal	Total EE - TJ
	Envelope - wall	Envelope - window	Envelope - roof	Non envelope		Heating and cooling	Hot water, home appliances, and lighting			
DB-XX-SG-CT*	0.35	0.05	0.02	0.29	0.02	1.09	4.60	0.04	0.03	**6.51**
DB-XX-SG-TT	0.35	0.05	0.04	0.29	0.02	1.08	4.60	0.04	0.03	**6.51**
DB-XX-SG-MS	0.35	0.05	0.07	0.29	0.02	1.09	4.60	0.04	0.03	**6.55**
DB-XX-DG-CT	0.35	0.06	0.02	0.29	0.02	0.90	4.60	0.04	0.03	**6.33**
DB-XX-DG-TT	0.35	0.06	0.04	0.29	0.02	0.90	4.60	0.04	0.03	**6.34**
DB-XX-DG-MS	0.35	0.06	0.07	0.29	0.02	0.91	4.60	0.04	0.03	**6.38**
DB-INS-SG-CT	0.38	0.05	0.02	0.29	0.02	0.82	4.60	0.05	0.03	**6.26**
DB-INS-SG-TT	0.38	0.05	0.04	0.29	0.02	0.81	4.60	0.05	0.03	**6.27**
DB-INS-SG-MS	0.38	0.05	0.07	0.29	0.02	0.82	4.60	0.04	0.03	**6.31**
DB-INS-DG-CT	0.38	0.06	0.02	0.29	0.02	0.65	4.60	0.05	0.03	**6.10**
DB-INS-DG-TT	0.38	0.06	0.04	0.29	0.02	0.65	4.60	0.05	0.03	**6.12**
DB-INS-DG-MS	0.38	0.06	0.07	0.29	0.02	0.66	4.60	0.04	0.03	**6.16**
BV-XX-SG-CT	0.19	0.05	0.02	0.29	0.02	1.19	4.60	0.05	0.03	**6.44**
BV-XX-SG-TT	0.19	0.05	0.04	0.29	0.02	1.18	4.60	0.05	0.03	**6.44**
BV-XX-SG-MS	0.19	0.05	0.07	0.29	0.02	1.19	4.60	0.05	0.03	**6.49**
BV-XX-DG-CT	0.19	0.06	0.02	0.29	0.02	0.95	4.60	0.05	0.03	**6.21**
BV-XX-DG-TT	0.19	0.06	0.04	0.29	0.02	0.94	4.60	0.05	0.03	**6.22**
BV-XX-DG-MS	0.19	0.06	0.07	0.29	0.02	0.96	4.60	0.05	0.03	**6.27**

Envelope options *reference case	Mining to material production stage				Transportation	Use stage		Construction	End of life demolition and disposal	Total EE - TJ
	Envelope - wall	Envelope - window	Envelope - roof	Non envelope		Heating and cooling	Hot water, home appliances, and lighting			
RBV-XX-SG-CT	0.35	0.05	0.02	0.29	0.02	0.84	4.60	0.05	0.03	**6.25**
RBV-XX-SG-TT	0.35	0.05	0.04	0.29	0.02	0.82	4.60	0.05	0.03	**6.25**
RBV-XX-SG-MS	0.35	0.05	0.07	0.29	0.02	0.83	4.60	0.05	0.03	**6.29**
RBV-XX-DG-CT	0.35	0.06	0.02	0.29	0.02	0.67	4.60	0.05	0.03	**6.09**
RBV-XX-DG-TT	0.35	0.06	0.04	0.29	0.02	0.66	4.60	0.05	0.03	**6.10**
RBV-XX-DG-MS	0.35	0.06	0.07	0.29	0.02	0.67	4.60	0.05	0.03	**6.14**
CB-XX-SG-CT	0.11	0.05	0.02	0.29	0.02	1.84	4.60	0.05	0.04	**7.02**
CB-XX-SG-TT	0.11	0.05	0.04	0.29	0.02	1.83	4.60	0.05	0.04	**7.03**
CB-XX-SG-MS	0.11	0.05	0.07	0.29	0.02	1.84	4.60	0.05	0.04	**7.07**
CB-XX-DG-CT	0.11	0.06	0.02	0.29	0.02	1.61	4.60	0.05	0.04	**6.80**
CB-XX-DG-TT	0.11	0.06	0.04	0.29	0.02	1.59	4.60	0.05	0.04	**6.80**
CB-XX-DG-MS	0.11	0.06	0.07	0.29	0.02	1.60	4.60	0.05	0.04	**6.84**
ACC-XX-SG-CT	0.48	0.05	0.02	0.29	0.02	0.92	4.60	0.04	0.03	**6.45**
ACC-XX-SG-TT	0.48	0.05	0.04	0.29	0.02	0.91	4.60	0.04	0.03	**6.46**
ACC-XX-SG-MS	0.48	0.05	0.07	0.29	0.02	0.92	4.60	0.04	0.03	**6.50**
ACC-XX-DG-CT	0.48	0.06	0.02	0.29	0.02	0.74	4.60	0.04	0.03	**6.27**
ACC-XX-DG-TT	0.48	0.06	0.04	0.29	0.02	0.72	4.60	0.04	0.03	**6.28**
ACC-XX-DG-MS	0.48	0.06	0.07	0.29	0.02	0.74	4.60	0.04	0.03	**6.32**
PCSW-XX-SG-CT	0.48	0.05	0.02	0.29	0.02	1.54	4.60	0.06	0.04	**7.10**

Envelope options *reference case	Mining to material production stage				Transportation	Use stage		Construction	End of life demolition and disposal	Total EE - TJ
	Envelope - wall	Envelope - window	Envelope - roof	Non envelope		Heating and cooling	Hot water, home appliances, and lighting			
PCSW-XX-SG-TT	0.48	0.05	0.04	0.29	0.02	1.53	4.60	0.06	0.04	**7.10**
PCSW-XX-SG-MS	0.48	0.05	0.07	0.29	0.02	1.54	4.60	0.06	0.04	**7.15**
PCSW-XX-DG-CT	0.48	0.06	0.02	0.29	0.02	1.28	4.60	0.06	0.04	**6.85**
PCSW-XX-DG-TT	0.48	0.06	0.04	0.29	0.02	1.26	4.60	0.06	0.04	**6.85**
PCSW-XX-DG-MS	0.48	0.06	0.07	0.29	0.02	1.28	4.60	0.06	0.04	**6.89**
TMB-XX-SG-CT	0.06	0.05	0.02	0.29	0.01	1.43	4.60	0.06	0.03	**6.56**
TMB-XX-SG-TT	0.06	0.05	0.04	0.29	0.01	1.42	4.60	0.06	0.03	**6.56**
TMB-XX-SG-MS	0.06	0.05	0.07	0.29	0.01	1.45	4.60	0.05	0.03	**6.62**
TMB-XX-DG-CT	0.06	0.06	0.02	0.29	0.01	1.19	4.60	0.06	0.03	**6.32**
TMB-XX-DG-TT	0.06	0.06	0.04	0.29	0.01	1.19	4.60	0.06	0.03	**6.34**
TMB-XX-DG-MS	0.06	0.06	0.07	0.29	0.01	1.20	4.60	0.05	0.03	**6.38**
CSW-POL-SG-CT	0.24	0.05	0.02	0.29	0.02	0.77	4.60	0.03	0.05	**6.06**
CSW-POL-SG-TT	0.24	0.05	0.04	0.29	0.02	0.77	4.60	0.03	0.05	**6.08**
CSW-POL-SG-MS	0.24	0.05	0.07	0.29	0.02	0.77	4.60	0.03	0.04	**6.12**
CSW-POL-DG-CT	0.24	0.06	0.02	0.29	0.02	0.63	4.60	0.03	0.05	**5.93**
CSW-POL-DG-TT	0.24	0.06	0.04	0.29	0.02	0.61	4.60	0.03	0.05	**5.93**
CSW-POL-DG-MS	0.24	0.06	0.07	0.29	0.02	0.63	4.60	0.03	0.04	**5.98**

Table D.20 Composition of alternative concrete mixes with input substitution

Concrete Mix	**Mix reference**	**Cementitious Contents**			**Course Aggregate**		**Fine Aggregate/Sand**	
		OPC	**Fly Ash (FA)**	**GGBFS (S)**	**Natural Aggregate (NA)**	**Recycled Aggregate (RCA)**	**Natural Sand (NS)**	**Manufactured Sand (MFS)**
Mix 1 (ref. mix)	C100FA0S0-NA100RCA0-NS100MFS0	100%	-	-	100%	-	100%	-
Mix 2	C100FA0S0-NA100RCA0-NS60MFS40	100%	-	-	100%	-	60%	40%
Mix 3	C100FA0S0-NA100RCA0-NS80MFS20	100%	-	-	100%	-	80%	20%
Mix 4	C100FA0S0-NA60RCA40-NS100MFS0	100%	-	-	60%	40%	100%	-
Mix 5	C100FA0S0-NA60RCA40-NS60MFS40	100%	-	-	60%	40%	60%	40%
Mix 6	C100FA0S0-NA60RCA40-NS80MFS20	100%	-	-	60%	40%	80%	20%
Mix 7	C100FA0S0-NA70RCA30-NS100MFS0	100%	-	-	70%	30%	100%	-
Mix 8	C100FA0S0-NA70RCA30-NS60MFS40	100%	-	-	70%	30%	60%	40%
Mix 9	C100FA0S0-NA70RCA30-NS80MFS20	100%	-	-	70%	30%	80%	20%
Mix 10	C100FA0S0-NA80RCA20-NS100MFS0	100%	-	-	80%	20%	100%	-
Mix 11	C100FA0S0-NA80RCA20-NS60MFS40	100%	-	-	80%	20%	60%	40%
Mix 12	C100FA0S0-NA80RCA20-NS80MFS20	100%	-	-	80%	20%	80%	20%
Mix 13	C70FA30S0-NA100RCA0-NS100MFS0	70%	30%	-	100%	-	100%	-
Mix 14	C70FA30S0-NA100RCA0-NS60MFS40	70%	30%	-	100%	-	60%	40%
Mix 15	C70FA30S0-NA100RCA0-NS80MFS20	70%	30%	-	100%	-	80%	20%
Mix 16	C70FA30S0-NA60RCA40-NS100MFS0	70%	30%	-	60%	40%	100%	-
Mix 17	C70FA30S0-NA60RCA40-NS60MFS40	70%	30%	-	60%	40%	60%	40%
Mix 18	C70FA30S0-NA60RCA40-NS80MFS20	70%	30%	-	60%	40%	80%	20%

Concrete Mix	Mix reference	Cementitious Contents			Course Aggregate		Fine Aggregate/Sand	
		OPC	Fly Ash (FA)	GGBFS (S)	Natural Aggregate (NA)	Recycled Aggregate (RCA)	Natural Sand (NS)	Manufactured Sand (MFS)
Mix 19	C70FA30S0-NA70RCA30-NS100MFS0	70%	30%	-	70%	30%	100%	-
Mix 20	C70FA30S0-NA70RCA30-NS60MFS40	70%	30%	-	70%	30%	60%	40%
Mix 21	C70FA30S0-NA70RCA30-NS80MFS20	70%	30%	-	70%	30%	80%	20%
Mix 22	C70FA30S0-NA80RCA20-NS100MFS0	70%	30%	-	80%	20%	100%	-
Mix 23	C70FA30S0-NA80RCA20-NS60MFS40	70%	30%	-	80%	20%	60%	40%
Mix 24	C70FA30S0-NA80RCA20-NS80MFS20	70%	30%	-	80%	20%	80%	20%
Mix 25	C70FA20S10-NA100RCA0-NS100MFS0	70%	20%	10%	100%	-	100%	-
Mix 26	C70FA20S10-NA100RCA0-NS60MFS40	70%	20%	10%	100%	-	60%	40%
Mix 27	C70FA20S10-NA100RCA0-NS80MFS20	70%	20%	10%	100%	-	80%	20%
Mix 28	C70FA20S10-NA60RCA40-NS100MFS0	70%	20%	10%	60%	40%	100%	-
Mix 29	C70FA20S10-NA60RCA40-NS60MFS40	70%	20%	10%	60%	40%	60%	40%
Mix 30	C70FA20S10-NA60RCA40-NS80MFS20	70%	20%	10%	60%	40%	80%	20%
Mix 31	C70FA20S10-NA70RCA30-NS100MFS0	70%	20%	10%	70%	30%	100%	-
Mix 32	C70FA20S10-NA70RCA30-NS60MFS40	70%	20%	10%	70%	30%	60%	40%
Mix 33	C70FA20S10-NA70RCA30-NS80MFS20	70%	20%	10%	70%	30%	80%	20%
Mix 34	C70FA20S10-NA80RCA20-NS100MFS0	70%	20%	10%	80%	20%	100%	-
Mix 35	C70FA20S10-NA80RCA20-NS60MFS40	70%	20%	10%	80%	20%	60%	40%
Mix 36	C70FA20S10-NA80RCA20-NS80MFS20	70%	20%	10%	80%	20%	80%	20%
Mix 37	C70FA15S15-NA100RCA0-NS100MFS0	70%	15%	15%	100%	-	100%	-
Mix 38	C70FA15S15-NA100RCA0-NS60MFS40	70%	15%	15%	100%	-	60%	40%

Concrete Mix	Mix reference	Cementitious Contents			Course Aggregate		Fine Aggregate/Sand	
		OPC	Fly Ash (FA)	GGBFS (S)	Natural Aggregate (NA)	Recycled Aggregate (RCA)	Natural Sand (NS)	Manufactured Sand (MFS)
Mix 39	C70FA15S15-NA100RCA0-NS80MFS20	70%	15%	15%	100%	-	80%	20%
Mix 40	C70FA15S15-NA60RCA40-NS100MFS0	70%	15%	15%	60%	40%	100%	-
Mix 41	C70FA15S15-NA60RCA40-NS60MFS40	70%	15%	15%	60%	40%	60%	40%
Mix 42	C70FA15S15-NA60RCA40-NS80MFS20	70%	15%	15%	60%	40%	80%	20%
Mix 43	C70FA15S15-NA70RCA30-NS100MFS0	70%	15%	15%	70%	30%	100%	-
Mix 44	C70FA15S15-NA70RCA30-NS60MFS40	70%	15%	15%	70%	30%	60%	40%
Mix 45	C70FA15S15-NA70RCA30-NS80MFS20	70%	15%	15%	70%	30%	80%	20%
Mix 46	C70FA15S15-NA80RCA20-NS100MFS0	70%	15%	15%	80%	20%	100%	-
Mix 47	C70FA15S15-NA80RCA20-NS60MFS40	70%	15%	15%	80%	20%	60%	40%
Mix 48	C70FA15S15-NA80RCA20-NS80MFS20	70%	15%	15%	80%	20%	80%	20%
Mix 49	C70FA10S20-NA100RCA0-NS100MFS0	70%	10%	20%	100%	-	100%	-
Mix 50	C70FA10S20-NA100RCA0-NS60MFS40	70%	10%	20%	100%	-	60%	40%
Mix 51	C70FA10S20-NA100RCA0-NS80MFS20	70%	10%	20%	100%	-	80%	20%
Mix 52	C70FA10S20-NA60RCA40-NS100MFS0	70%	10%	20%	60%	40%	100%	-
Mix 53	C70FA10S20-NA60RCA40-NS60MFS40	70%	10%	20%	60%	40%	60%	40%
Mix 54	C70FA10S20-NA60RCA40-NS80MFS20	70%	10%	20%	60%	40%	80%	20%
Mix 55	C70FA10S20-NA70RCA30-NS100MFS0	70%	10%	20%	70%	30%	100%	-
Mix 56	C70FA10S20-NA70RCA30-NS60MFS40	70%	10%	20%	70%	30%	60%	40%
Mix 57	C70FA10S20-NA70RCA30-NS80MFS20	70%	10%	20%	70%	30%	80%	20%
Mix 58	C70FA10S20-NA80RCA20-NS100MFS0	70%	10%	20%	80%	20%	100%	-

Concrete Mix	Mix reference	Cementitious Contents			Course Aggregate		Fine Aggregate/Sand	
		OPC	Fly Ash (FA)	GGBFS (S)	Natural Aggregate (NA)	Recycled Aggregate (RCA)	Natural Sand (NS)	Manufactured Sand (MFS)
Mix 59	C70FA10S20-NA80RCA20-NS60MFS40	70%	10%	20%	80%	20%	60%	40%
Mix 60	C70FA10S20-NA80RCA20-NS80MFS20	70%	10%	20%	80%	20%	80%	20%
Mix 61	C70FA0S30-NA100RCA0-NS100MFS0	70%	-	30%	100%	-	100%	-
Mix 62	C70FA0S30-NA100RCA0-NS60MFS40	70%	-	30%	100%	-	60%	40%
Mix 63	C70FA0S30-NA100RCA0-NS80MFS20	70%	-	30%	100%	-	80%	20%
Mix 64	C70FA0S30-NA60RCA40-NS100MFS0	70%	-	30%	60%	40%	100%	-
Mix 65	C70FA0S30-NA60RCA40-NS60MFS40	70%	-	30%	60%	40%	60%	40%
Mix 66	C70FA0S30-NA60RCA40-NS80MFS20	70%	-	30%	60%	40%	80%	20%
Mix 67	C70FA0S30-NA70RCA30-NS100MFS0	70%	-	30%	70%	30%	100%	-
Mix 68	C70FA0S30-NA70RCA30-NS60MFS40	70%	-	30%	70%	30%	60%	40%
Mix 69	C70FA0S30-NA70RCA30-NS80MFS20	70%	-	30%	70%	30%	80%	20%
Mix 70	C70FA0S30-NA80RCA20-NS100MFS0	70%	-	30%	80%	20%	100%	-
Mix 71	C70FA0S30-NA80RCA20-NS60MFS40	70%	-	30%	80%	20%	60%	40%
Mix 72	C70FA0S30-NA80RCA20-NS80MFS20	70%	-	30%	80%	20%	80%	20%

Table D.21 GHG emissions associated with the production of concrete mixes with alternative material compositions

Concrete Mixes		GHG emissions (kg CO_2 e-) per tonnes of concrete					
		C100FA0S0	**C70FA30S0**	**C70FA20S10**	**C70FA15S15**	**C70FA10S20**	**C70FA0S30**
NA100RCA0	**NS100MFS0**	135.74	102.28	105.58	107.24	108.89	112.19
	NS60MFS40	135.77	102.32	105.62	107.27	108.92	112.22
	NS80MFS20	135.76	102.30	105.60	107.25	108.90	112.20
NA60RCA40	**NS100MFS0**	134.03	100.57	103.87	105.53	107.18	110.48
	NS60MFS40	134.06	100.61	103.91	105.56	107.21	110.51
	NS80MFS20	134.05	100.59	103.89	105.54	107.19	110.49
NA70RCA30	**NS100MFS0**	134.46	101.00	104.30	105.95	107.60	110.91
	NS60MFS40	134.49	101.03	104.34	105.99	107.64	110.94
	NS80MFS20	134.47	101.02	104.32	105.97	107.62	110.92
NA80RCA20	**NS100MFS0**	134.88	101.43	104.73	106.38	108.03	111.33
	NS60MFS40	134.92	101.46	104.76	106.41	108.06	111.37
	NS80MFS20	134.90	101.44	104.75	106.40	108.05	111.35

Table D.22 EE consumption associated with the production of concrete mixes with alternative material compositions

Concrete Mixes		EE consumption (GJ) per tonnes of concrete					
		C100FA0S0	**C70FA30S0**	**C70FA20S10**	**C70FA15S15**	**C70FA10S20**	**C70FA0S30**
NA100RCA0	**NS100MFS0**	1.27	1.01	1.03	1.04	1.06	1.08
	NS60MFS40	1.27	1.01	1.03	1.04	1.06	1.08
	NS80MFS20	1.27	1.01	1.03	1.04	1.06	1.08
NA60RCA40	**NS100MFS0**	1.24	0.97	1.00	1.01	1.03	1.05
	NS60MFS40	1.24	0.98	1.00	1.01	1.03	1.05
	NS80MFS20	1.24	0.98	1.00	1.01	1.03	1.05
NA70RCA30	**NS100MFS0**	1.25	0.98	1.01	1.02	1.03	1.06
	NS60MFS40	1.25	0.98	1.01	1.02	1.03	1.06
	NS80MFS20	1.25	0.98	1.01	1.02	1.03	1.06
NA80RCA20	**NS100MFS0**	1.26	0.99	1.02	1.03	1.04	1.07
	NS60MFS40	1.26	0.99	1.02	1.03	1.04	1.07
	NS80MFS20	1.26	0.99	1.02	1.03	1.04	1.07

Table D.23 Energy and environmental impacts of a typical house due to change in orientation from East to South for alternative envelope options

Envelope options *reference case	East facing					South facing					Energy increase		GHG increase		EE increase	
	Heating	**Cooling**	**Total**	**GHG**	**EE**	**Heating**	**Cooling**	**Total**	**GHG**	**EE**						
	GJ			**tonnes CO_2 e-**	**TJ**	**GJ**			**tonnes CO_2 e-**	**TJ**	**GJ**		**tonnes CO_2 e-**		**TJ**	
DB-XX-SG-CT*	278.78	242.69	**521.47**	78.24	1.09	367.87	377.09	**744.96**	117.76	1.63	223.49	**42.86%**	39.52	**50.51%**	0.54	**49.27%**
DB-XX-SG-TT	279.55	240.38	**519.94**	77.70	1.08	367.87	374.78	**742.66**	117.18	1.62	222.72	**42.84%**	39.48	**50.81%**	0.54	**49.51%**
DB-XX-SG-MS	278.02	241.15	**519.17**	77.80	1.09	366.34	380.16	**746.50**	118.46	1.64	227.33	**43.79%**	40.65	**52.25%**	0.55	**50.88%**
DB-XX-DG-CT	258.05	192.77	**450.82**	64.28	0.90	346.37	328.70	**675.07**	104.15	1.45	224.26	**49.74%**	39.87	**62.02%**	0.54	**59.94%**
DB-XX-DG-TT	258.05	192.00	**450.05**	64.09	0.90	346.37	327.94	**674.30**	103.96	1.44	224.26	**49.83%**	39.87	**62.21%**	0.54	**60.11%**
DB-XX-DG-MS	256.51	195.84	**452.35**	64.98	0.91	344.83	333.31	**678.14**	105.24	1.46	225.79	**49.92%**	40.26	**61.96%**	0.55	**59.94%**
DB-INS-SG-CT	170.50	193.54	**364.03**	59.37	0.82	250.37	317.18	**567.55**	95.61	1.31	203.52	**55.91%**	36.24	**61.04%**	0.49	**60.26%**
DB-INS-SG-TT	171.26	191.23	**362.50**	58.83	0.81	250.37	315.65	**566.02**	95.22	1.31	203.52	**56.14%**	36.39	**61.86%**	0.49	**60.99%**
DB-INS-SG-MS	169.73	194.30	**364.03**	59.52	0.82	249.60	320.26	**569.86**	96.35	1.32	205.82	**56.54%**	36.83	**61.87%**	0.50	**61.06%**
DB-INS-DG-CT	148.99	150.53	**299.52**	47.13	0.65	228.10	277.25	**505.34**	84.11	1.15	205.82	**68.72%**	36.98	**78.45%**	0.50	**76.94%**
DB-INS-DG-TT	149.76	150.53	**300.29**	47.18	0.65	228.86	276.48	**505.34**	83.96	1.15	205.06	**68.29%**	36.78	**77.96%**	0.50	**76.45%**
DB-INS-DG-MS	148.22	152.83	**301.06**	47.68	0.66	227.33	279.55	**506.88**	84.66	1.16	205.82	**68.37%**	36.98	**77.56%**	0.50	**76.13%**
BV-XX-SG-CT	158.21	307.97	**466.18**	87.88	1.19	201.98	446.21	**648.19**	125.74	1.69	182.02	**39.04%**	37.86	**43.08%**	0.50	**42.54%**
BV-XX-SG-TT	158.21	304.90	**463.10**	87.10	1.18	202.75	443.14	**645.89**	125.00	1.68	182.78	**39.47%**	37.91	**43.52%**	0.51	**42.98%**
BV-XX-SG-MS	157.44	309.50	**466.94**	88.23	1.19	201.22	443.90	**645.12**	125.11	1.68	178.18	**38.16%**	36.88	**41.80%**	0.49	**41.31%**
BV-XX-DG-CT	132.86	244.22	**377.09**	70.13	0.95	178.94	387.84	**566.78**	109.49	1.47	189.70	**50.31%**	39.37	**56.14%**	0.52	**55.35%**
BV-XX-DG-TT	132.86	241.15	**374.02**	69.34	0.94	178.94	387.07	**566.02**	109.30	1.47	192.00	**51.33%**	39.96	**57.62%**	0.53	**56.77%**
BV-XX-DG-MS	132.10	248.83	**380.93**	71.26	0.96	178.18	391.68	**569.86**	110.43	1.48	188.93	**49.60%**	39.17	**54.97%**	0.52	**54.25%**
RBV-XX-SG-CT	170.50	198.91	**369.41**	60.75	0.84	248.83	322.56	**571.39**	96.90	1.33	201.98	**54.68%**	36.15	**59.51%**	0.49	**58.78%**
RBV-XX-SG-TT	170.50	195.07	**365.57**	59.77	0.82	249.60	320.26	**569.86**	96.35	1.32	204.29	**55.88%**	36.59	**61.22%**	0.50	**60.41%**

Envelope options *reference case	East facing					South facing					Energy increase		GHG increase		EE increase	
	Heating	Cooling	Total	GHG	EE	Heating	Cooling	Total	GHG	EE						
	GJ			tonnes CO_2 e-	TJ	GJ			tonnes CO_2 e-	TJ	GJ		tonnes CO_2 e-		TJ	
RBV-XX-SG-MS	169.73	198.91	**368.64**	60.70	0.83	248.06	323.33	**571.39**	97.05	1.33	202.75	**55.00%**	36.35	**59.88%**	0.49	**59.14%**
RBV-XX-DG-CT	148.99	155.14	**304.13**	48.31	0.67	227.33	282.62	**509.95**	85.44	1.17	205.82	**67.68%**	37.13	**76.85%**	0.50	**75.44%**
RBV-XX-DG-TT	148.99	152.83	**301.82**	47.72	0.66	227.33	280.32	**507.65**	84.85	1.16	205.82	**68.19%**	37.13	**77.80%**	0.50	**76.31%**
RBV-XX-DG-MS	148.22	156.67	**304.90**	48.66	0.67	226.56	283.39	**509.95**	85.59	1.17	205.06	**67.25%**	36.93	**75.90%**	0.50	**74.57%**
CB-XX-SG-CT	453.12	413.18	**866.30**	131.95	1.84	542.98	576.00	**1,118.98**	178.78	2.47	252.67	**29.17%**	46.82	**35.49%**	0.63	**34.47%**
CB-XX-SG-TT	453.89	410.88	**864.77**	131.41	1.83	542.98	573.70	**1,116.67**	178.19	2.46	251.90	**29.13%**	46.78	**35.60%**	0.63	**34.56%**
CB-XX-SG-MS	451.58	414.72	**866.30**	132.26	1.84	541.44	579.84	**1,121.28**	179.67	2.48	254.98	**29.43%**	47.41	**35.85%**	0.64	**34.82%**
CB-XX-DG-CT	430.08	350.98	**781.06**	114.72	1.61	519.94	517.63	**1,037.57**	162.53	2.25	256.51	**32.84%**	47.81	**41.67%**	0.65	**40.21%**
CB-XX-DG-TT	430.85	347.14	**777.98**	113.79	1.59	520.70	516.10	**1,036.80**	162.18	2.25	258.82	**33.27%**	48.39	**42.53%**	0.65	**41.00%**
CB-XX-DG-MS	428.54	350.21	**778.75**	114.44	1.60	518.40	520.70	**1,039.10**	163.22	2.26	260.35	**33.43%**	48.79	**42.63%**	0.66	**41.11%**
ACC-XX-SG-CT	155.14	229.63	**384.77**	67.70	0.92	212.74	363.26	**576.00**	105.19	1.43	191.23	**49.70%**	37.49	**55.38%**	0.50	**54.57%**
ACC-XX-SG-TT	155.14	227.33	**382.46**	67.11	0.91	212.74	360.96	**573.70**	104.60	1.42	191.23	**50.00%**	37.49	**55.86%**	0.50	**55.03%**
ACC-XX-SG-MS	154.37	230.40	**384.77**	67.85	0.92	211.97	364.80	**576.77**	105.53	1.43	192.00	**49.90%**	37.69	**55.54%**	0.51	**54.75%**
ACC-XX-DG-CT	132.10	180.48	**312.58**	53.80	0.74	188.93	317.95	**506.88**	92.23	1.25	194.30	**62.16%**	38.43	**71.42%**	0.52	**70.09%**
ACC-XX-DG-TT	132.10	177.41	**309.50**	53.01	0.72	188.93	316.42	**505.34**	91.83	1.25	195.84	**63.28%**	38.82	**73.22%**	0.52	**71.78%**
ACC-XX-DG-MS	131.33	182.02	**313.34**	54.15	0.74	188.16	318.72	**506.88**	92.38	1.25	193.54	**61.76%**	38.23	**70.60%**	0.51	**69.33%**
PCSW-XX-SG-CT	251.14	385.54	**636.67**	113.11	1.54	311.81	530.69	**842.50**	153.73	2.08	205.82	**32.33%**	40.61	**35.90%**	0.54	**35.40%**
PCSW-XX-SG-TT	251.90	382.46	**634.37**	112.37	1.53	311.81	527.62	**839.42**	152.94	2.07	205.06	**32.32%**	40.57	**36.10%**	0.54	**35.57%**
PCSW-XX-SG-MS	250.37	386.30	**636.67**	113.27	1.54	310.27	536.06	**846.34**	155.01	2.10	209.66	**32.93%**	41.74	**36.85%**	0.56	**36.30%**
PCSW-XX-DG-CT	225.02	314.88	**539.90**	93.55	1.28	286.46	465.41	**751.87**	135.57	1.84	211.97	**39.26%**	42.03	**44.93%**	0.56	**44.12%**
PCSW-XX-DG-TT	225.02	311.04	**536.06**	92.56	1.26	287.23	462.34	**749.57**	134.83	1.83	213.50	**39.83%**	42.27	**45.67%**	0.57	**44.82%**
PCSW-XX-DG-MS	223.49	315.65	**539.14**	93.65	1.28	285.70	471.55	**757.25**	137.10	1.86	218.11	**40.46%**	43.45	**46.39%**	0.58	**45.54%**

Envelope options *reference case	East facing					South facing					Energy increase		GHG increase		EE increase	
	Heating	Cooling	Total	GHG	EE	Heating	Cooling	Total	GHG	EE						
	GJ			tonnes CO_2 e-	TJ	GJ			tonnes CO_2 e-	TJ	GJ		tonnes CO_2 e-		TJ	
TMB-XX-SG-CT	199.68	369.41	**569.09**	105.99	1.43	242.69	504.58	**747.26**	143.03	1.93	178.18	**31.31%**	37.03	**34.94%**	0.49	**34.45%**
TMB-XX-SG-TT	199.68	367.10	**566.78**	105.41	1.42	242.69	503.04	**745.73**	142.63	1.92	178.94	**31.57%**	37.23	**35.32%**	0.50	**34.81%**
TMB-XX-SG-MS	199.68	374.78	**574.46**	107.37	1.45	242.69	509.18	**751.87**	144.20	1.94	177.41	**30.88%**	36.84	**34.31%**	0.49	**33.85%**
TMB-XX-DG-CT	173.57	304.13	**477.70**	87.80	1.19	218.11	456.96	**675.07**	129.43	1.74	197.38	**41.32%**	41.63	**47.42%**	0.55	**46.59%**
TMB-XX-DG-TT	173.57	304.13	**477.70**	87.80	1.19	218.11	453.89	**672.00**	128.65	1.73	194.30	**40.68%**	40.85	**46.52%**	0.54	**45.73%**
TMB-XX-DG-MS	173.57	308.74	**482.30**	88.98	1.20	218.11	452.35	**670.46**	128.25	1.73	188.16	**39.01%**	39.28	**44.15%**	0.52	**43.45%**
CSW-POL-SG-CT	136.70	189.70	**326.40**	56.42	0.77	185.86	324.86	**510.72**	93.81	1.27	184.32	**56.47%**	37.39	**66.27%**	0.50	**64.86%**
CSW-POL-SG-TT	136.70	188.93	**325.63**	56.23	0.77	185.86	323.33	**509.18**	93.42	1.26	183.55	**56.37%**	37.19	**66.15%**	0.50	**64.74%**
CSW-POL-SG-MS	135.94	191.23	**327.17**	56.77	0.77	185.09	327.94	**513.02**	94.55	1.28	185.86	**56.81%**	37.78	**66.55%**	0.50	**65.16%**
CSW-POL-DG-CT	113.66	153.60	**267.26**	45.86	0.63	163.58	276.48	**440.06**	80.15	1.09	172.80	**64.66%**	34.30	**74.79%**	0.46	**73.32%**
CSW-POL-DG-TT	113.66	149.76	**263.42**	44.88	0.61	163.58	272.64	**436.22**	79.17	1.07	172.80	**65.60%**	34.30	**76.42%**	0.46	**74.84%**
CSW-POL-DG-MS	112.90	155.90	**268.80**	46.40	0.63	162.82	278.78	**441.60**	80.70	1.09	172.80	**64.29%**	34.30	**73.91%**	0.46	**72.52%**

Table D.24 Life cycle operational energy for cooling of a typical house in Perth for all alternative envelope options with and without CC impacts (temperature rise)

Envelope options *reference case			**Life cycle cooling energy demand (GJ)**			**Additional cooling energy demand - GJ**	
			Without CC impacts	**With low CC impacts**	**With high CC impacts**	**Low CC impact scenario**	**High CC impact scenario**
DB-XX*	SG*	CT*	242.69	257.51	301.05	14.82	58.36
		TT	240.38	255.06	298.19	14.68	57.81
		MS	241.15	255.88	299.15	14.73	57.99
	DG	CT	192.77	204.54	239.13	11.77	46.36
		TT	192.00	203.73	238.17	11.73	46.17
		MS	195.84	207.80	242.94	11.96	47.10
DB-INS	SG	CT	193.54	205.36	240.08	11.82	46.54
		TT	191.23	202.91	237.22	11.68	45.99
		MS	194.30	206.17	241.03	11.87	46.73
	DG	CT	150.53	159.72	186.73	9.19	36.20
		TT	150.53	159.72	186.73	9.19	36.20
		MS	152.83	162.17	189.59	9.33	36.75
BV-XX	SG	CT	307.97	326.78	382.03	18.81	74.06
		TT	304.90	323.52	378.22	18.62	73.32
		MS	309.50	328.41	383.93	18.90	74.43
	DG	CT	244.22	259.14	302.96	14.91	58.73
		TT	241.15	255.88	299.15	14.73	57.99
		MS	248.83	264.03	308.67	15.20	59.84
RBV-XX	SG	CT	198.91	211.06	246.75	12.15	47.84
		TT	195.07	206.99	241.98	11.91	46.91

Envelope options *reference case			Life cycle cooling energy demand (GJ)			Additional cooling energy demand - GJ	
			Without CC impacts	With low CC impacts	With high CC impacts	Low CC impact scenario	High CC impact scenario
		MS	198.91	211.06	246.75	12.15	47.84
	DG	CT	155.14	164.61	192.44	9.47	37.31
		TT	152.83	162.17	189.59	9.33	36.75
		MS	156.67	166.24	194.35	9.57	37.68
CB-XX	SG	CT	413.18	438.42	512.55	25.23	99.36
		TT	410.88	435.97	509.69	25.09	98.81
		MS	414.72	440.05	514.45	25.33	99.73
	DG	CT	350.98	372.41	435.38	21.43	84.40
		TT	347.14	368.34	430.62	21.20	83.48
		MS	350.21	371.60	434.43	21.39	84.22
ACC-XX	SG	CT	229.63	243.66	284.85	14.02	55.22
		TT	227.33	241.21	282.00	13.88	54.67
		MS	230.40	244.47	285.81	14.07	55.41
	DG	CT	180.48	191.50	223.88	11.02	43.40
		TT	177.41	188.24	220.07	10.83	42.66
		MS	182.02	193.13	225.79	11.12	43.77
PCSW-XX	SG	CT	385.54	409.08	478.25	23.55	92.72
		TT	382.46	405.82	474.44	23.36	91.98
		MS	386.30	409.90	479.20	23.59	92.90
	DG	CT	314.88	334.11	390.60	19.23	75.72
		TT	311.04	330.04	385.84	19.00	74.80
		MS	315.65	334.92	391.56	19.28	75.91

Envelope options *reference case			Life cycle cooling energy demand (GJ)			Additional cooling energy demand - GJ	
			Without CC impacts	**With low CC impacts**	**With high CC impacts**	**Low CC impact scenario**	**High CC impact scenario**
TMB-XX	SG	CT	369.41	391.97	458.24	22.56	88.84
		TT	367.10	389.52	455.39	22.42	88.28
		MS	374.78	397.67	464.91	22.89	90.13
	DG	CT	304.13	322.70	377.27	18.57	73.14
		TT	304.13	322.70	377.27	18.57	73.14
		MS	308.74	327.59	382.98	18.85	74.25
CSW-POL	SG	CT	189.70	201.28	235.31	11.58	45.62
		TT	188.93	200.47	234.36	11.54	45.43
		MS	191.23	202.91	237.22	11.68	45.99
	DG	CT	153.60	162.98	190.54	9.38	36.94
		TT	149.76	158.91	185.77	9.15	36.01
		MS	155.90	165.43	193.40	9.52	37.49

Table D.25 Life cycle GHG emissions associated with operational energy for cooling of a typical house in Perth for all alternative envelope options with and without CC impacts (temperature rise)

Envelope options *reference case			**GHG emissions - tonnes CO_2 e-**			**Additional GHG emissions tonnes CO_2 e-**	
			Without CC impacts	**Low CC impact scenario**	**High CC impact scenario**	**Low CC impact scenario**	**High CC impact scenario**
DB-XX*	SG*	CT*	61.98	65.77	76.89	3.79	14.91
		TT	61.40	65.15	76.16	3.75	14.76
		MS	61.59	65.35	76.40	3.76	14.81
	DG	CT	49.23	52.24	61.08	3.01	11.84
		TT	49.04	52.03	60.83	2.99	11.79
		MS	50.02	53.07	62.05	3.05	12.03
DB-INS	SG	CT	49.43	52.45	61.32	3.02	11.89
		TT	48.84	51.83	60.59	2.98	11.75
		MS	49.63	52.66	61.56	3.03	11.93
	DG	CT	38.45	40.79	47.69	2.35	9.25
		TT	38.45	40.79	47.69	2.35	9.25
		MS	39.03	41.42	48.42	2.38	9.39
BV-XX	SG	CT	78.66	83.46	97.57	4.80	18.92
		TT	77.87	82.63	96.60	4.76	18.73
		MS	79.05	83.88	98.06	4.83	19.01
	DG	CT	62.38	66.19	77.38	3.81	15.00
		TT	61.59	65.35	76.40	3.76	14.81
		MS	63.55	67.44	78.84	3.88	15.28

Envelope options *reference case			GHG emissions - tonnes CO_2 e-			Additional GHG emissions tonnes CO_2 e-	
			Without CC impacts	**Low CC impact scenario**	**High CC impact scenario**	**Low CC impact scenario**	**High CC impact scenario**
RBV-XX	SG	CT	50.80	53.91	63.02	3.10	12.22
		TT	49.82	52.87	61.81	3.04	11.98
		MS	50.80	53.91	63.02	3.10	12.22
	DG	CT	39.62	42.04	49.15	2.42	9.53
		TT	39.03	41.42	48.42	2.38	9.39
		MS	40.02	42.46	49.64	2.44	9.62
CB-XX	SG	CT	105.53	111.98	130.91	6.44	25.38
		TT	104.94	111.35	130.18	6.41	25.24
		MS	105.92	112.39	131.40	6.47	25.47
	DG	CT	89.64	95.12	111.20	5.47	21.56
		TT	88.66	94.08	109.98	5.41	21.32
		MS	89.45	94.91	110.96	5.46	21.51
ACC-XX	SG	CT	58.65	62.23	72.75	3.58	14.10
		TT	58.06	61.61	72.02	3.55	13.96
		MS	58.85	62.44	73.00	3.59	14.15
	DG	CT	46.10	48.91	57.18	2.82	11.09
		TT	45.31	48.08	56.21	2.77	10.90
		MS	46.49	49.33	57.67	2.84	11.18
PCSW-XX	SG	CT	98.47	104.48	122.15	6.01	23.68
		TT	97.69	103.65	121.18	5.97	23.49

Envelope options *reference case			GHG emissions - tonnes CO_2 e-			Additional GHG emissions tonnes CO_2 e-	
			Without CC impacts	**Low CC impact scenario**	**High CC impact scenario**	**Low CC impact scenario**	**High CC impact scenario**
		MS	98.67	104.69	122.39	6.03	23.73
	DG	CT	80.42	85.34	99.76	4.91	19.34
		TT	79.44	84.29	98.55	4.85	19.10
		MS	80.62	85.54	100.01	4.92	19.39
TMB-XX	SG	CT	94.35	100.11	117.04	5.76	22.69
		TT	93.76	99.49	116.31	5.73	22.55
		MS	95.72	101.57	118.74	5.85	23.02
	DG	CT	77.68	82.42	96.36	4.74	18.68
		TT	77.68	82.42	96.36	4.74	18.68
		MS	78.85	83.67	97.82	4.82	18.96
CSW-POL	SG	CT	48.45	51.41	60.10	2.96	11.65
		TT	48.25	51.20	59.86	2.95	11.60
		MS	48.84	51.83	60.59	2.98	11.75
	DG	CT	39.23	41.63	48.67	2.40	9.43
		TT	38.25	40.59	47.45	2.34	9.20
		MS	39.82	42.25	49.40	2.43	9.58

Table D.26 Life cycle EE consumption associated with operational energy for cooling of a typical house in Perth for all alternative envelope options with and without CC impacts (temperature rise)

Envelope options *reference case			**EE consumption - TJ**			**Additional EE consumption - TJ**	
			Without CC impacts	**Low CC impact scenario**	**High CC impact scenario**	**Low CC impact scenario**	**High CC impact scenario**
DB-XX*	SG*	CT*	0.81	0.86	1.00	0.05	0.19
		TT	0.80	0.85	0.99	0.05	0.19
		MS	0.80	0.85	0.99	0.05	0.19
	DG	CT	0.64	0.68	0.80	0.04	0.15
		TT	0.64	0.68	0.79	0.04	0.15
		MS	0.65	0.69	0.81	0.04	0.16
DB-INS	SG	CT	0.64	0.68	0.80	0.04	0.15
		TT	0.64	0.67	0.79	0.04	0.15
		MS	0.65	0.69	0.80	0.04	0.16
	DG	CT	0.50	0.53	0.62	0.03	0.12
		TT	0.50	0.53	0.62	0.03	0.12
		MS	0.51	0.54	0.63	0.03	0.12
BV-XX	SG	CT	1.02	1.09	1.27	0.06	0.25
		TT	1.01	1.08	1.26	0.06	0.24
		MS	1.03	1.09	1.28	0.06	0.25
	DG	CT	0.81	0.86	1.01	0.05	0.20
		TT	0.80	0.85	0.99	0.05	0.19
		MS	0.83	0.88	1.03	0.05	0.20
RBV-XX	SG	CT	0.66	0.70	0.82	0.04	0.16

Envelope options *reference case			EE consumption - TJ			Additional EE consumption - TJ	
			Without CC impacts	Low CC impact scenario	High CC impact scenario	Low CC impact scenario	High CC impact scenario
		TT	0.65	0.69	0.80	0.04	0.16
		MS	0.66	0.70	0.82	0.04	0.16
	DG	CT	0.52	0.55	0.64	0.03	0.12
		TT	0.51	0.54	0.63	0.03	0.12
		MS	0.52	0.55	0.65	0.03	0.13
CB-XX	SG	CT	1.37	1.46	1.70	0.08	0.33
		TT	1.37	1.45	1.69	0.08	0.33
		MS	1.38	1.46	1.71	0.08	0.33
	DG	CT	1.17	1.24	1.45	0.07	0.28
		TT	1.15	1.22	1.43	0.07	0.28
		MS	1.16	1.24	1.44	0.07	0.28
ACC-XX	SG	CT	0.76	0.81	0.95	0.05	0.18
		TT	0.76	0.80	0.94	0.05	0.18
		MS	0.77	0.81	0.95	0.05	0.18
	DG	CT	0.60	0.64	0.74	0.04	0.14
		TT	0.59	0.63	0.73	0.04	0.14
		MS	0.61	0.64	0.75	0.04	0.15
PCSW-XX	SG	CT	1.28	1.36	1.59	0.08	0.31
		TT	1.27	1.35	1.58	0.08	0.31
		MS	1.28	1.36	1.59	0.08	0.31
	DG	CT	1.05	1.11	1.30	0.06	0.25

Envelope options *reference case			EE consumption - TJ			Additional EE consumption - TJ	
			Without CC impacts	**Low CC impact scenario**	**High CC impact scenario**	**Low CC impact scenario**	**High CC impact scenario**
		TT	1.03	1.10	1.28	0.06	0.25
		MS	1.05	1.11	1.30	0.06	0.25
TMB-XX	SG	CT	1.23	1.30	1.52	0.08	0.30
		TT	1.22	1.30	1.51	0.07	0.29
		MS	1.25	1.32	1.55	0.08	0.30
	DG	CT	1.01	1.07	1.25	0.06	0.24
		TT	1.01	1.07	1.25	0.06	0.24
		MS	1.03	1.09	1.27	0.06	0.25
CSW-POL	SG	CT	0.63	0.67	0.78	0.04	0.15
		TT	0.63	0.67	0.78	0.04	0.15
		MS	0.64	0.67	0.79	0.04	0.15
	DG	CT	0.51	0.54	0.63	0.03	0.12
		TT	0.50	0.53	0.62	0.03	0.12
		MS	0.52	0.55	0.64	0.03	0.12

Table D.27 Summary of GHG emissions of a typical house in Perth after implementation of CPS

Envelope Options			**GHG savings potential tonnes CO_2 e-**					**GHG emissions of a typical reference house after CPS tonnes CO_2 e-**			**Ranking + (effective) - (worse)**
			Roof top solar PV			**Roof top SWH**	**Green concrete**				
			1kWp	**1.5kWp**	**3kWp**			**1kWp**	**1.5kWp**	**3kWp**	
	Reference case - DB-XX-SG-CT (467.19tonnes CO_2 e-)										
GHG emissions saving potential - tonnes CO_2 e-	**DB-XX-SG-CT**	**N/A**	-71.43	-103.61	-200.14	-22.7	-2.76	370.30	338.12	241.59	0
	DB-XX-SG-TT	+.44	-71.43	-103.61	-200.14	-22.7	-2.76	370.74	338.56	242.03	**-1**
	DB-XX-SG-MS	+.89	-71.43	-103.61	-200.14	-22.7	-2.76	371.19	339.01	242.48	**-2**
	DB-XX-DG-CT	-13.38	-71.43	-103.61	-200.14	-22.7	-2.76	356.92	324.74	228.21	**+16**
	DB-XX-DG-TT	-12.59	-71.43	-103.61	-200.14	-22.7	-2.76	357.71	325.53	229.00	**+19**
	DB-XX-DG-MS	-11.35	-71.43	-103.61	-200.14	-22.7	-2.76	358.95	326.77	230.24	**+20**
	DB-INS-SG-CT	-17.57	-71.43	-103.61	-200.14	-22.7	-2.76	352.73	320.55	224.02	**+13**
	DB-INS-SG-TT	-17.13	-71.43	-103.61	-200.14	-22.7	-2.76	353.17	320.99	224.46	**+14**
	DB-INS-SG-MS	-16.09	-71.43	-103.61	-200.14	-22.7	-2.76	354.21	322.03	225.50	**+15**
	DB-INS-DG-CT	-29.23	-71.43	-103.61	-200.14	-22.7	-2.76	341.07	308.89	212.36	**+7**
	DB-INS-DG-TT	-28.20	-71.43	-103.61	-200.14	-22.7	-2.76	342.10	309.92	213.39	**+8**
	DB-INS-DG-MS	-27.36	-71.43	-103.61	-200.14	-22.7	-2.76	342.94	310.76	214.23	**+9**
	BV-XX-SG-CT	+4.20	-71.43	-103.61	-200.14	-22.7	-2.76	374.50	342.32	245.79	**-5**
	BV-XX-SG-TT	+4.40	-71.43	-103.61	-200.14	-22.7	-2.76	374.70	342.52	245.99	**-6**
	BV-XX-SG-MS	+5.88	-71.43	-103.61	-200.14	-22.7	-2.76	376.18	344.00	247.47	**-8**
	BV-XX-DG-CT	-12.97	-71.43	-103.61	-200.14	-22.7	-2.76	357.33	325.15	228.62	**+17**
	BV-XX-DG-TT	-12.78	-71.43	-103.61	-200.14	-22.7	-2.76	357.52	325.34	228.81	**+18**
	BV-XX-DG-MS	-10.42	-71.43	-103.61	-200.14	-22.7	-2.76	359.88	327.70	231.17	**+23**
	RBV-XX-SG-CT	-11.28	-71.43	-103.61	-200.14	-22.7	-2.76	359.02	326.84	230.31	**+21**

Envelope Options			GHG savings potential tonnes CO_2 e-					GHG emissions of a typical reference house after CPS tonnes CO_2 e-			Ranking + (effective) - (worse)
			Roof top solar PV			Roof top SWH	Green concrete				
			1kWp	1.5kWp	3kWp			1kWp	1.5kWp	3kWp	
	RBV-XX-SG-TT	-11.28	-71.43	-103.61	-200.14	-22.7	-2.76	359.02	326.84	230.31	**+22**
	RBV-XX-SG-MS	-10.00	-71.43	-103.61	-200.14	-22.7	-2.76	360.30	328.12	231.59	**+24**
	RBV-XX-DG-CT	-23.13	-71.43	-103.61	-200.14	-22.7	-2.76	347.17	314.99	218.46	**+10**
	RBV-XX-DG-TT	-22.74	-71.43	-103.61	-200.14	-22.7	-2.76	347.56	315.38	218.85	**+11**
	RBV-XX-DG-MS	-21.46	-71.43	-103.61	-200.14	-22.7	-2.76	348.84	316.66	220.13	**+12**
	CB-XX-SG-CT	+43.85	-71.43	-103.61	-200.14	-22.7	-2.76	414.15	381.97	285.44	**-18**
	CB-XX-SG-TT	+44.29	-71.43	-103.61	-200.14	-22.7	-2.76	414.59	382.41	285.88	**-19**
	CB-XX-SG-MS	+45.48	-71.43	-103.61	-200.14	-22.7	-2.76	415.78	383.60	287.07	**-20**
	CB-XX-DG-CT	+27.20	-71.43	-103.61	-200.14	-22.7	-2.76	397.50	365.32	268.79	**-12**
	CB-XX-DG-TT	+27.24	-71.43	-103.61	-200.14	-22.7	-2.76	397.54	365.36	268.83	**-13**
	CB-XX-DG-MS	+28.24	-71.43	-103.61	-200.14	-22.7	-2.76	398.54	366.36	269.83	**-14**
	ACC-XX-SG-CT	+3.71	-71.43	-103.61	-200.14	-22.7	-2.76	374.01	341.83	245.30	**-3**
	ACC-XX-SG-TT	+4.11	-71.43	-103.61	-200.14	-22.7	-2.76	374.41	342.23	245.70	**-4**
	ACC-XX-SG-MS	+5.19	-71.43	-103.61	-200.14	-22.7	-2.76	375.49	343.31	246.78	**-7**
	ACC-XX-DG-CT	-9.60	-71.43	-103.61	-200.14	-22.7	-2.76	360.70	328.52	231.99	**+25**
	ACC-XX-DG-TT	-9.40	-71.43	-103.61	-200.14	-22.7	-2.76	360.90	328.72	232.19	**+26**
	ACC-XX-DG-MS	-7.93	-71.43	-103.61	-200.14	-22.7	-2.76	362.37	330.19	233.66	**+27**
	PCSW-XX-SG-CT	+61.32	-71.43	-103.61	-200.14	-22.7	-2.76	431.62	399.44	302.91	**-21**
	PCSW-XX-SG-TT	+61.57	-71.43	-103.61	-200.14	-22.7	-2.76	431.87	399.69	303.16	**-22**
	PCSW-XX-SG-MS	+62.80	-71.43	-103.61	-200.14	-22.7	-2.76	433.10	400.92	304.39	**-23**
	PCSW-XX-DG-CT	+42.34	-71.43	-103.61	-200.14	-22.7	-2.76	412.64	380.46	283.93	**-15**

Envelope Options			**GHG savings potential tonnes CO_2 e-**					**GHG emissions of a typical reference house after CPS tonnes CO_2 e-**			**Ranking + (effective) - (worse)**
			Roof top solar PV			**Roof top SWH**	**Green concrete**				
			1kWp	**1.5kWp**	**3kWp**			**1kWp**	**1.5kWp**	**3kWp**	
	PCSW-XX-DG-TT	+42.34	-71.43	-103.61	-200.14	-22.7	-2.76	412.64	380.46	283.93	**-16**
	PCSW-XX-DG-MS	+43.77	-71.43	-103.61	-200.14	-22.7	-2.76	414.07	381.89	285.36	**-17**
	TMB-XX-SG-CT	+13.63	-71.43	-103.61	-200.14	-22.7	-2.76	383.93	351.75	255.22	**-9**
	TMB-XX-SG-TT	+14.02	-71.43	-103.61	-200.14	-22.7	-2.76	384.32	352.14	255.61	**-10**
	TMB-XX-SG-MS	+16.19	-71.43	-103.61	-200.14	-22.7	-2.76	386.49	354.31	257.78	**-11**
	TMB-XX-DG-CT	-3.98	-71.43	-103.61	-200.14	-22.7	-2.76	366.32	334.14	237.61	**+28**
	TMB-XX-DG-TT	-3.00	-71.43	-103.61	-200.14	-22.7	-2.76	367.30	335.12	238.59	**+29**
	TMB-XX-DG-MS	-1.62	-71.43	-103.61	-200.14	-22.7	-2.76	368.68	336.50	239.97	**+30**
	CSW-POL-SG-CT	-28.84	-71.43	-103.61	-200.14	-22.7	-5.11	339.11	306.93	210.40	**+4**
	CSW-POL-SG-TT	-28.05	-71.43	-103.61	-200.14	-22.7	-5.11	339.90	307.72	211.19	**+5**
	CSW-POL-SG-MS	-27.16	-71.43	-103.61	-200.14	-22.7	-5.11	340.79	308.61	212.08	**+6**
	CSW-POL-DG-CT	-38.82	-71.43	-103.61	-200.14	-22.7	-5.11	329.13	296.95	200.42	**+1**
	CSW-POL-DG-TT	-38.82	-71.43	-103.61	-200.14	-22.7	-5.11	329.13	296.95	200.42	**+2**
	CSW-POL-DG-MS	-36.95	-71.43	-103.61	-200.14	-22.7	-5.11	331.00	298.82	202.29	**+3**

Table D.28 Summary of EE consumption after implementation of CPS

Envelope options			EE consumption savings potential TJ					EE consumption of a typical reference house after CPS TJ			Ranking + (effective) - (worse)
			Roof top solar PV			Roof top SWH	Green concrete				
			1kWp	1.5kWp	3kWp			1kWp	1.5kWp	3kWp	
	Reference case - DB-XX-SG-CT (6.51TJ)										
EE consumption saving potential - TJ	**DB-XX-SG-CT**	**N/A**	-0.94	-1.37	-2.68	-0.6	-0.02	4.95	4.52	3.21	0
	DB-XX-SG-TT	+0.01	-0.94	-1.37	-2.68	-0.6	-0.02	4.96	4.53	3.22	**-1**
	DB-XX-SG-MS	+0.04	-0.94	-1.37	-2.68	-0.6	-0.02	4.99	4.56	3.25	**-2**
	DB-XX-DG-CT	-0.18	-0.94	-1.37	-2.68	-0.6	-0.02	4.77	4.34	3.03	**+26**
	DB-XX-DG-TT	-0.17	-0.94	-1.37	-2.68	-0.6	-0.02	4.78	4.35	3.04	**+28**
	DB-XX-DG-MS	-0.12	-0.94	-1.37	-2.68	-0.6	-0.02	4.83	4.40	3.09	**+30**
	DB-INS-SG-CT	-0.25	-0.94	-1.37	-2.68	-0.6	-0.02	4.70	4.27	2.96	**+17**
	DB-INS-SG-TT	-0.24	-0.94	-1.37	-2.68	-0.6	-0.02	4.71	4.28	2.97	**+18**
	DB-INS-SG-MS	-0.20	-0.94	-1.37	-2.68	-0.6	-0.02	4.75	4.32	3.01	**+23**
	DB-INS-DG-CT	-0.40	-0.94	-1.37	-2.68	-0.6	-0.02	4.55	4.12	2.81	**+9**
	DB-INS-DG-TT	-0.39	-0.94	-1.37	-2.68	-0.6	-0.02	4.56	4.13	2.82	**+10**
	DB-INS-DG-MS	-0.35	-0.94	-1.37	-2.68	-0.6	-0.02	4.60	4.17	2.86	**+12**
	BV-XX-SG-CT	-0.07	-0.94	-1.37	-2.68	-0.6	-0.02	4.88	4.45	3.14	**+31**
	BV-XX-SG-TT	-0.06	-0.94	-1.37	-2.68	-0.6	-0.02	4.89	4.46	3.15	**+32**
	BV-XX-SG-MS	-0.01	-0.94	-1.37	-2.68	-0.6	-0.02	4.94	4.51	3.20	**+35**
	BV-XX-DG-CT	-0.29	-0.94	-1.37	-2.68	-0.6	-0.02	4.66	4.23	2.92	**+13**
	BV-XX-DG-TT	-0.29	-0.94	-1.37	-2.68	-0.6	-0.02	4.66	4.23	2.92	**+14**
	BV-XX-DG-MS	-0.23	-0.94	-1.37	-2.68	-0.6	-0.02	4.72	4.29	2.98	**+20**

Envelope options			EE consumption savings potential TJ					EE consumption of a typical reference house after CPS TJ			Ranking + (effective) - (worse)
			Roof top solar PV			Roof top SWH	Green concrete				
			1kWp	**1.5kWp**	**3kWp**			**1kWp**	**1.5kWp**	**3kWp**	
	RBV-XX-SG-CT	-0.26	-0.94	-1.37	-2.68	-0.6	-0.02	4.69	4.26	2.95	**+15**
	RBV-XX-SG-TT	-0.25	-0.94	-1.37	-2.68	-0.6	-0.02	4.70	4.27	2.96	**+16**
	RBV-XX-SG-MS	-0.21	-0.94	-1.37	-2.68	-0.6	-0.02	4.74	4.31	3.00	**+22**
	RBV-XX-DG-CT	-0.41	-0.94	-1.37	-2.68	-0.6	-0.02	4.54	4.11	2.80	**+6**
	RBV-XX-DG-TT	-0.41	-0.94	-1.37	-2.68	-0.6	-0.02	4.54	4.11	2.80	**+8**
	RBV-XX-DG-MS	-0.36	-0.94	-1.37	-2.68	-0.6	-0.02	4.59	4.16	2.85	**+11**
	CB-XX-SG-CT	+0.51	-0.94	-1.37	-2.68	-0.6	-0.02	5.46	5.03	3.72	**-12**
	CB-XX-SG-TT	+0.52	-0.94	-1.37	-2.68	-0.6	-0.02	5.47	5.04	3.73	**-13**
	CB-XX-SG-MS	+0.56	-0.94	-1.37	-2.68	-0.6	-0.02	5.51	5.08	3.77	**-14**
	CB-XX-DG-CT	+0.29	-0.94	-1.37	-2.68	-0.6	-0.02	5.24	4.81	3.50	**-6**
	CB-XX-DG-TT	+0.29	-0.94	-1.37	-2.68	-0.6	-0.02	5.24	4.81	3.50	**-7**
	CB-XX-DG-MS	+0.33	-0.94	-1.37	-2.68	-0.6	-0.02	5.28	4.85	3.54	**-8**
	ACC-XX-SG-CT	-0.05	-0.94	-1.37	-2.68	-0.6	-0.02	4.90	4.47	3.16	**+33**
	ACC-XX-SG-TT	-0.05	-0.94	-1.37	-2.68	-0.6	-0.02	4.90	4.47	3.16	**+34**
	ACC-XX-SG-MS	-0.01	-0.94	-1.37	-2.68	-0.6	-0.02	4.94	4.51	3.20	**+36**
	ACC-XX-DG-CT	-0.23	-0.94	-1.37	-2.68	-0.6	-0.02	4.72	4.29	2.98	**+19**
	ACC-XX-DG-TT	-0.23	-0.94	-1.37	-2.68	-0.6	-0.02	4.72	4.29	2.98	**+21**
	ACC-XX-DG-MS	-0.18	-0.94	-1.37	-2.68	-0.6	-0.02	4.77	4.34	3.03	**+25**
	PCSW-XX-SG-CT	+0.59	-0.94	-1.37	-2.68	-0.6	-0.02	5.54	5.11	3.80	**-15**
	PCSW-XX-SG-TT	+0.60	-0.94	-1.37	-2.68	-0.6	-0.02	5.55	5.12	3.81	**-16**

Envelope options			EE consumption savings potential TJ					EE consumption of a typical reference house after CPS TJ			Ranking + (effective) - (worse)
			Roof top solar PV			Roof top SWH	Green concrete				
			1kWp	**1.5kWp**	**3kWp**			**1kWp**	**1.5kWp**	**3kWp**	
	PCSW-XX-SG-MS	+0.64	-0.94	-1.37	-2.68	-0.6	-0.02	5.59	5.16	3.85	**-17**
	PCSW-XX-DG-CT	+0.34	-0.94	-1.37	-2.68	-0.6	-0.02	5.29	4.86	3.55	**-9**
	PCSW-XX-DG-TT	+0.34	-0.94	-1.37	-2.68	-0.6	-0.02	5.29	4.86	3.55	**-10**
	PCSW-XX-DG-MS	+0.39	-0.94	-1.37	-2.68	-0.6	-0.02	5.34	4.91	3.60	**-11**
	TMB-XX-SG-CT	+0.05	-0.94	-1.37	-2.68	-0.6	-0.02	5.00	4.57	3.26	**-3**
	TMB-XX-SG-TT	+0.06	-0.94	-1.37	-2.68	-0.6	-0.02	5.01	4.58	3.27	**-4**
	TMB-XX-SG-MS	+0.11	-0.94	-1.37	-2.68	-0.6	-0.02	5.06	4.63	3.32	**-5**
	TMB-XX-DG-CT	-0.18	-0.94	-1.37	-2.68	-0.6	-0.02	4.77	4.34	3.03	**+24**
	TMB-XX-DG-TT	-0.17	-0.94	-1.37	-2.68	-0.6	-0.02	4.78	4.35	3.04	**+27**
	TMB-XX-DG-MS	-0.12	-0.94	-1.37	-2.68	-0.6	-0.02	4.83	4.40	3.09	**+29**
	CSW-POL-SG-CT	-0.44	-0.94	-1.37	-2.68	-0.6	-0.04	4.49	4.06	2.75	**+4**
	CSW-POL-SG-TT	-0.43	-0.94	-1.37	-2.68	-0.6	-0.04	4.50	4.07	2.76	**+5**
	CSW-POL-SG-MS	-0.39	-0.94	-1.37	-2.68	-0.6	-0.04	4.54	4.11	2.80	**+7**
	CSW-POL-DG-CT	-0.58	-0.94	-1.37	-2.68	-0.6	-0.04	4.35	3.92	2.61	**+1**
	CSW-POL-DG-TT	-0.57	-0.94	-1.37	-2.68	-0.6	-0.04	4.36	3.93	2.62	**+2**
	CSW-POL-DG-MS	-0.52	-0.94	-1.37	-2.68	-0.6	-0.04	4.41	3.98	2.67	**+3**

Appendix E

Table E.1 Environmentally viable CPS options with their GHG emissions reduction and EE consumption saving potential for a typical reference house in Perth

CPS options						GHG emissions reduction potential		EE saving potential	
						%	Ranking	%	Ranking
Reference house (DB-XX-SG-CT) - GHG emissions – 467.19 tonnes CO2 e-, EE consumption – 6.51TJ									
DB-XX	SG	CT	SPV	SWH	GC	-48.29%	***0***	-50.73%	***0***
CSW-POL	DG	CT	SPV	SWH	GC	-57.10%	***1***	-59.87%	***1***
CSW-POL	DG	TT	SPV	SWH	GC	-57.10%	***2***	-59.84%	***2***
CSW-POL	DG	MS	SPV	SWH	GC	-56.70%	***3***	-59.05%	***3***
CSW-POL	SG	CT	SPV	SWH	GC	-54.96%	***4***	-57.81%	***4***
CSW-POL	SG	TT	SPV	SWH	GC	-54.80%	***5***	-57.62%	***5***
CSW-POL	SG	MS	SPV	SWH	GC	-54.61%	***6***	-57.02%	***7***
DB-INS	DG	CT	SPV	SWH	GC	-54.55%	***7***	-56.89%	***9***
DB-INS	DG	TT	SPV	SWH	GC	-54.33%	***8***	-56.65%	***10***
DB-INS	DG	MS	SPV	SWH	GC	-54.15%	***9***	-56.07%	***12***
RBV-XX	DG	CT	SPV	SWH	GC	-53.24%	***10***	-57.10%	***6***
RBV-XX	DG	TT	SPV	SWH	GC	-53.16%	***11***	-56.99%	***8***
RBV-XX	DG	MS	SPV	SWH	GC	-52.88%	***12***	-56.31%	***11***
DB-INS	SG	CT	SPV	SWH	GC	-52.05%	***13***	-54.50%	***17***
DB-INS	SG	TT	SPV	SWH	GC	-51.96%	***14***	-54.38%	***18***
DB-INS	SG	MS	SPV	SWH	GC	-51.73%	***15***	-53.75%	***23***
DB-XX	DG	CT	SPV	SWH	GC	-51.15%	***16***	-53.46%	***26***
BV-XX	DG	CT	SPV	SWH	GC	-51.07%	***17***	-55.25%	***13***
BV-XX	DG	TT	SPV	SWH	GC	-51.02%	***18***	-55.18%	***14***
DB-XX	DG	TT	SPV	SWH	GC	-50.98%	***19***	-53.27%	***28***
DB-XX	DG	MS	SPV	SWH	GC	-50.72%	***20***	-52.60%	***30***
RBV-XX	SG	CT	SPV	SWH	GC	-50.70%	***21***	-54.67%	***15***
RBV-XX	SG	TT	SPV	SWH	GC	-50.70%	***22***	-54.64%	***16***
BV-XX	DG	MS	SPV	SWH	GC	-50.52%	***23***	-54.29%	***20***
RBV-XX	SG	MS	SPV	SWH	GC	-50.43%	***24***	-53.96%	***22***
ACC-XX	DG	CT	SPV	SWH	GC	-50.34%	***25***	-54.29%	***19***
ACC-XX	DG	TT	SPV	SWH	GC	-50.30%	***26***	-54.22%	***21***
ACC-XX	DG	MS	SPV	SWH	GC	-49.99%	***27***	-53.50%	***25***
TMB-XX	DG	CT	SPV	SWH	GC	-49.14%	***28***	-53.54%	***24***
TMB-XX	DG	TT	SPV	SWH	GC	-48.93%	***29***	-53.31%	***27***
TMB-XX	DG	MS	SPV	SWH	GC	-48.64%	***30***	-52.62%	***29***
Note: SPV- roof top solar PV, SWH- roof top solar water heater, GC-green concrete									

Table E.2 Breakdown of capital cost of construction of a typical reference (DB-XX-SG-CT) house in Perth

	Items	Qty.	Unit	Unit Rate (AUD)	Amount (AUD)	GST (10%)	Total Amount (AUD)
1	**PRELIMINARIES**						
	Site feature survey	1	item	425.00	425.00	42.50	467.50
	Re-pegging of lot	1	item	200.00	200.00	20.00	220.00
	Working drawings	243	m^2	15.00	3,645.00	364.50	4,009.50
	Geotechnical investigation report	1	item	200.00	200.00	20.00	220.00
	Engineering drawings	1	item	3000.00	3,000.00	300.00	3,300.00
	Energy efficiency report	1	item	350.00	350.00	35.00	385.00
	Building Surveyor certification	1	item	800.00	800.00	80.00	880.00
					8,620.00	**862.00**	**9,482.00**
2	**INSURANCES**						
	Indemnity Insurance	1	item	1,350.00	1,350.00	135.00	1,485.00
	Public liability & construction insurance	1	item	765.00	765.00	76.50	841.50
	Workers compensation insurance	1	item	2,272.50	2,272.50	227.25	2,499.75
					4,387.50	**438.75**	**4,826.25**
3	**COUNCIL FEE**						
	Construction training levy	1	item	450.00	450.00	45.00	495.00
	Building service levy	1	item	308.25	308.25	30.83	339.08
	Building application fee	1	item	427.50	427.50	42.75	470.25
	Development planning fee	1	item	720.00	720.00	72.00	792.00
	footpath repair allowance	1	item	1,000.00	1,000.00	100.00	1,100.00
					2,905.75	**290.58**	**3,196.33**
4	**WATER CORPORATION FEE**						

	Items	Qty.	Unit	Unit Rate (AUD)	Amount (AUD)	GST (10%)	Total Amount (AUD)
	Service activation fee + sewer connection	1	item	151.29	151.29	15.13	166.42
	Water mains connection	1	nos.	1168.00	1,168.00	116.80	1,284.80
					1,319.29	**131.93**	**1,451.22**
5	**SITE FACILITIES**						
	Site signboard	1.00	item	300.00	300.00	30.00	330.00
	WC	30.00	weeks	55.00	1,650.00	165.00	1,815.00
	Storage Shed	30.00	weeks	40.00	1,200.00	120.00	1,320.00
					2,850.00	**285.00**	**3,135.00**
6	**EARTHWORKS**						
	Clear site of vegetation and cart away	500	m^2	0.44	220.00	22.00	242.00
	Excavation over site to reduce level	8.13	m^3	15.30	124.39	12.44	136.83
	Excavate trench	7.65	m^2	28.80	220.32	22.03	242.35
	Additional cost for carting excavated material	15.78	m^3	28.50	449.73	44.97	494.70
	Clean sand filling to make up levels	21.15	m^3	15.70	332.06	33.21	365.26
	Compaction - trench	25.5	m^2	3.15	80.33	8.03	88.36
	Compaction - ground under slab	211.5	m^2	2.50	528.75	52.88	581.63
					1,955.57	**195.56**	**2,151.13**
7	**STORMWATER DRAINS**						
	Trench excavation	60	m	8.25	495.00	49.50	544.50
					495.00	**49.50**	**544.50**
8	**MOISTURE BARRIER**						
	Termite treatment - below ground slab & perimeter	211.5	m^2	2.80	592.20	59.22	651.42
	Perimeter barrier to edge of slab and turned into cavity walls	69.60	m^2	17.00	1,183.20	118.32	1,301.52

	Items	Qty.	Unit	Unit Rate (AUD)	Amount (AUD)	GST (10%)	Total Amount (AUD)
	Polythene film - black	272.25	m^2	2.50	680.63	68.06	748.69
					2,456.03	**245.60**	**2,701.63**
9	**CONCRETE SUPPLY AND POURING**						
	Footings	7.65	m^3	256.00	1,958.40	195.84	2,154.24
	Ground slab + thickening	25.00	m^3	274.00	6,849.32	684.93	7,534.25
	Concrete Pumping	32.65	m^3	15.00	489.71	48.97	538.68
	Formwork around the ground slab	69.60	m	13.00	904.80	90.48	995.28
	Fabric reinforcement	253.69	m^2	8.10	2,054.89	205.49	2,260.38
	Slab reinforcement - R12 re-entry bar 2 m long	11.04	kg	2.39	26.39	2.64	29.02
		32.6475			**12,283.50**	**1,228.35**	**13,511.85**
10	**METAL DOOR FRAMES**						
	Single	9	nos.	118.00	1,062.00	106.20	1,168.20
	Double	1	nos.	141.00	141.00	14.10	155.10
	Sliding single	1	nos.	118.00	118.00	11.80	129.80
	Sliding double	2	nos.	141.00	282.00	28.20	310.20
					1,603.00	**160.30**	**1,763.30**
11	**ALUMINIUM WINDOWS**						
	Sliding windows (50% opening)	40.99	m^2	307.00	12,583.93	1,258.39	13,842.32
	Insect screens	10.25	m^2	62.00	635.35	63.53	698.88
					13,219.28	**1,321.93**	**14,541.20**
12	**GALVANIZED LINTELS, T-BARS, COLUMNS**						
	Angles - 150x90x8	36.7	m	69.90	2,565.33	256.53	2,821.86
	T-bars - 200x200x10	4.2	m	134.50	564.90	56.49	621.39

	Items	Qty.	Unit	Unit Rate (AUD)	Amount (AUD)	GST (10%)	Total Amount (AUD)
	Columns - 150x50x3 post - 2 nos.	55.68	kg	6.55	364.70	36.47	401.17
					3,494.93	**349.49**	**3,844.43**
13	**BRICK SUPPLY**						
	Face brick 2c 290x110x162	3026.56	1000	2,145.00	6,491.96	649.20	7,141.16
	Utility brick - vertical cored 305x90x162	6464.64	1000	1,320.00	8,533.32	853.33	9,386.66
	Freight charges	9491.2	1000	185.00	1,755.87	175.59	1,931.46
					16,781.16	**1,678.12**	**18,459.27**
14	**BRICK MORTAR AND LABOUR**						
	Cement, sand and lime mortar	9491.2	1000	90.10	855.16	85.52	940.67
	Face brick 2c 290x110x162	3026.56	1000	1,380.00	4,176.65	417.66	4,594.31
	Utility brick - vertical cored 305x90x162	6464.64	1000	1,400.00	9,050.50	905.05	9,955.55
					14,082.30	**1,408.23**	**15,490.53**
15	**WELDER**						
	Lintel and Column welding work	4	hr	125.00	500.00	50.00	550.00
					500.00	**50.00**	**550.00**
16	**CRANE HIRE**						
	Allocation for lifting of roof beams	6	hours	140.00	840.00	84.00	924.00
					840.00	**84.00**	**924.00**
17	**SCAFFOLDING**						
	Brickies kit pack	6	week	190.00	1,140.00	114.00	1,254.00
	Roof guardrail	6	m	25.00	150.00	15.00	165.00
					1,290.00	**129.00**	**1,419.00**
18	**ROOF (TIMBER + CARPENTER + PLUMBER)**						

	Items	Qty.	Unit	Unit Rate (AUD)	Amount (AUD)	GST (10%)	Total Amount (AUD)
	Roof timber including Beam LVL, battens, ceiling joist, bolting plate, eave trim, hanger, hip, rafter, ridge, ridge plate, split hanger, strut, under purlin, valley, valley board, wall plate, hanger to ceiling joist, bolting plate to brick wall, fascia, hardieflex eave board, and insulation batts	264	m^2	112.00	29,568.00	2,956.80	32,524.80
	Roof plumbing including gutters, downpipes and soak wells	264	m^2	30.00	7,920.00	792.00	8,712.00
					37,488.00	**3,748.80**	**41,236.80**
19	**ROOF COVER**						
	Concrete roof tiles	264	m^2	43.00	11,204.10	1,120.40	12,324.51
					11,204.10	**1,120.40**	**12,324.51**
20	**CEILING**						
	Gyprock ceiling including cornices and manhole	264	m^2	41.95	11,074.80	1,107.48	12,182.28
					11,074.80	**1,107.48**	**12,182.28**
21	**PLASTERING**						
	Cement render including metal beads	531	m^2	24.80	13,168.80	1,316.88	14,485.68
	White set	531	m^2	21.10	11,204.10	1,120.41	12,324.51
					24,372.90	2,437.29	26,810.19
22	**DOORS INCLUDING LOCKS & LATCHES AND FIXING**						
	External double shutter	1	nos.	1,199.00	1,199.00	119.90	1,318.90
	External single shutter	1	nos.	372.00	372.00	37.20	409.20
	Internal single shutter	8	nos.	321.50	2,572.00	257.20	2,829.20
	Sliding single	1	nos.	232.00	232.00	23.20	255.20
	Sliding double	2	nos.	414.00	828.00	82.80	910.80

	Items	Qty.	Unit	Unit Rate (AUD)	Amount (AUD)	GST (10%)	Total Amount (AUD)
					5,203.00	**520.30**	**5,723.30**
23	**CERAMIC TILES INCLUDING FIXING**						
	Floor tiles including adhesive and pointing	182.21	m^2	108.50	19,769.79	1,976.98	21,746.76
	Wall tiles including adhesive and pointing	26.4	m^2	102.50	2,706.00	270.60	2,976.60
	Waterproofing for wet area	10	m^2	16.85	168.50	16.85	185.35
					22,644.29	**2,264.43**	**24,908.71**
	Total				**201,218.29**	**20,121.83**	**221,340.12**
	Total in US$ (1 AUD = 0.7229 US$)						**160,007.00**
	Note: Painting, Electrical works, Sanitary and Plumbing works including accessories, cabinets, soft furniture, garage door, home appliances, external site development are excluded **Cost data source:**(Rawlinsons 2015)						

Table E.3 Breakdown of operational cost for electricity and natural gas for a typical reference (DB-XX-SG-CT) house in Perth

Activity	Utility	Unit	Life cycle energy demand	Utility Prices	Amount (AUD)	Present value (AUD)
Heating	Gas	GJ	278.78	Supply charges @20.58 cents per day First 12 units of gas used on average per day @14.20 cents per unit Over 12 units of gas used on average per day @12.81 cents per unit	56,946.97	24,963.03
Hot Water	Gas	GJ	1,130.50			
Cooling	Electricity	GJ	242.69	Supply charges @47.1834 cents per day Electricity charges @25.7029 cents per unit	100,002.06	43,836.48
Lighting	Electricity	GJ	320.35			
Home appliances	Electricity	GJ	717.00			
				Total	**156,949.02**	**68,799.51**
					Total US$ (1AUD = 0.7229US$)	**49,735.17**

Note: PV is based on 3% inflation rate and 7% discount factor (RBA 2015; DRDL 2012). 1 Unit of electricity = 1kWh, and 1 Unit of natural gas = 3.6MJ. **Cost data source:** (DOF 2015b; Alintaenergy 2015)

Table E.4 Breakdown of the end of life demolition and disposal cost for a typical reference (DB-XX-SG-CT) house in Perth

Items	Qty.	Unit	Unit Rate AUD	Amount (AUD)	GST (10%)	Amount (AUD)	Present value (PV) (AUD)
End of life demolition and disposal	243	m^2	40.20	9,768.60	976.86	10,745.46	1,599.18
Inert landfill levy	65.36	tonnes	70.00	4,575.20	457.52	5,032.72	748.99
					Total	**15,778.18**	**2,348.17**
						Total US$ (1AUD = 0.7229US$)	**1,697.49**
Note: PV is based on 3% inflation rate and 7% discount factor (RBA 2015; DRDL 2012). After the year 2020, only 25% of the C&D waste will be landfilled (WAWA 2015, 2016) **Cost data source:**(Rawlinsons 2015; DER 2015)							

Table E.5 Breakdown of life cycle cost of a typical house due to environmentally viable CPS options

GHG emission reduction benefits ranking	Cleaner production options	GHG emissions reduction potential tonnes CO_2 e-	EE consumption reduction potential TJ	Cost implication due to change in envelope (US$)			Cost implication due to roof top solar PV 3kWp (US$)		Cost implication due to solar water heater (US$)		Cost implication due to green concrete (US$)	Total cost implication (US$) +increment -reduction
				Capital cost	Operational cost	End of life cost	Capital + replacement cost	Operational cost	Capital + replacement cost	Operational cost		
Reference house (DB-XX-SG-CT) - GHG emissions – 467.19 tonnes CO_2 e-, EE consumption – 6.51TJ, LCC - US$211,439.43, **(1AUD = 0.7229US$)**												
4	CSW-POL-SG-CT-SPV-SWH-GC	-256.79	-3.76	-11,703.36	-2,801.02	+39.70	+3,806.76	-19,621.20	+6,062.80	-8,626.26	-327.27	-33,169.85
6	CSW-POL-SG-MS-SPV-SWH-GC	-255.11	-3.71	-10,863.64	-2,774.93	+13.03	+3,806.76	-19,621.20	+6,062.80	-8,627.20	-327.27	-32,331.65
5	CSW-POL-SG-TT-SPV-SWH-GC	-256.00	-3.75	-8,974.27	-2,818.39	+33.74	+3,806.76	-19,621.20	+6,062.80	-8,626.26	-327.27	-30,464.10
17	BV-XX-DG-CT-SPV-SWH-GC	-238.57	-3.59	-9,219.00	-1,610.63	-206.00	+3,806.76	-19,621.20	+6,062.80	-8,630.95	-168.76	-29,586.99
1	CSW-POL-DG-CT-SPV-SWH-GC	-266.77	-3.90	-6,194.83	-3,877.48	+40.78	+3,806.76	-19,621.20	+6,062.80	-8,654.45	-327.27	-28,764.90
23	BV-XX-DG-MS-SPV-SWH-GC	-236.02	-3.53	-8,379.28	-1,515.03	-232.76	+3,806.76	-19,621.20	+6,062.80	-8,631.89	-168.76	-28,679.37
3	CSW-POL-DG-MS-SPV-SWH-GC	-264.90	-3.84	-5,355.11	-3,834.02	+14.02	+3,806.76	-19,621.20	+6,062.80	-8,655.39	-327.27	-27,909.41
28	TMB-XX-DG-CT-SPV-SWH-GC	-229.58	-3.48	-8,302.62	+203.67	-361.80	+3,806.76	-19,621.20	+6,062.80	-8,581.15	-168.76	-26,962.30

GHG emission reduction benefits ranking	Cleaner production options	GHG emissions reduction potential tonnes CO_2 e-	EE consumption reduction potential TJ	Cost implication due to change in envelope (US$)			Cost implication due to roof top solar PV 3kWp (US$)		Cost implication due to solar water heater (US$)		Cost implication due to green concrete (US$)	Total cost implication (US$) +increment -reduction
				Capital cost	Operational cost	End of life cost	Capital + replacement cost	Operational cost	Capital + replacement cost	Operational cost		
18	BV-XX-DG-TT-SPV-SWH-GC	-238.38	-3.59	-6,489.91	-1,680.13	-212.05	+3,806.76	-19,621.20	+6,062.80	-8,630.95	-168.76	-26,933.45
2	CSW-POL-DG-TT-SPV-SWH-GC	-266.77	-3.89	-3,465.74	-3,964.36	+34.73	+3,806.76	-19,621.20	+6,062.80	-8,654.45	-327.27	-26,128.74
30	TMB-XX-DG-MS-SPV-SWH-GC	-227.22	-3.42	-7,462.90	+307.92	-388.47	+3,806.76	-19,621.20	+6,062.80	-8,581.15	-168.76	-26,045.00
29	TMB-XX-DG-TT-SPV-SWH-GC	-228.60	-3.47	-5,573.52	+203.67	-367.85	+3,806.76	-19,621.20	+6,062.80	-8,581.15	-168.76	-24,239.26
21	RBV-XX-SG-CT-SPV-SWH-GC	-236.88	-3.56	+596.00	-2,211.47	-111.81	+3,806.76	-19,621.20	+6,062.80	-8,584.91	-168.76	-20,232.59
24	RBV-XX-SG-MS-SPV-SWH-GC	-235.60	-3.51	+1,435.72	-2,220.13	-138.49	+3,806.76	-19,621.20	+6,062.80	-8,585.85	-168.76	-19,429.15
13	DB-INS-SG-CT-SPV-SWH-GC	-243.17	-3.55	+2,125.26	-2,333.10	+0.41	+3,806.76	-19,621.20	+6,062.80	-8,584.91	-168.76	-18,712.75
0	DB-XX-SG-CT -SPV-SWH-GC	-225.60	-3.30	-	-	-	+3,806.76	-19,621.20	+6,062.80	-8,452.42	-168.76	-18,372.82
15	DB-INS-SG-MS-SPV-SWH-GC	-241.69	-3.50	+2,964.98	-2,324.39	-26.26	+3,806.76	-19,621.20	+6,062.80	-8,585.85	-168.76	-17,891.92

GHG emission reduction benefits ranking	Cleaner production options	GHG emissions reduction potential tonnes CO_2 e-	EE consumption reduction potential TJ	Cost implication due to change in envelope (US$)			Cost implication due to roof top solar PV 3kWp (US$)		Cost implication due to solar water heater (US$)		Cost implication due to green concrete (US$)	Total cost implication (US$) +increment -reduction
				Capital cost	Operational cost	End of life cost	Capital + replacement cost	Operational cost	Capital + replacement cost	Operational cost		
22	RBV-XX-SG-TT-SPV-SWH-GC	-236.88	-3.55	+3,325.09	-2,298.35	-117.86	+3,806.76	-19,621.20	+6,062.80	-8,584.91	-168.76	-17,596.43
14	DB-INS-SG-TT-SPV-SWH-GC	-242.73	-3.54	+4,854.35	-2,376.57	-5.55	+3,806.76	-19,621.20	+6,062.80	-8,583.97	-168.76	-16,032.15
10	RBV-XX-DG-CT-SPV-SWH-GC	-248.73	-3.71	+6,104.53	-3,444.38	-110.82	+3,806.76	-19,621.20	+6,062.80	-8,611.22	-168.76	-15,982.29
12	RBV-XX-DG-MS-SPV-SWH-GC	-247.06	-3.66	+6,944.25	-3,418.28	-137.49	+3,806.76	-19,621.20	+6,062.80	-8,612.16	-168.76	-15,144.09
7	DB-INS-DG-CT-SPV-SWH-GC	-254.83	-3.70	+7,633.78	-3,548.63	+1.49	+3,806.76	-19,621.20	+6,062.80	-8,611.22	-168.76	-14,444.98
16	DB-XX-DG-CT-SPV-SWH-GC	-238.98	-3.48	+5,508.53	-1,363.25	+1.08	+3,806.76	-19,621.20	+6,062.80	-8,477.79	-168.76	-14,251.84
9	DB-INS-DG-MS-SPV-SWH-GC	-252.96	-3.65	+8,473.50	-3,505.16	-25.27	+3,806.76	-19,621.20	+6,062.80	-8,612.16	-168.76	-13,589.49
20	DB-XX-DG-MS-SPV-SWH-GC	-236.95	-3.42	+6,348.25	-1,311.07	-25.68	+3,806.76	-19,621.20	+6,062.80	-8,479.67	-168.76	-13,388.57
11	RBV-XX-DG-TT-SPV-SWH-GC	-248.34	-3.71	+8,833.62	-3,496.50	-116.78	+3,806.76	-19,621.20	+6,062.80	-8,611.22	-168.76	-13,311.29

GHG emission reduction benefits ranking	Cleaner production options	GHG emissions reduction potential tonnes CO_2 e-	EE consumption reduction potential TJ	Cost implication due to change in envelope (US$)			Cost implication due to roof top solar PV 3kWp (US$)		Cost implication due to solar water heater (US$)		Cost implication due to green concrete (US$)	Total cost implication (US$) +increment -reduction
				Capital cost	Operational cost	End of life cost	Capital + replacement cost	Operational cost	Capital + replacement cost	Operational cost		
8	DB-INS-DG-TT-SPV-SWH-GC	-253.80	-3.69	+10,362.88	-3,539.97	-4.56	+3,806.76	-19,621.20	+6,062.80	-8,610.28	-168.76	-11,712.34
19	DB-XX-DG-TT-SPV-SWH-GC	-238.19	-3.47	+8,237.62	-1,380.63	-4.97	+3,806.76	-19,621.20	+6,062.80	-8,477.79	-168.76	-11,546.17
25	ACC-XX-DG-CT-SPV-SWH-GC	-235.20	-3.53	+20,682.72	-3,061.49	-315.08	+3,806.76	-19,621.20	+6,062.80	-8,631.89	-168.76	-1,246.14
27	ACC-XX-DG-MS-SPV-SWH-GC	-233.53	-3.48	+21,522.44	-3,035.40	-341.83	+3,806.76	-19,621.20	+6,062.80	-8,632.83	-168.76	-408.03
26	ACC-XX-DG-TT-SPV-SWH-GC	-235.00	-3.53	+23,411.81	-3,130.99	-321.12	+3,806.76	-19,621.20	+6,062.80	-8,631.89	-168.76	+1,407.40

Table E.6 Breakdown of capital cost of a typical reference house in Perth for environmentally viable envelope options

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	Capital cost (US$)					Economic impact (US$) +increment -reduction
		Non envelope elements and preliminaries	Wall elements	Window element	Roof element	Total	
0	DB-XX-SG-CT	91,674.05	48,793.89	10,511.84	9,027.00	160,006.77	-
1	CSW-POL-DG-CT	91,674.05	37,090.52	16,020.36	9,027.00	153,811.94	-6,194.83
2	CSW-POL-DG-TT	91,674.05	37,090.52	16,020.36	11,756.09	156,541.03	-3,465.74
3	CSW-POL-DG-MS	91,674.05	37,090.52	16,020.36	9,866.72	154,651.66	-5,355.11
4	CSW-POL-SG-CT	91,674.05	37,090.52	10,511.84	9,027.00	148,303.41	-11,703.36
5	CSW-POL-SG-TT	91,674.05	37,090.52	10,511.84	11,756.09	151,032.50	-8,974.27
6	CSW-POL-SG-MS	91,674.05	37,090.52	10,511.84	9,866.72	149,143.13	-10,863.64
7	DB-INS-DG-CT	91,674.05	50,919.14	16,020.36	9,027.00	167,640.56	+7,633.78
8	DB-INS-DG-TT	91,674.05	50,919.14	16,020.36	11,756.09	170,369.65	+10,362.88
9	DB-INS-DG-MS	91,674.05	50,919.14	16,020.36	9,866.72	168,480.28	+8,473.50
10	RBV-XX-DG-CT	91,674.05	49,389.89	16,020.36	9,027.00	166,111.30	+6,104.53
11	RBV-XX-DG-TT	91,674.05	49,389.89	16,020.36	11,756.09	168,840.39	+8,833.62
12	RBV-XX-DG-MS	91,674.05	49,389.89	16,020.36	9,866.72	166,951.02	+6,944.25
13	DB-INS-SG-CT	91,674.05	50,919.14	10,511.84	9,027.00	162,132.03	+2,125.26
14	DB-INS-SG-TT	91,674.05	50,919.14	10,511.84	11,756.09	164,861.12	+4,854.35
15	DB-INS-SG-MS	91,674.05	50,919.14	10,511.84	9,866.72	162,971.75	+2,964.98
16	DB-XX-DG-CT	91,674.05	48,793.89	16,020.36	9,027.00	165,515.30	+5,508.53
17	BV-XX-DG-CT	91,674.05	34,066.35	16,020.36	9,027.00	150,787.77	-9,219.00
18	BV-XX-DG-TT	91,674.05	34,066.35	16,020.36	11,756.09	153,516.86	-6,489.91
19	DB-XX-DG-TT	91,674.05	48,793.89	16,020.36	11,756.09	168,244.39	+8,237.62

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	Capital cost (US$)					Economic impact (US$) +increment -reduction
		Non envelope elements and preliminaries	Wall elements	Window element	Roof element	Total	
20	DB-XX-DG-MS	91,674.05	48,793.89	16,020.36	9,866.72	166,355.02	+6,348.25
21	RBV-XX-SG-CT	91,674.05	49,389.89	10,511.84	9,027.00	160,602.77	+596.00
22	RBV-XX-SG-TT	91,674.05	49,389.89	10,511.84	11,756.09	163,331.87	+3,325.09
23	BV-XX-DG-MS	91,674.05	34,066.35	16,020.36	9,866.72	151,627.49	-8,379.28
24	RBV-XX-SG-MS	91,674.05	49,389.89	10,511.84	9,866.72	161,442.49	+1,435.72
25	ACC-XX-DG-CT	91,674.05	63,968.08	16,020.36	9,027.00	180,689.49	+20,682.72
26	ACC-XX-DG-TT	91,674.05	63,968.08	16,020.36	11,756.09	183,418.58	+23,411.81
27	ACC-XX-DG-MS	91,674.05	63,968.08	16,020.36	9,866.72	181,529.21	+21,522.44
28	TMB-XX-DG-CT	91,674.05	34,982.74	16,020.36	9,027.00	151,704.16	-8,302.62
29	TMB-XX-DG-TT	91,674.05	34,982.74	16,020.36	11,756.09	154,433.25	-5,573.52
30	TMB-XX-DG-MS	91,674.05	34,982.74	16,020.36	9,866.72	152,543.88	-7,462.90

Table E.7 Breakdown of operational cost of a typical the reference house in Perth for environmentally viable envelope options

GHG emission reduction benefits ranking	**Envelope option (1AUD = 0.7229US$)**	**life cycle operational energy (GJ)**	**Operational energy reduction (GJ)**	**Operational cost (US$)**	**Economic impact (US$) +increment -reduction**
	DB-XX-SG-CT	2,689.32	-	49,735.16	-
1	CSW-POL-DG-CT	2,435.11	-254.21	45,857.68	-3,877.48
2	CSW-POL-DG-TT	2,431.27	-258.05	45,770.80	-3,964.36
3	CSW-POL-DG-MS	2,436.65	-252.67	45,901.15	-3,834.02
4	CSW-POL-SG-CT	2,494.25	-195.07	46,934.14	-2,801.02
5	CSW-POL-SG-TT	2,493.48	-195.84	46,916.77	-2,818.39
6	CSW-POL-SG-MS	2,495.02	-194.30	46,960.24	-2,774.93
7	DB-INS-DG-CT	2,467.37	-221.95	46,186.53	-3,548.63
8	DB-INS-DG-TT	2,468.14	-221.18	46,195.19	-3,539.97
9	DB-INS-DG-MS	2,468.91	-220.42	46,230.00	-3,505.16
10	RBV-XX-DG-CT	2,471.98	-217.34	46,290.79	-3,444.38
11	RBV-XX-DG-TT	2,469.67	-219.65	46,238.66	-3,496.50
12	RBV-XX-DG-MS	2,472.75	-216.58	46,316.88	-3,418.28
13	DB-INS-SG-CT	2,531.88	-157.44	47,402.06	-2,333.10
14	DB-INS-SG-TT	2,530.35	-158.98	47,358.59	-2,376.57
15	DB-INS-SG-MS	2,531.88	-157.44	47,410.78	-2,324.39
16	DB-XX-DG-CT	2,618.67	-70.66	48,371.91	-1,363.25
17	BV-XX-DG-CT	2,544.94	-144.38	48,124.53	-1,610.63
18	BV-XX-DG-TT	2,541.87	-147.46	48,055.03	-1,680.13
19	DB-XX-DG-TT	2,617.90	-71.42	48,354.54	-1,380.63

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	life cycle operational energy (GJ)	Operational energy reduction (GJ)	Operational cost (US$)	Economic impact (US$) +increment -reduction
20	DB-XX-DG-MS	2,620.20	-69.12	48,424.10	-1,311.07
21	RBV-XX-SG-CT	2,537.26	-152.06	47,523.69	-2,211.47
22	RBV-XX-SG-TT	2,533.42	-155.90	47,436.81	-2,298.35
23	BV-XX-DG-MS	2,548.78	-140.54	48,220.13	-1,515.03
24	RBV-XX-SG-MS	2,536.49	-152.83	47,515.03	-2,220.13
25	ACC-XX-DG-CT	2,480.43	-208.90	46,673.67	-3,061.49
26	ACC-XX-DG-TT	2,477.35	-211.97	46,604.17	-3,130.99
27	ACC-XX-DG-MS	2,481.19	-208.13	46,699.77	-3,035.40
28	TMB-XX-DG-CT	2,645.55	-43.78	49,938.83	+203.67
29	TMB-XX-DG-TT	2,645.55	-43.78	49,938.83	+203.67
30	TMB-XX-DG-MS	2,650.15	-39.17	50,043.09	+307.92

Table E.8 Breakdown of the end of life demolition and disposal cost of a typical reference house in Perth for environmentally viable envelope options

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	End of life demolition and disposal cost (US$)	Economic impact (US$) +increment -reduction
	DB-XX-SG-CT	1,697.49	-
1	CSW-POL-DG-CT	1,738.27	+40.78
2	CSW-POL-DG-TT	1,732.22	+34.73
3	CSW-POL-DG-MS	1,711.51	+14.02
4	CSW-POL-SG-CT	1,737.20	+39.70
5	CSW-POL-SG-TT	1,731.23	+33.74
6	CSW-POL-SG-MS	1,710.52	+13.03
7	DB-INS-DG-CT	1,698.98	+1.49
8	DB-INS-DG-TT	1,692.93	-4.56
9	DB-INS-DG-MS	1,672.22	-25.27
10	RBV-XX-DG-CT	1,586.67	-110.82
11	RBV-XX-DG-TT	1,580.71	-116.78
12	RBV-XX-DG-MS	1,560.00	-137.49
13	DB-INS-SG-CT	1,697.91	+0.41
14	DB-INS-SG-TT	1,691.94	-5.55
15	DB-INS-SG-MS	1,671.23	-26.26
16	DB-XX-DG-CT	1,698.57	+1.08
17	BV-XX-DG-CT	1,491.49	-206.00
18	BV-XX-DG-TT	1,485.44	-212.05
19	DB-XX-DG-TT	1,692.52	-4.97
20	DB-XX-DG-MS	1,671.81	-25.68
21	RBV-XX-SG-CT	1,585.68	-111.81
22	RBV-XX-SG-TT	1,579.63	-117.86
23	BV-XX-DG-MS	1,464.73	-232.76
24	RBV-XX-SG-MS	1,559.01	-138.49
25	ACC-XX-DG-CT	1,382.41	-315.08
26	ACC-XX-DG-TT	1,376.37	-321.12
27	ACC-XX-DG-MS	1,355.66	-341.83
28	TMB-XX-DG-CT	1,335.69	-361.80
29	TMB-XX-DG-TT	1,329.64	-367.85
30	TMB-XX-DG-MS	1,309.02	-388.47

Table E.9 Breakdown of cost due to installation of $3kW_p$ grid connected roof top solar PV for a typical reference house in Perth for environmentally viable envelope options

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	Capital cost (US$)			Operational cost (US$)			Total saving (US$)
		Initial cost	Replacement cost	Total	Without SPV	With SPV	Saving	
0	DB-XX-SG-CT-SPV	2,747.02	1,059.74	3,806.76	49,735.16	30,113.96	19,621.20	15,814.44
1	CSW-POL-DG-CT-SPV	2,747.02	1,059.74	3,806.76	45,857.68	26,236.48	19,621.20	15,814.44
2	CSW-POL-DG-TT-SPV	2,747.02	1,059.74	3,806.76	45,770.80	26,149.60	19,621.20	15,814.44
3	CSW-POL-DG-MS-SPV	2,747.02	1,059.74	3,806.76	45,901.15	26,279.95	19,621.20	15,814.44
4	CSW-POL-SG-CT-SPV	2,747.02	1,059.74	3,806.76	46,934.14	27,312.95	19,621.20	15,814.44
5	CSW-POL-SG-TT-SPV	2,747.02	1,059.74	3,806.76	46,916.77	27,295.57	19,621.20	15,814.44
6	CSW-POL-SG-MS-SPV	2,747.02	1,059.74	3,806.76	46,960.24	27,339.04	19,621.20	15,814.44
7	DB-INS-DG-CT-SPV	2,747.02	1,059.74	3,806.76	46,186.53	26,565.33	19,621.20	15,814.44
8	DB-INS-DG-TT-SPV	2,747.02	1,059.74	3,806.76	46,195.19	26,573.99	19,621.20	15,814.44
9	DB-INS-DG-MS-SPV	2,747.02	1,059.74	3,806.76	46,230.00	26,608.80	19,621.20	15,814.44
10	RBV-XX-DG-CT-SPV	2,747.02	1,059.74	3,806.76	46,290.79	26,669.59	19,621.20	15,814.44
11	RBV-XX-DG-TT-SPV	2,747.02	1,059.74	3,806.76	46,238.66	26,617.46	19,621.20	15,814.44
12	RBV-XX-DG-MS-SPV	2,747.02	1,059.74	3,806.76	46,316.88	26,695.68	19,621.20	15,814.44
13	DB-INS-SG-CT-SPV	2,747.02	1,059.74	3,806.76	47,402.06	27,780.86	19,621.20	15,814.44
14	DB-INS-SG-TT-SPV	2,747.02	1,059.74	3,806.76	47,358.59	27,737.39	19,621.20	15,814.44
15	DB-INS-SG-MS-SPV	2,747.02	1,059.74	3,806.76	47,410.78	27,789.58	19,621.20	15,814.44
16	DB-XX-DG-CT-SPV	2,747.02	1,059.74	3,806.76	48,371.91	28,750.71	19,621.20	15,814.44
17	BV-XX-DG-CT-SPV	2,747.02	1,059.74	3,806.76	48,124.53	28,503.34	19,621.20	15,814.44

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	Capital cost (US$)			Operational cost (US$)			Total saving (US$)
		Initial cost	Replacement cost	Total	Without SPV	With SPV	Saving	
18	BV-XX-DG-TT-SPV	2,747.02	1,059.74	3,806.76	48,055.03	28,433.83	19,621.20	15,814.44
19	DB-XX-DG-TT-SPV	2,747.02	1,059.74	3,806.76	48,354.54	28,733.34	19,621.20	15,814.44
20	DB-XX-DG-MS-SPV	2,747.02	1,059.74	3,806.76	48,424.10	28,802.90	19,621.20	15,814.44
21	RBV-XX-SG-CT-SPV	2,747.02	1,059.74	3,806.76	47,523.69	27,902.49	19,621.20	15,814.44
22	RBV-XX-SG-TT-SPV	2,747.02	1,059.74	3,806.76	47,436.81	27,815.61	19,621.20	15,814.44
23	BV-XX-DG-MS-SPV	2,747.02	1,059.74	3,806.76	48,220.13	28,598.93	19,621.20	15,814.44
24	RBV-XX-SG-MS-SPV	2,747.02	1,059.74	3,806.76	47,515.03	27,893.83	19,621.20	15,814.44
25	ACC-XX-DG-CT-SPV	2,747.02	1,059.74	3,806.76	46,673.67	27,052.47	19,621.20	15,814.44
26	ACC-XX-DG-TT-SPV	2,747.02	1,059.74	3,806.76	46,604.17	26,982.97	19,621.20	15,814.44
27	ACC-XX-DG-MS-SPV	2,747.02	1,059.74	3,806.76	46,699.77	27,078.57	19,621.20	15,814.44
28	TMB-XX-DG-CT-SPV	2,747.02	1,059.74	3,806.76	49,938.83	30,317.63	19,621.20	15,814.44
29	TMB-XX-DG-TT-SPV	2,747.02	1,059.74	3,806.76	49,938.83	30,317.63	19,621.20	15,814.44
30	TMB-XX-DG-MS-SPV	2,747.02	1,059.74	3,806.76	50,043.09	30,421.89	19,621.20	15,814.44

Data Source: (Solarchoice 2015, Solare, WA 2015; Advanced Solar Technology, WA 2015; Solaire Connect, WA 2015)

Table E.10 Breakdown of cost due to integration of gas hot water system with roof top solar water heater for a typical reference house in Perth for environmentally viable envelope options

GHG emission reduction benefits ranking	**Envelope option (1AUD = 0.7229US$)**	**Capital cost (US$)**			**Operational cost (US$)**			**Total saving (US$)**
		Initial cost	**Replacement cost**	**Total**	**Without SWH**	**With SWH**	**Saving**	
0	DB-XX-SG-CT-SWH	2,747.02	3,315.78	6,062.80	49,735.16	41,282.75	8,452.42	2,389.62
1	CSW-POL-DG-CT-SWH	2,747.02	3,315.78	6,062.80	45,857.68	37,203.23	8,452.42	2,389.62
2	CSW-POL-DG-TT-SWH	2,747.02	3,315.78	6,062.80	45,770.80	37,116.35	8,452.42	2,389.62
3	CSW-POL-DG-MS-SWH	2,747.02	3,315.78	6,062.80	45,901.15	37,245.76	8,452.42	2,389.62
4	CSW-POL-SG-CT-SWH	2,747.02	3,315.78	6,062.80	46,934.14	38,307.89	8,452.42	2,389.62
5	CSW-POL-SG-TT-SWH	2,747.02	3,315.78	6,062.80	46,916.77	38,290.51	8,452.42	2,389.62
6	CSW-POL-SG-MS-SWH	2,747.02	3,315.78	6,062.80	46,960.24	38,333.04	8,452.42	2,389.62
7	DB-INS-DG-CT-SWH	2,747.02	3,315.78	6,062.80	46,186.53	37,575.31	8,452.42	2,389.62
8	DB-INS-DG-TT-SWH	2,747.02	3,315.78	6,062.80	46,195.19	37,584.91	8,452.42	2,389.62
9	DB-INS-DG-MS-SWH	2,747.02	3,315.78	6,062.80	46,230.00	37,617.84	8,452.42	2,389.62
10	RBV-XX-DG-CT-SWH	2,747.02	3,315.78	6,062.80	46,290.79	37,679.57	8,452.42	2,389.62
11	RBV-XX-DG-TT-SWH	2,747.02	3,315.78	6,062.80	46,238.66	37,627.44	8,452.42	2,389.62
12	RBV-XX-DG-MS-SWH	2,747.02	3,315.78	6,062.80	46,316.88	37,704.72	8,452.42	2,389.62
13	DB-INS-SG-CT-SWH	2,747.02	3,315.78	6,062.80	47,402.06	38,817.15	8,452.42	2,389.62
14	DB-INS-SG-TT-SWH	2,747.02	3,315.78	6,062.80	47,358.59	38,774.62	8,452.42	2,389.62
15	DB-INS-SG-MS-SWH	2,747.02	3,315.78	6,062.80	47,410.78	38,824.93	8,452.42	2,389.62
16	DB-XX-DG-CT-SWH	2,747.02	3,315.78	6,062.80	48,371.91	39,894.12	8,452.42	2,389.62
17	BV-XX-DG-CT-SWH	2,747.02	3,315.78	6,062.80	48,124.53	39,493.58	8,452.42	2,389.62

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	Capital cost (US$)			Operational cost (US$)			Total saving (US$)
		Initial cost	Replacement cost	Total	Without SWH	With SWH	Saving	
18	BV-XX-DG-TT-SWH	2,747.02	3,315.78	6,062.80	48,055.03	39,424.08	8,452.42	2,389.62
19	DB-XX-DG-TT-SWH	2,747.02	3,315.78	6,062.80	48,354.54	39,876.75	8,452.42	2,389.62
20	DB-XX-DG-MS-SWH	2,747.02	3,315.78	6,062.80	48,424.10	39,944.43	8,452.42	2,389.62
21	RBV-XX-SG-CT-SWH	2,747.02	3,315.78	6,062.80	47,523.69	38,938.78	8,452.42	2,389.62
22	RBV-XX-SG-TT-SWH	2,747.02	3,315.78	6,062.80	47,436.81	38,851.90	8,452.42	2,389.62
23	BV-XX-DG-MS-SWH	2,747.02	3,315.78	6,062.80	48,220.13	39,588.24	8,452.42	2,389.62
24	RBV-XX-SG-MS-SWH	2,747.02	3,315.78	6,062.80	47,515.03	38,929.18	8,452.42	2,389.62
25	ACC-XX-DG-CT-SWH	2,747.02	3,315.78	6,062.80	46,673.67	38,041.78	8,452.42	2,389.62
26	ACC-XX-DG-TT-SWH	2,747.02	3,315.78	6,062.80	46,604.17	37,972.28	8,452.42	2,389.62
27	ACC-XX-DG-MS-SWH	2,747.02	3,315.78	6,062.80	46,699.77	38,066.93	8,452.42	2,389.62
28	TMB-XX-DG-CT-SWH	2,747.02	3,315.78	6,062.80	49,938.83	41,357.68	8,452.42	2,389.62
29	TMB-XX-DG-TT-SWH	2,747.02	3,315.78	6,062.80	49,938.83	41,357.68	8,452.42	2,389.62
30	TMB-XX-DG-MS-SWH	2,747.02	3,315.78	6,062.80	50,043.09	41,461.93	8,452.42	2,389.62
Data Source: (Rawlinsons 2015); (Solarchoice 2015, Solare, WA 2015; Advanced Solar Technology, WA 2015; Solaire Connect, WA 2015)								

Table E.11 Economic implications of the replacement of conventional concrete with green concrete for a typical reference house in Perth for environmentally viable envelope options

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	Capital cost of conventional concrete (US$)	Capital cost of green concrete (US$)	Saving (US$)
	DB-XX-SG-CT-GC	7,004.35	6,835.59	-168.76
1	CSW-POL-DG-CT-GC	13,356.03	13,028.75	-327.27
2	CSW-POL-DG-TT-GC	13,356.03	13,028.75	-327.27
3	CSW-POL-DG-MS-GC	13,356.03	13,028.75	-327.27
4	CSW-POL-SG-CT-GC	13,356.03	13,028.75	-327.27
5	CSW-POL-SG-TT-GC	13,356.03	13,028.75	-327.27
6	CSW-POL-SG-MS-GC	13,356.03	13,028.75	-327.27
7	DB-INS-DG-CT-GC	7,004.35	6,835.59	-168.76
8	DB-INS-DG-TT-GC	7,004.35	6,835.59	-168.76
9	DB-INS-DG-MS-GC	7,004.35	6,835.59	-168.76
10	RBV-XX-DG-CT-GC	7,004.35	6,835.59	-168.76
11	RBV-XX-DG-TT-GC	7,004.35	6,835.59	-168.76
12	RBV-XX-DG-MS-GC	7,004.35	6,835.59	-168.76
13	DB-INS-SG-CT-GC	7,004.35	6,835.59	-168.76
14	DB-INS-SG-TT-GC	7,004.35	6,835.59	-168.76
15	DB-INS-SG-MS-GC	7,004.35	6,835.59	-168.76
16	DB-XX-DG-CT-GC	7,004.35	6,835.59	-168.76
17	BV-XX-DG-CT-GC	7,004.35	6,835.59	-168.76
18	BV-XX-DG-TT-GC	7,004.35	6,835.59	-168.76
19	DB-XX-DG-TT-GC	7,004.35	6,835.59	-168.76

GHG emission reduction benefits ranking	Envelope option (1AUD = 0.7229US$)	Capital cost of conventional concrete (US$)	Capital cost of green concrete (US$)	Saving (US$)
20	DB-XX-DG-MS-GC	7,004.35	6,835.59	-168.76
21	RBV-XX-SG-CT-GC	7,004.35	6,835.59	-168.76
22	RBV-XX-SG-TT-GC	7,004.35	6,835.59	-168.76
23	BV-XX-DG-MS-GC	7,004.35	6,835.59	-168.76
24	RBV-XX-SG-MS-GC	7,004.35	6,835.59	-168.76
25	ACC-XX-DG-CT-GC	7,004.35	6,835.59	-168.76
26	ACC-XX-DG-TT-GC	7,004.35	6,835.59	-168.76
27	ACC-XX-DG-MS-GC	7,004.35	6,835.59	-168.76
28	TMB-XX-DG-CT-GC	7,004.35	6,835.59	-168.76
29	TMB-XX-DG-TT-GC	7,004.35	6,835.59	-168.76
30	TMB-XX-DG-MS-GC	7,004.35	6,835.59	-168.76
Note: The above capital cost is for material only (labour cost excluded, which will remain same for both options)				
Cost data source:(Rawlinsons 2015) and BGC Concrete; Boral Technical Services; Hanson Concrete				

Table E.12 Summary of LCC, GHG emissions, and EE consumption results of a typical reference house in Perth for CPS options

Envelope options including all CPS (1AUD = 0.7229US$)	**Net life cycle cost**		**Net GHG emissions**		**Net EE consumption**	
	US$	***Ranking***	**tonnes CO_2 e-**	***Ranking***	**TJ**	***Ranking***
DB-XX-SG-CT	211,439.43	***Reference***	467.19	***Reference***	6.51	***Reference***
DB-XX-SG-CT-SPV-SWH-GC	193,066.61	***0***	241.59	***0***	3.21	***0***
CSW-POL-DG-CT-SPV-SWH-GC	182,674.52	***5***	161.60	***1***	2.04	***1***
CSW-POL-DG-TT-SPV-SWH-GC	185,310.69	***10***	161.60	***2***	2.04	***2***
CSW-POL-DG-MS-SPV-SWH-GC	183,530.02	***7***	165.34	***3***	2.14	***3***
CSW-POL-SG-CT-SPV-SWH-GC	178,269.57	***1***	181.56	***4***	2.30	***4***
CSW-POL-SG-TT-SPV-SWH-GC	180,975.33	***3***	183.14	***5***	2.33	***5***
CSW-POL-SG-MS-SPV-SWH-GC	179,107.77	***2***	184.91	***6***	2.41	***7***
DB-INS-DG-CT-SPV-SWH-GC	196,994.44	***21***	183.12	***7***	2.40	***9***
DB-INS-DG-TT-SPV-SWH-GC	199,727.09	***26***	185.18	***8***	2.43	***10***
DB-INS-DG-MS-SPV-SWH-GC	197,849.94	***23***	186.87	***9***	2.51	***12***
RBV-XX-DG-CT-SPV-SWH-GC	195,457.14	***19***	195.32	***10***	2.38	***6***
RBV-XX-DG-TT-SPV-SWH-GC	198,128.14	***25***	196.11	***11***	2.39	***8***
RBV-XX-DG-MS-SPV-SWH-GC	196,295.34	***20***	198.67	***12***	2.48	***11***
DB-INS-SG-CT-SPV-SWH-GC	192,726.68	***15***	206.44	***13***	2.71	***17***
DB-INS-SG-TT-SPV-SWH-GC	195,407.28	***18***	207.32	***14***	2.73	***18***
DB-INS-SG-MS-SPV-SWH-GC	193,547.50	***16***	209.40	***15***	2.81	***23***
DB-XX-DG-CT-SPV-SWH-GC	197,187.59	***22***	214.83	***16***	2.85	***26***
BV-XX-DG-CT-SPV-SWH-GC	181,852.43	***4***	215.64	***17***	2.62	***13***
BV-XX-DG-TT-SPV-SWH-GC	184,505.97	***9***	216.04	***18***	2.63	***14***
DB-XX-DG-TT-SPV-SWH-GC	199,893.26	***27***	216.40	***19***	2.87	***28***
DB-XX-DG-MS-SPV-SWH-GC	198,050.86	***24***	218.88	***20***	2.96	***30***

Envelope options including all CPS (1AUD = 0.7229US$)	Net life cycle cost		Net GHG emissions		Net EE consumption	
	US$	*Ranking*	tonnes CO_2 e-	*Ranking*	TJ	*Ranking*
RBV-XX-SG-CT-SPV-SWH-GC	191,206.83	***13***	219.03	***21***	2.69	***15***
RBV-XX-SG-TT-SPV-SWH-GC	193,843.00	***17***	219.03	***22***	2.70	***16***
BV-XX-DG-MS-SPV-SWH-GC	182,760.05	***6***	220.75	***23***	2.74	***20***
RBV-XX-SG-MS-SPV-SWH-GC	192,010.28	***14***	221.60	***24***	2.78	***22***
ACC-XX-DG-CT-SPV-SWH-GC	210,193.28	***28***	222.38	***25***	2.74	***19***
ACC-XX-DG-TT-SPV-SWH-GC	212,846.82	***30***	222.78	***26***	2.75	***21***
ACC-XX-DG-MS-SPV-SWH-GC	211,031.40	***29***	225.72	***27***	2.84	***25***
TMB-XX-DG-CT-SPV-SWH-GC	184,477.12	***8***	233.62	***28***	2.84	***24***
TMB-XX-DG-TT-SPV-SWH-GC	187,200.17	***12***	235.58	***29***	2.87	***27***
TMB-XX-DG-MS-SPV-SWH-GC	185,394.42	***11***	238.35	***30***	2.96	***29***

Table E.13 LCC of a typical reference house in Perth for CPS options under different discount rates

Environmentally viable CPS options	**Life cycle cost (US$)(1AUD = 0.7229US$)**		
	Discount rate: 7%	**Discount rate: 4%**	**Discount rate: 10%**
DB-XX-SG-CT	211,439.43	256,589.45	192,575.02
DB-XX-SG-CT-SPV-SWH-GC	193,066.60	219,970.74	182,165.10
CSW-POL-DG-CT-SPV-SWH-GC	182,674.52	206,441.39	173,185.52
CSW-POL-DG-TT-SPV-SWH-GC	185,310.69	208,988.99	175,856.95
CSW-POL-DG-MS-SPV-SWH-GC	183,530.01	207,246.77	174,046.01
CSW-POL-SG-CT-SPV-SWH-GC	178,269.57	202,917.29	168,390.63
CSW-POL-SG-TT-SPV-SWH-GC	180,975.32	205,590.38	171,106.99
CSW-POL-SG-MS-SPV-SWH-GC	179,107.77	203,691.73	169,239.91
DB-INS-DG-CT-SPV-SWH-GC	196,994.44	220,935.58	187,403.25
DB-INS-DG-TT-SPV-SWH-GC	199,727.09	223,656.89	190,137.03
DB-INS-DG-MS-SPV-SWH-GC	197,849.93	221,740.96	188,263.75
RBV-XX-DG-CT-SPV-SWH-GC	195,457.13	219,128.52	185,913.20
RBV-XX-DG-TT-SPV-SWH-GC	198,128.13	221,739.03	188,607.10
RBV-XX-DG-MS-SPV-SWH-GC	196,295.33	219,902.96	186,762.48
DB-INS-SG-CT-SPV-SWH-GC	192,726.68	217,658.48	182,697.02
DB-INS-SG-TT-SPV-SWH-GC	195,407.27	220,286.28	185,397.13
DB-INS-SG-MS-SPV-SWH-GC	193,547.50	218,401.63	183,535.07
DB-XX-DG-CT-SPV-SWH-GC	197,187.58	222,983.56	186,776.47
BV-XX-DG-CT-SPV-SWH-GC	181,852.43	206,676.53	171,738.12
BV-XX-DG-TT-SPV-SWH-GC	184,505.97	209,255.41	174,420.77
DB-XX-DG-TT-SPV-SWH-GC	199,893.25	225,656.30	189,492.82
DB-XX-DG-MS-SPV-SWH-GC	198,050.85	223,802.94	187,641.99
RBV-XX-SG-CT-SPV-SWH-GC	191,206.83	215,883.05	181,218.21
RBV-XX-SG-TT-SPV-SWH-GC	193,842.99	218,430.65	183,889.64
BV-XX-DG-MS-SPV-SWH-GC	182,760.05	207,575.76	172,632.30
RBV-XX-SG-MS-SPV-SWH-GC	192,010.27	216,594.92	182,045.03
ACC-XX-DG-CT-SPV-SWH-GC	210,193.28	233,512.21	200,674.22
ACC-XX-DG-TT-SPV-SWH-GC	212,846.82	236,091.10	203,356.87
ACC-XX-DG-MS-SPV-SWH-GC	211,031.39	234,286.31	201,523.48
TMB-XX-DG-CT-SPV-SWH-GC	184,477.12	210,303.39	173,820.12
TMB-XX-DG-TT-SPV-SWH-GC	187,200.16	213,007.41	176,547.70
TMB-XX-DG-MS-SPV-SWH-GC	185,394.42	211,220.25	174,720.53

Table E.14 Summary of LCC, GHG emissions, and EE consumption results of a typical reference house in Perth for CPS options under different discount rates

CPS options (1AUD = 0.7229US$)	Net life cycle cost Discount rate: 7%		Net life cycle cost Discount rate: 4%		Net life cycle cost Discount rate: 10%		Net GHG emissions		Net EE consumption	
	US$	**Ranking**	**US$**	**Ranking**	**US$**	***Ranking***	**tonnes CO_2 e-**	***Ranking***	**TJ**	***Ranking***
DB-XX-SG-CT*	211,439.43	***Ref.***	256,589.45	***Ref.***	192,575.02	***Ref.***	467.19	***Ref.***	6.51	***Ref.***
DB-XX-SG-CT-SPV-SWH-GC	193,066.61	***0***	219,970.74	***0***	182,165.10	***0***	241.59	***0***	3.21	***0***
CSW-POL-DG-CT-SPV-SWH-GC	182,674.52	***5***	206,441.39	***4***	173,185.52	***6***	161.60	***1***	2.04	***1***
CSW-POL-DG-TT-SPV-SWH-GC	185,310.69	***10***	208,988.99	***8***	175,856.95	***11***	161.60	***2***	2.04	***2***
CSW-POL-DG-MS-SPV-SWH-GC	183,530.02	***7***	207,246.77	***6***	174,046.01	***8***	165.34	***3***	2.14	***3***
CSW-POL-SG-CT-SPV-SWH-GC	178,269.57	***1***	202,917.29	***1***	168,390.63	***1***	181.56	***4***	2.30	***4***
CSW-POL-SG-TT-SPV-SWH-GC	180,975.33	***3***	205,590.38	***3***	171,106.99	***3***	183.14	***5***	2.33	***5***
CSW-POL-SG-MS-SPV-SWH-GC	179,107.77	***2***	203,691.73	***2***	169,239.91	***2***	184.91	***6***	2.41	***7***
DB-INS-DG-CT-SPV-SWH-GC	196,994.44	***21***	220,935.58	***21***	187,403.25	***22***	183.12	***7***	2.40	***9***
DB-INS-DG-TT-SPV-SWH-GC	199,727.09	***26***	223,656.89	***25***	190,137.03	***27***	185.18	***8***	2.43	***10***
DB-INS-DG-MS-SPV-SWH-GC	197,849.94	***23***	221,740.96	***23***	188,263.75	***24***	186.87	***9***	2.51	***12***
RBV-XX-DG-CT-SPV-SWH-GC	195,457.14	***19***	219,128.52	***18***	185,913.20	***19***	195.32	***10***	2.38	***6***
RBV-XX-DG-TT-SPV-SWH-GC	198,128.14	***25***	221,739.03	***22***	188,607.10	***25***	196.11	***11***	2.39	***8***
RBV-XX-DG-MS-SPV-SWH-GC	196,295.34	***20***	219,902.96	***19***	186,762.48	***20***	198.67	***12***	2.48	***11***
DB-INS-SG-CT-SPV-SWH-GC	192,726.68	***15***	217,658.48	***15***	182,697.02	***15***	206.44	***13***	2.71	***17***
DB-INS-SG-TT-SPV-SWH-GC	195,407.28	***18***	220,286.28	***20***	185,397.13	***18***	207.32	***14***	2.73	***18***
DB-INS-SG-MS-SPV-SWH-GC	193,547.50	***16***	218,401.63	***16***	183,535.07	***16***	209.40	***15***	2.81	***23***

CPS options (1AUD = 0.7229US$)	Net life cycle cost Discount rate: 7%		Net life cycle cost Discount rate: 4%		Net life cycle cost Discount rate: 10%		Net GHG emissions		Net EE consumption	
	US$	Ranking	US$	Ranking	US$	*Ranking*	tonnes CO_2 e-	*Ranking*	TJ	*Ranking*
DB-XX-DG-CT-SPV-SWH-GC	197,187.59	***22***	222,983.56	***24***	186,776.47	***21***	214.83	***16***	2.85	***26***
BV-XX-DG-CT-SPV-SWH-GC	181,852.43	***4***	206,676.53	***5***	171,738.12	***4***	215.64	***17***	2.62	***13***
BV-XX-DG-TT-SPV-SWH-GC	184,505.97	***9***	209,255.41	***9***	174,420.77	***9***	216.04	***18***	2.63	***14***
DB-XX-DG-TT-SPV-SWH-GC	199,893.26	***27***	225,656.30	***27***	189,492.82	***26***	216.40	***19***	2.87	***28***
DB-XX-DG-MS-SPV-SWH-GC	198,050.86	***24***	223,802.94	***26***	187,641.99	***23***	218.88	***20***	2.96	***30***
RBV-XX-SG-CT-SPV-SWH-GC	191,206.83	***13***	215,883.05	***13***	181,218.21	***13***	219.03	***21***	2.69	***15***
RBV-XX-SG-TT-SPV-SWH-GC	193,843.00	***17***	218,430.65	***17***	183,889.64	***17***	219.03	***22***	2.70	***16***
BV-XX-DG-MS-SPV-SWH-GC	182,760.05	***6***	207,575.76	***7***	172,632.30	***5***	220.75	***23***	2.74	***20***
RBV-XX-SG-MS-SPV-SWH-GC	192,010.28	***14***	216,594.92	***14***	182,045.03	***14***	221.60	***24***	2.78	***22***
ACC-XX-DG-CT-SPV-SWH-GC	210,193.28	***28***	233,512.21	***28***	200,674.22	***28***	222.38	***25***	2.74	***19***
ACC-XX-DG-TT-SPV-SWH-GC	212,846.82	***30***	236,091.10	***30***	203,356.87	***30***	222.78	***26***	2.75	***21***
ACC-XX-DG-MS-SPV-SWH-GC	211,031.40	***29***	234,286.31	***29***	201,523.48	***29***	225.72	***27***	2.84	***25***
TMB-XX-DG-CT-SPV-SWH-GC	184,477.12	***8***	210,303.39	***10***	173,820.12	***7***	233.62	***28***	2.84	***24***
TMB-XX-DG-TT-SPV-SWH-GC	187,200.17	***12***	213,007.41	***12***	176,547.70	***12***	235.58	***29***	2.87	***27***
TMB-XX-DG-MS-SPV-SWH-GC	185,394.42	***11***	211,220.25	***11***	174,720.53	***10***	238.35	***30***	2.96	***29***

Table E.15 Implications of probable carbon tax for a typical reference house in Perth for CPS options under different discount rates

Cleaner production options	Carbon Tax (US$)(1AUD = 0.7229US$)		
	Discount rate: 7%	Discount rate: 4%	Discount rate: 10%
DB-XX-SG-CT*	4,926.38	8,869.79	3183.77
DB-XX-SG-CT-SPV-SWH-GC	2,243.00	4,038.46	1,449.58
CSW-POL-DG-CT-SPV-SWH-GC	1,854.66	3,339.25	1,198.61
CSW-POL-DG-TT-SPV-SWH-GC	1,842.85	3,317.99	1,190.97
CSW-POL-DG-MS-SPV-SWH-GC	1,861.20	3,351.04	1,202.84
CSW-POL-SG-CT-SPV-SWH-GC	1,981.85	3,568.26	1,280.81
CSW-POL-SG-TT-SPV-SWH-GC	1,979.49	3,564.01	1,279.28
CSW-POL-SG-MS-SPV-SWH-GC	1,986.04	3,575.80	1,283.51
DB-INS-DG-CT-SPV-SWH-GC	1,870.02	3,366.90	1,208.53
DB-INS-DG-TT-SPV-SWH-GC	1,870.55	3,367.88	1,208.88
DB-INS-DG-MS-SPV-SWH-GC	1,876.56	3,378.69	1,212.76
RBV-XX-DG-CT-SPV-SWH-GC	1,884.19	3,392.42	1,217.69
RBV-XX-DG-TT-SPV-SWH-GC	1,877.10	3,379.66	1,213.11
RBV-XX-DG-MS-SPV-SWH-GC	1,888.37	3,399.96	1,220.40
DB-INS-SG-CT-SPV-SWH-GC	2,017.39	3,632.25	1,303.78
DB-INS-SG-TT-SPV-SWH-GC	2,010.84	3,620.46	1,299.55
DB-INS-SG-MS-SPV-SWH-GC	2,019.21	3,635.53	1,304.95
DB-XX-DG-CT-SPV-SWH-GC	2,076.51	3,738.69	1,341.98
BV-XX-DG-CT-SPV-SWH-GC	2,146.86	3,865.35	1,387.45
BV-XX-DG-TT-SPV-SWH-GC	2,137.41	3,848.34	1,381.34
DB-XX-DG-TT-SPV-SWH-GC	2,074.14	3,734.43	1,340.46
DB-XX-DG-MS-SPV-SWH-GC	2,084.88	3,753.76	1,347.39
RBV-XX-SG-CT-SPV-SWH-GC	2,033.92	3,662.02	1,314.46
RBV-XX-SG-TT-SPV-SWH-GC	2,022.11	3,640.75	1,306.83
BV-XX-DG-MS-SPV-SWH-GC	2,160.49	3,889.90	1,396.26
RBV-XX-SG-MS-SPV-SWH-GC	2,033.38	3,661.05	1,314.11
ACC-XX-DG-CT-SPV-SWH-GC	1,950.27	3,511.40	1,260.40
ACC-XX-DG-TT-SPV-SWH-GC	1,940.82	3,494.39	1,254.29
ACC-XX-DG-MS-SPV-SWH-GC	1,954.46	3,518.94	1,263.10
TMB-XX-DG-CT-SPV-SWH-GC	2,359.68	4,248.53	1,524.99
TMB-XX-DG-TT-SPV-SWH-GC	2,359.68	4,248.53	1,524.99
TMB-XX-DG-MS-SPV-SWH-GC	2,373.85	4,274.05	1,534.15

Appendix F

Table F.1 Location wise climate and NatHERS zones in WA

Location	Postal Code	Climate Zone	NatHERS Zone
Perth	6000	5	13
Albany	6330	6	58
Armadale	6112	5	47
Augusta	6290	5	58
Broome	6725	1	33
Bunbury	6230	5	54
Busselton	6280	5	57
Carnarvon	6701	3	4
Esperance	6450	5	55
Geraldton	6530	5	12
Joondalup	6027	5	52
Kalgoorlie	6430	4	44
Kununurra	6743	1	30
Laverton	6440	4	41
Mandurah	6210	5	54
Mount Magnet	6638	4	42
Newman	6753	3	40
Yanchep	6035	5	52

Table F.2 Source of information on the use of bottled gas/electric water heaters in regional WA

Location	Builders/Contractors
Augusta	Capewest Builders – +61 438 581 471 Kleenheat - +61 8 8641 2304
Broome	H&M Tracey Const. Pty Ltd – +61 8 9192 1437 Broome Plumbing & Gas - +61 8 9192 2198
Carnarvon	Northern Aspect Construction – +61 407 776 361 Carnarvon Plumbing Service - +61 8 9192 2198
Esperance	WA Country Builders – +61 8 9072 1001 Dixon Const. WA - +61 8 9071 7734
Kununurra	McLean Enterprises Pty Ltd – +61 8 9169 1088 Barclay Mowlem Construction - +61 8 9168 1675
Laverton	Powerchill Electrical & Refrigeration – +61 8 9031 1172 PWT Electrical - +61 8 9031 1146
Mount Magnet	SR Plumbing and Gas – +61 428 442 209 MTF Services - +61 8 9963 4371
Newman	Wide Glide Cons. – +61 8 9175 1885 S&N Contracting Const. - +61 8 9175 7088

Table F.3 Life cycle operational energy demand for heating and cooling of a reference house for alternative envelope options for 17 locations in regional WA

Location	DB-XX-SG-CT	DB-XX-DG-CT	DB-INS-SG-CT	DB-INS-DG-CT	CSW-POL-SG-CT	CSW-POL-DG-CT	BV-XX-SG-CT	BV-XX-DG-CT	RBV-XX-SG-CT	RBV-XX-DG-CT	PCSW-XX-SG-CT	PCSW-XX-DG-CT	CB-XX-SG-CT	CB-XX-DG-CT	ACC-XX-SG-CT	ACC-XX-DG-CT	TMB-XX-SG-CT	TMB-XX-DG-CT
	GJ																	
Perth	521	451	364	300	326	267	466	377	369	304	637	540	866	781	385	313	569	478
Albany	998	931	734	668	594	525	650	575	730	664	884	806	1,375	1,305	660	586	759	682
Augusta	989	923	731	661	594	524	653	579	727	657	886	809	1,366	1,294	661	591	760	686
Armadale	902	828	670	599	574	492	680	588	669	600	909	814	1,286	1,197	644	563	812	710
Broome	3,393	3,192	3,103	2,906	2,948	2,756	2,928	2,715	3,104	2,906	3,266	3,057	3,875	3,656	2,993	2,796	3,027	2,823
Bunbury	538	485	389	336	335	280	442	372	391	336	598	518	834	763	388	328	530	456
Busselton	1,300	1,194	984	880	819	718	905	790	978	878	1,201	1,080	1,768	1,654	904	792	1,049	930
Carnarvon	641	589	573	516	553	495	569	509	572	519	651	594	793	730	571	516	608	548
Esperance	680	621	488	431	405	341	468	399	490	430	644	571	982	918	455	391	551	481
Geraldton	422	346	316	247	303	237	425	340	319	252	541	449	670	592	356	276	498	410
Joondalup	334	296	227	193	205	163	290	233	230	194	388	330	541	489	243	199	347	300
Kalgoorlie	540	476	365	304	310	248	459	369	367	306	638	543	895	812	373	304	565	474
Kununurra	5,175	4,848	4,559	4,246	4,232	3,922	4,382	4,064	4,570	4,251	5,076	4,734	6,269	5,926	4,370	4,063	4,610	4,285
Laverton	922	783	706	574	628	506	854	703	711	577	1,063	900	1,367	1,204	727	584	964	808
Mandurah	538	485	392	337	336	276	441	369	392	339	598	518	837	762	387	327	529	454
Mount Magnet	584	492	434	352	385	304	561	458	442	356	710	597	907	809	450	366	650	544
Newman	1,378	1,217	1,114	966	997	862	1,236	1,068	1,123	976	1,501	1,326	1,889	1,723	1,101	958	1,377	1,206
Yanchep	335	296	228	194	205	163	287	233	230	195	388	331	542	490	245	199	348	298

Note: For presentation purpose, all the values have been rounded up as whole numbers. However, all calculations are based on real values

Table F.4 Ranking of life cycle operational energy demand for heating and cooling of a reference house for alternative envelope options for 17 locations in regional WA

Locations	Perth	Albany	Augusta	Armadale	Broome	Bunbury	Busselton	Carnarvon	Esperance	Geraldton	Joondalup	Kalgoorlie	Kununurra	Laverton	Mandurah	Mount Magnet	Newman	Yanchep
DB-XX-SG-CT	13	16	16	15	16	15	16	15	16	12	14	13	16	14	15	13	15	14
DB-XX-DG-CT	10	15	15	14	14	12	14	12	14	9	11	12	14	10	12	10	11	11
DB-INS-SG-CT	6	11	11	9	12	8	11	11	10	6	6	6	10	7	8	6	8	6
DB-INS-DG-CT	2	8	8	5	5	4	6	3	6	2	2	2	5	2	4	2	3	2
CSW-POL-SG-CT	5	4	4	3	8	3	4	7	4	5	5	5	4	5	3	5	5	5
CSW-POL-DG-CT	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1
BV-XX-SG-CT	11	5	5	10	7	10	8	8	8	13	10	10	9	12	10	12	12	10
BV-XX-DG-CT	8	2	2	4	1	6	2	2	3	8	8	8	3	6	6	9	6	8
RBV-XX-SG-CT	7	10	10	8	13	9	10	10	11	7	7	7	11	8	9	7	9	7
RBV-XX-DG-CT	3	7	6	6	6	5	5	5	5	3	3	4	6	3	5	3	4	3
PCSW-XX-SG-CT	16	14	14	16	15	16	15	16	15	16	16	16	15	16	16	16	16	16
PCSW-XX-DG-CT	14	13	13	13	11	13	13	13	13	14	13	14	13	13	13	14	13	13
CB-XX-SG-CT	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
CB-XX-DG-CT	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
ACC-XX-SG-CT	9	6	7	7	9	7	7	9	7	10	9	9	8	9	7	8	7	9
ACC-XX-DG-CT	4	3	3	2	3	2	3	4	2	4	4	3	2	4	2	4	2	4
TMB-XX-SG-CT	15	12	12	12	10	14	12	14	12	15	15	15	12	15	14	15	14	15
TMB-XX-DG-CT	12	9	9	11	4	11	9	6	9	11	12	11	7	11	11	11	10	12

Table F.5 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Albany and Augusta

Envelope options	Life cycle operational energy - GJ											
	Albany						Augusta					
	Heating	Cooling	Hot water	Lighting	Home Appliances	Total	Heating	Cooling	Hot water	Lighting	Home Appliances	Total
DB-XX-SG-CT	951.55	46.85	1,214.50	320.35	717.00	3,250.25	938.50	50.69	1,214.50	320.35	717.00	3,241.03
DB-XX-DG-CT	894.72	36.10	1,214.50	320.35	717.00	3,182.67	883.97	39.17	1,214.50	320.35	717.00	3,174.99
DB-INS-SG-CT	693.50	40.70	1,214.50	320.35	717.00	2,986.06	685.82	45.31	1,214.50	320.35	717.00	2,982.99
DB-INS-DG-CT	635.14	33.02	1,214.50	320.35	717.00	2,920.01	627.46	33.79	1,214.50	320.35	717.00	2,913.10
CSW-POL-SG-CT	549.12	45.31	1,214.50	320.35	717.00	2,846.28	542.98	51.46	1,214.50	320.35	717.00	2,846.28
CSW-POL-DG-CT	489.98	35.33	1,214.50	320.35	717.00	2,777.16	485.38	38.40	1,214.50	320.35	717.00	2,775.63
BV-XX-SG-CT	576.77	73.73	1,214.50	320.35	717.00	2,902.35	574.46	78.34	1,214.50	320.35	717.00	2,904.65
BV-XX-DG-CT	516.86	58.37	1,214.50	320.35	717.00	2,827.08	517.63	61.44	1,214.50	320.35	717.00	2,830.92
RBV-XX-SG-CT	688.90	41.47	1,214.50	320.35	717.00	2,982.22	681.22	46.08	1,214.50	320.35	717.00	2,979.15
RBV-XX-DG-CT	629.76	33.79	1,214.50	320.35	717.00	2,915.40	622.85	33.79	1,214.50	320.35	717.00	2,908.49
PCSW-XX-SG-CT	801.02	82.94	1,214.50	320.35	717.00	3,135.82	797.95	87.55	1,214.50	320.35	717.00	3,137.35
PCSW-XX-DG-CT	738.82	66.82	1,214.50	320.35	717.00	3,057.48	738.82	69.89	1,214.50	320.35	717.00	3,060.55
CB-XX-SG-CT	1,296.38	79.10	1,214.50	320.35	717.00	3,627.34	1,279.49	86.78	1,214.50	320.35	717.00	3,618.12
CB-XX-DG-CT	1,238.78	66.05	1,214.50	320.35	717.00	3,556.68	1,224.96	69.12	1,214.50	320.35	717.00	3,545.93
ACC-XX-SG-CT	605.18	55.30	1,214.50	320.35	717.00	2,912.33	603.65	57.60	1,214.50	320.35	717.00	2,913.10
ACC-XX-DG-CT	545.28	40.70	1,214.50	320.35	717.00	2,837.83	546.05	45.31	1,214.50	320.35	717.00	2,843.21
TMB-XX-SG-CT	669.70	89.09	1,214.50	320.35	717.00	3,010.63	665.86	93.70	1,214.50	320.35	717.00	3,011.40
TMB-XX-DG-CT	610.56	71.42	1,214.50	320.35	717.00	2,933.83	610.56	75.26	1,214.50	320.35	717.00	2,937.67

Table F.6 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Armadale and Broome

Envelope options	Life cycle operational energy - GJ											
	Armadale						Broome					
	Heating	Cooling	Hot water	Lighting	Home Appliances	Total	Heating	Cooling	Hot water	Lighting	Home Appliances	Total
DB-XX-SG-CT	768.00	133.63	1,130.50	320.35	717.00	3,069.48	0.00	3,393.02	1,066.00	320.35	717.00	5,496.37
DB-XX-DG-CT	719.62	108.29	1,130.50	320.35	717.00	2,995.75	0.00	3,191.81	1,066.00	320.35	717.00	5,295.16
DB-INS-SG-CT	559.87	110.59	1,130.50	320.35	717.00	2,838.31	0.00	3,102.72	1,066.00	320.35	717.00	5,206.07
DB-INS-DG-CT	510.72	88.32	1,130.50	320.35	717.00	2,766.89	0.00	2,906.11	1,066.00	320.35	717.00	5,009.46
CSW-POL-SG-CT	452.35	121.34	1,130.50	320.35	717.00	2,741.55	0.00	2,948.35	1,066.00	320.35	717.00	5,051.70
CSW-POL-DG-CT	400.13	92.16	1,130.50	320.35	717.00	2,660.14	0.00	2,755.58	1,066.00	320.35	717.00	4,858.93
BV-XX-SG-CT	475.39	205.06	1,130.50	320.35	717.00	2,848.30	0.00	2,927.62	1,066.00	320.35	717.00	5,030.97
BV-XX-DG-CT	427.01	161.28	1,130.50	320.35	717.00	2,756.14	0.00	2,714.88	1,066.00	320.35	717.00	4,818.23
RBV-XX-SG-CT	557.57	111.36	1,130.50	320.35	717.00	2,836.78	0.00	3,104.26	1,066.00	320.35	717.00	5,207.61
RBV-XX-DG-CT	508.42	91.39	1,130.50	320.35	717.00	2,767.66	0.00	2,906.11	1,066.00	320.35	717.00	5,009.46
PCSW-XX-SG-CT	671.23	237.31	1,130.50	320.35	717.00	3,076.39	0.00	3,266.30	1,066.00	320.35	717.00	5,369.65
PCSW-XX-DG-CT	618.24	195.84	1,130.50	320.35	717.00	2,981.93	0.00	3,056.64	1,066.00	320.35	717.00	5,159.99
CB-XX-SG-CT	1,063.68	221.95	1,130.50	320.35	717.00	3,453.48	0.00	3,874.56	1,066.00	320.35	717.00	5,977.91
CB-XX-DG-CT	1,013.76	183.55	1,130.50	320.35	717.00	3,365.16	0.00	3,656.45	1,066.00	320.35	717.00	5,759.80
ACC-XX-SG-CT	499.20	145.15	1,130.50	320.35	717.00	2,812.20	0.00	2,992.90	1,066.00	320.35	717.00	5,096.25
ACC-XX-DG-CT	450.05	112.90	1,130.50	320.35	717.00	2,730.79	0.00	2,795.52	1,066.00	320.35	717.00	4,898.87
TMB-XX-SG-CT	553.73	258.05	1,130.50	320.35	717.00	2,979.63	0.00	3,027.46	1,066.00	320.35	717.00	5,130.81
TMB-XX-DG-CT	504.58	205.82	1,130.50	320.35	717.00	2,878.25	0.00	2,823.17	1,066.00	320.35	717.00	4,926.52

Table F.7 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Bunbury and Busselton

Envelope options	Life cycle operational energy - GJ											
	Bunbury						Busselton					
	Heating	Cooling	Hot water	Lighting	Home Appliances	Total	Heating	Cooling	Hot water	Lighting	Home Appliances	Total
DB-XX-SG-CT	312.58	225.79	1,130.50	320.35	717.00	2,706.22	1,179.65	120.58	1,130.50	320.35	717.00	3,468.07
DB-XX-DG-CT	292.61	192.77	1,130.50	320.35	717.00	2,653.23	1,108.22	86.02	1,130.50	320.35	717.00	3,362.09
DB-INS-SG-CT	198.14	190.46	1,130.50	320.35	717.00	2,556.46	881.66	102.14	1,130.50	320.35	717.00	3,151.66
DB-INS-DG-CT	180.48	155.14	1,130.50	320.35	717.00	2,503.47	807.94	72.19	1,130.50	320.35	717.00	3,047.98
CSW-POL-SG-CT	141.31	193.54	1,130.50	320.35	717.00	2,502.70	710.40	109.06	1,130.50	320.35	717.00	2,987.31
CSW-POL-DG-CT	122.88	156.67	1,130.50	320.35	717.00	2,447.40	635.90	82.18	1,130.50	320.35	717.00	2,885.93
BV-XX-SG-CT	168.96	272.64	1,130.50	320.35	717.00	2,609.45	720.38	184.32	1,130.50	320.35	717.00	3,072.55
BV-XX-DG-CT	147.46	224.26	1,130.50	320.35	717.00	2,539.56	648.96	141.31	1,130.50	320.35	717.00	2,958.12
RBV-XX-SG-CT	198.14	192.77	1,130.50	320.35	717.00	2,558.76	874.75	103.68	1,130.50	320.35	717.00	3,146.28
RBV-XX-DG-CT	178.94	157.44	1,130.50	320.35	717.00	2,504.23	801.79	76.03	1,130.50	320.35	717.00	3,045.67
PCSW-XX-SG-CT	272.64	324.86	1,130.50	320.35	717.00	2,765.35	987.65	213.50	1,130.50	320.35	717.00	3,369.00
PCSW-XX-DG-CT	248.06	270.34	1,130.50	320.35	717.00	2,686.25	911.62	168.19	1,130.50	320.35	717.00	3,247.66
CB-XX-SG-CT	486.14	347.90	1,130.50	320.35	717.00	3,001.90	1,569.79	198.14	1,130.50	320.35	717.00	3,935.79
CB-XX-DG-CT	464.64	298.75	1,130.50	320.35	717.00	2,931.24	1,497.60	155.90	1,130.50	320.35	717.00	3,821.35
ACC-XX-SG-CT	169.73	218.11	1,130.50	320.35	717.00	2,555.69	771.07	132.86	1,130.50	320.35	717.00	3,071.79
ACC-XX-DG-CT	149.76	178.18	1,130.50	320.35	717.00	2,495.79	698.11	93.70	1,130.50	320.35	717.00	2,959.66
TMB-XX-SG-CT	210.43	319.49	1,130.50	320.35	717.00	2,697.77	822.53	226.56	1,130.50	320.35	717.00	3,216.94
TMB-XX-DG-CT	188.16	268.03	1,130.50	320.35	717.00	2,624.04	750.34	179.71	1,130.50	320.35	717.00	3,097.90

Table F.8 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Carnarvon and Esperance

Envelope options	Life cycle operational energy - GJ											
	Carnarvon						Esperance					
	Heating	Cooling	Hot water	Lighting	Home Appliances	Total	Heating	Cooling	Hot water	Lighting	Home Appliances	Total
DB-XX-SG-CT	5.38	635.14	1,066.00	320.35	717.00	2,743.86	581.38	99.07	1,214.50	320.35	717.00	2,932.30
DB-XX-DG-CT	4.61	584.45	1,066.00	320.35	717.00	2,692.41	541.44	79.87	1,214.50	320.35	717.00	2,873.16
DB-INS-SG-CT	0.77	572.16	1,066.00	320.35	717.00	2,676.28	406.27	82.18	1,214.50	320.35	717.00	2,740.30
DB-INS-DG-CT	0.00	516.10	1,066.00	320.35	717.00	2,619.45	366.34	64.51	1,214.50	320.35	717.00	2,682.70
CSW-POL-SG-CT	0.00	552.96	1,066.00	320.35	717.00	2,656.31	314.88	89.86	1,214.50	320.35	717.00	2,656.59
CSW-POL-DG-CT	0.00	494.59	1,066.00	320.35	717.00	2,597.94	274.18	66.82	1,214.50	320.35	717.00	2,592.84
BV-XX-SG-CT	3.07	566.02	1,066.00	320.35	717.00	2,672.44	341.76	125.95	1,214.50	320.35	717.00	2,719.56
BV-XX-DG-CT	2.30	506.88	1,066.00	320.35	717.00	2,612.53	298.75	100.61	1,214.50	320.35	717.00	2,651.21
RBV-XX-SG-CT	0.77	571.39	1,066.00	320.35	717.00	2,675.51	404.74	85.25	1,214.50	320.35	717.00	2,741.83
RBV-XX-DG-CT	0.00	519.17	1,066.00	320.35	717.00	2,622.52	364.03	66.05	1,214.50	320.35	717.00	2,681.93
PCSW-XX-SG-CT	13.82	637.44	1,066.00	320.35	717.00	2,754.61	496.13	148.22	1,214.50	320.35	717.00	2,896.20
PCSW-XX-DG-CT	12.29	581.38	1,066.00	320.35	717.00	2,697.01	450.82	120.58	1,214.50	320.35	717.00	2,823.24
CB-XX-SG-CT	33.79	759.55	1,066.00	320.35	717.00	2,896.69	826.37	155.90	1,214.50	320.35	717.00	3,234.12
CB-XX-DG-CT	32.26	697.34	1,066.00	320.35	717.00	2,832.95	785.66	132.10	1,214.50	320.35	717.00	3,169.61
ACC-XX-SG-CT	0.77	569.86	1,066.00	320.35	717.00	2,673.97	354.05	101.38	1,214.50	320.35	717.00	2,707.27
ACC-XX-DG-CT	0.77	515.33	1,066.00	320.35	717.00	2,619.45	312.58	78.34	1,214.50	320.35	717.00	2,642.76
TMB-XX-SG-CT	6.91	601.34	1,066.00	320.35	717.00	2,711.61	404.74	146.69	1,214.50	320.35	717.00	2,803.27
TMB-XX-DG-CT	5.38	542.98	1,066.00	320.35	717.00	2,651.70	360.96	119.81	1,214.50	320.35	717.00	2,732.62

Table F.9 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Geraldton and Joondalup

Envelope options	**Life cycle operational energy - GJ**											
	Geraldton						**Joondalup**					
	Heating	**Cooling**	**Hot water**	**Lighting**	**Home Appliances**	**Total**	**Heating**	**Cooling**	**Hot water**	**Lighting**	**Home Appliances**	**Total**
DB-XX-SG-CT	96.00	326.40	1,130.50	320.35	717.00	2,590.25	168.96	165.12	1,130.50	320.35	717.00	2,501.93
DB-XX-DG-CT	83.71	261.89	1,130.50	320.35	717.00	2,513.45	155.90	139.78	1,130.50	320.35	717.00	2,463.53
DB-INS-SG-CT	48.38	268.03	1,130.50	320.35	717.00	2,484.27	91.39	135.94	1,130.50	320.35	717.00	2,395.18
DB-INS-DG-CT	36.10	211.20	1,130.50	320.35	717.00	2,415.15	79.10	113.66	1,130.50	320.35	717.00	2,360.62
CSW-POL-SG-CT	41.47	261.89	1,130.50	320.35	717.00	2,471.21	62.21	142.85	1,130.50	320.35	717.00	2,372.91
CSW-POL-DG-CT	29.18	208.13	1,130.50	320.35	717.00	2,405.16	49.15	113.66	1,130.50	320.35	717.00	2,330.67
BV-XX-SG-CT	59.90	365.57	1,130.50	320.35	717.00	2,593.32	96.77	192.77	1,130.50	320.35	717.00	2,457.39
BV-XX-DG-CT	46.08	294.14	1,130.50	320.35	717.00	2,508.07	79.87	153.60	1,130.50	320.35	717.00	2,401.32
RBV-XX-SG-CT	49.15	269.57	1,130.50	320.35	717.00	2,486.57	92.93	136.70	1,130.50	320.35	717.00	2,397.48
RBV-XX-DG-CT	37.63	214.27	1,130.50	320.35	717.00	2,419.75	79.87	114.43	1,130.50	320.35	717.00	2,362.15
PCSW-XX-SG-CT	106.75	434.69	1,130.50	320.35	717.00	2,709.29	165.89	221.95	1,130.50	320.35	717.00	2,555.69
PCSW-XX-DG-CT	90.62	357.89	1,130.50	320.35	717.00	2,616.36	148.22	182.02	1,130.50	320.35	717.00	2,498.09
CB-XX-SG-CT	199.68	470.02	1,130.50	320.35	717.00	2,837.55	302.59	238.85	1,130.50	320.35	717.00	2,709.29
CB-XX-DG-CT	185.86	406.27	1,130.50	320.35	717.00	2,759.98	287.23	201.98	1,130.50	320.35	717.00	2,657.07
ACC-XX-SG-CT	51.46	304.13	1,130.50	320.35	717.00	2,523.43	83.71	159.74	1,130.50	320.35	717.00	2,411.31
ACC-XX-DG-CT	37.63	238.08	1,130.50	320.35	717.00	2,443.56	69.12	129.79	1,130.50	320.35	717.00	2,366.76
TMB-XX-SG-CT	84.48	413.95	1,130.50	320.35	717.00	2,666.28	128.26	218.88	1,130.50	320.35	717.00	2,514.99
TMB-XX-DG-CT	69.12	340.99	1,130.50	320.35	717.00	2,577.96	112.13	187.39	1,130.50	320.35	717.00	2,467.37

Table F.10 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Kalgoorlie and Kununurra

Envelope options	Life cycle operational energy - GJ											
	Kalgoorlie						Kununurra					
	Heating	Cooling	Hot water	Lighting	Home Appliances	Total	Heating	Cooling	Hot water	Lighting	Home Appliances	Total
DB-XX-SG-CT	343.30	196.61	1,130.50	320.35	717.00	2,707.75	0.00	5,174.78	1,066.00	320.35	717.00	7,278.13
DB-XX-DG-CT	319.49	156.67	1,130.50	320.35	717.00	2,644.01	0.00	4,847.62	1,066.00	320.35	717.00	6,950.97
DB-INS-SG-CT	211.97	152.83	1,130.50	320.35	717.00	2,532.65	0.00	4,558.85	1,066.00	320.35	717.00	6,662.20
DB-INS-DG-CT	188.93	115.20	1,130.50	320.35	717.00	2,471.98	0.00	4,246.27	1,066.00	320.35	717.00	6,349.62
CSW-POL-SG-CT	161.28	148.99	1,130.50	320.35	717.00	2,478.12	0.00	4,232.45	1,066.00	320.35	717.00	6,335.80
CSW-POL-DG-CT	138.24	109.82	1,130.50	320.35	717.00	2,415.91	0.00	3,922.18	1,066.00	320.35	717.00	6,025.53
BV-XX-SG-CT	198.91	260.35	1,130.50	320.35	717.00	2,627.11	0.00	4,382.21	1,066.00	320.35	717.00	6,485.56
BV-XX-DG-CT	172.03	197.38	1,130.50	320.35	717.00	2,537.26	0.00	4,064.26	1,066.00	320.35	717.00	6,167.61
RBV-XX-SG-CT	212.74	154.37	1,130.50	320.35	717.00	2,534.95	0.00	4,569.60	1,066.00	320.35	717.00	6,672.95
RBV-XX-DG-CT	188.16	118.27	1,130.50	320.35	717.00	2,474.28	0.00	4,250.88	1,066.00	320.35	717.00	6,354.23
PCSW-XX-SG-CT	318.72	319.49	1,130.50	320.35	717.00	2,806.06	0.00	5,075.71	1,066.00	320.35	717.00	7,179.06
PCSW-XX-DG-CT	291.07	251.90	1,130.50	320.35	717.00	2,710.83	0.00	4,733.95	1,066.00	320.35	717.00	6,837.30
CB-XX-SG-CT	555.26	340.22	1,130.50	320.35	717.00	3,063.34	0.00	6,269.18	1,066.00	320.35	717.00	8,372.53
CB-XX-DG-CT	525.31	286.46	1,130.50	320.35	717.00	2,979.63	0.00	5,925.89	1,066.00	320.35	717.00	8,029.24
ACC-XX-SG-CT	194.30	178.94	1,130.50	320.35	717.00	2,541.10	0.00	4,369.92	1,066.00	320.35	717.00	6,473.27
ACC-XX-DG-CT	169.73	134.40	1,130.50	320.35	717.00	2,471.98	0.00	4,063.49	1,066.00	320.35	717.00	6,166.84
TMB-XX-SG-CT	248.06	317.18	1,130.50	320.35	717.00	2,733.10	0.00	4,609.54	1,066.00	320.35	717.00	6,712.89
TMB-XX-DG-CT	221.95	251.90	1,130.50	320.35	717.00	2,641.71	0.00	4,284.67	1,066.00	320.35	717.00	6,388.02

Table F.11 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Laverton and Mandurah

Envelope options	Life cycle operational energy - GJ											
	Laverton						Mandurah					
	Heating	Cooling	Hot water	Lighting	Home Appliances	Total	Heating	Cooling	Hot water	Lighting	Home Appliances	Total
DB-XX-SG-CT	90.62	830.98	1,066.00	320.35	717.00	3,024.95	314.11	223.49	1,130.50	320.35	717.00	2,705.45
DB-XX-DG-CT	82.94	699.65	1,066.00	320.35	717.00	2,885.94	294.91	189.70	1,130.50	320.35	717.00	2,652.46
DB-INS-SG-CT	43.78	662.02	1,066.00	320.35	717.00	2,809.14	200.45	191.23	1,130.50	320.35	717.00	2,559.53
DB-INS-DG-CT	36.86	536.83	1,066.00	320.35	717.00	2,677.05	182.02	155.14	1,130.50	320.35	717.00	2,505.00
CSW-POL-SG-CT	29.18	599.04	1,066.00	320.35	717.00	2,731.57	142.85	192.77	1,130.50	320.35	717.00	2,503.47
CSW-POL-DG-CT	23.04	483.07	1,066.00	320.35	717.00	2,609.46	123.65	152.83	1,130.50	320.35	717.00	2,444.33
BV-XX-SG-CT	45.31	808.70	1,066.00	320.35	717.00	2,957.37	170.50	270.34	1,130.50	320.35	717.00	2,608.68
BV-XX-DG-CT	36.10	666.62	1,066.00	320.35	717.00	2,806.07	147.46	221.18	1,130.50	320.35	717.00	2,536.49
RBV-XX-SG-CT	44.54	666.62	1,066.00	320.35	717.00	2,814.52	200.45	191.23	1,130.50	320.35	717.00	2,559.53
RBV-XX-DG-CT	36.86	539.90	1,066.00	320.35	717.00	2,680.12	181.25	157.44	1,130.50	320.35	717.00	2,506.54
PCSW-XX-SG-CT	89.09	973.82	1,066.00	320.35	717.00	3,166.26	274.18	323.33	1,130.50	320.35	717.00	2,765.35
PCSW-XX-DG-CT	78.34	821.76	1,066.00	320.35	717.00	3,003.45	249.60	268.03	1,130.50	320.35	717.00	2,685.48
CB-XX-SG-CT	180.48	1,186.56	1,066.00	320.35	717.00	3,470.39	489.22	347.90	1,130.50	320.35	717.00	3,004.97
CB-XX-DG-CT	168.96	1,035.26	1,066.00	320.35	717.00	3,307.57	467.71	294.14	1,130.50	320.35	717.00	2,929.71
ACC-XX-SG-CT	40.70	685.82	1,066.00	320.35	717.00	2,829.88	171.26	215.81	1,130.50	320.35	717.00	2,554.92
ACC-XX-DG-CT	33.02	551.42	1,066.00	320.35	717.00	2,687.80	151.30	175.87	1,130.50	320.35	717.00	2,495.02
TMB-XX-SG-CT	62.21	901.63	1,066.00	320.35	717.00	3,067.19	211.97	317.18	1,130.50	320.35	717.00	2,697.00
TMB-XX-DG-CT	52.22	755.71	1,066.00	320.35	717.00	2,911.29	188.93	264.96	1,130.50	320.35	717.00	2,621.74

Table F.12 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Mount Magnet and Newman

Envelope options	Life cycle operational energy - GJ											
	Mount Magnet						Newman					
	Heating	Cooling	Hot water	Lighting	Home Appliances	Total	Heating	Cooling	Hot water	Lighting	Home Appliances	Total
DB-XX-SG-CT	61.44	522.24	1,130.50	320.35	717.00	2,751.53	14.59	1,363.20	1,066.00	320.35	717.00	3,481.14
DB-XX-DG-CT	55.30	436.22	1,130.50	320.35	717.00	2,659.37	13.82	1,203.46	1,066.00	320.35	717.00	3,320.63
DB-INS-SG-CT	26.11	407.81	1,130.50	320.35	717.00	2,601.77	3.07	1,111.30	1,066.00	320.35	717.00	3,217.72
DB-INS-DG-CT	22.27	329.47	1,130.50	320.35	717.00	2,519.59	2.30	963.84	1,066.00	320.35	717.00	3,069.49
CSW-POL-SG-CT	15.36	369.41	1,130.50	320.35	717.00	2,552.62	0.77	996.10	1,066.00	320.35	717.00	3,100.21
CSW-POL-DG-CT	12.29	291.84	1,130.50	320.35	717.00	2,471.98	0.77	861.70	1,066.00	320.35	717.00	2,965.81
BV-XX-SG-CT	28.42	532.22	1,130.50	320.35	717.00	2,728.49	6.91	1,229.57	1,066.00	320.35	717.00	3,339.83
BV-XX-DG-CT	23.04	435.46	1,130.50	320.35	717.00	2,626.35	5.38	1,062.91	1,066.00	320.35	717.00	3,171.64
RBV-XX-SG-CT	26.11	415.49	1,130.50	320.35	717.00	2,609.45	3.07	1,119.74	1,066.00	320.35	717.00	3,226.17
RBV-XX-DG-CT	22.27	334.08	1,130.50	320.35	717.00	2,524.20	3.07	973.06	1,066.00	320.35	717.00	3,079.48
PCSW-XX-SG-CT	66.05	643.58	1,130.50	320.35	717.00	2,877.48	25.34	1,476.10	1,066.00	320.35	717.00	3,604.79
PCSW-XX-DG-CT	58.37	538.37	1,130.50	320.35	717.00	2,764.59	22.27	1,304.06	1,066.00	320.35	717.00	3,429.69
CB-XX-SG-CT	141.31	765.70	1,130.50	320.35	717.00	3,074.86	60.67	1,827.84	1,066.00	320.35	717.00	3,991.86
CB-XX-DG-CT	133.63	675.07	1,130.50	320.35	717.00	2,976.55	58.37	1,664.26	1,066.00	320.35	717.00	3,825.97
ACC-XX-SG-CT	23.81	426.24	1,130.50	320.35	717.00	2,617.90	3.07	1,097.47	1,066.00	320.35	717.00	3,203.89
ACC-XX-DG-CT	19.97	346.37	1,130.50	320.35	717.00	2,534.19	3.07	955.39	1,066.00	320.35	717.00	3,061.81
TMB-XX-SG-CT	41.47	608.26	1,130.50	320.35	717.00	2,817.58	14.59	1,362.43	1,066.00	320.35	717.00	3,480.37
TMB-XX-DG-CT	35.33	508.42	1,130.50	320.35	717.00	2,711.59	12.29	1,193.47	1,066.00	320.35	717.00	3,309.11

Table F.13 Breakdown of life cycle operational energy demand for heating, cooling, hot water, lighting, and home appliances of a reference house for alternative envelope options for Yanchep

Envelope options	**Life cycle operational energy - GJ**					
	Yanchep					
	Heating	**Cooling**	**Hot water**	**Lighting**	**Home Appliances**	**Total**
DB-XX-SG-CT	169.73	165.12	1,130.50	320.35	717.00	2,502.70
DB-XX-DG-CT	156.67	139.78	1,130.50	320.35	717.00	2,464.30
DB-INS-SG-CT	92.16	135.94	1,130.50	320.35	717.00	2,395.95
DB-INS-DG-CT	79.87	113.66	1,130.50	320.35	717.00	2,361.39
CSW-POL-SG-CT	62.21	142.85	1,130.50	320.35	717.00	2,372.91
CSW-POL-DG-CT	49.15	113.66	1,130.50	320.35	717.00	2,330.67
BV-XX-SG-CT	96.00	191.23	1,130.50	320.35	717.00	2,455.08
BV-XX-DG-CT	79.87	152.83	1,130.50	320.35	717.00	2,400.55
RBV-XX-SG-CT	92.93	136.70	1,130.50	320.35	717.00	2,397.48
RBV-XX-DG-CT	79.87	115.20	1,130.50	320.35	717.00	2,362.92
PCSW-XX-SG-CT	166.66	221.18	1,130.50	320.35	717.00	2,555.69
PCSW-XX-DG-CT	148.22	182.78	1,130.50	320.35	717.00	2,498.86
CB-XX-SG-CT	303.36	238.85	1,130.50	320.35	717.00	2,710.06
CB-XX-DG-CT	288.00	201.98	1,130.50	320.35	717.00	2,657.83
ACC-XX-SG-CT	84.48	160.51	1,130.50	320.35	717.00	2,412.84
ACC-XX-DG-CT	69.89	129.02	1,130.50	320.35	717.00	2,366.76
TMB-XX-SG-CT	128.26	219.65	1,130.50	320.35	717.00	2,515.75
TMB-XX-DG-CT	112.13	185.86	1,130.50	320.35	717.00	2,465.83

Table F.14 Breakdown of tkm (tonnes kilometre travelled) of a reference house for alternative envelope options in 17 locations in regional WA

Envelope options	**Albany**	**Augusta**	**Armadale**	**Broome**		**Bunbury**	**Busselton**	**Carnarvon**		**Esperance**	**Geraldton**
	T	**T**	**T**	**T**	**S**	**T**	**T**	**T**	**S**	**T**	**T**
DB-XX-SG-CT	4,461	15,091	5,589	4,461	178,735	5,589	4,461	13,073	61,805	4,461	6,716
DB-XX-DG-CT	4,469	15,112	5,599	4,469	178,735	5,599	4,469	13,098	61,805	4,469	6,729
DB-INS-SG-CT	4,464	15,100	5,593	4,464	178,735	5,593	4,464	13,083	61,805	4,464	6,721
DB-INS-DG-CT	4,472	15,121	5,603	4,472	178,735	5,603	4,472	13,108	61,805	4,472	6,734
CSW-POL-SG-CT	3,749	8,556	4,639	3,749	0	4,639	3,749	10,699	12,008	3,749	5,529
CSW-POL-DG-CT	3,757	8,577	4,649	3,757	0	4,649	3,757	10,724	12,008	3,757	5,542
BV-XX-SG-CT	3,565	9,639	4,394	3,565	62,889	4,394	3,565	10,087	37,550	3,565	5,223
BV-XX-DG-CT	3,573	9,660	4,404	3,573	62,889	4,404	3,573	10,112	37,550	3,573	5,236
RBV-XX-SG-CT	4,255	13,229	5,314	4,255	128,152	5,314	4,255	12,386	54,772	4,255	6,373
RBV-XX-DG-CT	4,263	13,250	5,324	4,263	128,152	5,324	4,263	12,411	54,772	4,263	6,385
PCSW-XX-SG-CT	3,256	7,175	3,982	3,256	0	3,982	3,256	9,056	26,892	3,256	4,708
PCSW-XX-DG-CT	3,264	7,196	3,992	3,264	0	3,992	3,264	9,081	26,892	3,264	4,720
CB-XX-SG-CT	4,029	12,392	5,012	4,029	120,184	5,012	4,029	11,631	44,986	4,029	5,995
CB-XX-DG-CT	4,036	12,413	5,022	4,036	120,184	5,022	4,036	11,656	44,986	4,036	6,008
ACC-XX-SG-CT	3,379	8,792	4,146	3,379	50,047	4,146	3,379	9,467	24,838	3,379	4,913
ACC-XX-DG-CT	3,387	8,813	4,156	3,387	50,047	4,156	3,387	9,492	24,838	3,387	4,926
TMB-XX-SG-CT	3,041	6,574	3,695	3,041	0	3,695	3,041	8,339	19,095	3,041	4,349
TMB-XX-DG-CT	3,049	6,595	3,705	3,049	0	3,705	3,049	8,364	19,095	3,049	4,362
Note: T – Truck 16-28t fleet average, S – Shipping domestic freight											

Table F.15 Breakdown of tkm (tonnes kilometre travelled) of a reference house for alternative envelope options in 17 locations in regional WA

Envelope options	Joondalup	Kalgoorlie	Kununurra		Laverton	Mandurah	Mount Magnet	Newman		Yanchep
	T	T	T	S	T	T	T	T	S	T
DB-XX-SG-CT	6,308	6,308	16,174	61,670	76,154	7,435	47,724	62,648	210,142	8,933
DB-XX-DG-CT	6,318	6,318	16,184	61,670	76,334	7,448	47,894	62,876	210,958	8,948
DB-INS-SG-CT	6,312	6,312	16,194	61,770	76,226	7,440	47,793	62,739	210,469	8,939
DB-INS-DG-CT	6,322	6,322	16,204	61,770	76,406	7,453	47,963	62,967	211,286	8,954
CSW-POL-SG-CT	5,358	5,358	7,811	15,328	65,170	6,249	16,577	20,378	53,523	7,139
CSW-POL-DG-CT	5,368	5,368	7,821	15,328	65,350	6,261	16,747	20,606	54,340	7,154
BV-XX-SG-CT	5,113	5,113	11,653	40,874	59,739	5,942	32,196	41,978	137,757	6,833
BV-XX-DG-CT	5,123	5,123	11,663	40,874	59,919	5,955	32,366	42,206	138,574	6,848
RBV-XX-SG-CT	6,033	6,033	15,081	56,557	72,228	7,092	44,012	57,700	192,749	8,459
RBV-XX-DG-CT	6,043	6,043	15,091	56,557	72,408	7,104	44,182	57,928	193,566	8,474
PCSW-XX-SG-CT	4,701	4,701	9,695	31,218	53,337	5,427	26,144	33,893	109,127	6,153
PCSW-XX-DG-CT	4,711	4,711	9,705	31,218	53,517	5,439	26,314	34,121	109,944	6,168
CB-XX-SG-CT	5,731	5,731	13,173	46,518	65,667	6,714	37,820	49,361	162,514	8,074
CB-XX-DG-CT	5,741	5,741	13,183	46,518	65,847	6,727	37,990	49,589	163,331	8,089
ACC-XX-SG-CT	4,865	4,865	10,214	33,432	56,295	5,632	28,938	37,641	122,552	6,399
ACC-XX-DG-CT	4,875	4,875	10,224	33,432	56,475	5,645	29,108	37,869	123,369	6,414
TMB-XX-SG-CT	4,414	4,414	8,430	25,102	48,179	5,069	21,272	27,360	85,723	5,723
TMB-XX-DG-CT	4,424	4,424	8,440	25,102	48,359	5,081	21,442	27,588	86,540	5,738
Note: T – Truck 16-28t fleet average, S – Shipping domestic freight										

Table F.16 Emission factors for location specific electricity generation mix, reticulated natural gas, and bottled gas in 17 locations in regional WA for operational energy

Location	Electricity			Natural/Bottled Gas		
	Source	**tonnes CO_2 e-/GJ of electricity**	**GJ/GJ of electricity**	**Source**	**tonnes CO_2 e-/GJ of gas**	**GJ/GJ of gas**
Albany	SWIS	0.26	3.33	ATCO	0.058	1.02
Armadale	SWIS	0.26	3.33	ATCO	0.058	1.02
Augusta	SWIS	0.26	3.33	Bottled	0.061	1.10
Broome	Gas	0.19	3.23	Bottled	0.061	1.10
Bunbury	SWIS	0.26	3.33	ATCO	0.058	1.02
Busselton	SWIS	0.26	3.33	ATCO	0.058	1.02
Carnarvon	Gas	0.19	3.23	Bottled	0.061	1.10
Esperance	SWIS	0.26	3.33	Bottled	0.061	1.10
Geraldton	SWIS	0.26	3.33	ATCO	0.058	1.02
Joondalup	SWIS	0.26	3.33	ATCO	0.058	1.02
Kalgoorlie	SWIS	0.26	3.33	ATCO	0.058	1.02
Kununurra	Diesel	0.33	4.86	Bottled	0.061	1.10
Laverton	Diesel	0.33	4.86	Bottled	0.061	1.10
Mandurah	SWIS	0.26	3.33	ATCO	0.058	1.02
Mount Magnet	Gas	0.19	3.23	Bottled	0.061	1.10
Newman	Gas	0.19	3.23	Bottled	0.061	1.10
Yanchep	SWIS	0.26	3.33	ATCO	0.058	1.02

Note: SWIS – South West Interconnected System i.e. the primary electricity grid, ATCO – ATCO Gas Australia.

Table F.17 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Albany

Albany	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
SPV – Solar PV **SWH** – Solar water heater **GC** – Green concrete	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
Envelope options	**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	57.13	9	403.34	15	163.90	20.17	2.76	**273.63**	**14**	0.80	9	5.8	16	2.20	0.54	0.02	**3.9**	**14**
DB-XX-DG-CT	57.71	10	397.28	13	163.90	20.17	2.76	**268.15**	**12**	0.81	11	5.7	14	2.20	0.54	0.02	**3.8**	**13**
DB-INS-SG-CT	58.42	11	386.72	9	163.90	20.17	2.76	**258.31**	**8**	0.83	13	5.5	10	2.20	0.54	0.02	**3.6**	**11**
DB-INS-DG-CT	59.00	12	381.35	6	163.90	20.17	2.76	**253.52**	**6**	0.84	14	5.4	6	2.20	0.54	0.02	**3.5**	**8**
CSW-POL-SG-CT	50.31	5	379.47	3	163.90	20.17	5.11	**240.60**	**2**	0.69	7	5.4	3	2.20	0.54	0.04	**3.3**	**3**
CSW-POL-DG-CT	50.89	6	373.47	1	163.90	20.17	5.11	**235.18**	**1**	0.69	8	5.3	1	2.20	0.54	0.04	**3.2**	**1**
BV-XX-SG-CT	51.91	7	388.35	10	163.90	20.17	2.76	**253.42**	**5**	0.65	5	5.5	8	2.20	0.54	0.02	**3.4**	**5**
BV-XX-DG-CT	52.49	8	380.93	4	163.90	20.17	2.76	**246.59**	**3**	0.65	6	5.4	4	2.20	0.54	0.02	**3.3**	**2**
RBV-XX-SG-CT	63.39	13	386.65	8	163.90	20.17	2.76	**263.21**	**10**	0.80	10	5.5	9	2.20	0.54	0.02	**3.6**	**10**
RBV-XX-DG-CT	63.97	14	381.23	5	163.90	20.17	2.76	**258.37**	**9**	0.81	12	5.4	5	2.20	0.54	0.02	**3.5**	**7**
PCSW-XX-SG-CT	83.85	17	403.78	16	163.90	20.17	2.76	**300.80**	**18**	0.95	17	5.8	15	2.20	0.54	0.02	**4.0**	**16**
PCSW-XX-DG-CT	84.43	18	396.03	12	163.90	20.17	2.76	**293.63**	**17**	0.96	18	5.7	12	2.20	0.54	0.02	**3.9**	**15**
CB-XX-SG-CT	47.34	3	431.69	18	163.90	20.17	2.76	**292.20**	**16**	0.57	3	6.3	18	2.20	0.54	0.02	**4.1**	**18**
CB-XX-DG-CT	47.92	4	424.99	17	163.90	20.17	2.76	**286.08**	**15**	0.58	4	6.2	17	2.20	0.54	0.02	**4.0**	**17**
ACC-XX-SG-CT	71.61	15	385.30	7	163.90	20.17	2.76	**270.07**	**13**	0.92	15	5.5	7	2.20	0.54	0.02	**3.7**	**12**
ACC-XX-DG-CT	72.19	16	378.07	2	163.90	20.17	2.76	**263.43**	**11**	0.93	16	5.4	2	2.20	0.54	0.02	**3.6**	**9**
TMB-XX-SG-CT	43.33	1	397.69	14	163.90	20.17	2.76	**254.19**	**7**	0.52	1	5.7	13	2.20	0.54	0.02	**3.4**	**6**
TMB-XX-DG-CT	43.91	2	389.73	11	163.90	20.17	2.76	**246.81**	**4**	0.53	2	5.6	11	2.20	0.54	0.02	**3.3**	**4**

Table F.18 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Augusta (Scenario 1 - use of bottled gas for heating and hot water)

Augusta	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	59.08	9	409.44	15	163.90	21.96	2.76	**279.89**	**14**	0.83	10	6.0	16	2.20	0.59	0.02	**4.0**	**15**
DB-XX-DG-CT	59.66	10	403.17	13	163.90	21.96	2.76	**274.20**	**12**	0.84	12	5.9	14	2.20	0.59	0.02	**3.9**	**13**
DB-INS-SG-CT	60.37	11	392.64	9	163.90	21.96	2.76	**264.39**	**9**	0.86	13	5.7	10	2.20	0.59	0.02	**3.7**	**11**
DB-INS-DG-CT	60.95	12	386.13	5	163.90	21.96	2.76	**258.46**	**5**	0.87	14	5.6	6	2.20	0.59	0.02	**3.7**	**8**
CSW-POL-SG-CT	51.19	5	385.49	3	163.90	21.96	5.11	**245.70**	**2**	0.70	7	5.6	3	2.20	0.59	0.04	**3.4**	**3**
CSW-POL-DG-CT	51.77	6	378.63	1	163.90	21.96	5.11	**239.43**	**1**	0.71	8	5.5	1	2.20	0.59	0.04	**3.3**	**1**
BV-XX-SG-CT	53.02	7	394.28	10	163.90	21.96	2.76	**258.68**	**6**	0.66	5	5.7	8	2.20	0.59	0.02	**3.5**	**5**
BV-XX-DG-CT	53.61	8	386.49	6	163.90	21.96	2.76	**251.47**	**3**	0.67	6	5.6	4	2.20	0.59	0.02	**3.4**	**2**
RBV-XX-SG-CT	65.04	13	392.55	8	163.90	21.96	2.76	**268.97**	**11**	0.83	9	5.7	9	2.20	0.59	0.02	**3.7**	**10**
RBV-XX-DG-CT	65.62	14	385.85	4	163.90	21.96	2.76	**262.85**	**8**	0.83	11	5.6	5	2.20	0.59	0.02	**3.6**	**7**
PCSW-XX-SG-CT	84.57	17	410.28	16	163.90	21.96	2.76	**306.22**	**18**	0.96	17	6.0	15	2.20	0.59	0.02	**4.1**	**16**
PCSW-XX-DG-CT	85.15	18	402.15	12	163.90	21.96	2.76	**298.68**	**16**	0.97	18	5.8	13	2.20	0.59	0.02	**4.0**	**14**
CB-XX-SG-CT	48.87	3	439.48	18	163.90	21.96	2.76	**299.73**	**17**	0.59	3	6.5	18	2.20	0.59	0.02	**4.3**	**18**
CB-XX-DG-CT	49.46	4	431.64	17	163.90	21.96	2.76	**292.47**	**15**	0.60	4	6.4	17	2.20	0.59	0.02	**4.2**	**17**
ACC-XX-SG-CT	72.60	15	390.76	7	163.90	21.96	2.76	**274.74**	**13**	0.93	15	5.6	7	2.20	0.59	0.02	**3.8**	**12**
ACC-XX-DG-CT	73.19	16	384.10	2	163.90	21.96	2.76	**268.67**	**10**	0.94	16	5.5	2	2.20	0.59	0.02	**3.7**	**9**
TMB-XX-SG-CT	43.98	1	403.78	14	163.90	21.96	2.76	**259.14**	**7**	0.53	1	5.8	12	2.20	0.59	0.02	**3.6**	**6**
TMB-XX-DG-CT	44.56	2	395.70	11	163.90	21.96	2.76	**251.63**	**4**	0.54	2	5.7	11	2.20	0.59	0.02	**3.4**	**4**

Table F.19 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Augusta (Scenario 2 - use of electricity for heating and hot water)

Augusta	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	59.08	9	828.08	16	163.90	99.19	2.76	**621.31**	**16**	0.83	10	10.8	16	2.20	1.36	0.02	**8.0**	**16**
DB-XX-DG-CT	59.66	10	811.21	15	163.90	99.19	2.76	**605.01**	**14**	0.84	12	10.6	15	2.20	1.36	0.02	**7.8**	**15**
DB-INS-SG-CT	60.37	11	762.15	11	163.90	99.19	2.76	**556.67**	**11**	0.86	13	9.9	11	2.20	1.36	0.02	**7.2**	**12**
DB-INS-DG-CT	60.95	12	744.30	8	163.90	99.19	2.76	**539.40**	**7**	0.87	14	9.7	8	2.20	1.36	0.02	**7.0**	**9**
CSW-POL-SG-CT	51.19	5	727.23	4	163.90	99.19	5.11	**510.21**	**2**	0.70	7	9.5	4	2.20	1.36	0.04	**6.6**	**3**
CSW-POL-DG-CT	51.77	6	709.17	1	163.90	99.19	5.11	**492.74**	**1**	0.71	8	9.2	1	2.20	1.36	0.04	**6.3**	**1**
BV-XX-SG-CT	53.02	7	742.14	5	163.90	99.19	2.76	**529.31**	**5**	0.66	5	9.7	5	2.20	1.36	0.02	**6.7**	**5**
BV-XX-DG-CT	53.61	8	723.30	2	163.90	99.19	2.76	**511.05**	**3**	0.67	6	9.4	2	2.20	1.36	0.02	**6.5**	**2**
RBV-XX-SG-CT	65.04	13	761.17	10	163.90	99.19	2.76	**560.36**	**12**	0.83	9	9.9	10	2.20	1.36	0.02	**7.2**	**11**
RBV-XX-DG-CT	65.62	14	743.12	6	163.90	99.19	2.76	**542.89**	**8**	0.83	11	9.7	6	2.20	1.36	0.02	**6.9**	**7**
PCSW-XX-SG-CT	84.57	17	801.59	14	163.90	99.19	2.76	**620.31**	**15**	0.96	17	10.4	14	2.20	1.36	0.02	**7.8**	**14**
PCSW-XX-DG-CT	85.15	18	781.97	13	163.90	99.19	2.76	**601.27**	**13**	0.97	18	10.2	13	2.20	1.36	0.02	**7.6**	**13**
CB-XX-SG-CT	48.87	3	924.43	18	163.90	99.19	2.76	**707.45**	**18**	0.59	3	12.0	18	2.20	1.36	0.02	**9.0**	**18**
CB-XX-DG-CT	49.46	4	905.99	17	163.90	99.19	2.76	**689.59**	**17**	0.60	4	11.8	17	2.20	1.36	0.02	**8.8**	**17**
ACC-XX-SG-CT	72.60	15	744.30	7	163.90	99.19	2.76	**551.05**	**10**	0.93	15	9.7	7	2.20	1.36	0.02	**7.0**	**10**
ACC-XX-DG-CT	73.19	16	726.44	3	163.90	99.19	2.76	**533.77**	**6**	0.94	16	9.5	3	2.20	1.36	0.02	**6.8**	**6**
TMB-XX-SG-CT	43.98	1	769.41	12	163.90	99.19	2.76	**547.54**	**9**	0.53	1	10.0	12	2.20	1.36	0.02	**7.0**	**8**
TMB-XX-DG-CT	44.56	2	750.58	9	163.90	99.19	2.76	**529.28**	**4**	0.54	2	9.8	9	2.20	1.36	0.02	**6.7**	**4**

Table F.20 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Armadale

Armadale	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.33	9	409.91	11	200.3	22.73	2.76	**241.42**	**12**	0.81	10	5.8	13	2.7	0.61	0.02	**3.3**	**14**
DB-XX-DG-CT	57.91	10	400.61	10	200.3	22.73	2.76	**232.70**	**10**	0.81	12	5.7	10	2.7	0.61	0.02	**3.2**	**11**
DB-INS-SG-CT	58.63	11	391.88	6	200.3	22.73	2.76	**224.69**	**6**	0.83	13	5.5	6	2.7	0.61	0.02	**3.0**	**9**
DB-INS-DG-CT	59.21	12	383.32	2	200.3	22.73	2.76	**216.71**	**3**	0.84	14	5.4	2	2.7	0.61	0.02	**2.9**	**5**
CSW-POL-SG-CT	50.47	5	388.36	5	200.3	22.73	5.11	**210.66**	**2**	0.69	7	5.5	5	2.7	0.61	0.04	**2.8**	**2**
CSW-POL-DG-CT	51.05	6	377.86	1	200.3	22.73	5.11	**200.74**	**1**	0.70	8	5.3	1	2.7	0.61	0.04	**2.7**	**1**
BV-XX-SG-CT	52.06	7	411.09	12	200.3	22.73	2.76	**237.33**	**11**	0.65	5	5.8	11	2.7	0.61	0.02	**3.1**	**10**
BV-XX-DG-CT	52.64	8	397.08	8	200.3	22.73	2.76	**223.91**	**5**	0.66	6	5.6	8	2.7	0.61	0.02	**2.9**	**3**
RBV-XX-SG-CT	63.59	13	391.94	7	200.3	22.73	2.76	**229.71**	**7**	0.81	9	5.5	7	2.7	0.61	0.02	**3.0**	**7**
RBV-XX-DG-CT	64.17	14	383.98	3	200.3	22.73	2.76	**222.32**	**4**	0.81	11	5.4	3	2.7	0.61	0.02	**2.9**	**4**
PCSW-XX-SG-CT	83.99	17	430.75	16	200.3	22.73	2.76	**288.92**	**18**	0.95	17	6.1	16	2.7	0.61	0.02	**3.7**	**18**
PCSW-XX-DG-CT	84.57	18	417.07	14	200.3	22.73	2.76	**275.81**	**17**	0.96	18	5.9	14	2.7	0.61	0.02	**3.5**	**16**
CB-XX-SG-CT	47.52	3	449.72	18	200.3	22.73	2.76	**271.42**	**16**	0.57	3	6.4	18	2.7	0.61	0.02	**3.7**	**17**
CB-XX-DG-CT	48.10	4	436.99	17	200.3	22.73	2.76	**259.27**	**15**	0.58	4	6.2	17	2.7	0.61	0.02	**3.5**	**15**
ACC-XX-SG-CT	71.75	15	397.17	9	200.3	22.73	2.76	**243.11**	**13**	0.92	15	5.6	9	2.7	0.61	0.02	**3.2**	**12**
ACC-XX-DG-CT	72.33	16	386.07	4	200.3	22.73	2.76	**232.58**	**9**	0.93	16	5.4	4	2.7	0.61	0.02	**3.0**	**8**
TMB-XX-SG-CT	43.45	1	429.20	15	200.3	22.73	2.76	**246.83**	**14**	0.52	1	6.0	15	2.7	0.61	0.02	**3.2**	**13**
TMB-XX-DG-CT	44.03	2	412.99	13	200.3	22.73	2.76	**231.20**	**8**	0.53	2	5.8	12	2.7	0.61	0.02	**3.0**	**6**

Table F.21 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Broome (Scenario 1 - use of bottled gas for hot water)

Broome	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	62.34	9	888.91	16	159.1	28.54	2.76	**760.85**	**16**	0.88	11	15.5	16	2.9	0.77	0.02	**12.7**	**16**
DB-XX-DG-CT	62.92	10	851.49	14	159.1	28.54	2.76	**724.01**	**14**	0.89	12	14.8	14	2.9	0.77	0.02	**12.0**	**14**
DB-INS-SG-CT	63.63	11	834.93	12	159.1	28.54	2.76	**708.16**	**11**	0.91	13	14.6	12	2.9	0.77	0.02	**11.8**	**13**
DB-INS-DG-CT	64.21	12	798.37	5	159.1	28.54	2.76	**672.18**	**7**	0.92	14	13.9	5	2.9	0.77	0.02	**11.2**	**9**
CSW-POL-SG-CT	50.31	3	806.22	8	159.1	28.54	5.11	**663.78**	**5**	0.69	7	14.1	8	2.9	0.77	0.04	**11.0**	**6**
CSW-POL-DG-CT	50.89	5	770.38	2	159.1	28.54	5.11	**628.51**	**2**	0.69	8	13.4	2	2.9	0.77	0.04	**10.4**	**2**
BV-XX-SG-CT	53.74	7	802.37	7	159.1	28.54	2.76	**665.71**	**6**	0.67	5	14.0	7	2.9	0.77	0.02	**11.0**	**5**
BV-XX-DG-CT	54.32	8	762.81	1	159.1	28.54	2.76	**626.73**	**1**	0.68	6	13.3	1	2.9	0.77	0.02	**10.3**	**1**
RBV-XX-SG-CT	67.13	13	835.21	13	159.1	28.54	2.76	**711.94**	**12**	0.86	9	14.6	13	2.9	0.77	0.02	**11.7**	**12**
RBV-XX-DG-CT	67.71	14	798.37	6	159.1	28.54	2.76	**675.68**	**9**	0.87	10	13.9	6	2.9	0.77	0.02	**11.1**	**7**
PCSW-XX-SG-CT	83.85	17	865.35	15	159.1	28.54	2.76	**758.80**	**15**	0.95	16	15.1	15	2.9	0.77	0.02	**12.3**	**15**
PCSW-XX-DG-CT	84.43	18	826.36	11	159.1	28.54	2.76	**720.39**	**13**	0.96	18	14.4	11	2.9	0.77	0.02	**11.7**	**11**
CB-XX-SG-CT	50.84	4	978.45	18	159.1	28.54	2.76	**838.89**	**18**	0.63	3	17.0	18	2.9	0.77	0.02	**14.0**	**18**
CB-XX-DG-CT	51.42	6	937.89	17	159.1	28.54	2.76	**798.92**	**17**	0.64	4	16.3	17	2.9	0.77	0.02	**13.3**	**17**
ACC-XX-SG-CT	73.07	15	814.51	9	159.1	28.54	2.76	**697.18**	**10**	0.94	15	14.2	9	2.9	0.77	0.02	**11.5**	**10**
ACC-XX-DG-CT	73.65	16	777.80	3	159.1	28.54	2.76	**661.05**	**4**	0.95	17	13.6	3	2.9	0.77	0.02	**10.8**	**4**
TMB-XX-SG-CT	43.33	1	820.93	10	159.1	28.54	2.76	**673.86**	**8**	0.52	1	14.3	10	2.9	0.77	0.02	**11.1**	**8**
TMB-XX-DG-CT	43.91	2	782.94	4	159.1	28.54	2.76	**636.46**	**3**	0.53	2	13.7	4	2.9	0.77	0.02	**10.5**	**3**

Table F.22 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Broome (Scenario 2 - use of electricity for hot water)

Broome	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	62.34	9	1,022.05	16	159.1	78.37	2.76	**844.16**	**16**	0.88	11	17.8	16	2.9	1.5	0.02	**14.2**	**16**
DB-XX-DG-CT	62.92	10	984.63	14	159.1	78.37	2.76	**807.32**	**14**	0.89	12	17.1	14	2.9	1.5	0.02	**13.6**	**14**
DB-INS-SG-CT	63.63	11	968.07	12	159.1	78.37	2.76	**791.47**	**11**	0.91	13	16.8	12	2.9	1.5	0.02	**13.3**	**13**
DB-INS-DG-CT	64.21	12	931.51	5	159.1	78.37	2.76	**755.49**	**7**	0.92	14	16.2	5	2.9	1.5	0.02	**12.7**	**9**
CSW-POL-SG-CT	50.31	3	939.36	8	159.1	78.37	5.11	**747.09**	**5**	0.69	7	16.3	8	2.9	1.5	0.04	**12.6**	**6**
CSW-POL-DG-CT	50.89	5	903.52	2	159.1	78.37	5.11	**711.83**	**2**	0.69	8	15.7	2	2.9	1.5	0.04	**12.0**	**2**
BV-XX-SG-CT	53.74	7	935.51	7	159.1	78.37	2.76	**749.02**	**6**	0.67	5	16.3	7	2.9	1.5	0.02	**12.5**	**5**
BV-XX-DG-CT	54.32	8	895.95	1	159.1	78.37	2.76	**710.04**	**1**	0.68	6	15.6	1	2.9	1.5	0.02	**11.8**	**1**
RBV-XX-SG-CT	67.13	13	968.35	13	159.1	78.37	2.76	**795.25**	**12**	0.86	9	16.8	13	2.9	1.5	0.02	**13.3**	**12**
RBV-XX-DG-CT	67.71	14	931.51	6	159.1	78.37	2.76	**758.99**	**9**	0.87	10	16.2	6	2.9	1.5	0.02	**12.6**	**7**
PCSW-XX-SG-CT	83.85	17	998.49	15	159.1	78.37	2.76	**842.11**	**15**	0.95	16	17.4	15	2.9	1.5	0.02	**13.9**	**15**
PCSW-XX-DG-CT	84.43	18	959.50	11	159.1	78.37	2.76	**803.70**	**13**	0.96	18	16.7	11	2.9	1.5	0.02	**13.2**	**11**
CB-XX-SG-CT	50.84	4	1,111.59	18	159.1	78.37	2.76	**922.21**	**18**	0.63	3	19.3	18	2.9	1.5	0.02	**15.5**	**18**
CB-XX-DG-CT	51.42	6	1,071.03	17	159.1	78.37	2.76	**882.23**	**17**	0.64	4	18.6	17	2.9	1.5	0.02	**14.8**	**17**
ACC-XX-SG-CT	73.07	15	947.65	9	159.1	78.37	2.76	**780.49**	**10**	0.94	15	16.5	9	2.9	1.5	0.02	**13.0**	**10**
ACC-XX-DG-CT	73.65	16	910.94	3	159.1	78.37	2.76	**744.37**	**4**	0.95	17	15.8	3	2.9	1.5	0.02	**12.4**	**4**
TMB-XX-SG-CT	43.33	1	954.07	10	159.1	78.37	2.76	**757.18**	**8**	0.52	1	16.6	10	2.9	1.5	0.02	**12.7**	**8**
TMB-XX-DG-CT	43.91	2	916.09	4	159.1	78.37	2.76	**719.77**	**3**	0.53	2	15.9	4	2.9	1.5	0.02	**12.0**	**3**

Table F.23 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Bunbury

Bunbury	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.33	9	406.89	11	200.3	22.73	2.76	**238.41**	**12**	0.81	10	5.7	11	2.7	0.61	0.02	**3.1**	**14**
DB-XX-DG-CT	57.91	10	397.29	10	200.3	22.73	2.76	**229.38**	**8**	0.81	12	5.5	10	2.7	0.61	0.02	**3.0**	**11**
DB-INS-SG-CT	58.63	11	391.19	6	200.3	22.73	2.76	**224.00**	**6**	0.83	13	5.4	6	2.7	0.61	0.02	**2.9**	**8**
DB-INS-DG-CT	59.21	12	381.14	2	200.3	22.73	2.76	**214.52**	**3**	0.84	14	5.3	2	2.7	0.61	0.02	**2.8**	**4**
CSW-POL-SG-CT	50.47	5	388.66	5	200.3	22.73	5.11	**210.96**	**2**	0.69	7	5.4	5	2.7	0.61	0.04	**2.7**	**2**
CSW-POL-DG-CT	51.05	6	378.17	1	200.3	22.73	5.11	**201.05**	**1**	0.70	8	5.3	1	2.7	0.61	0.04	**2.6**	**1**
BV-XX-SG-CT	52.06	7	410.49	13	200.3	22.73	2.76	**236.73**	**11**	0.65	5	5.7	12	2.7	0.61	0.02	**3.0**	**10**
BV-XX-DG-CT	52.64	8	396.87	9	200.3	22.73	2.76	**223.69**	**5**	0.66	6	5.5	8	2.7	0.61	0.02	**2.8**	**5**
RBV-XX-SG-CT	63.59	13	391.78	7	200.3	22.73	2.76	**229.55**	**9**	0.81	9	5.4	7	2.7	0.61	0.02	**2.9**	**7**
RBV-XX-DG-CT	64.17	14	381.64	3	200.3	22.73	2.76	**219.98**	**4**	0.81	11	5.3	3	2.7	0.61	0.02	**2.8**	**3**
PCSW-XX-SG-CT	83.99	17	429.88	16	200.3	22.73	2.76	**288.04**	**18**	0.95	17	6.0	16	2.7	0.61	0.02	**3.6**	**18**
PCSW-XX-DG-CT	84.57	18	414.51	14	200.3	22.73	2.76	**273.26**	**17**	0.96	18	5.8	14	2.7	0.61	0.02	**3.4**	**16**
CB-XX-SG-CT	47.52	3	448.22	18	200.3	22.73	2.76	**269.92**	**16**	0.57	3	6.3	18	2.7	0.61	0.02	**3.5**	**17**
CB-XX-DG-CT	48.10	4	434.40	17	200.3	22.73	2.76	**256.68**	**15**	0.58	4	6.1	17	2.7	0.61	0.02	**3.3**	**15**
ACC-XX-SG-CT	71.75	15	396.60	8	200.3	22.73	2.76	**242.53**	**14**	0.92	15	5.5	9	2.7	0.61	0.02	**3.1**	**13**
ACC-XX-DG-CT	72.33	16	385.23	4	200.3	22.73	2.76	**231.74**	**10**	0.93	16	5.3	4	2.7	0.61	0.02	**3.0**	**9**
TMB-XX-SG-CT	43.45	1	424.88	15	200.3	22.73	2.76	**242.51**	**13**	0.52	1	5.9	15	2.7	0.61	0.02	**3.1**	**12**
TMB-XX-DG-CT	44.03	2	410.43	12	200.3	22.73	2.76	**228.64**	**7**	0.53	2	5.7	13	2.7	0.61	0.02	**2.9**	**6**

Table F.24 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Busselton

Busselton	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	57.13	9	430.58	14	200.3	22.73	2.76	**261.89**	**14**	0.80	9	6.2	15	2.7	0.61	0.02	**3.7**	**14**
DB-XX-DG-CT	57.71	10	417.58	10	200.3	22.73	2.76	**249.47**	**11**	0.81	11	6.0	12	2.7	0.61	0.02	**3.5**	**13**
DB-INS-SG-CT	58.42	11	408.49	8	200.3	22.73	2.76	**241.09**	**7**	0.83	13	5.8	9	2.7	0.61	0.02	**3.3**	**10**
DB-INS-DG-CT	59.00	12	396.54	3	200.3	22.73	2.76	**229.72**	**3**	0.84	14	5.7	3	2.7	0.61	0.02	**3.2**	**6**
CSW-POL-SG-CT	50.31	5	400.27	5	200.3	22.73	5.11	**222.41**	**2**	0.69	7	5.7	5	2.7	0.61	0.04	**3.0**	**2**
CSW-POL-DG-CT	50.89	6	389.06	1	200.3	22.73	5.11	**211.77**	**1**	0.69	8	5.5	1	2.7	0.61	0.04	**2.9**	**1**
BV-XX-SG-CT	51.91	7	420.08	11	200.3	22.73	2.76	**246.17**	**10**	0.65	5	6.0	10	2.7	0.61	0.02	**3.3**	**8**
BV-XX-DG-CT	52.49	8	404.93	6	200.3	22.73	2.76	**231.60**	**4**	0.65	6	5.7	6	2.7	0.61	0.02	**3.1**	**3**
RBV-XX-SG-CT	63.39	13	408.48	7	200.3	22.73	2.76	**246.05**	**9**	0.80	10	5.8	8	2.7	0.61	0.02	**3.3**	**9**
RBV-XX-DG-CT	63.97	14	397.16	4	200.3	22.73	2.76	**235.31**	**5**	0.81	12	5.7	4	2.7	0.61	0.02	**3.2**	**4**
PCSW-XX-SG-CT	83.85	17	443.12	16	200.3	22.73	2.76	**301.16**	**18**	0.95	17	6.3	16	2.7	0.61	0.02	**3.9**	**17**
PCSW-XX-DG-CT	84.43	18	427.11	13	200.3	22.73	2.76	**285.72**	**16**	0.96	18	6.1	13	2.7	0.61	0.02	**3.7**	**15**
CB-XX-SG-CT	47.34	3	473.15	18	200.3	22.73	2.76	**294.67**	**17**	0.57	3	6.9	18	2.7	0.61	0.02	**4.1**	**18**
CB-XX-DG-CT	47.92	4	458.15	17	200.3	22.73	2.76	**280.25**	**15**	0.58	4	6.7	17	2.7	0.61	0.02	**3.9**	**16**
ACC-XX-SG-CT	71.61	15	409.89	9	200.3	22.73	2.76	**255.68**	**13**	0.92	15	5.8	7	2.7	0.61	0.02	**3.4**	**12**
ACC-XX-DG-CT	72.19	16	395.63	2	200.3	22.73	2.76	**242.00**	**8**	0.93	16	5.6	2	2.7	0.61	0.02	**3.2**	**7**
TMB-XX-SG-CT	43.33	1	436.83	15	200.3	22.73	2.76	**254.34**	**12**	0.52	1	6.2	14	2.7	0.61	0.02	**3.4**	**11**
TMB-XX-DG-CT	43.91	2	420.65	12	200.3	22.73	2.76	**238.74**	**6**	0.53	2	6.0	11	2.7	0.61	0.02	**3.2**	**5**

Table F.25 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Carnarvon (Scenario 1 - use of bottled gas for heating and hot water)

Carnarvon	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	60.51	9	376.41	15	159.1	28.54	2.76	**246.52**	**13**	0.85	10	6.6	15	2.9	0.77	0.02	**3.8**	**16**
DB-XX-DG-CT	61.09	10	366.94	13	159.1	28.54	2.76	**237.63**	**11**	0.86	12	6.4	13	2.9	0.77	0.02	**3.6**	**12**
DB-INS-SG-CT	61.80	11	364.42	11	159.1	28.54	2.76	**235.82**	**9**	0.88	13	6.4	11	2.9	0.77	0.02	**3.6**	**11**
DB-INS-DG-CT	62.39	12	353.94	4	159.1	28.54	2.76	**225.93**	**6**	0.89	14	6.2	4	2.9	0.77	0.02	**3.4**	**8**
CSW-POL-SG-CT	51.93	5	360.80	7	159.1	28.54	5.11	**219.98**	**4**	0.71	7	6.3	7	2.9	0.77	0.04	**3.3**	**4**
CSW-POL-DG-CT	52.52	6	349.95	1	159.1	28.54	5.11	**209.71**	**1**	0.72	8	6.1	1	2.9	0.77	0.04	**3.1**	**1**
BV-XX-SG-CT	54.20	7	363.41	8	159.1	28.54	2.76	**227.21**	**7**	0.68	5	6.4	8	2.9	0.77	0.02	**3.4**	**6**
BV-XX-DG-CT	54.78	8	352.37	2	159.1	28.54	2.76	**216.75**	**3**	0.69	6	6.2	2	2.9	0.77	0.02	**3.2**	**3**
RBV-XX-SG-CT	66.48	13	364.27	10	159.1	28.54	2.76	**240.35**	**12**	0.85	9	6.4	10	2.9	0.77	0.02	**3.5**	**10**
RBV-XX-DG-CT	67.06	14	354.52	5	159.1	28.54	2.76	**231.18**	**8**	0.86	11	6.2	5	2.9	0.77	0.02	**3.4**	**7**
PCSW-XX-SG-CT	85.70	17	377.35	16	159.1	28.54	2.76	**272.65**	**18**	0.98	17	6.6	16	2.9	0.77	0.02	**3.9**	**17**
PCSW-XX-DG-CT	86.28	18	366.83	12	159.1	28.54	2.76	**262.72**	**17**	0.99	18	6.4	12	2.9	0.77	0.02	**3.7**	**14**
CB-XX-SG-CT	50.05	3	401.28	18	159.1	28.54	2.76	**260.92**	**16**	0.61	3	7.0	18	2.9	0.77	0.02	**3.9**	**18**
CB-XX-DG-CT	50.63	4	389.62	17	159.1	28.54	2.76	**249.84**	**15**	0.62	4	6.8	17	2.9	0.77	0.02	**3.7**	**15**
ACC-XX-SG-CT	73.45	15	363.99	9	159.1	28.54	2.76	**247.04**	**14**	0.95	15	6.4	9	2.9	0.77	0.02	**3.6**	**13**
ACC-XX-DG-CT	74.03	16	353.85	3	159.1	28.54	2.76	**237.48**	**10**	0.96	16	6.2	3	2.9	0.77	0.02	**3.5**	**9**
TMB-XX-SG-CT	44.86	1	370.22	14	159.1	28.54	2.76	**224.68**	**5**	0.54	1	6.5	14	2.9	0.77	0.02	**3.3**	**5**
TMB-XX-DG-CT	45.44	2	359.27	6	159.1	28.54	2.76	**214.31**	**2**	0.55	2	6.3	6	2.9	0.77	0.02	**3.1**	**2**

Table F.26 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Carnarvon (Scenario 2 - use of electricity for heating and hot water)

Carnarvon	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	60.51	9	510.22	15	159.1	78.37	2.76	**330.50**	**14**	0.85	10	8.9	15	2.9	1.5	0.02	**5.3**	**15**
DB-XX-DG-CT	61.09	10	500.65	12	159.1	78.37	2.76	**321.51**	**11**	0.86	12	8.7	12	2.9	1.5	0.02	**5.1**	**12**
DB-INS-SG-CT	61.80	11	497.65	11	159.1	78.37	2.76	**319.23**	**9**	0.88	13	8.6	11	2.9	1.5	0.02	**5.1**	**11**
DB-INS-DG-CT	62.39	12	487.09	3	159.1	78.37	2.76	**309.24**	**6**	0.89	14	8.5	3	2.9	1.5	0.02	**4.9**	**8**
CSW-POL-SG-CT	51.93	5	493.94	7	159.1	78.37	5.11	**303.29**	**4**	0.71	7	8.6	7	2.9	1.5	0.04	**4.9**	**4**
CSW-POL-DG-CT	52.52	6	483.09	1	159.1	78.37	5.11	**293.02**	**1**	0.72	8	8.4	1	2.9	1.5	0.04	**4.7**	**1**
BV-XX-SG-CT	54.20	7	496.94	8	159.1	78.37	2.76	**310.91**	**7**	0.68	5	8.6	8	2.9	1.5	0.02	**4.9**	**6**
BV-XX-DG-CT	54.78	8	485.80	2	159.1	78.37	2.76	**300.35**	**3**	0.69	6	8.4	2	2.9	1.5	0.02	**4.7**	**3**
RBV-XX-SG-CT	66.48	13	497.51	10	159.1	78.37	2.76	**323.76**	**12**	0.85	9	8.6	10	2.9	1.5	0.02	**5.1**	**10**
RBV-XX-DG-CT	67.06	14	487.66	5	159.1	78.37	2.76	**314.49**	**8**	0.86	11	8.5	5	2.9	1.5	0.02	**4.9**	**7**
PCSW-XX-SG-CT	85.70	17	512.22	16	159.1	78.37	2.76	**357.69**	**18**	0.98	17	8.9	16	2.9	1.5	0.02	**5.5**	**17**
PCSW-XX-DG-CT	86.28	18	501.51	13	159.1	78.37	2.76	**347.56**	**16**	0.99	18	8.7	13	2.9	1.5	0.02	**5.3**	**14**
CB-XX-SG-CT	50.05	3	538.64	18	159.1	78.37	2.76	**348.46**	**17**	0.61	3	9.4	18	2.9	1.5	0.02	**5.6**	**18**
CB-XX-DG-CT	50.63	4	526.79	17	159.1	78.37	2.76	**337.19**	**15**	0.62	4	9.2	17	2.9	1.5	0.02	**5.4**	**16**
ACC-XX-SG-CT	73.45	15	497.23	9	159.1	78.37	2.76	**330.45**	**13**	0.95	15	8.6	9	2.9	1.5	0.02	**5.2**	**13**
ACC-XX-DG-CT	74.03	16	487.09	4	159.1	78.37	2.76	**320.89**	**10**	0.96	16	8.5	4	2.9	1.5	0.02	**5.0**	**9**
TMB-XX-SG-CT	44.86	1	504.22	14	159.1	78.37	2.76	**308.85**	**5**	0.54	1	8.8	14	2.9	1.5	0.02	**4.9**	**5**
TMB-XX-DG-CT	45.44	2	493.08	6	159.1	78.37	2.76	**298.30**	**2**	0.55	2	8.6	6	2.9	1.5	0.02	**4.7**	**2**

Table F.27 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Esperance (Scenario 1 - use of bottled gas for heating and hot water)

Esperance	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.13	9	400.00	14	163.9	21.96	2.76	**268.50**	**13**	0.80	9	5.8	15	2.2	0.59	0.02	**3.8**	**14**
DB-XX-DG-CT	57.71	10	392.65	12	163.9	21.96	2.76	**261.74**	**11**	0.81	11	5.7	12	2.2	0.59	0.02	**3.7**	**13**
DB-INS-SG-CT	58.42	11	384.99	7	163.9	21.96	2.76	**254.79**	**7**	0.83	13	5.5	7	2.2	0.59	0.02	**3.5**	**11**
DB-INS-DG-CT	59.00	12	378.04	2	163.9	21.96	2.76	**248.42**	**5**	0.84	14	5.4	3	2.2	0.59	0.02	**3.4**	**8**
CSW-POL-SG-CT	50.31	5	381.37	5	163.9	21.96	5.11	**240.71**	**2**	0.69	7	5.4	5	2.2	0.59	0.04	**3.3**	**2**
CSW-POL-DG-CT	50.89	6	373.00	1	163.9	21.96	5.11	**232.92**	**1**	0.69	8	5.3	1	2.2	0.59	0.04	**3.2**	**1**
BV-XX-SG-CT	51.91	7	392.24	11	163.9	21.96	2.76	**255.53**	**8**	0.65	5	5.6	10	2.2	0.59	0.02	**3.4**	**6**
BV-XX-DG-CT	52.49	8	383.13	6	163.9	21.96	2.76	**247.00**	**3**	0.65	6	5.5	6	2.2	0.59	0.02	**3.3**	**3**
RBV-XX-SG-CT	63.39	13	385.68	8	163.9	21.96	2.76	**260.45**	**10**	0.80	10	5.5	9	2.2	0.59	0.02	**3.5**	**9**
RBV-XX-DG-CT	63.97	14	378.29	4	163.9	21.96	2.76	**253.64**	**6**	0.81	12	5.4	4	2.2	0.59	0.02	**3.4**	**5**
PCSW-XX-SG-CT	83.85	17	407.35	16	163.9	21.96	2.76	**302.58**	**18**	0.95	17	5.8	16	2.2	0.59	0.02	**4.0**	**17**
PCSW-XX-DG-CT	84.43	18	397.52	13	163.9	21.96	2.76	**293.33**	**17**	0.96	18	5.7	13	2.2	0.59	0.02	**3.8**	**15**
CB-XX-SG-CT	47.34	3	429.47	18	163.9	21.96	2.76	**288.19**	**16**	0.57	3	6.2	18	2.2	0.59	0.02	**4.0**	**18**
CB-XX-DG-CT	47.92	4	420.91	17	163.9	21.96	2.76	**280.21**	**15**	0.58	4	6.1	17	2.2	0.59	0.02	**3.9**	**16**
ACC-XX-SG-CT	71.61	15	386.71	9	163.9	21.96	2.76	**269.70**	**14**	0.92	15	5.5	8	2.2	0.59	0.02	**3.6**	**12**
ACC-XX-DG-CT	72.19	16	378.29	3	163.9	21.96	2.76	**261.86**	**12**	0.93	16	5.4	2	2.2	0.59	0.02	**3.5**	**10**
TMB-XX-SG-CT	43.33	1	401.38	15	163.9	21.96	2.76	**256.09**	**9**	0.52	1	5.7	14	2.2	0.59	0.02	**3.4**	**7**
TMB-XX-DG-CT	43.91	2	391.84	10	163.9	21.96	2.76	**247.13**	**4**	0.53	2	5.6	11	2.2	0.59	0.02	**3.3**	**4**

Table F.28 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Esperance (Scenario 2 - use of electricity for heating and hot water)

Esperance	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.13	9	749.20	16	163.9	99.19	2.76	**540.48**	**15**	0.80	9	9.8	16	2.2	1.32	0.02	**7.0**	**15**
DB-XX-DG-CT	57.71	10	734.09	14	163.9	99.19	2.76	**525.95**	**13**	0.81	11	9.6	14	2.2	1.32	0.02	**6.8**	**14**
DB-INS-SG-CT	58.42	11	700.15	10	163.9	99.19	2.76	**492.72**	**9**	0.83	13	9.1	10	2.2	1.32	0.02	**6.4**	**12**
DB-INS-DG-CT	59.00	12	685.43	6	163.9	99.19	2.76	**478.58**	**5**	0.84	14	8.9	6	2.2	1.32	0.02	**6.2**	**8**
CSW-POL-SG-CT	50.31	5	678.76	4	163.9	99.19	5.11	**460.87**	**2**	0.69	7	8.8	4	2.2	1.32	0.04	**6.0**	**3**
CSW-POL-DG-CT	50.89	6	662.47	1	163.9	99.19	5.11	**445.16**	**1**	0.69	8	8.6	1	2.2	1.32	0.04	**5.8**	**1**
BV-XX-SG-CT	51.91	7	694.85	8	163.9	99.19	2.76	**480.91**	**6**	0.65	5	9.0	8	2.2	1.32	0.02	**6.1**	**5**
BV-XX-DG-CT	52.49	8	677.38	3	163.9	99.19	2.76	**464.02**	**3**	0.65	6	8.8	3	2.2	1.32	0.02	**5.9**	**2**
RBV-XX-SG-CT	63.39	13	700.54	11	163.9	99.19	2.76	**498.08**	**12**	0.80	10	9.1	11	2.2	1.32	0.02	**6.4**	**10**
RBV-XX-DG-CT	63.97	14	685.23	5	163.9	99.19	2.76	**483.36**	**8**	0.81	12	8.9	5	2.2	1.32	0.02	**6.2**	**7**
PCSW-XX-SG-CT	83.85	17	739.98	15	163.9	99.19	2.76	**557.98**	**16**	0.95	17	9.6	15	2.2	1.32	0.02	**7.0**	**16**
PCSW-XX-DG-CT	84.43	18	721.34	13	163.9	99.19	2.76	**539.92**	**14**	0.96	18	9.4	13	2.2	1.32	0.02	**6.8**	**13**
CB-XX-SG-CT	47.34	3	826.32	18	163.9	99.19	2.76	**607.81**	**18**	0.57	3	10.8	18	2.2	1.32	0.02	**7.8**	**18**
CB-XX-DG-CT	47.92	4	809.84	17	163.9	99.19	2.76	**591.90**	**17**	0.58	4	10.5	17	2.2	1.32	0.02	**7.6**	**17**
ACC-XX-SG-CT	71.61	15	691.71	7	163.9	99.19	2.76	**497.47**	**11**	0.92	15	9.0	7	2.2	1.32	0.02	**6.4**	**11**
ACC-XX-DG-CT	72.19	16	675.23	2	163.9	99.19	2.76	**481.57**	**7**	0.93	16	8.8	2	2.2	1.32	0.02	**6.2**	**6**
TMB-XX-SG-CT	43.33	1	716.24	12	163.9	99.19	2.76	**493.72**	**10**	0.52	1	9.3	12	2.2	1.32	0.02	**6.3**	**9**
TMB-XX-DG-CT	43.91	2	698.18	9	163.9	99.19	2.76	**476.25**	**4**	0.53	2	9.1	9	2.2	1.32	0.02	**6.1**	**4**

Table F.29 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Geraldton

Geraldton	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.54	9	419.97	11	200.3	22.73	2.76	**251.69**	**11**	0.81	10	5.8	11	2.7	0.61	0.02	**3.3**	**14**
DB-XX-DG-CT	58.12	10	402.77	8	200.3	22.73	2.76	**235.07**	**5**	0.82	12	5.6	8	2.7	0.61	0.02	**3.0**	**9**
DB-INS-SG-CT	58.83	11	402.28	6	200.3	22.73	2.76	**235.29**	**6**	0.84	13	5.5	6	2.7	0.61	0.02	**3.1**	**10**
DB-INS-DG-CT	59.42	12	387.04	2	200.3	22.73	2.76	**220.64**	**2**	0.85	14	5.3	2	2.7	0.61	0.02	**2.9**	**4**
CSW-POL-SG-CT	50.63	5	400.30	5	200.3	22.73	5.11	**222.77**	**3**	0.69	7	5.5	5	2.7	0.61	0.04	**2.9**	**3**
CSW-POL-DG-CT	51.21	6	385.85	1	200.3	22.73	5.11	**208.90**	**1**	0.70	8	5.3	1	2.7	0.61	0.04	**2.7**	**1**
BV-XX-SG-CT	52.21	7	427.87	14	200.3	22.73	2.76	**254.26**	**12**	0.65	5	5.9	13	2.7	0.61	0.02	**3.2**	**11**
BV-XX-DG-CT	52.79	8	408.81	9	200.3	22.73	2.76	**235.79**	**7**	0.66	6	5.6	9	2.7	0.61	0.02	**3.0**	**5**
RBV-XX-SG-CT	63.78	13	402.71	7	200.3	22.73	2.76	**240.68**	**10**	0.81	9	5.6	7	2.7	0.61	0.02	**3.0**	**7**
RBV-XX-DG-CT	64.36	14	387.91	3	200.3	22.73	2.76	**226.46**	**4**	0.82	11	5.4	3	2.7	0.61	0.02	**2.8**	**2**
PCSW-XX-SG-CT	84.12	17	448.26	17	200.3	22.73	2.76	**306.56**	**18**	0.96	17	6.2	17	2.7	0.61	0.02	**3.8**	**18**
PCSW-XX-DG-CT	84.70	18	427.70	13	200.3	22.73	2.76	**286.58**	**17**	0.96	18	5.9	14	2.7	0.61	0.02	**3.5**	**16**
CB-XX-SG-CT	47.70	3	462.71	18	200.3	22.73	2.76	**284.59**	**16**	0.58	3	6.4	18	2.7	0.61	0.02	**3.6**	**17**
CB-XX-DG-CT	48.28	4	445.62	16	200.3	22.73	2.76	**268.08**	**15**	0.59	4	6.1	16	2.7	0.61	0.02	**3.4**	**15**
ACC-XX-SG-CT	71.89	15	411.68	10	200.3	22.73	2.76	**257.75**	**13**	0.92	15	5.7	10	2.7	0.61	0.02	**3.3**	**13**
ACC-XX-DG-CT	72.47	16	394.00	4	200.3	22.73	2.76	**240.65**	**9**	0.93	16	5.4	4	2.7	0.61	0.02	**3.0**	**8**
TMB-XX-SG-CT	43.57	1	441.67	15	200.3	22.73	2.76	**259.42**	**14**	0.52	1	6.1	15	2.7	0.61	0.02	**3.3**	**12**
TMB-XX-DG-CT	44.15	2	422.13	12	200.3	22.73	2.76	**240.46**	**8**	0.53	2	5.8	12	2.7	0.61	0.02	**3.0**	**6**

Table F.30 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Joondalup

Joondalup	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.47	9	383.02	11	200.3	22.73	2.76	**214.66**	**12**	0.81	10	5.3	11	2.7	0.61	0.02	**2.8**	**13**
DB-XX-DG-CT	58.05	10	375.78	9	200.3	22.73	2.76	**208.00**	**8**	0.82	12	5.2	10	2.7	0.61	0.02	**2.7**	**12**
DB-INS-SG-CT	58.76	11	371.04	5	200.3	22.73	2.76	**203.97**	**7**	0.84	13	5.1	6	2.7	0.61	0.02	**2.7**	**9**
DB-INS-DG-CT	59.34	12	364.63	2	200.3	22.73	2.76	**198.15**	**3**	0.84	14	5.1	2	2.7	0.61	0.02	**2.6**	**6**
CSW-POL-SG-CT	50.60	5	371.10	6	200.3	22.73	5.11	**193.53**	**2**	0.69	7	5.1	5	2.7	0.61	0.04	**2.5**	**2**
CSW-POL-DG-CT	51.18	6	362.88	1	200.3	22.73	5.11	**185.89**	**1**	0.70	8	5.0	1	2.7	0.61	0.04	**2.4**	**1**
BV-XX-SG-CT	52.19	7	385.87	13	200.3	22.73	2.76	**212.24**	**11**	0.65	5	5.3	13	2.7	0.61	0.02	**2.7**	**10**
BV-XX-DG-CT	52.77	8	374.88	8	200.3	22.73	2.76	**201.83**	**4**	0.66	6	5.2	8	2.7	0.61	0.02	**2.5**	**3**
RBV-XX-SG-CT	63.72	13	371.32	7	200.3	22.73	2.76	**209.22**	**9**	0.81	9	5.2	7	2.7	0.61	0.02	**2.6**	**7**
RBV-XX-DG-CT	64.30	14	364.87	3	200.3	22.73	2.76	**203.35**	**5**	0.82	11	5.1	3	2.7	0.61	0.02	**2.6**	**5**
PCSW-XX-SG-CT	84.12	17	397.36	16	200.3	22.73	2.76	**255.65**	**18**	0.96	17	5.5	16	2.7	0.61	0.02	**3.1**	**18**
PCSW-XX-DG-CT	84.70	18	386.12	14	200.3	22.73	2.76	**245.00**	**17**	0.96	18	5.4	14	2.7	0.61	0.02	**3.0**	**17**
CB-XX-SG-CT	47.65	3	409.65	18	200.3	22.73	2.76	**231.48**	**16**	0.58	3	5.7	18	2.7	0.61	0.02	**3.0**	**16**
CB-XX-DG-CT	48.23	4	399.33	17	200.3	22.73	2.76	**221.74**	**14**	0.58	4	5.6	17	2.7	0.61	0.02	**2.8**	**15**
ACC-XX-SG-CT	71.88	15	376.67	10	200.3	22.73	2.76	**222.73**	**15**	0.92	15	5.2	9	2.7	0.61	0.02	**2.8**	**14**
ACC-XX-DG-CT	72.46	16	368.17	4	200.3	22.73	2.76	**214.81**	**13**	0.93	16	5.1	4	2.7	0.61	0.02	**2.7**	**11**
TMB-XX-SG-CT	43.58	1	394.38	15	200.3	22.73	2.76	**212.14**	**10**	0.52	1	5.5	15	2.7	0.61	0.02	**2.7**	**8**
TMB-XX-DG-CT	44.16	2	385.39	12	200.3	22.73	2.76	**203.74**	**6**	0.53	2	5.3	12	2.7	0.61	0.02	**2.5**	**4**

Table F.31 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Kalgoorlie

Kalgoorlie	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.47	9	401.23	11	200.3	22.73	2.76	**232.87**	**11**	0.81	10	5.6	11	2.7	0.61	0.02	**3.1**	**13**
DB-XX-DG-CT	58.05	10	389.64	9	200.3	22.73	2.76	**221.86**	**9**	0.82	12	5.5	10	2.7	0.61	0.02	**2.9**	**10**
DB-INS-SG-CT	58.76	11	382.38	6	200.3	22.73	2.76	**215.32**	**5**	0.84	13	5.3	6	2.7	0.61	0.02	**2.8**	**8**
DB-INS-DG-CT	59.34	12	371.43	2	200.3	22.73	2.76	**204.95**	**3**	0.84	14	5.2	2	2.7	0.61	0.02	**2.7**	**4**
CSW-POL-SG-CT	50.60	5	378.45	5	200.3	22.73	5.11	**200.88**	**2**	0.69	7	5.3	5	2.7	0.61	0.04	**2.6**	**2**
CSW-POL-DG-CT	51.18	6	367.10	1	200.3	22.73	5.11	**190.11**	**1**	0.70	8	5.1	1	2.7	0.61	0.04	**2.5**	**1**
BV-XX-SG-CT	52.19	7	409.09	13	200.3	22.73	2.76	**235.47**	**13**	0.65	5	5.7	13	2.7	0.61	0.02	**3.0**	**12**
BV-XX-DG-CT	52.77	8	391.44	10	200.3	22.73	2.76	**218.39**	**6**	0.66	6	5.4	9	2.7	0.61	0.02	**2.8**	**5**
RBV-XX-SG-CT	63.72	13	382.82	7	200.3	22.73	2.76	**220.72**	**7**	0.81	9	5.3	7	2.7	0.61	0.02	**2.8**	**6**
RBV-XX-DG-CT	64.30	14	372.17	3	200.3	22.73	2.76	**210.64**	**4**	0.82	11	5.2	3	2.7	0.61	0.02	**2.7**	**3**
PCSW-XX-SG-CT	84.12	17	431.19	16	200.3	22.73	2.76	**289.49**	**18**	0.96	17	6.0	16	2.7	0.61	0.02	**3.6**	**18**
PCSW-XX-DG-CT	84.70	18	412.31	14	200.3	22.73	2.76	**271.19**	**16**	0.96	18	5.7	14	2.7	0.61	0.02	**3.4**	**16**
CB-XX-SG-CT	47.65	3	450.28	18	200.3	22.73	2.76	**272.12**	**17**	0.58	3	6.3	18	2.7	0.61	0.02	**3.5**	**17**
CB-XX-DG-CT	48.23	4	434.80	17	200.3	22.73	2.76	**257.21**	**15**	0.58	4	6.1	17	2.7	0.61	0.02	**3.3**	**15**
ACC-XX-SG-CT	71.88	15	388.03	8	200.3	22.73	2.76	**234.09**	**12**	0.92	15	5.4	8	2.7	0.61	0.02	**3.0**	**11**
ACC-XX-DG-CT	72.46	16	375.21	4	200.3	22.73	2.76	**221.86**	**8**	0.93	16	5.2	4	2.7	0.61	0.02	**2.8**	**7**
TMB-XX-SG-CT	43.58	1	426.48	15	200.3	22.73	2.76	**244.25**	**14**	0.52	1	5.9	15	2.7	0.61	0.02	**3.1**	**14**
TMB-XX-DG-CT	44.16	2	408.28	12	200.3	22.73	2.76	**226.62**	**10**	0.53	2	5.7	12	2.7	0.61	0.02	**2.9**	**9**

Table F.32 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Kununurra (Scenario 1 - use of bottled gas for hot water)

Kununurra	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	61.07	9	2,104.99	16	299.5	28.54	2.76	**1835.31**	**16**	0.86	10	31.3	16	4.5	0.77	0.02	**26.9**	**16**
DB-XX-DG-CT	61.65	10	1,997.56	14	299.5	28.54	2.76	**1728.45**	**14**	0.87	12	29.8	14	4.5	0.77	0.02	**25.3**	**14**
DB-INS-SG-CT	62.37	11	1,902.74	10	299.5	28.54	2.76	**1634.35**	**11**	0.89	13	28.4	10	4.5	0.77	0.02	**23.9**	**11**
DB-INS-DG-CT	62.95	12	1,800.09	5	299.5	28.54	2.76	**1532.29**	**6**	0.90	14	26.8	5	4.5	0.77	0.02	**22.4**	**7**
CSW-POL-SG-CT	51.50	5	1,795.55	4	299.5	28.54	5.11	**1513.94**	**4**	0.70	7	26.8	4	4.5	0.77	0.04	**22.2**	**4**
CSW-POL-DG-CT	52.08	6	1,693.67	1	299.5	28.54	5.11	**1412.64**	**1**	0.71	8	25.3	1	4.5	0.77	0.04	**20.7**	**1**
BV-XX-SG-CT	54.58	7	1,844.73	9	299.5	28.54	2.76	**1568.56**	**8**	0.68	5	27.5	9	4.5	0.77	0.02	**22.9**	**8**
BV-XX-DG-CT	55.16	8	1,740.32	3	299.5	28.54	2.76	**1464.73**	**2**	0.69	6	25.9	3	4.5	0.77	0.02	**21.4**	**2**
RBV-XX-SG-CT	67.03	13	1,906.27	11	299.5	28.54	2.76	**1642.53**	**12**	0.86	9	28.4	11	4.5	0.77	0.02	**24.0**	**12**
RBV-XX-DG-CT	67.61	14	1,801.61	6	299.5	28.54	2.76	**1538.45**	**7**	0.87	11	26.9	6	4.5	0.77	0.02	**22.4**	**6**
PCSW-XX-SG-CT	85.94	17	2,072.46	15	299.5	28.54	2.76	**1827.64**	**15**	0.98	17	30.9	15	4.5	0.77	0.02	**26.6**	**15**
PCSW-XX-DG-CT	86.52	18	1,960.24	13	299.5	28.54	2.76	**1716.00**	**13**	0.99	18	29.2	13	4.5	0.77	0.02	**24.9**	**13**
CB-XX-SG-CT	50.37	3	2,464.37	18	299.5	28.54	2.76	**2183.98**	**18**	0.62	3	36.7	18	4.5	0.77	0.02	**32.0**	**18**
CB-XX-DG-CT	50.95	4	2,351.64	17	299.5	28.54	2.76	**2071.83**	**17**	0.63	4	35.0	17	4.5	0.77	0.02	**30.3**	**17**
ACC-XX-SG-CT	73.84	15	1,840.70	8	299.5	28.54	2.76	**1583.78**	**9**	0.95	15	27.4	8	4.5	0.77	0.02	**23.1**	**9**
ACC-XX-DG-CT	74.42	16	1,740.07	2	299.5	28.54	2.76	**1483.73**	**3**	0.96	16	25.9	2	4.5	0.77	0.02	**21.6**	**3**
TMB-XX-SG-CT	45.05	1	1,919.38	12	299.5	28.54	2.76	**1633.67**	**10**	0.54	1	28.6	12	4.5	0.77	0.02	**23.8**	**10**
TMB-XX-DG-CT	45.63	2	1,812.70	7	299.5	28.54	2.76	**1527.58**	**5**	0.55	2	27.0	7	4.5	0.77	0.02	**22.3**	**5**

Table F.33 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Kununurra (Scenario 2 - use of electricity for hot water)

Kununurra	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	61.07	9	2,389.96	16	299.5	158.7	2.76	**1990.17**	**16**	0.86	10	35.3	16	4.5	2.45	0.02	**29.2**	**16**
DB-XX-DG-CT	61.65	10	2,282.53	14	299.5	158.7	2.76	**1883.31**	**14**	0.87	12	33.8	14	4.5	2.45	0.02	**27.7**	**14**
DB-INS-SG-CT	62.37	11	2,187.71	10	299.5	158.7	2.76	**1789.21**	**11**	0.89	13	32.3	10	4.5	2.45	0.02	**26.3**	**11**
DB-INS-DG-CT	62.95	12	2,085.06	5	299.5	158.7	2.76	**1687.15**	**6**	0.90	14	30.8	5	4.5	2.45	0.02	**24.8**	**7**
CSW-POL-SG-CT	51.50	5	2,080.52	4	299.5	158.7	5.11	**1668.80**	**4**	0.70	7	30.8	4	4.5	2.45	0.04	**24.5**	**4**
CSW-POL-DG-CT	52.08	6	1,978.64	1	299.5	158.7	5.11	**1567.50**	**1**	0.71	8	29.3	1	4.5	2.45	0.04	**23.0**	**1**
BV-XX-SG-CT	54.58	7	2,129.70	9	299.5	158.7	2.76	**1723.42**	**8**	0.68	5	31.5	9	4.5	2.45	0.02	**25.2**	**8**
BV-XX-DG-CT	55.16	8	2,025.29	3	299.5	158.7	2.76	**1619.59**	**2**	0.69	6	29.9	3	4.5	2.45	0.02	**23.7**	**2**
RBV-XX-SG-CT	67.03	13	2,191.24	11	299.5	158.7	2.76	**1797.39**	**12**	0.86	9	32.4	11	4.5	2.45	0.02	**26.3**	**12**
RBV-XX-DG-CT	67.61	14	2,086.58	6	299.5	158.7	2.76	**1693.31**	**7**	0.87	11	30.9	6	4.5	2.45	0.02	**24.8**	**6**
PCSW-XX-SG-CT	85.94	17	2,357.43	15	299.5	158.7	2.76	**1982.50**	**15**	0.98	17	34.9	15	4.5	2.45	0.02	**28.9**	**15**
PCSW-XX-DG-CT	86.52	18	2,245.21	13	299.5	158.7	2.76	**1870.86**	**13**	0.99	18	33.2	13	4.5	2.45	0.02	**27.2**	**13**
CB-XX-SG-CT	50.37	3	2,749.34	18	299.5	158.7	2.76	**2338.84**	**18**	0.62	3	40.7	18	4.5	2.45	0.02	**34.3**	**18**
CB-XX-DG-CT	50.95	4	2,636.61	17	299.5	158.7	2.76	**2226.69**	**17**	0.63	4	39.0	17	4.5	2.45	0.02	**32.6**	**17**
ACC-XX-SG-CT	73.84	15	2,125.67	8	299.5	158.7	2.76	**1738.64**	**9**	0.95	15	31.4	8	4.5	2.45	0.02	**25.4**	**9**
ACC-XX-DG-CT	74.42	16	2,025.04	2	299.5	158.7	2.76	**1638.59**	**3**	0.96	16	29.9	2	4.5	2.45	0.02	**23.9**	**3**
TMB-XX-SG-CT	45.05	1	2,204.35	12	299.5	158.7	2.76	**1788.53**	**10**	0.54	1	32.6	12	4.5	2.45	0.02	**26.2**	**10**
TMB-XX-DG-CT	45.63	2	2,097.67	7	299.5	158.7	2.76	**1682.43**	**5**	0.55	2	31.0	7	4.5	2.45	0.02	**24.6**	**5**

Table F.34 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Laverton (Scenario 1 - use of bottled gas for heating and hot water)

Laverton	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	70.27	9	684.13	14	299.5	28.54	2.76	**423.64**	**13**	0.99	10	10.3	14	4.5	0.77	0.02	**6.0**	**14**
DB-XX-DG-CT	70.88	10	640.53	10	299.5	28.54	2.76	**380.66**	**10**	1.00	12	9.7	10	4.5	0.77	0.02	**5.4**	**11**
DB-INS-SG-CT	71.58	11	625.78	6	299.5	28.54	2.76	**366.60**	**7**	1.02	13	9.5	6	4.5	0.77	0.02	**5.2**	**8**
DB-INS-DG-CT	72.19	12	584.25	2	299.5	28.54	2.76	**325.68**	**2**	1.03	14	8.9	2	4.5	0.77	0.02	**4.6**	**3**
CSW-POL-SG-CT	61.57	5	604.21	5	299.5	28.54	5.11	**332.67**	**4**	0.84	7	9.2	5	4.5	0.77	0.04	**4.7**	**4**
CSW-POL-DG-CT	62.18	6	565.76	1	299.5	28.54	5.11	**294.83**	**1**	0.85	8	8.6	1	4.5	0.77	0.04	**4.1**	**1**
BV-XX-SG-CT	62.21	7	674.05	12	299.5	28.54	2.76	**405.50**	**12**	0.79	5	10.2	12	4.5	0.77	0.02	**5.7**	**12**
BV-XX-DG-CT	62.82	8	626.83	7	299.5	28.54	2.76	**358.89**	**6**	0.80	6	9.5	7	4.5	0.77	0.02	**5.0**	**6**
RBV-XX-SG-CT	75.86	13	627.34	8	299.5	28.54	2.76	**372.44**	**8**	0.98	9	9.5	8	4.5	0.77	0.02	**5.2**	**7**
RBV-XX-DG-CT	76.47	14	585.26	3	299.5	28.54	2.76	**330.97**	**3**	0.99	11	8.9	3	4.5	0.77	0.02	**4.6**	**2**
PCSW-XX-SG-CT	93.03	17	730.94	16	299.5	28.54	2.76	**493.21**	**17**	1.08	17	11.0	16	4.5	0.77	0.02	**6.8**	**16**
PCSW-XX-DG-CT	93.65	18	680.35	13	299.5	28.54	2.76	**443.24**	**15**	1.09	18	10.3	13	4.5	0.77	0.02	**6.1**	**15**
CB-XX-SG-CT	58.64	3	806.38	18	299.5	28.54	2.76	**534.26**	**18**	0.73	3	12.2	18	4.5	0.77	0.02	**7.6**	**18**
CB-XX-DG-CT	59.25	4	755.99	17	299.5	28.54	2.76	**484.48**	**16**	0.74	4	11.4	17	4.5	0.77	0.02	**6.9**	**17**
ACC-XX-SG-CT	81.31	15	633.41	9	299.5	28.54	2.76	**383.97**	**11**	1.06	15	9.6	9	4.5	0.77	0.02	**5.4**	**10**
ACC-XX-DG-CT	81.93	16	588.81	4	299.5	28.54	2.76	**339.98**	**5**	1.07	16	8.9	4	4.5	0.77	0.02	**4.7**	**5**
TMB-XX-SG-CT	51.61	1	705.59	15	299.5	28.54	2.76	**426.44**	**14**	0.63	1	10.7	15	4.5	0.77	0.02	**6.0**	**13**
TMB-XX-DG-CT	52.22	2	657.07	11	299.5	28.54	2.76	**378.53**	**9**	0.64	2	9.9	11	4.5	0.77	0.02	**5.3**	**9**

Table F.35 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Laverton (Scenario 2 - use of electricity for heating and hot water)

Laverton	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	70.27	9	993.32	14	299.5	148.8	2.76	**612.57**	**14**	0.99	10	14.7	14	4.5	2.3	0.02	**8.9**	**15**
DB-XX-DG-CT	70.88	10	947.67	10	299.5	148.8	2.76	**567.54**	**11**	1.00	12	14.0	10	4.5	2.3	0.02	**8.2**	**11**
DB-INS-SG-CT	71.58	11	922.45	7	299.5	148.8	2.76	**543.01**	**7**	1.02	13	13.6	7	4.5	2.3	0.02	**7.8**	**8**
DB-INS-DG-CT	72.19	12	879.08	2	299.5	148.8	2.76	**500.25**	**2**	1.03	14	13.0	2	4.5	2.3	0.02	**7.2**	**3**
CSW-POL-SG-CT	61.57	5	896.98	5	299.5	148.8	5.11	**505.18**	**3**	0.84	7	13.3	5	4.5	2.3	0.04	**7.3**	**4**
CSW-POL-DG-CT	62.18	6	856.88	1	299.5	148.8	5.11	**465.70**	**1**	0.85	8	12.7	1	4.5	2.3	0.04	**6.7**	**1**
BV-XX-SG-CT	62.21	7	971.13	12	299.5	148.8	2.76	**582.32**	**12**	0.79	5	14.4	12	4.5	2.3	0.02	**8.3**	**12**
BV-XX-DG-CT	62.82	8	921.45	6	299.5	148.8	2.76	**533.25**	**6**	0.80	6	13.6	6	4.5	2.3	0.02	**7.6**	**6**
RBV-XX-SG-CT	75.86	13	924.22	8	299.5	148.8	2.76	**549.06**	**8**	0.98	9	13.7	8	4.5	2.3	0.02	**7.8**	**7**
RBV-XX-DG-CT	76.47	14	880.09	3	299.5	148.8	2.76	**505.53**	**4**	0.99	11	13.0	3	4.5	2.3	0.02	**7.2**	**2**
PCSW-XX-SG-CT	93.03	17	1,039.72	16	299.5	148.8	2.76	**681.74**	**16**	1.08	17	15.4	16	4.5	2.3	0.02	**9.6**	**16**
PCSW-XX-DG-CT	93.65	18	986.26	13	299.5	148.8	2.76	**628.89**	**15**	1.09	18	14.6	13	4.5	2.3	0.02	**8.9**	**14**
CB-XX-SG-CT	58.64	3	1,139.59	18	299.5	148.8	2.76	**747.21**	**18**	0.73	3	16.9	18	4.5	2.3	0.02	**10.8**	**18**
CB-XX-DG-CT	59.25	4	1,086.13	17	299.5	148.8	2.76	**694.36**	**17**	0.74	4	16.1	17	4.5	2.3	0.02	**10.0**	**17**
ACC-XX-SG-CT	81.31	15	929.26	9	299.5	148.8	2.76	**559.56**	**10**	1.06	15	13.7	9	4.5	2.3	0.02	**8.0**	**10**
ACC-XX-DG-CT	81.93	16	882.61	4	299.5	148.8	2.76	**513.51**	**5**	1.07	16	13.1	4	4.5	2.3	0.02	**7.3**	**5**
TMB-XX-SG-CT	51.61	1	1,007.19	15	299.5	148.8	2.76	**607.78**	**13**	0.63	1	14.9	15	4.5	2.3	0.02	**8.7**	**13**
TMB-XX-DG-CT	52.22	2	956.00	11	299.5	148.8	2.76	**557.20**	**9**	0.64	2	14.1	11	4.5	2.3	0.02	**8.0**	**9**

Table F.36 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Mandurah

Mandurah	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.67	9	406.39	11	200.3	22.73	2.76	**238.25**	**12**	0.81	10	5.7	11	2.7	0.61	0.02	**3.1**	**14**
DB-XX-DG-CT	58.25	10	396.64	10	200.3	22.73	2.76	**229.07**	**8**	0.82	12	5.5	10	2.7	0.61	0.02	**3.0**	**11**
DB-INS-SG-CT	58.97	11	391.52	6	200.3	22.73	2.76	**224.67**	**6**	0.84	13	5.4	6	2.7	0.61	0.02	**3.0**	**9**
DB-INS-DG-CT	59.55	12	381.23	2	200.3	22.73	2.76	**214.95**	**3**	0.85	14	5.3	2	2.7	0.61	0.02	**2.8**	**5**
CSW-POL-SG-CT	50.77	5	388.56	5	200.3	22.73	5.11	**211.15**	**2**	0.69	7	5.4	5	2.7	0.61	0.04	**2.7**	**2**
CSW-POL-DG-CT	51.35	6	377.23	1	200.3	22.73	5.11	**200.41**	**1**	0.70	8	5.2	1	2.7	0.61	0.04	**2.6**	**1**
BV-XX-SG-CT	52.35	7	409.99	13	200.3	22.73	2.76	**236.51**	**11**	0.65	5	5.7	12	2.7	0.61	0.02	**3.0**	**10**
BV-XX-DG-CT	52.93	8	396.09	8	200.3	22.73	2.76	**223.19**	**5**	0.66	6	5.5	8	2.7	0.61	0.02	**2.8**	**4**
RBV-XX-SG-CT	63.91	13	391.52	7	200.3	22.73	2.76	**229.62**	**9**	0.81	9	5.4	7	2.7	0.61	0.02	**2.9**	**7**
RBV-XX-DG-CT	64.49	14	381.77	3	200.3	22.73	2.76	**220.44**	**4**	0.82	11	5.3	3	2.7	0.61	0.02	**2.8**	**3**
PCSW-XX-SG-CT	84.25	17	429.57	16	200.3	22.73	2.76	**288.00**	**18**	0.96	17	6.0	16	2.7	0.61	0.02	**3.6**	**18**
PCSW-XX-DG-CT	84.83	18	414.01	14	200.3	22.73	2.76	**273.02**	**17**	0.97	18	5.7	14	2.7	0.61	0.02	**3.4**	**16**
CB-XX-SG-CT	47.83	3	448.39	18	200.3	22.73	2.76	**270.41**	**16**	0.58	3	6.3	18	2.7	0.61	0.02	**3.5**	**17**
CB-XX-DG-CT	48.41	4	433.40	17	200.3	22.73	2.76	**256.00**	**15**	0.59	4	6.1	17	2.7	0.61	0.02	**3.3**	**15**
ACC-XX-SG-CT	72.03	15	396.10	9	200.3	22.73	2.76	**242.31**	**14**	0.93	15	5.5	9	2.7	0.61	0.02	**3.1**	**13**
ACC-XX-DG-CT	72.61	16	384.73	4	200.3	22.73	2.76	**231.52**	**10**	0.94	16	5.3	4	2.7	0.61	0.02	**2.9**	**8**
TMB-XX-SG-CT	43.70	1	424.38	15	200.3	22.73	2.76	**242.26**	**13**	0.52	1	5.9	15	2.7	0.61	0.02	**3.1**	**12**
TMB-XX-DG-CT	44.28	2	409.69	12	200.3	22.73	2.76	**228.15**	**7**	0.53	2	5.7	13	2.7	0.61	0.02	**2.9**	**6**

Table F.37 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Mount Magnet (Scenario 1 - use of bottled gas for heating and hot water)

Mount Magnet	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	65.06	9	362.78	13	140	24.75	2.76	**260.32**	**14**	0.91	10	6.4	13	2.6	0.67	0.02	**4.0**	**14**
DB-XX-DG-CT	65.67	10	346.41	10	140	24.75	2.76	**244.55**	**10**	0.92	12	6.1	10	2.6	0.67	0.02	**3.7**	**11**
DB-INS-SG-CT	66.37	11	339.34	6	140	24.75	2.76	**238.19**	**7**	0.94	13	5.9	6	2.6	0.67	0.02	**3.6**	**9**
DB-INS-DG-CT	66.97	12	324.54	2	140	24.75	2.76	**223.99**	**3**	0.95	14	5.7	2	2.6	0.67	0.02	**3.4**	**4**
CSW-POL-SG-CT	52.66	3	331.54	5	140	24.75	5.11	**214.33**	**2**	0.72	5	5.8	5	2.6	0.67	0.04	**3.2**	**2**
CSW-POL-DG-CT	53.27	4	316.93	1	140	24.75	5.11	**200.33**	**1**	0.73	7	5.6	1	2.6	0.67	0.04	**3.0**	**1**
BV-XX-SG-CT	57.16	7	362.62	12	140	24.75	2.76	**252.26**	**12**	0.72	6	6.4	12	2.6	0.67	0.02	**3.8**	**12**
BV-XX-DG-CT	57.77	8	344.29	9	140	24.75	2.76	**234.54**	**5**	0.73	8	6.0	9	2.6	0.67	0.02	**3.5**	**6**
RBV-XX-SG-CT	70.68	13	340.77	7	140	24.75	2.76	**243.93**	**9**	0.90	9	6.0	7	2.6	0.67	0.02	**3.6**	**8**
RBV-XX-DG-CT	71.29	14	325.40	3	140	24.75	2.76	**229.17**	**4**	0.91	11	5.7	3	2.6	0.67	0.02	**3.3**	**3**
PCSW-XX-SG-CT	88.05	17	385.62	16	140	24.75	2.76	**306.15**	**18**	1.01	17	6.8	16	2.6	0.67	0.02	**4.5**	**17**
PCSW-XX-DG-CT	88.66	18	365.59	14	140	24.75	2.76	**286.72**	**16**	1.02	18	6.4	14	2.6	0.67	0.02	**4.1**	**15**
CB-XX-SG-CT	53.54	5	412.92	18	140	24.75	2.76	**298.94**	**17**	0.66	3	7.2	18	2.6	0.67	0.02	**4.6**	**18**
CB-XX-DG-CT	54.14	6	395.60	17	140	24.75	2.76	**282.23**	**15**	0.67	4	6.9	17	2.6	0.67	0.02	**4.3**	**16**
ACC-XX-SG-CT	76.30	15	342.63	8	140	24.75	2.76	**251.41**	**11**	0.99	15	6.0	8	2.6	0.67	0.02	**3.7**	**10**
ACC-XX-DG-CT	76.91	16	327.54	4	140	24.75	2.76	**236.93**	**6**	1.00	16	5.7	4	2.6	0.67	0.02	**3.4**	**5**
TMB-XX-SG-CT	46.67	1	377.55	15	140	24.75	2.76	**256.71**	**13**	0.56	1	6.6	15	2.6	0.67	0.02	**3.9**	**13**
TMB-XX-DG-CT	47.28	2	358.61	11	140	24.75	2.76	**238.37**	**8**	0.57	2	6.3	11	2.6	0.67	0.02	**3.6**	**7**

Table F.38 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Mount Magnet (Scenario 2 - use of electricity for heating and hot water)

Mount Magnet	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	65.06	9	511.65	13	140	74.64	2.76	**359.30**	**14**	0.91	10	8.9	13	2.6	1.43	0.02	**5.8**	**14**
DB-XX-DG-CT	65.67	10	494.51	10	140	74.64	2.76	**342.77**	**10**	0.92	12	8.6	10	2.6	1.43	0.02	**5.5**	**11**
DB-INS-SG-CT	66.37	11	483.80	6	140	74.64	2.76	**332.75**	**7**	0.94	13	8.4	6	2.6	1.43	0.02	**5.3**	**9**
DB-INS-DG-CT	66.97	12	468.52	2	140	74.64	2.76	**318.08**	**3**	0.95	14	8.1	2	2.6	1.43	0.02	**5.0**	**4**
CSW-POL-SG-CT	52.66	3	474.66	5	140	74.64	5.11	**307.56**	**2**	0.72	5	8.2	5	2.6	1.43	0.04	**4.9**	**2**
CSW-POL-DG-CT	53.27	4	459.66	1	140	74.64	5.11	**293.17**	**1**	0.73	7	8.0	1	2.6	1.43	0.04	**4.6**	**1**
BV-XX-SG-CT	57.16	7	507.36	12	140	74.64	2.76	**347.11**	**12**	0.72	6	8.8	12	2.6	1.43	0.02	**5.5**	**12**
BV-XX-DG-CT	57.77	8	488.37	9	140	74.64	2.76	**328.73**	**5**	0.73	8	8.5	9	2.6	1.43	0.02	**5.2**	**6**
RBV-XX-SG-CT	70.68	13	485.23	7	140	74.64	2.76	**338.50**	**9**	0.90	9	8.4	7	2.6	1.43	0.02	**5.3**	**8**
RBV-XX-DG-CT	71.29	14	469.38	3	140	74.64	2.76	**323.26**	**4**	0.91	11	8.2	3	2.6	1.43	0.02	**5.0**	**3**
PCSW-XX-SG-CT	88.05	17	535.07	16	140	74.64	2.76	**405.71**	**17**	1.01	17	9.3	16	2.6	1.43	0.02	**6.3**	**17**
PCSW-XX-DG-CT	88.66	18	514.07	14	140	74.64	2.76	**385.32**	**15**	1.02	18	8.9	14	2.6	1.43	0.02	**5.9**	**15**
CB-XX-SG-CT	53.54	5	571.77	18	140	74.64	2.76	**407.90**	**18**	0.66	3	9.9	18	2.6	1.43	0.02	**6.5**	**18**
CB-XX-DG-CT	54.14	6	553.49	17	140	74.64	2.76	**390.23**	**16**	0.67	4	9.6	17	2.6	1.43	0.02	**6.2**	**16**
ACC-XX-SG-CT	76.30	15	486.80	8	140	74.64	2.76	**345.69**	**11**	0.99	15	8.5	8	2.6	1.43	0.02	**5.4**	**10**
ACC-XX-DG-CT	76.91	16	471.23	4	140	74.64	2.76	**330.73**	**6**	1.00	16	8.2	4	2.6	1.43	0.02	**5.1**	**5**
TMB-XX-SG-CT	46.67	1	523.93	15	140	74.64	2.76	**353.19**	**13**	0.56	1	9.1	15	2.6	1.43	0.02	**5.6**	**13**
TMB-XX-DG-CT	47.28	2	504.22	11	140	74.64	2.76	**334.09**	**8**	0.57	2	8.8	11	2.6	1.43	0.02	**5.3**	**7**

Table F.39 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Newman (Scenario 1 - use of bottled gas for heating and hot water)

Newman	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	73.92	9	512.35	15	159.1	28.54	2.76	**395.88**	**14**	1.05	11	9.0	15	2.9	0.77	0.02	**6.3**	**15**
DB-XX-DG-CT	74.57	10	482.60	11	159.1	28.54	2.76	**366.77**	**12**	1.06	12	8.4	11	2.9	0.77	0.02	**5.8**	**12**
DB-INS-SG-CT	75.24	11	464.81	8	159.1	28.54	2.76	**349.65**	**8**	1.08	15	8.1	8	2.9	0.77	0.02	**5.5**	**10**
DB-INS-DG-CT	75.89	12	437.34	3	159.1	28.54	2.76	**322.83**	**3**	1.09	17	7.6	3	2.9	0.77	0.02	**5.0**	**5**
CSW-POL-SG-CT	54.92	3	443.25	5	159.1	28.54	5.11	**305.41**	**2**	0.75	3	7.7	5	2.9	0.77	0.04	**4.8**	**2**
CSW-POL-DG-CT	55.56	4	418.26	1	159.1	28.54	5.11	**281.07**	**1**	0.76	5	7.3	1	2.9	0.77	0.04	**4.4**	**1**
BV-XX-SG-CT	62.97	7	487.04	12	159.1	28.54	2.76	**359.61**	**11**	0.81	7	8.5	12	2.9	0.77	0.02	**5.6**	**11**
BV-XX-DG-CT	63.61	8	455.95	6	159.1	28.54	2.76	**329.17**	**6**	0.82	8	8.0	6	2.9	0.77	0.02	**5.1**	**6**
RBV-XX-SG-CT	78.81	13	466.38	9	159.1	28.54	2.76	**354.79**	**10**	1.03	9	8.2	9	2.9	0.77	0.02	**5.5**	**9**
RBV-XX-DG-CT	79.46	14	439.10	4	159.1	28.54	2.76	**328.16**	**5**	1.04	10	7.7	4	2.9	0.77	0.02	**5.0**	**4**
PCSW-XX-SG-CT	92.65	17	534.00	16	159.1	28.54	2.76	**436.25**	**16**	1.08	16	9.3	16	2.9	0.77	0.02	**6.7**	**16**
PCSW-XX-DG-CT	93.29	18	501.83	13	159.1	28.54	2.76	**404.72**	**15**	1.09	18	8.8	13	2.9	0.77	0.02	**6.2**	**14**
CB-XX-SG-CT	60.39	5	601.57	18	159.1	28.54	2.76	**471.56**	**18**	0.76	4	10.5	18	2.9	0.77	0.02	**7.6**	**18**
CB-XX-DG-CT	61.03	6	571.01	17	159.1	28.54	2.76	**441.64**	**17**	0.77	6	10.0	17	2.9	0.77	0.02	**7.1**	**17**
ACC-XX-SG-CT	81.47	15	462.24	7	159.1	28.54	2.76	**353.31**	**9**	1.07	13	8.1	7	2.9	0.77	0.02	**5.5**	**8**
ACC-XX-DG-CT	82.11	16	435.82	2	159.1	28.54	2.76	**327.53**	**4**	1.08	14	7.6	2	2.9	0.77	0.02	**5.0**	**3**
TMB-XX-SG-CT	50.29	1	512.21	14	159.1	28.54	2.76	**372.10**	**13**	0.62	1	8.9	14	2.9	0.77	0.02	**5.9**	**13**
TMB-XX-DG-CT	50.93	2	480.65	10	159.1	28.54	2.76	**341.19**	**7**	0.63	2	8.4	10	2.9	0.77	0.02	**5.3**	**7**

Table F.40 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Newman (Scenario 2 - use of electricity for heating and hot water)

Newman	**GHG emissions - tonnes CO_2 e-**									**Embodied energy - TJ**								
Envelope options	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**	**Construction**		**Operational**		**Savings due to CPS**			**Life cycle**	**Rank**
	Value	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**			**Value**	**Rank**	**Value**	**Rank**	**SPV**	**SWH**	**GC**		
DB-XX-SG-CT	73.92	9	647.32	15	159.1	78.37	2.76	**481.01**	**14**	1.05	11	11.2	15	2.9	1.5	0.02	**7.9**	**15**
DB-XX-DG-CT	74.57	10	617.47	11	159.1	78.37	2.76	**451.81**	**12**	1.06	12	10.7	11	2.9	1.5	0.02	**7.4**	**12**
DB-INS-SG-CT	75.24	11	598.33	8	159.1	78.37	2.76	**433.35**	**8**	1.08	15	10.4	8	2.9	1.5	0.02	**7.1**	**10**
DB-INS-DG-CT	75.89	12	570.77	3	159.1	78.37	2.76	**406.43**	**3**	1.09	17	9.9	3	2.9	1.5	0.02	**6.6**	**5**
CSW-POL-SG-CT	54.92	3	576.48	5	159.1	78.37	5.11	**388.82**	**2**	0.75	3	10.0	5	2.9	1.5	0.04	**6.3**	**2**
CSW-POL-DG-CT	55.56	4	551.49	1	159.1	78.37	5.11	**364.47**	**1**	0.76	5	9.6	1	2.9	1.5	0.04	**5.9**	**1**
BV-XX-SG-CT	62.97	7	621.04	12	159.1	78.37	2.76	**443.78**	**11**	0.81	7	10.8	12	2.9	1.5	0.02	**7.2**	**11**
BV-XX-DG-CT	63.61	8	589.77	6	159.1	78.37	2.76	**413.15**	**6**	0.82	8	10.2	6	2.9	1.5	0.02	**6.6**	**6**
RBV-XX-SG-CT	78.81	13	599.91	9	159.1	78.37	2.76	**438.49**	**10**	1.03	9	10.4	9	2.9	1.5	0.02	**7.0**	**9**
RBV-XX-DG-CT	79.46	14	572.63	4	159.1	78.37	2.76	**411.85**	**5**	1.04	10	10.0	4	2.9	1.5	0.02	**6.6**	**4**
PCSW-XX-SG-CT	92.65	17	670.31	16	159.1	78.37	2.76	**522.73**	**16**	1.08	16	11.6	16	2.9	1.5	0.02	**8.3**	**16**
PCSW-XX-DG-CT	93.29	18	637.75	13	159.1	78.37	2.76	**490.81**	**15**	1.09	18	11.1	13	2.9	1.5	0.02	**7.8**	**14**
CB-XX-SG-CT	60.39	5	742.29	18	159.1	78.37	2.76	**562.45**	**18**	0.76	4	12.9	18	2.9	1.5	0.02	**9.2**	**18**
CB-XX-DG-CT	61.03	6	711.44	17	159.1	78.37	2.76	**532.24**	**17**	0.77	6	12.4	17	2.9	1.5	0.02	**8.7**	**17**
ACC-XX-SG-CT	81.47	15	595.76	7	159.1	78.37	2.76	**437.00**	**9**	1.07	13	10.4	7	2.9	1.5	0.02	**7.0**	**8**
ACC-XX-DG-CT	82.11	16	569.34	2	159.1	78.37	2.76	**411.22**	**4**	1.08	14	9.9	2	2.9	1.5	0.02	**6.5**	**3**
TMB-XX-SG-CT	50.29	1	647.18	14	159.1	78.37	2.76	**457.24**	**13**	0.62	1	11.2	14	2.9	1.5	0.02	**7.4**	**13**
TMB-XX-DG-CT	50.93	2	615.33	10	159.1	78.37	2.76	**426.03**	**7**	0.63	2	10.7	10	2.9	1.5	0.02	**6.9**	**7**

Table F.41 Breakdown of life cycle GHG emissions and EE consumption of a reference house for alternative envelope options in Yanchep

Yanchep	GHG emissions - tonnes CO_2 e-									Embodied energy - TJ								
Envelope options	Construction		Operational		Savings due to CPS			Life cycle	Rank	Construction		Operational		Savings due to CPS			Life cycle	Rank
	Value	Rank	Value	Rank	SPV	SWH	GC			Value	Rank	Value	Rank	SPV	SWH	GC		
DB-XX-SG-CT	57.95	9	383.06	11	200.3	22.73	2.76	**215.19**	**13**	0.81	10	5.3	11	2.7	0.61	0.02	**2.8**	**13**
DB-XX-DG-CT	58.53	10	375.82	9	200.3	22.73	2.76	**208.53**	**8**	0.82	12	5.2	10	2.7	0.61	0.02	**2.7**	**12**
DB-INS-SG-CT	59.24	11	371.08	5	200.3	22.73	2.76	**204.50**	**7**	0.84	13	5.1	6	2.7	0.61	0.02	**2.7**	**10**
DB-INS-DG-CT	59.82	12	364.67	2	200.3	22.73	2.76	**198.68**	**3**	0.85	14	5.1	2	2.7	0.61	0.02	**2.6**	**6**
CSW-POL-SG-CT	50.93	5	371.10	6	200.3	22.73	5.11	**193.86**	**2**	0.69	7	5.1	5	2.7	0.61	0.04	**2.5**	**2**
CSW-POL-DG-CT	51.51	6	362.88	1	200.3	22.73	5.11	**186.22**	**1**	0.70	8	5.0	1	2.7	0.61	0.04	**2.4**	**1**
BV-XX-SG-CT	52.51	7	385.43	13	200.3	22.73	2.76	**212.12**	**10**	0.65	5	5.3	13	2.7	0.61	0.02	**2.7**	**9**
BV-XX-DG-CT	53.09	8	374.68	8	200.3	22.73	2.76	**201.95**	**4**	0.66	6	5.2	8	2.7	0.61	0.02	**2.5**	**3**
RBV-XX-SG-CT	64.16	13	371.32	7	200.3	22.73	2.76	**209.66**	**9**	0.81	9	5.2	7	2.7	0.61	0.02	**2.6**	**7**
RBV-XX-DG-CT	64.74	14	365.07	3	200.3	22.73	2.76	**203.99**	**6**	0.82	11	5.1	3	2.7	0.61	0.02	**2.6**	**5**
PCSW-XX-SG-CT	84.38	17	397.21	16	200.3	22.73	2.76	**255.77**	**18**	0.96	17	5.5	16	2.7	0.61	0.02	**3.1**	**18**
PCSW-XX-DG-CT	84.96	18	386.32	14	200.3	22.73	2.76	**245.46**	**17**	0.97	18	5.4	14	2.7	0.61	0.02	**3.0**	**17**
CB-XX-SG-CT	48.08	3	409.69	18	200.3	22.73	2.76	**231.95**	**16**	0.58	3	5.7	18	2.7	0.61	0.02	**3.0**	**16**
CB-XX-DG-CT	48.66	4	399.38	17	200.3	22.73	2.76	**222.22**	**14**	0.59	4	5.6	17	2.7	0.61	0.02	**2.8**	**15**
ACC-XX-SG-CT	72.17	15	376.91	10	200.3	22.73	2.76	**223.26**	**15**	0.93	15	5.2	9	2.7	0.61	0.02	**2.8**	**14**
ACC-XX-DG-CT	72.75	16	368.02	4	200.3	22.73	2.76	**214.94**	**12**	0.94	16	5.1	4	2.7	0.61	0.02	**2.7**	**11**
TMB-XX-SG-CT	43.82	1	394.57	15	200.3	22.73	2.76	**212.58**	**11**	0.52	1	5.5	15	2.7	0.61	0.02	**2.7**	**8**
TMB-XX-DG-CT	44.40	2	385.00	12	200.3	22.73	2.76	**203.58**	**5**	0.53	2	5.3	12	2.7	0.61	0.02	**2.5**	**4**

Table F.42 Summary of life cycle GHG emissions of a reference house for alternative CPS options in 17 locations in regional WA

Location	DB-XX-SG-CT-SPV-SWH-GC	DB-XX-DG-CT-SPV-SWH-GC	DB-INS-SG-CT-SPV-SWH-GC	DB-INS-DG-CT-SPV-SWH-GC	CSW-POL-SG-CT-SPV-SWH-GC	CSW-POL-DG-CT-SPV-SWH-GC	BV-XX-SG-CT-SPV-SWH-GC	BV-XX-DG-CT-SPV-SWH-GC	RBV-XX-SG-CT-SPV-SWH-GC	RBV-XX-DG-CT-SPV-SWH-GC	PCSW-XX-SG-CT-SPV-SWH-GC	PCSW-XX-DG-CT-SPV-SWH-GC	CB-XX-SG-CT-SPV-SWH-GC	CB-XX-DG-CT-SPV-SWH-GC	ACC-XX-SG-CT-SPV-SWH-GC	ACC-XX-DG-CT-SPV-SWH-GC	TMB-XX-SG-CT-SPV-SWH-GC	TMB-XX-DG-CT-SPV-SWH-GC
	tonnes CO_2 e-																	
Albany	273.63	268.15	258.31	253.52	240.60	235.18	253.42	246.59	263.21	258.37	300.80	293.63	292.20	286.08	270.07	263.43	254.19	246.81
Augusta (b)	279.89	274.20	264.39	258.46	245.70	239.43	258.68	251.47	268.97	262.85	306.22	298.68	299.73	292.47	274.74	268.67	259.14	251.63
Augusta (e)	621.31	605.01	556.67	539.40	510.21	492.74	529.31	511.05	560.36	542.89	620.31	601.27	707.45	689.59	551.05	533.77	547.54	529.28
Armadale	241.42	232.70	224.69	216.71	210.66	200.74	237.33	223.91	229.71	222.32	288.92	275.81	271.42	259.27	243.11	232.58	246.83	231.20
Broome (b)	760.85	724.01	708.16	672.18	663.78	628.51	665.71	626.73	711.94	675.68	758.80	720.39	838.89	798.92	697.18	661.05	673.86	636.46
Broome (e)	844.16	807.32	791.47	755.49	747.09	711.83	749.02	710.04	795.25	758.99	842.11	803.70	922.21	882.23	780.49	744.37	757.18	719.77
Bunbury	238.41	229.38	224.00	214.52	210.96	201.05	236.73	223.69	229.55	219.98	288.04	273.26	269.92	256.68	242.53	231.74	242.51	228.64
Busselton	261.89	249.47	241.09	229.72	222.41	211.77	246.17	231.60	246.05	235.31	301.16	285.72	294.67	280.25	255.68	242.00	254.34	238.74
Carnarvon (b)	246.52	237.63	235.82	225.93	219.98	209.71	227.21	216.75	240.35	231.18	272.65	262.72	260.92	249.84	247.04	237.48	224.68	214.31
Carnarvon (e)	330.50	321.51	319.23	309.24	303.29	293.02	310.91	300.35	323.76	314.49	357.69	347.56	348.46	337.19	330.45	320.89	308.85	298.30
Esperance (b)	268.50	261.74	254.79	248.42	240.71	232.92	255.53	247.00	260.45	253.64	302.58	293.33	288.19	280.21	269.70	261.86	256.09	247.13
Esperance (e)	540.48	525.95	492.72	478.58	460.87	445.16	480.91	464.02	498.08	483.36	557.98	539.92	607.81	591.90	497.47	481.57	493.72	476.25
Geraldton	251.69	235.07	235.29	220.64	222.77	208.90	254.26	235.79	240.68	226.46	306.56	286.58	284.59	268.08	257.75	240.65	259.42	240.46
Joondalup	214.66	208.00	203.97	198.15	193.53	185.89	212.24	201.83	209.22	203.35	255.65	245.00	231.48	221.74	222.73	214.81	212.14	203.74
Kalgoorlie	232.87	221.86	215.32	204.95	200.88	190.11	235.47	218.39	220.72	210.64	289.49	271.19	272.12	257.21	234.09	221.86	244.25	226.62
Kununurra (b)	1835	1728	1634	1532	1514	1413	1569	1465	1643	1538	1828	1716	2184	2072	1584	1484	1634	1528

Location	DB-XX-SG-CT-SPV-SWH-GC	DB-XX-DG-CT-SPV-SWH-GC	DB-INS-SG-CT-SPV-SWH-GC	DB-INS-DG-CT-SPV-SWH-GC	CSW-POL-SG-CT-SPV-SWH-GC	CSW-POL-DG-CT-SPV-SWH-GC	BV-XX-SG-CT-SPV-SWH-GC	BV-XX-DG-CT-SPV-SWH-GC	RBV-XX-SG-CT-SPV-SWH-GC	RBV-XX-DG-CT-SPV-SWH-GC	PCSW-XX-SG-CT-SPV-SWH-GC	PCSW-XX-DG-CT-SPV-SWH-GC	CB-XX-SG-CT-SPV-SWH-GC	CB-XX-DG-CT-SPV-SWH-GC	ACC-XX-SG-CT-SPV-SWH-GC	ACC-XX-DG-CT-SPV-SWH-GC	TMB-XX-SG-CT-SPV-SWH-GC	TMB-XX-DG-CT-SPV-SWH-GC
	tonnes CO_2 e-																	
Kununurra (e)	1990	1883	1789	1687	1669	1568	1723	1620	1797	1693	1983	1871	2339	2227	1739	1639	1789	1682
Laverton (b)	423.64	380.66	366.60	325.68	332.67	294.83	405.50	358.89	372.44	330.97	493.21	443.24	534.26	484.48	383.97	339.98	426.44	378.53
Laverton (e)	612.57	567.54	543.01	500.25	505.18	465.70	582.32	533.25	549.06	505.53	681.74	628.89	747.21	694.36	559.56	513.51	607.78	557.20
Mandurah	238.25	229.07	224.67	214.95	211.15	200.41	236.51	223.19	229.62	220.44	288.00	273.02	270.41	256.00	242.31	231.52	242.26	228.15
Mount Magnet (b)	260.32	244.55	238.19	223.99	214.33	200.33	252.26	234.54	243.93	229.17	306.15	286.72	298.94	282.23	251.41	236.93	256.71	238.37
Mount Magnet (e)	359.30	342.77	332.75	318.08	307.56	293.17	347.11	328.73	338.50	323.26	405.71	385.32	407.90	390.23	345.69	330.73	353.19	334.09
Newman (b)	395.88	366.77	349.65	322.83	305.41	281.07	359.61	329.17	354.79	328.16	436.25	404.72	471.56	441.64	353.31	327.53	372.10	341.19
Newman (e)	481.01	451.81	433.35	406.43	388.82	364.47	443.78	413.15	438.49	411.85	522.73	490.81	562.45	532.24	437.00	411.22	457.24	426.03
Yanchep	215.19	208.53	204.50	198.68	193.86	186.22	212.12	201.95	209.66	203.99	255.77	245.46	231.95	222.22	223.26	214.94	212.58	203.58
Note: (b) – if bottled gas is used for heating and hot water, (e) – if electricity is used for heating and hot water																		

Table F.43 Summary of life cycle EE consumption of a reference house for alternative CPS options in 17 locations in regional WA

Location	**DB-XX-SG-CT-SPV-SWH-GC**	**DB-XX-DG-CT-SPV-SWH-GC**	**DB-INS-SG-CT-SPV-SWH-GC**	**DB-INS-DG-CT-SPV-SWH-GC**	**CSW-POL-SG-CT-SPV-SWH-GC**	**CSW-POL-DG-CT-SPV-SWH-GC**	**BV-XX-SG-CT-SPV-SWH-GC**	**BV-XX-DG-CT-SPV-SWH-GC**	**RBV-XX-SG-CT-SPV-SWH-GC**	**RBV-XX-DG-CT-SPV-SWH-GC**	**PCSW-XX-SG-CT-SPV-SWH-GC**	**PCSW-XX-DG-CT-SPV-SWH-GC**	**CB-XX-SG-CT-SPV-SWH-GC**	**CB-XX-DG-CT-SPV-SWH-GC**	**ACC-XX-SG-CT-SPV-SWH-GC**	**ACC-XX-DG-CT-SPV-SWH-GC**	**TMB-XX-SG-CT-SPV-SWH-GC**	**TMB-XX-DG-CT-SPV-SWH-GC**
	TJ																	
Albany	3.9	3.8	3.6	3.5	3.3	3.2	3.4	3.3	3.6	3.5	4.0	3.9	4.1	4.0	3.7	3.6	3.4	3.3
Augusta (b)	4.0	3.9	3.7	3.7	3.4	3.3	3.5	3.4	3.7	3.6	4.1	4.0	4.3	4.2	3.8	3.7	3.6	3.4
Augusta (e)	8.0	7.8	7.2	7.0	6.6	6.3	6.7	6.5	7.2	6.9	7.8	7.6	9.0	8.8	7.0	6.8	7.0	6.7
Armadale	3.3	3.2	3.0	2.9	2.8	2.7	3.1	2.9	3.0	2.9	3.7	3.5	3.7	3.5	3.2	3.0	3.2	3.0
Broome (b)	12.7	12.0	11.8	11.2	11.0	10.4	11.0	10.3	11.7	11.1	12.3	11.7	14.0	13.3	11.5	10.8	11.1	10.5
Broome (e)	14.2	13.6	13.3	12.7	12.6	12.0	12.5	11.8	13.3	12.6	13.9	13.2	15.5	14.8	13.0	12.4	12.7	12.0
Bunbury	3.1	3.0	2.9	2.8	2.7	2.6	3.0	2.8	2.9	2.8	3.6	3.4	3.5	3.3	3.1	3.0	3.1	2.9
Busselton	3.7	3.5	3.3	3.2	3.0	2.9	3.3	3.1	3.3	3.2	3.9	3.7	4.1	3.9	3.4	3.2	3.4	3.2
Carnarvon (b)	3.8	3.6	3.6	3.4	3.3	3.1	3.4	3.2	3.5	3.4	3.9	3.7	3.9	3.7	3.6	3.5	3.3	3.1
Carnarvon (e)	5.3	5.1	5.1	4.9	4.9	4.7	4.9	4.7	5.1	4.9	5.5	5.3	5.6	5.4	5.2	5.0	4.9	4.7
Esperance (b)	3.8	3.7	3.5	3.4	3.3	3.2	3.4	3.3	3.5	3.4	4.0	3.8	4.0	3.9	3.6	3.5	3.4	3.3
Esperance (e)	7.0	6.8	6.4	6.2	6.0	5.8	6.1	5.9	6.4	6.2	7.0	6.8	7.8	7.6	6.4	6.2	6.3	6.1
Geraldton	3.3	3.0	3.1	2.9	2.9	2.7	3.2	3.0	3.0	2.8	3.8	3.5	3.6	3.4	3.3	3.0	3.3	3.0
Joondalup	2.8	2.7	2.7	2.6	2.5	2.4	2.7	2.5	2.6	2.6	3.1	3.0	3.0	2.8	2.8	2.7	2.7	2.5
Kalgoorlie	3.1	2.9	2.8	2.7	2.6	2.5	3.0	2.8	2.8	2.7	3.6	3.4	3.5	3.3	3.0	2.8	3.1	2.9
Kununurra (b)	26.9	25.3	23.9	22.4	22.2	20.7	22.9	21.4	24.0	22.4	26.6	24.9	32.0	30.3	23.1	21.6	23.8	22.3

Location	DB-XX-SG-CT-SPV-SWH-GC	DB-XX-DG-CT-SPV-SWH-GC	DB-INS-SG-CT-SPV-SWH-GC	DB-INS-DG-CT-SPV-SWH-GC	CSW-POL-SG-CT-SPV-SWH-GC	CSW-POL-DG-CT-SPV-SWH-GC	BV-XX-SG-CT-SPV-SWH-GC	BV-XX-DG-CT-SPV-SWH-GC	RBV-XX-SG-CT-SPV-SWH-GC	RBV-XX-DG-CT-SPV-SWH-GC	PCSW-XX-SG-CT-SPV-SWH-GC	PCSW-XX-DG-CT-SPV-SWH-GC	CB-XX-SG-CT-SPV-SWH-GC	CB-XX-DG-CT-SPV-SWH-GC	ACC-XX-SG-CT-SPV-SWH-GC	ACC-XX-DG-CT-SPV-SWH-GC	TMB-XX-SG-CT-SPV-SWH-GC	TMB-XX-DG-CT-SPV-SWH-GC
	TJ																	
Kununurra (e)	29.2	27.7	26.3	24.8	24.5	23.0	25.2	23.7	26.3	24.8	28.9	27.2	34.3	32.6	25.4	23.9	26.2	24.6
Laverton (b)	6.0	5.4	5.2	4.6	4.7	4.1	5.7	5.0	5.2	4.6	6.8	6.1	7.6	6.9	5.4	4.7	6.0	5.3
Laverton (e)	8.9	8.2	7.8	7.2	7.3	6.7	8.3	7.6	7.8	7.2	9.6	8.9	10.8	10.0	8.0	7.3	8.7	8.0
Mandurah	3.1	3.0	3.0	2.8	2.7	2.6	3.0	2.8	2.9	2.8	3.6	3.4	3.5	3.3	3.1	2.9	3.1	2.9
Mount Magnet (b)	4.0	3.7	3.6	3.4	3.2	3.0	3.8	3.5	3.6	3.3	4.5	4.1	4.6	4.3	3.7	3.4	3.9	3.6
Mount Magnet (e)	5.8	5.5	5.3	5.0	4.9	4.6	5.5	5.2	5.3	5.0	6.3	5.9	6.5	6.2	5.4	5.1	5.6	5.3
Newman (b)	6.3	5.8	5.5	5.0	4.8	4.4	5.6	5.1	5.5	5.0	6.7	6.2	7.6	7.1	5.5	5.0	5.9	5.3
Newman (e)	7.9	7.4	7.1	6.6	6.3	5.9	7.2	6.6	7.0	6.6	8.3	7.8	9.2	8.7	7.0	6.5	7.4	6.9
Yanchep	2.8	2.7	2.7	2.6	2.5	2.4	2.7	2.5	2.6	2.6	3.1	3.0	3.0	2.8	2.8	2.7	2.7	2.5

Note: (b) – if bottled gas is used for heating and hot water, (e) – if electricity is used for heating and hot water

Table F.44 Building price indices for construction of a house in regional WA

Location	Price indices
Perth*	100
Albany	115
Armadale	100
Augusta	125
Broome	150
Bunbury	105
Busselton	110
Carnarvon	150
Esperance	130
Geraldton	110
Joondalup	100
Kalgoorlie	135
Kununurra	160
Laverton	150
Mandurah	100
Mount Magnet	150
Newman	165
Yanchep	110
Source:(Rawlinsons 2015)	

Table F.45 Natural gas tariff in regional WA

Location	Supply charges(Cents)/day	Energy charges (Cents)/unit First 12 units	Energy charges (Cents)/unit Next 24 units
Albany	22.21	16.15	N.A
Armadale	20.58	14.2	12.81
Bunbury	20.58	14.2	12.81
Busselton	20.58	14.2	12.81
Geraldton	20.58	14.2	12.81
Joondalup	20.58	14.2	12.81
Kalgoorlie	46.26	13.19	N.A
Mandurah	20.58	14.2	12.81
Perth	20.58	14.2	12.81
Yanchep	20.58	14.2	12.81
Note: 1 unit = 3.6MJ, Cents – Australian Cents **Source**:(DOF 2015b, 2015c)			

Table F.46 Price structure of bottled gas in regional WA

Location	Price per 45kg LPG bottle (AUD)	Reference
Augusta	129.00	Kleenheat Gas, Augusta - +61 8 6410 2304
Broome	189.00	Kleenheat Gas House, Broome - +61 8 9192 3733
Carnarvon	129.00	Mitre 10, Carnarvon - +61 8 9941 1009
Esperance	102.60	Kleenheat Gas, Esperance - +61 8 9071 1300
Kununurra	155.00	Mitre 10, Carnarvon - +61 8 9968 1340
Laverton	111.00	Kleenheat Gas, Laverton - +61 8 9021 2066
Mount Magnet	110.50	Kleenheat Gas House, Mount Magnet - +61 8 9021 2066
Newman	182.00	Newman Hardware, Newman - +61 8 9175 1310, +61 8 9175 0481
Note: Each 45kg liquid petroleum gas (LPG) bottle contains 2.268GJ energy		

Table F.47 Breakdown of LCC of a reference house for alternative CPS options in 17 locations in regional WA

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
Albany										
DB-INS-SG-CT	186,451.83	55,528.00	1,952.59	243,932.43	4,377.77	6,972.21	194.07	16,053.71	9,297.21	229,737.42
DB-INS-DG-CT	192,786.64	54,524.49	1,953.83	249,264.96	4,377.77	6,972.21	194.07	16,053.71	9,297.21	235,069.95
CSW-POL-SG-CT	170,548.92	53,579.71	1,997.77	226,126.40	4,377.77	6,972.21	376.36	16,053.71	9,297.21	211,749.11
CSW-POL-DG-CT	176,883.73	52,513.15	1,999.01	231,395.89	4,377.77	6,972.21	376.36	16,053.71	9,297.21	217,018.59
BV-XX-DG-CT	173,405.93	53,416.55	1,715.21	228,537.70	4,377.77	6,972.21	194.07	16,053.71	9,297.21	214,342.69
RBV-XX-SG-CT	184,693.19	55,479.87	1,823.53	241,996.60	4,377.77	6,972.21	194.07	16,053.71	9,297.21	227,801.59
RBV-XX-DG-CT	191,028.00	54,465.44	1,824.68	247,318.11	4,377.77	6,972.21	194.07	16,053.71	9,297.21	233,123.10
ACC-XX-DG-CT	207,792.91	53,420.86	1,589.78	262,803.55	4,377.77	6,972.21	194.07	16,053.71	9,297.21	248,608.55
TMB-XX-DG-CT	174,459.78	55,043.91	1,536.05	231,039.74	4,377.77	6,972.21	194.07	16,053.71	9,297.21	216,844.73
Armadale										
DB-INS-SG-CT	162,132.03	49,916.03	1,697.91	213,745.96	3,806.76	6,062.80	168.76	19,621.20	8,310.34	195,515.21
DB-INS-DG-CT	167,640.56	48,857.89	1,698.98	218,197.43	3,806.76	6,062.80	168.76	19,621.20	8,310.34	199,966.68
CSW-POL-SG-CT	148,303.41	48,946.91	1,737.20	198,987.51	3,806.76	6,062.80	327.27	19,621.20	8,310.34	180,598.25
CSW-POL-DG-CT	153,811.94	47,697.75	1,738.27	203,247.96	3,806.76	6,062.80	327.27	19,621.20	8,310.34	184,858.70
BV-XX-DG-CT	150,787.77	49,564.68	1,491.49	201,843.93	3,806.76	6,062.80	168.76	19,621.20	8,310.34	183,613.18
RBV-XX-SG-CT	160,602.77	49,907.43	1,585.68	212,095.88	3,806.76	6,062.80	168.76	19,621.20	8,310.34	193,865.13

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	**(b)**	**(c)**	**(d=a+b+c)**	**(e)**	**(f)**	**(g)**	**(h)**	**(i)**	**(d+e+f-g-h-i)**
RBV-XX-DG-CT	166,111.30	48,901.42	1,586.67	216,599.39	3,806.76	6,062.80	168.76	19,621.20	8,310.34	198,368.64
ACC-XX-DG-CT	180,689.49	48,729.79	1,382.41	230,801.70	3,806.76	6,062.80	168.76	19,621.20	8,310.34	212,570.95
TMB-XX-DG-CT	151,704.16	51,447.13	1,335.69	204,486.98	3,806.76	6,062.80	168.76	19,621.20	8,310.34	186,256.23
Augusta (e)										
DB-INS-SG-CT	202,665.03	70,218.38	2,122.38	275,005.80	4,758.45	7,578.49	210.95	8,310.34	9,841.82	268,979.62
DB-INS-DG-CT	209,550.69	68,637.17	2,123.73	280,311.59	4,758.45	7,578.49	210.95	8,310.34	9,841.82	274,285.42
CSW-POL-SG-CT	185,379.26	67,125.47	2,171.49	254,676.22	4,758.45	7,578.49	409.09	8,310.34	9,841.82	248,451.91
CSW-POL-DG-CT	192,264.92	65,526.88	2,172.84	259,964.65	4,758.45	7,578.49	409.09	8,310.34	9,841.82	253,740.33
BV-XX-DG-CT	188,484.71	66,777.95	1,864.36	257,127.02	4,758.45	7,578.49	210.95	8,310.34	9,841.82	251,100.85
RBV-XX-SG-CT	200,753.47	70,131.50	1,982.10	272,867.07	4,758.45	7,578.49	210.95	8,310.34	9,841.82	266,840.89
RBV-XX-DG-CT	207,639.13	68,532.92	1,983.34	278,155.39	4,758.45	7,578.49	210.95	8,310.34	9,841.82	272,129.21
ACC-XX-DG-CT	225,861.86	67,055.96	1,728.02	294,645.85	4,758.45	7,578.49	210.95	8,310.34	9,841.82	288,619.67
TMB-XX-DG-CT	189,630.19	69,193.20	1,669.62	260,493.01	4,758.45	7,578.49	210.95	8,310.34	9,841.82	254,466.83
Augusta (b)										
DB-INS-SG-CT	202,665.03	61,475.25	2,122.38	266,262.67	4,758.45	7,578.49	210.95	16,053.71	11,787.71	250,547.24
DB-INS-DG-CT	209,550.69	60,162.59	2,123.73	271,837.01	4,758.45	7,578.49	210.95	16,053.71	11,787.71	256,121.58
CSW-POL-SG-CT	185,379.26	59,039.57	2,171.49	246,590.32	4,758.45	7,578.49	409.09	16,053.71	11,787.71	230,676.76
CSW-POL-DG-CT	192,264.92	57,705.99	2,172.84	252,143.75	4,758.45	7,578.49	409.09	16,053.71	11,787.71	236,230.19

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
BV-XX-DG-CT	188,484.71	58,808.65	1,864.36	249,157.72	4,758.45	7,578.49	210.95	16,053.71	11,787.71	233,442.30
RBV-XX-SG-CT	200,753.47	61,409.57	1,982.10	264,145.14	4,758.45	7,578.49	210.95	16,053.71	11,787.71	248,429.72
RBV-XX-DG-CT	207,639.13	60,079.53	1,983.34	269,702.00	4,758.45	7,578.49	210.95	16,053.71	11,787.71	253,986.58
ACC-XX-DG-CT	225,861.86	58,955.93	1,728.02	286,545.81	4,758.45	7,578.49	210.95	16,053.71	11,787.71	270,830.38
TMB-XX-DG-CT	189,630.19	60,796.35	1,669.62	252,096.16	4,758.45	7,578.49	210.95	16,053.71	11,787.71	236,380.74
Broome (e)										
DB-INS-SG-CT	243,198.04	120,515.38	2,546.86	366,260.28	5,710.14	9,094.19	253.14	22,296.82	11,188.00	347,326.65
DB-INS-DG-CT	251,460.83	116,067.15	2,548.47	370,076.46	5,710.14	9,094.19	253.14	22,296.82	11,188.00	351,142.83
CSW-POL-SG-CT	222,455.11	117,022.83	2,605.79	342,083.73	5,710.14	9,094.19	490.91	22,296.82	11,188.00	322,912.34
CSW-POL-DG-CT	230,717.90	112,661.47	2,607.41	345,986.79	5,710.14	9,094.19	490.91	22,296.82	11,188.00	326,815.39
BV-XX-DG-CT	226,181.65	111,740.55	2,237.24	340,159.44	5,710.14	9,094.19	253.14	22,296.82	11,188.00	321,225.81
RBV-XX-SG-CT	240,904.16	120,550.14	2,378.52	363,832.82	5,710.14	9,094.19	253.14	22,296.82	11,188.00	344,899.19
RBV-XX-DG-CT	249,166.95	116,067.15	2,380.01	367,614.12	5,710.14	9,094.19	253.14	22,296.82	11,188.00	348,680.48
ACC-XX-DG-CT	271,034.24	113,565.02	2,073.62	386,672.88	5,710.14	9,094.19	253.14	22,296.82	11,188.00	367,739.25
TMB-XX-DG-CT	227,556.23	114,190.55	2,003.54	343,750.32	5,710.14	9,094.19	253.14	22,296.82	11,188.00	324,816.69
Broome (b)										
DB-INS-SG-CT	243,198.04	124,547.43	2,546.86	370,292.32	5,710.14	9,094.19	253.14	22,296.82	22,446.19	340,100.51
DB-INS-DG-CT	251,460.83	120,099.19	2,548.47	374,108.50	5,710.14	9,094.19	253.14	22,296.82	22,446.19	343,916.68

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
CSW-POL-SG-CT	222,455.11	121,054.87	2,605.79	346,115.77	5,710.14	9,094.19	490.91	22,296.82	22,446.19	315,686.19
CSW-POL-DG-CT	230,717.90	116,693.52	2,607.41	350,018.83	5,710.14	9,094.19	490.91	22,296.82	22,446.19	319,589.25
BV-XX-DG-CT	226,181.65	115,772.59	2,237.24	344,191.48	5,710.14	9,094.19	253.14	22,296.82	22,446.19	313,999.66
RBV-XX-SG-CT	240,904.16	124,582.18	2,378.52	367,864.86	5,710.14	9,094.19	253.14	22,296.82	22,446.19	337,673.04
RBV-XX-DG-CT	249,166.95	120,099.19	2,380.01	371,646.16	5,710.14	9,094.19	253.14	22,296.82	22,446.19	341,454.34
ACC-XX-DG-CT	271,034.24	117,597.06	2,073.62	390,704.92	5,710.14	9,094.19	253.14	22,296.82	22,446.19	360,513.10
TMB-XX-DG-CT	227,556.23	118,222.60	2,003.54	347,782.37	5,710.14	9,094.19	253.14	22,296.82	22,446.19	317,590.55
Bunbury										
DB-INS-SG-CT	170,238.63	47,644.31	1,782.80	219,665.74	3,997.09	6,365.94	177.20	19,621.20	8,551.08	201,679.29
DB-INS-DG-CT	176,022.58	46,645.84	1,783.93	224,452.36	3,997.09	6,365.94	177.20	19,621.20	8,572.69	206,444.29
CSW-POL-SG-CT	155,718.58	47,072.98	1,824.05	204,615.62	3,997.09	6,365.94	343.63	19,621.20	8,620.62	186,393.20
CSW-POL-DG-CT	161,502.53	46,031.10	1,825.19	209,358.82	3,997.09	6,365.94	343.63	19,621.20	8,643.17	191,113.85
BV-XX-DG-CT	158,327.15	47,837.30	1,566.07	207,730.52	3,997.09	6,365.94	177.20	19,621.20	8,613.10	189,682.05
RBV-XX-SG-CT	168,632.91	47,696.44	1,664.96	217,994.32	3,997.09	6,365.94	177.20	19,621.20	8,551.08	200,007.87
RBV-XX-DG-CT	174,416.87	46,680.65	1,666.01	222,763.53	3,997.09	6,365.94	177.20	19,621.20	8,574.57	204,753.58
ACC-XX-DG-CT	189,723.97	46,820.72	1,451.53	237,996.22	3,997.09	6,365.94	177.20	19,621.20	8,610.28	219,950.57
TMB-XX-DG-CT	159,289.36	49,286.70	1,402.48	209,978.54	3,997.09	6,365.94	177.20	19,621.20	8,563.30	191,979.87
Busselton										

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
DB-INS-SG-CT	178,345.23	53,353.39	1,867.70	233,566.32	4,187.43	6,669.07	185.64	19,621.20	8,310.34	216,305.65
DB-INS-DG-CT	184,404.61	51,844.38	1,868.88	238,117.87	4,187.43	6,669.07	185.64	19,621.20	8,310.34	220,857.20
CSW-POL-SG-CT	163,133.75	51,578.62	1,910.91	216,623.28	4,187.43	6,669.07	360.00	19,621.20	8,310.34	199,188.25
CSW-POL-DG-CT	169,193.13	50,130.45	1,912.10	221,235.68	4,187.43	6,669.07	360.00	19,621.20	8,310.34	203,800.65
BV-XX-DG-CT	165,866.54	51,615.61	1,640.64	219,122.80	4,187.43	6,669.07	185.64	19,621.20	8,310.34	201,862.12
RBV-XX-SG-CT	176,663.05	53,310.20	1,744.25	231,717.50	4,187.43	6,669.07	185.64	19,621.20	8,310.34	214,456.83
RBV-XX-DG-CT	182,722.43	51,861.98	1,745.34	236,329.75	4,187.43	6,669.07	185.64	19,621.20	8,310.34	219,069.08
ACC-XX-DG-CT	198,758.44	51,092.54	1,520.66	251,371.64	4,187.43	6,669.07	185.64	19,621.20	8,310.34	234,110.96
TMB-XX-DG-CT	166,874.57	53,627.52	1,469.26	221,971.35	4,187.43	6,669.07	185.64	19,621.20	8,310.34	204,710.68
Carnarvon (e)										
DB-INS-SG-CT	243,198.04	63,279.15	2,546.86	309,024.05	5,710.14	9,094.19	253.14	22,296.82	11,188.00	290,090.42
DB-INS-DG-CT	251,460.83	61,993.33	2,548.47	316,002.64	5,710.14	9,094.19	253.14	22,296.82	11,188.00	297,069.01
CSW-POL-SG-CT	222,455.11	62,827.37	2,605.79	287,888.28	5,710.14	9,094.19	490.91	22,296.82	11,188.00	268,716.88
CSW-POL-DG-CT	230,717.90	61,506.81	2,607.41	294,832.12	5,710.14	9,094.19	490.91	22,296.82	11,188.00	275,660.72
BV-XX-DG-CT	226,181.65	61,836.95	2,237.24	290,255.83	5,710.14	9,094.19	253.14	22,296.82	11,188.00	271,322.20
RBV-XX-SG-CT	240,904.16	63,261.77	2,378.52	306,544.45	5,710.14	9,094.19	253.14	22,296.82	11,188.00	287,610.82
RBV-XX-DG-CT	249,166.95	62,062.83	2,380.01	313,609.80	5,710.14	9,094.19	253.14	22,296.82	11,188.00	294,676.17
ACC-XX-DG-CT	271,034.24	61,993.33	2,073.62	335,101.19	5,710.14	9,094.19	253.14	22,296.82	11,188.00	316,167.56

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
TMB-XX-DG-CT	227,556.23	62,723.12	2,003.54	292,282.89	5,710.14	9,094.19	253.14	22,296.82	11,188.00	273,349.26
Carnarvon (b)										
DB-INS-SG-CT	243,198.04	58,371.10	2,546.86	304,116.00	5,710.14	9,094.19	253.14	22,296.82	15,320.41	281,049.95
DB-INS-DG-CT	251,460.83	57,088.81	2,548.47	311,098.12	5,710.14	9,094.19	253.14	22,296.82	15,320.41	288,032.08
CSW-POL-SG-CT	222,455.11	57,922.86	2,605.79	282,983.76	5,710.14	9,094.19	490.91	22,296.82	15,320.41	259,679.95
CSW-POL-DG-CT	230,717.90	56,602.29	2,607.41	289,927.60	5,710.14	9,094.19	490.91	22,296.82	15,320.41	266,623.79
BV-XX-DG-CT	226,181.65	56,921.83	2,237.24	285,340.72	5,710.14	9,094.19	253.14	22,296.82	15,320.41	262,274.67
RBV-XX-SG-CT	240,904.16	58,353.72	2,378.52	301,636.40	5,710.14	9,094.19	253.14	22,296.82	15,320.41	278,570.36
RBV-XX-DG-CT	249,166.95	57,158.32	2,380.01	308,705.28	5,710.14	9,094.19	253.14	22,296.82	15,320.41	285,639.24
ACC-XX-DG-CT	271,034.24	57,085.28	2,073.62	330,193.14	5,710.14	9,094.19	253.14	22,296.82	15,320.41	307,127.09
TMB-XX-DG-CT	227,556.23	57,793.87	2,003.54	287,353.64	5,710.14	9,094.19	253.14	22,296.82	15,320.41	264,287.59
Esperance (e)										
DB-INS-SG-CT	210,771.64	64,727.59	2,207.28	277,706.51	4,948.78	7,881.63	219.39	16,053.71	9,841.82	264,422.00
DB-INS-DG-CT	217,932.72	63,424.40	2,208.68	283,565.80	4,948.78	7,881.63	219.39	16,053.71	9,841.82	270,281.30
CSW-POL-SG-CT	192,794.43	62,833.62	2,258.35	257,886.40	4,948.78	7,881.63	425.45	16,053.71	9,841.82	244,395.84
CSW-POL-DG-CT	199,955.52	61,391.42	2,259.75	263,606.69	4,948.78	7,881.63	425.45	16,053.71	9,841.82	250,116.13
BV-XX-DG-CT	196,024.10	62,711.99	1,938.94	260,675.02	4,948.78	7,881.63	219.39	16,053.71	9,841.82	247,390.52
RBV-XX-SG-CT	208,783.61	64,762.34	2,061.38	275,607.34	4,948.78	7,881.63	219.39	16,053.71	9,841.82	262,322.83

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
RBV-XX-DG-CT	215,944.69	63,407.02	2,062.68	281,414.39	4,948.78	7,881.63	219.39	16,053.71	9,841.82	268,129.89
ACC-XX-DG-CT	234,896.34	62,520.85	1,797.14	299,214.33	4,948.78	7,881.63	219.39	16,053.71	9,841.82	285,929.83
TMB-XX-DG-CT	197,215.40	64,553.83	1,736.40	263,505.64	4,948.78	7,881.63	219.39	16,053.71	9,841.82	250,221.13
Esperance (b)										
DB-INS-SG-CT	210,771.64	51,292.21	2,207.28	264,271.12	4,948.78	7,881.63	219.39	16,053.71	9,375.34	251,453.10
DB-INS-DG-CT	217,932.72	50,320.06	2,208.68	270,461.46	4,948.78	7,881.63	219.39	16,053.71	9,375.34	257,643.45
CSW-POL-SG-CT	192,794.43	50,155.83	2,258.35	245,208.61	4,948.78	7,881.63	425.45	16,053.71	9,375.34	232,184.53
CSW-POL-DG-CT	199,955.52	49,051.04	2,259.75	251,266.31	4,948.78	7,881.63	425.45	16,053.71	9,375.34	238,242.23
BV-XX-DG-CT	196,024.10	50,167.89	1,938.94	248,130.92	4,948.78	7,881.63	219.39	16,053.71	9,375.34	235,312.91
RBV-XX-SG-CT	208,783.61	51,339.69	2,061.38	262,184.68	4,948.78	7,881.63	219.39	16,053.71	9,375.34	249,366.67
RBV-XX-DG-CT	215,944.69	50,321.79	2,062.68	268,329.16	4,948.78	7,881.63	219.39	16,053.71	9,375.34	255,511.14
ACC-XX-DG-CT	234,896.34	49,862.16	1,797.14	286,555.64	4,948.78	7,881.63	219.39	16,053.71	9,375.34	273,737.62
TMB-XX-DG-CT	197,215.40	51,494.06	1,736.40	250,445.86	4,948.78	7,881.63	219.39	16,053.71	9,375.34	237,627.85
Geraldton										
DB-INS-SG-CT	178,345.23	47,710.60	1,867.70	227,923.52	4,187.43	6,669.07	185.64	19,621.20	8,734.32	210,238.88
DB-INS-DG-CT	184,404.61	46,286.22	1,868.88	232,559.71	4,187.43	6,669.07	185.64	19,621.20	8,749.35	214,860.03
CSW-POL-SG-CT	163,133.75	47,493.65	1,910.91	212,538.32	4,187.43	6,669.07	360.00	19,621.20	8,742.78	194,670.85
CSW-POL-DG-CT	169,193.13	46,138.78	1,912.10	217,244.01	4,187.43	6,669.07	360.00	19,621.20	8,757.81	199,361.51

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
BV-XX-DG-CT	165,866.54	48,275.40	1,640.64	215,782.58	4,187.43	6,669.07	185.64	19,621.20	8,737.14	198,095.12
RBV-XX-SG-CT	176,663.05	47,754.01	1,744.25	226,161.31	4,187.43	6,669.07	185.64	19,621.20	8,733.38	208,477.60
RBV-XX-DG-CT	182,722.43	46,373.05	1,745.34	230,840.82	4,187.43	6,669.07	185.64	19,621.20	8,747.47	213,143.02
ACC-XX-DG-CT	198,758.44	46,911.70	1,520.66	247,190.80	4,187.43	6,669.07	185.64	19,621.20	8,747.47	229,492.99
TMB-XX-DG-CT	166,874.57	49,595.13	1,469.26	217,938.96	4,187.43	6,669.07	185.64	19,621.20	8,708.95	200,279.68
Joondalup										
DB-INS-SG-CT	162,132.03	45,206.90	1,697.91	209,036.83	3,806.76	6,062.80	168.76	19,621.20	8,681.70	190,434.73
DB-INS-DG-CT	167,640.56	44,564.44	1,698.98	213,903.97	3,806.76	6,062.80	168.76	19,621.20	8,696.73	195,286.84
CSW-POL-SG-CT	148,303.41	45,034.20	1,737.20	195,074.81	3,806.76	6,062.80	327.27	19,621.20	8,717.41	176,278.49
CSW-POL-DG-CT	153,811.94	44,226.70	1,738.27	199,776.91	3,806.76	6,062.80	327.27	19,621.20	8,733.38	180,964.61
BV-XX-DG-CT	150,787.77	45,476.64	1,491.49	197,755.90	3,806.76	6,062.80	168.76	19,621.20	8,695.79	179,139.70
RBV-XX-SG-CT	160,602.77	45,241.59	1,585.68	207,430.05	3,806.76	6,062.80	168.76	19,621.20	8,679.82	188,829.82
RBV-XX-DG-CT	166,111.30	44,590.47	1,586.67	212,288.45	3,806.76	6,062.80	168.76	19,621.20	8,695.79	193,672.25
ACC-XX-DG-CT	180,689.49	44,816.75	1,382.41	226,888.66	3,806.76	6,062.80	168.76	19,621.20	8,708.95	208,259.30
TMB-XX-DG-CT	151,704.16	46,604.90	1,335.69	199,644.75	3,806.76	6,062.80	168.76	19,621.20	8,656.33	181,068.01
Kalgoorlie										
DB-INS-SG-CT	218,878.24	47,918.31	2,292.17	269,088.71	5,139.12	8,184.77	227.83	19,621.20	8,556.87	254,006.72
DB-INS-DG-CT	226,314.75	46,799.38	2,293.63	275,407.76	5,139.12	8,184.77	227.83	19,621.20	8,556.87	260,325.76

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
CSW-POL-SG-CT	200,209.60	47,242.92	2,345.21	249,797.73	5,139.12	8,184.77	441.81	19,621.20	8,556.87	234,501.75
CSW-POL-DG-CT	207,646.11	46,089.24	2,346.67	256,082.02	5,139.12	8,184.77	441.81	19,621.20	8,556.87	240,786.04
BV-XX-DG-CT	203,563.48	48,462.43	2,013.51	254,039.43	5,139.12	8,184.77	227.83	19,621.20	8,556.87	238,957.44
RBV-XX-SG-CT	216,813.74	47,961.97	2,140.67	266,916.39	5,139.12	8,184.77	227.83	19,621.20	8,556.87	251,834.39
RBV-XX-DG-CT	224,250.26	46,859.97	2,142.01	273,252.24	5,139.12	8,184.77	227.83	19,621.20	8,556.87	258,170.24
ACC-XX-DG-CT	243,930.81	47,010.86	1,866.26	292,807.93	5,139.12	8,184.77	227.83	19,621.20	8,556.87	277,725.94
TMB-XX-DG-CT	204,800.61	50,275.72	1,803.18	256,879.51	5,139.12	8,184.77	227.83	19,621.20	8,556.87	241,797.51
Kununurra (e)										
DB-INS-SG-CT	259,411.24	153,460.10	2,716.65	415,587.99	6,090.81	9,700.47	270.02	22,296.82	11,188.00	397,624.44
DB-INS-DG-CT	268,224.89	146,388.11	2,718.37	417,331.37	6,090.81	9,700.47	270.02	22,296.82	11,188.00	399,367.82
CSW-POL-SG-CT	237,285.45	146,075.34	2,779.51	386,140.31	6,090.81	9,700.47	523.63	22,296.82	11,188.00	367,923.14
CSW-POL-DG-CT	246,099.10	139,055.48	2,781.24	387,935.81	6,090.81	9,700.47	523.63	22,296.82	11,188.00	369,718.64
BV-XX-DG-CT	241,260.43	142,270.02	2,386.39	385,916.83	6,090.81	9,700.47	270.02	22,296.82	11,188.00	367,953.28
RBV-XX-SG-CT	256,964.44	153,703.36	2,537.09	413,204.89	6,090.81	9,700.47	270.02	22,296.82	11,188.00	395,241.34
RBV-XX-DG-CT	265,778.08	146,492.36	2,538.68	414,809.13	6,090.81	9,700.47	270.02	22,296.82	11,188.00	396,845.57
ACC-XX-DG-CT	289,103.19	142,252.64	2,211.86	433,567.69	6,090.81	9,700.47	270.02	22,296.82	11,188.00	415,604.14
TMB-XX-DG-CT	242,726.65	147,256.90	2,137.11	392,120.66	6,090.81	9,700.47	270.02	22,296.82	11,188.00	374,157.11
Kununurra (b)										

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	**(b)**	**(c)**	**(d=a+b+c)**	**(e)**	**(f)**	**(g)**	**(h)**	**(i)**	**(d+e+f-g-h-i)**
DB-INS-SG-CT	259,411.24	152,428.09	2,716.65	414,555.99	6,090.81	9,700.47	270.02	22,296.82	18,408.25	389,372.19
DB-INS-DG-CT	268,224.89	145,356.10	2,718.37	416,299.36	6,090.81	9,700.47	270.02	22,296.82	18,408.25	391,115.56
CSW-POL-SG-CT	237,285.45	145,043.33	2,779.51	385,108.30	6,090.81	9,700.47	523.63	22,296.82	18,408.25	359,670.88
CSW-POL-DG-CT	246,099.10	138,023.47	2,781.24	386,903.80	6,090.81	9,700.47	523.63	22,296.82	18,408.25	361,466.39
BV-XX-DG-CT	241,260.43	141,238.01	2,386.39	384,884.82	6,090.81	9,700.47	270.02	22,296.82	18,408.25	359,701.02
RBV-XX-SG-CT	256,964.44	152,671.36	2,537.09	412,172.88	6,090.81	9,700.47	270.02	22,296.82	18,408.25	386,989.08
RBV-XX-DG-CT	265,778.08	145,460.35	2,538.68	413,777.12	6,090.81	9,700.47	270.02	22,296.82	18,408.25	388,593.32
ACC-XX-DG-CT	289,103.19	141,220.63	2,211.86	432,535.68	6,090.81	9,700.47	270.02	22,296.82	18,408.25	407,351.88
TMB-XX-DG-CT	242,726.65	146,224.89	2,137.11	391,088.65	6,090.81	9,700.47	270.02	22,296.82	18,408.25	365,904.85
Laverton (e)										
DB-INS-SG-CT	243,198.04	66,285.18	2,546.86	312,030.08	5,710.14	9,094.19	253.14	22,296.82	11,188.00	293,096.45
DB-INS-DG-CT	251,460.83	63,296.52	2,548.47	317,305.83	5,710.14	9,094.19	253.14	22,296.82	11,188.00	298,372.20
CSW-POL-SG-CT	222,455.11	64,530.21	2,605.79	289,591.12	5,710.14	9,094.19	490.91	22,296.82	11,188.00	270,419.72
CSW-POL-DG-CT	230,717.90	61,767.44	2,607.41	295,092.76	5,710.14	9,094.19	490.91	22,296.82	11,188.00	275,921.36
BV-XX-DG-CT	226,181.65	66,215.68	2,237.24	294,634.56	5,710.14	9,094.19	253.14	22,296.82	11,188.00	275,700.93
RBV-XX-SG-CT	240,904.16	66,406.81	2,378.52	309,689.49	5,710.14	9,094.19	253.14	22,296.82	11,188.00	290,755.86
RBV-XX-DG-CT	249,166.95	63,366.03	2,380.01	314,912.99	5,710.14	9,094.19	253.14	22,296.82	11,188.00	295,979.36
ACC-XX-DG-CT	271,034.24	63,539.79	2,073.62	336,647.64	5,710.14	9,094.19	253.14	22,296.82	11,188.00	317,714.01

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
TMB-XX-DG-CT	227,556.23	68,596.18	2,003.54	298,155.95	5,710.14	9,094.19	253.14	22,296.82	11,188.00	279,222.32
Laverton (b)										
DB-INS-SG-CT	243,198.04	58,388.19	2,546.86	304,133.09	5,710.14	9,094.19	253.14	22,296.82	13,182.68	283,204.78
DB-INS-DG-CT	251,460.83	55,448.72	2,548.47	309,458.03	5,710.14	9,094.19	253.14	22,296.82	13,182.68	288,529.72
CSW-POL-SG-CT	222,455.11	56,737.06	2,605.79	281,797.97	5,710.14	9,094.19	490.91	22,296.82	13,182.68	260,631.89
CSW-POL-DG-CT	230,717.90	54,018.01	2,607.41	287,343.32	5,710.14	9,094.19	490.91	22,296.82	13,182.68	266,177.25
BV-XX-DG-CT	226,181.65	58,373.34	2,237.24	286,792.22	5,710.14	9,094.19	253.14	22,296.82	13,182.68	265,863.91
RBV-XX-SG-CT	240,904.16	58,504.36	2,378.52	301,787.04	5,710.14	9,094.19	253.14	22,296.82	13,182.68	280,858.73
RBV-XX-DG-CT	249,166.95	55,518.22	2,380.01	307,065.19	5,710.14	9,094.19	253.14	22,296.82	13,182.68	286,136.88
ACC-XX-DG-CT	271,034.24	55,719.31	2,073.62	328,827.16	5,710.14	9,094.19	253.14	22,296.82	13,182.68	307,898.85
TMB-XX-DG-CT	227,556.23	60,639.07	2,003.54	290,198.84	5,710.14	9,094.19	253.14	22,296.82	13,182.68	269,270.53
Mandurah										
DB-INS-SG-CT	162,132.03	47,687.67	1,697.91	211,517.60	3,806.76	6,062.80	168.76	19,621.20	8,548.26	193,048.93
DB-INS-DG-CT	167,640.56	46,663.16	1,698.98	216,002.70	3,806.76	6,062.80	168.76	19,621.20	8,570.82	197,511.48
CSW-POL-SG-CT	148,303.41	47,072.93	1,737.20	197,113.53	3,806.76	6,062.80	327.27	19,621.20	8,618.74	178,415.88
CSW-POL-DG-CT	153,811.94	45,952.88	1,738.27	201,503.09	3,806.76	6,062.80	327.27	19,621.20	8,642.23	182,781.94
BV-XX-DG-CT	150,787.77	47,767.80	1,491.49	200,047.05	3,806.76	6,062.80	168.76	19,621.20	8,613.10	181,513.54
RBV-XX-SG-CT	160,602.77	47,687.67	1,585.68	209,876.12	3,806.76	6,062.80	168.76	19,621.20	8,548.26	191,407.45

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	**(b)**	**(c)**	**(d=a+b+c)**	**(e)**	**(f)**	**(g)**	**(h)**	**(i)**	**(d+e+f-g-h-i)**
RBV-XX-DG-CT	166,111.30	46,706.63	1,586.67	214,404.61	3,806.76	6,062.80	168.76	19,621.20	8,571.76	195,912.44
ACC-XX-DG-CT	180,689.49	46,785.92	1,382.41	228,857.82	3,806.76	6,062.80	168.76	19,621.20	8,608.40	210,329.01
TMB-XX-DG-CT	151,704.16	49,225.86	1,335.69	202,265.70	3,806.76	6,062.80	168.76	19,621.20	8,562.36	183,782.94
Mount Magnet (e)										
DB-INS-SG-CT	243,198.04	61,593.41	2,546.86	307,338.31	5,710.14	9,094.19	253.14	19,621.20	10,656.32	291,611.98
DB-INS-DG-CT	251,460.83	59,734.19	2,548.47	313,743.50	5,710.14	9,094.19	253.14	19,621.20	10,656.32	298,017.17
CSW-POL-SG-CT	222,455.11	60,481.36	2,605.79	285,542.26	5,710.14	9,094.19	490.91	19,621.20	10,656.32	269,578.17
CSW-POL-DG-CT	230,717.90	58,656.89	2,607.41	291,982.20	5,710.14	9,094.19	490.91	19,621.20	10,656.32	276,018.11
BV-XX-DG-CT	226,181.65	62,149.44	2,237.24	290,568.33	5,710.14	9,094.19	253.14	19,621.20	10,656.32	274,842.00
RBV-XX-SG-CT	240,904.16	61,767.17	2,378.52	305,049.85	5,710.14	9,094.19	253.14	19,621.20	10,656.32	289,323.53
RBV-XX-DG-CT	249,166.95	59,838.45	2,380.01	311,385.41	5,710.14	9,094.19	253.14	19,621.20	10,656.32	295,659.08
ACC-XX-DG-CT	271,034.24	60,064.33	2,073.62	333,172.19	5,710.14	9,094.19	253.14	19,621.20	10,656.32	317,445.86
TMB-XX-DG-CT	227,556.23	64,078.17	2,003.54	293,637.94	5,710.14	9,094.19	253.14	19,621.20	10,656.32	277,911.61
Mount Magnet (b)										
DB-INS-SG-CT	243,198.04	53,282.35	2,546.86	299,027.25	5,710.14	9,094.19	253.14	19,621.20	11,378.67	282,578.56
DB-INS-DG-CT	251,460.83	51,450.72	2,548.47	305,460.02	5,710.14	9,094.19	253.14	19,621.20	11,378.67	289,011.34
CSW-POL-SG-CT	222,455.11	52,247.55	2,605.79	277,308.46	5,710.14	9,094.19	490.91	19,621.20	11,378.67	260,622.01
CSW-POL-DG-CT	230,717.90	50,445.15	2,607.41	283,770.47	5,710.14	9,094.19	490.91	19,621.20	11,378.67	267,084.02

CPS options 1AUD = 0.7229US$	Present value - US$			Life cycle cost - US$	Present value of additional capital and replacement cost - US$		Present value of capital cost and life cycle operational cost saving - US$			Net life cycle cost - US$
	Capital cost	Life cycle operational cost	End of life demolition and disposal cost		SPV	SWH	GC	SPV	SWH	
	(a)	(b)	(c)	(d=a+b+c)	(e)	(f)	(g)	(h)	(i)	(d+e+f-g-h-i)
BV-XX-DG-CT	226,181.65	53,860.45	2,237.24	282,279.34	5,710.14	9,094.19	253.14	19,621.20	11,378.67	265,830.65
RBV-XX-SG-CT	240,904.16	53,456.11	2,378.52	296,738.79	5,710.14	9,094.19	253.14	19,621.20	11,378.67	280,290.10
RBV-XX-DG-CT	249,166.95	51,554.97	2,380.01	303,101.94	5,710.14	9,094.19	253.14	19,621.20	11,378.67	286,653.25
ACC-XX-DG-CT	271,034.24	51,797.42	2,073.62	324,905.27	5,710.14	9,094.19	253.14	19,621.20	11,378.67	308,456.59
TMB-XX-DG-CT	227,556.23	55,700.88	2,003.54	285,260.65	5,710.14	9,094.19	253.14	19,621.20	11,378.67	268,811.96
Newman (e)										
DB-INS-SG-CT	267,517.85	75,529.16	2,801.54	345,848.55	6,281.15	10,003.61	278.45	22,296.82	11,188.00	328,370.04
DB-INS-DG-CT	276,606.92	72,175.61	2,803.32	351,585.85	6,281.15	10,003.61	278.45	22,296.82	11,188.00	334,107.34
CSW-POL-SG-CT	244,700.62	72,870.65	2,866.37	320,437.65	6,281.15	10,003.61	540.00	22,296.82	11,188.00	302,697.59
CSW-POL-DG-CT	253,789.70	69,829.86	2,868.15	326,487.71	6,281.15	10,003.61	540.00	22,296.82	11,188.00	308,747.66
BV-XX-DG-CT	248,799.81	74,486.61	2,460.96	325,747.38	6,281.15	10,003.61	278.45	22,296.82	11,188.00	308,268.87
RBV-XX-SG-CT	264,994.58	75,720.30	2,616.37	343,331.25	6,281.15	10,003.61	278.45	22,296.82	11,188.00	325,852.73
RBV-XX-DG-CT	274,083.65	72,401.50	2,618.01	349,103.16	6,281.15	10,003.61	278.45	22,296.82	11,188.00	331,624.65
ACC-XX-DG-CT	298,137.66	72,001.85	2,280.98	372,420.50	6,281.15	10,003.61	278.45	22,296.82	11,188.00	354,941.98
TMB-XX-DG-CT	250,311.86	77,596.89	2,203.89	330,112.64	6,281.15	10,003.61	278.45	22,296.82	11,188.00	312,634.13
Newman (b)										
DB-INS-SG-CT	267,517.85	78,527.22	2,801.54	348,846.61	6,281.15	10,003.61	278.45	22,296.82	21,614.85	320,941.25
DB-INS-DG-CT	276,606.92	75,171.52	2,803.32	354,581.75	6,281.15	10,003.61	278.45	22,296.82	21,614.85	326,676.39

CPS options 1AUD = 0.7229US$	**Present value - US$**			**Life cycle cost - US$**	**Present value of additional capital and replacement cost - US$**		**Present value of capital cost and life cycle operational cost saving - US$**			**Net life cycle cost - US$**
	Capital cost	**Life cycle operational cost**	**End of life demolition and disposal cost**		**SPV**	**SWH**	**GC**	**SPV**	**SWH**	
	(a)	**(b)**	**(c)**	**(d=a+b+c)**	**(e)**	**(f)**	**(g)**	**(h)**	**(i)**	**(d+e+f-g-h-i)**
CSW-POL-SG-CT	244,700.62	75,862.25	2,866.37	323,429.24	6,281.15	10,003.61	540.00	22,296.82	21,614.85	295,262.34
CSW-POL-DG-CT	253,789.70	72,821.46	2,868.15	329,479.31	6,281.15	10,003.61	540.00	22,296.82	21,614.85	301,312.41
BV-XX-DG-CT	248,799.81	77,491.13	2,460.96	328,751.90	6,281.15	10,003.61	278.45	22,296.82	21,614.85	300,846.54
RBV-XX-SG-CT	264,994.58	78,718.35	2,616.37	346,329.30	6,281.15	10,003.61	278.45	22,296.82	21,614.85	318,423.95
RBV-XX-DG-CT	274,083.65	75,399.56	2,618.01	352,101.22	6,281.15	10,003.61	278.45	22,296.82	21,614.85	324,195.86
ACC-XX-DG-CT	298,137.66	74,999.91	2,280.98	375,418.55	6,281.15	10,003.61	278.45	22,296.82	21,614.85	347,513.20
TMB-XX-DG-CT	250,311.86	80,620.80	2,203.89	333,136.55	6,281.15	10,003.61	278.45	22,296.82	21,614.85	305,231.19
Yanchep										
DB-INS-SG-CT	178,345.23	45,215.56	1,867.70	225,428.48	4,187.43	6,669.07	185.64	19,621.20	8,680.76	207,797.40
DB-INS-DG-CT	184,404.61	44,573.10	1,868.88	230,846.59	4,187.43	6,669.07	185.64	19,621.20	8,695.79	213,200.47
CSW-POL-SG-CT	163,133.75	45,034.20	1,910.91	210,078.87	4,187.43	6,669.07	360.00	19,621.20	8,717.41	192,236.77
CSW-POL-DG-CT	169,193.13	44,226.70	1,912.10	215,331.93	4,187.43	6,669.07	360.00	19,621.20	8,733.38	197,473.86
BV-XX-DG-CT	165,866.54	45,459.27	1,640.64	212,966.45	4,187.43	6,669.07	185.64	19,621.20	8,695.79	195,320.33
RBV-XX-SG-CT	176,663.05	45,241.59	1,744.25	223,648.89	4,187.43	6,669.07	185.64	19,621.20	8,679.82	206,018.75
RBV-XX-DG-CT	182,722.43	44,607.85	1,745.34	229,075.62	4,187.43	6,669.07	185.64	19,621.20	8,695.79	211,429.50
ACC-XX-DG-CT	198,758.44	44,808.04	1,520.66	245,087.13	4,187.43	6,669.07	185.64	19,621.20	8,708.01	227,428.80
TMB-XX-DG-CT	166,874.57	46,570.15	1,469.26	214,913.98	4,187.43	6,669.07	185.64	19,621.20	8,656.33	197,307.33
Note: (b) – use of bottled gas for heating and hot water, (e) – use of electricity for heating and hot water										

Table F.48 Savings to investment ratios of SPV and SWH in 17 locations in regional WA

	Solar radiation zone	Savings to investment ratio		
		SPV	SWH	Combined SPV+SWH
Broome (b)	2	3.9	2.5	3.0
Broome (e)	2	3.9	1.2	2.3
Carnarvon (b)	2	3.9	1.7	2.5
Carnarvon (e)	2	3.9	1.2	2.3
Kununurra (b)	2	3.7	1.9	2.6
Kununurra (e)	2	3.7	1.2	2.1
Laverton (b)	2	3.9	1.4	2.4
Laverton (e)	2	3.9	1.2	2.3
Newman (b)	2	3.5	2.2	2.7
Newman (e)	2	3.5	1.1	2.1
Armadale	3	5.2	1.4	2.8
Bunbury	3	4.9	1.3	2.7
Busselton	3	4.7	1.2	2.6
Geraldton	3	4.7	1.3	2.6
Joondalup	3	5.2	1.4	2.9
Kalgoorlie	3	3.8	1.0	2.1
Mandurah	3	5.2	1.4	2.9
Mount Magnet (b)	3	3.4	1.3	2.1
Mount Magnet (e)	3	3.4	1.2	2.0
Yanchep	3	4.7	1.3	2.6
Albany	4	3.7	1.3	2.2
Augusta (b)	4	3.4	1.6	2.3
Augusta (e)	4	3.4	1.3	2.1
Esperance (b)	4	3.2	1.2	2.0
Esperance (e)	4	3.2	1.2	2.0
Note: (b) – use of bottled gas for heating and hot water, (e) – use of electricity for heating and hot water				

Table F.49 Normalized values of LCC, GHG emissions, and EE consumption of a reference house for alternative CPS options in all locations in regional WA

Locations	**DB-INS-SG**			**DB-INS-DG**			**CSW-POL-SG**			**CSW-POL-DG**			**BV-XX-DG**			**RBV-XX-SG**			**RBV-XX-DG**			**ACC-XX-DG**			**TMB-XX-DG**		
	CT-SPV-SWH-GC																										
	LCC	**GHG**	**EE**	**LCC**	**GHG**	**EE**	**LCC**	**GHG**	**EE**	**LCC**	**GHG**	**EE**	**LCC**	**GHG**	**EE**	**LCC**	**GHG**	**EE**	**LCC**	**GHG**	**EE**	**LCC**	**GHG**	**EE**	**LCC**	**GHG**	**EE**
Perth	1.08	1.12	1.13	1.11	1.06	1.07	1.00	1.05	1.05	**1.02**	**1.00**	**1.00**	1.02	1.14	1.11	1.07	1.15	1.13	1.10	1.09	1.07	1.18	1.16	1.14	1.03	1.19	1.16
Joondalup	1.08	1.10	1.14	1.11	1.07	1.09	1.00	1.04	1.06	**1.03**	**1.00**	**1.00**	1.02	1.09	1.09	1.07	1.13	1.13	1.10	1.09	1.08	1.18	1.16	1.14	1.03	1.10	1.11
Mandurah	1.08	1.12	1.14	1.11	1.07	1.10	1.00	1.05	1.05	**1.02**	**1.00**	**1.00**	1.02	1.11	1.09	1.07	1.15	1.13	1.10	1.10	1.09	1.18	1.16	1.14	1.03	1.14	1.13
Armadale	1.08	1.12	1.13	1.11	1.08	1.08	1.00	1.05	1.05	**1.02**	**1.00**	**1.00**	1.02	1.12	1.09	1.07	1.14	1.13	1.10	1.11	1.08	1.18	1.16	1.14	1.03	1.15	1.11
Bunbury	1.08	1.11	1.12	1.11	1.07	1.08	1.00	1.05	1.04	**1.03**	**1.00**	**1.00**	1.02	1.11	1.06	1.07	1.14	1.11	1.10	1.09	1.07	1.18	1.15	1.14	1.03	1.14	1.06
Yanchep	1.08	1.10	1.14	1.11	1.07	1.07	1.00	1.04	1.07	**1.03**	**1.00**	**1.00**	1.02	1.08	1.11	1.07	1.13	1.13	1.10	1.10	1.06	1.18	1.15	1.14	1.03	1.09	1.12
Geraldton	1.08	1.13	1.16	1.10	1.06	1.11	1.00	1.07	1.05	**1.02**	**1.00**	**1.00**	1.02	1.13	1.07	1.07	1.15	1.15	1.09	1.08	1.10	1.18	1.15	1.12	1.03	1.15	1.10
Busselton	1.09	1.14	1.11	1.11	1.08	1.08	1.00	1.05	1.04	**1.02**	**1.00**	**1.00**	1.01	1.09	1.06	1.08	1.16	1.10	1.10	1.11	1.07	1.18	1.14	1.14	1.03	1.13	1.07
Albany	1.08	1.10	1.12	1.11	1.08	1.09	1.00	1.02	1.03	**1.02**	**1.00**	**1.00**	1.01	1.05	1.03	1.08	1.12	1.11	1.10	1.10	1.09	1.17	1.12	1.10	1.02	1.05	1.03
Augusta (b)	1.09	1.10	1.12	1.11	1.08	1.10	1.00	1.03	1.03	**1.02**	**1.00**	**1.00**	1.01	1.05	1.03	1.08	1.12	1.11	1.10	1.10	1.09	1.17	1.12	1.10	1.02	1.05	1.03
Augusta (e)	1.09	1.13	1.14	1.11	1.09	1.10	1.00	1.04	1.04	**1.02**	**1.00**	**1.00**	1.01	1.04	1.03	1.08	1.14	1.13	1.10	1.10	1.09	1.17	1.08	1.08	1.02	1.07	1.06
Esperance (b)	1.08	1.09	1.11	1.11	1.07	1.08	1.00	1.03	1.04	**1.03**	**1.00**	**1.00**	1.01	1.06	1.04	1.07	1.12	1.10	1.10	1.09	1.07	1.18	1.12	1.11	1.02	1.06	1.04
Esperance (e)	1.08	1.11	1.11	1.11	1.08	1.08	1.00	1.04	1.04	**1.02**	**1.00**	**1.00**	1.01	1.04	1.03	1.07	1.12	1.11	1.10	1.09	1.08	1.17	1.08	1.07	1.02	1.07	1.06
Kalgoorlie	1.08	1.13	1.15	1.11	1.08	1.10	1.00	1.06	1.06	**1.03**	**1.00**	**1.00**	1.02	1.15	1.12	1.07	1.16	1.14	1.10	1.11	1.09	1.18	1.17	1.15	1.03	1.19	1.17
Carnarvon (b)	1.08	1.12	1.14	1.11	1.08	1.08	1.00	1.05	1.06	**1.03**	**1.00**	**1.00**	1.01	1.03	1.01	1.07	1.15	1.13	1.10	1.10	1.08	1.18	1.13	1.10	1.02	1.02	1.00
Carnarvon (e)	1.08	1.09	1.09	1.11	1.06	1.06	1.00	1.04	1.04	**1.03**	**1.00**	**1.00**	1.01	1.03	1.01	1.07	1.10	1.09	1.10	1.07	1.05	1.18	1.10	1.07	1.02	1.02	1.01
Laverton (b)	1.09	1.24	1.26	1.11	1.10	1.11	1.00	1.13	1.14	**1.02**	**1.00**	**1.00**	1.02	1.22	1.21	1.08	1.26	1.26	1.10	1.12	1.11	1.18	1.15	1.14	1.03	1.28	1.28

Locations	DB-INS-SG			DB-INS-DG			CSW-POL-SG			CSW-POL-DG			BV-XX-DG			RBV-XX-SG			RBV-XX-DG			ACC-XX-DG			TMB-XX-DG		
	CT-SPV-SWH-GC																										
	LCC	GHG	EE	LCC	GHG	EE	LCC	GHG	EE	LCC	GHG	EE	LCC	GHG	EE	LCC	GHG	EE	LCC	GHG	EE	LCC	GHG	EE	LCC	GHG	EE
Laverton (e)	1.08	1.17	1.17	1.10	1.07	1.08	1.00	1.08	1.09	**1.02**	**1.00**	**1.00**	1.02	1.15	1.14	1.08	1.18	1.17	1.09	1.09	1.07	1.17	1.10	1.09	1.03	1.20	1.19
Mount Magnet (b)	1.08	1.19	1.21	1.11	1.12	1.13	1.00	1.07	1.08	**1.02**	**1.00**	**1.00**	1.02	1.17	1.17	1.08	1.22	1.21	1.10	1.14	1.12	1.18	1.18	1.16	1.03	1.19	1.20
Mount Magnet (e)	1.08	1.14	1.14	1.11	1.08	1.09	1.00	1.05	1.05	**1.02**	**1.00**	**1.00**	1.02	1.12	1.11	1.07	1.15	1.14	1.10	1.10	1.08	1.18	1.13	1.11	1.03	1.14	1.14
Newman (b)	1.09	1.24	1.26	1.11	1.15	1.15	1.00	1.09	1.10	**1.02**	**1.00**	**1.00**	1.02	1.17	1.17	1.08	1.26	1.26	1.10	1.17	1.15	1.18	1.17	1.15	1.03	1.21	1.22
Newman (e)	1.08	1.19	1.19	1.10	1.12	1.12	1.00	1.07	1.07	**1.02**	**1.00**	**1.00**	1.02	1.13	1.13	1.08	1.20	1.19	1.10	1.13	1.11	1.17	1.13	1.11	1.03	1.17	1.17
Broome (b)	1.08	1.13	1.14	1.10	1.07	1.08	1.01	1.06	1.07	**1.02**	**1.00**	**1.01**	1.00	1.00	1.00	1.08	1.14	1.14	1.09	1.08	1.08	1.15	1.05	1.05	1.01	1.02	1.02
Broome (e)	1.08	1.11	1.13	1.09	1.06	1.07	1.01	1.05	1.06	**1.02**	**1.00**	**1.01**	1.00	1.00	1.00	1.07	1.12	1.12	1.09	1.07	1.07	1.14	1.05	1.04	1.01	1.01	1.02
Kununurra (b)	1.08	1.16	1.16	1.09	1.08	1.09	1.00	1.07	1.07	**1.00**	**1.00**	**1.00**	1.00	1.04	1.03	1.08	1.16	1.16	1.08	1.09	1.09	1.13	1.05	1.05	1.02	1.08	1.08
Kununurra (e)	1.08	1.14	1.14	1.09	1.08	1.08	1.00	1.06	1.07	**1.00**	**1.00**	**1.00**	1.00	1.03	1.03	1.07	1.15	1.14	1.08	1.08	1.08	1.13	1.05	1.04	1.02	1.07	1.07
Note: (b) – use of bottled gas for heating and hot water, (e) – use of electricity for heating and hot water																											