UNIVERSITY OF SOUTHERN QUEENSLAND
AUSTRALIA

Sustainable Construction

Potential Carbon Emission Reductions (PCER) in Australian Construction Systems through the Use of Bioclimatic Design Principles

A thesis submitted by

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For the award of

Doctor of Philosophy

2017

ABSTRACT

The building sector is responsible for 40 per cent of global energy use. By 2030, a total of 60 Mt of carbon-reduction opportunities will be available in the Australian building sector. The reduction of carbon emissions from Australian buildings is thus a priority for the Federal Government, and thus the Australian government recently announced plans to cut emissions by 26 to 28 per cent by 2030 (Hasham, Bourke & Cox 2015).

This study focuses on the amount of energy consumed during building construction processes, and the degree to which carbon emissions can be reduced through the incorporation of bioclimatic design principles into these processes. These principles include the use of local facilities to reduce transportation, sustainable and efficient use of materials, replacement of Portland cement with geopolymer cement, and similar environmentally-friendly initiatives.

Criteria for the research model proposed in this study have been developed through the application of bioclimatic design principles to six case studies from Australia and the United Kingdom. This was done in order to measure the potential reductions in construction carbon emissions that might be achieved in the pre-construction and construction stages of the building life cycle.

The outcomes of this research demonstrate that use of bioclimatic criteria can achieve reductions in carbon emissions from 48 to 65 per cent for whole building systems, and from 57 to 93 per cent when applied to building elements of general Australian construction systems. However, a more significant finding is that application of the research tool to elements of general Australian construction systems consistently achieved significantly higher reductions in carbon emissions than in current building practice, or through application of a currently-used green rating system (i.e. Green Star tool) to building elements. The future of the green construction industry should thus include consideration of bioclimatic design principles.

CERTIFICATION OF THESIS

This thesis is entirely the work of Sattar Sattary except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Student and supervisors signatures of endorsement are held at USQ.

Sattar Sattary

Principal Supervisor

Associate Professor David Thorpe

Associate Supervisor

Doctor Ian Craig

PREFACE

I have worked in the building industry for more than two decades. When working in this field in Iran, I observed that materials that would construct one square metre of a building in Germany would produce two and a half square metres in Iran. However, whereas the average lifespan of a building in Tehran is 27.5 years, in the UK it is 102 years. Following these observations about the quantity of materials used, as well as the resulting quality of the buildings, I began studying in Australia and became involved in developing the Green Globe standards in Queensland. However, these standards can only be applied to a specific class of building.

In 2002, the Green Building Council of Australia launched the Green Star rating system. I began work with them in 2006, and was assigned to apply this rating system to the Administration Office at the Kelvin Grove QUT campus. This was a pilot study, field testing the Education Tool of the Green Star system. However, ultimately this Education Tool could not be fully applied as the heating and cooling systems in this building were conjoined and not individual. I also found that the Green Star system could be applied to only 5 to 10 per cent of a given building under limited conditions, and that all the sustainability features achieved in this particular building could not be evaluated. Nevertheless, this pilot project was considered one of the most successful environmental assessments for buildings at that time.

A second study in which I participated concerned the green infrastructure assessment tool of the Australian Green Infrastructure Council (AGIC), now the Infrastructure Sustainability Council of Australia (ISCA). I was involved in the initial trials of this tool, and in the evaluation and assessment of specific areas of sustainability. It was of interest to me that this tool could measure and provide for only a small sustainability credit in a given project, but nevertheless be of considerable importance to the construction industry. In fact, this was also the case for several other green infrastructure tools.

The limitations of these green tools led me to reflect on what other considerations might be applied to the assessment of sustainability in the construction industry. An additional impetus to my interest and study in this area were the global summits and various emission reduction targets proposed by some developed countries. For example, the UK intends to reduce carbon emissions by 47 per cent, and Australia has set targets of 26 to 28 per cent over the next twenty years (Hasham, Bourke & Cox 2015). Such emission reduction targets are driven by findings such as that there are some 1.7 trillion tonnes of steel in the existing building infrastructure of the UK that in many cases is recyclable. Also, in the construction industry up to 90 per cent of construction carbon emissions can potentially be reduced (UK Indemand 2014). Other research done in the European Union also notes that humans consume 20 per cent more than nature can produce (Edwards 1999).

The above considerations have driven me towards the development of generic sustainability assessment criteria, that can be applied to single cases or all areas of the construction industry and its activities. Such criteria can potentially assist Australia and other countries to meet the emission reduction targets set in the Paris Summit of 2015. The focus of this study is thus to develop criteria that can be applied towards reducing construction carbon emissions from any single building element system (floor, wall and/or roof) in an Australian construction system without having to consider building classes and typology.

ACKNOWLEDGMENTS

First, appreciation must go to my principal supervisor, Associate Professor David Thorpe, and my associate supervisor, Dr Ian Craig. Both are from the School of Engineering and Surveying at the University of Southern Queensland (USQ), and I thank them for their valuable support, insight, and great patience in working with me.

For their professional advice and support, I would like to thank the following people: Professor John Cole, Executive Director, Institute for Resilient Regions, USQ; and Professor Richard Hyde, Professor of Architectural Science at the University of Sydney. I would also like to express my gratitude to the Green Building Council of Australia (GBCA); the Australian Institute of Architects (Queensland Chapter); and the Shahid Beheshti University and the Yazd University in Iran. Thank you to Mr. Nicholas Lambert as the external editor for this Thesis.

For providing the data for the case studies within this research, I send my thanks and best wishes to Dr Bill Lawson, and Mr Simon Pearl, Associate Director, Planning, Projects and Space at USQ. I would also like to extend my thanks to the USQ library staff for their support during my research.

Finally, I would like to acknowledge the consideration, love, advice, support and patience of my family: my wife Atousa, and my daughters Yasmine and Nassy.

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ABBREVIATIONS

ADAA	Ash Development Association of Australia
AECOM	Architecture, Engineering, Consulting, Operations, and Maintenance
AIBS	Australian Institute of Building Surveyors
AGIC	Australian Green Infrastructure Council
ASA	Australian Standard Associations
ASI	Australian Steel Institute
ASTM	American Society for Testing and Materials
BCSA	British Constructional Steel Association
BES	Building Environmental System
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Methodology
BFS	Blast Furnace Slag
CCAA	Cement, Concrete, Aggregates & Australia
CEEQUAL	Civil Engineering Environmental Quality
CSIRO	Commonwealth Scientific & Industrial Research Organization
EDG	Environmental Design Guide
EE	Embodied Energy
EEA	European Union Agency
EEC	European Economic Community
EC	Embodied Carbon
EDP	Energy Designs Partnership
EU	European Union
FSC	Forest Stewardship Council
GBCA	Green Building Council of Australia
GC	Geopolymer Cement
GHG	Green House Gas
GER	Gross energy requirement
GS	Green Star
ICE	Institution of Civil Engineers
IECC	International Energy Conservation Code
IMPACT	Integrated Material Profile and Costing Tool
IPCC	Intergovernmental Panel on Climate Change
ISCA	Infrastructure Sustainability Council of Australia
LEED	Leadership in Energy and Environmental Design
LEED-NC	LEED New Construction
LCA	Leftover Concrete Aggregate

LCLCRC	Low Carbon Living Capital Research Centre
LTU	Louisiana Technology University
MARSS	Materials from Alternative Recycled and Secondary Sources
NMSB	Nationale Milieu database Stichting Bouwkaliteit
NRMCA	National Ready Mixed Concrete Association
OECD	Organization for Economic Co-operation and Development
PC	Portland Cement
PCER	Potential Carbon Emission Reductions
PER	Process Energy Requirement
PFA	Pulverised Fuel Ash
PER	Process Energy Requirement
RCA	Recycled Concrete Aggregate
RA	Recycled Aggregate
RMIT	Royal Melbourne Institute of Technology
SCM	Supplementary Cementitious Materials
SEDA	Sustainable Energy Development Agency
SUT	Swinburne University of Technology
UNCED	United Nations Conference on Environment and Development
UNEPA	United Nations Environmental Protection Agency
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
UNEP-SBCI	UNEP Sustainable Buildings and Climate Initiative
UNSW	University of New South Wales
USGBC	US Green Building Council
USQ	University of Southern Queensland
VOA	Voice of America
WCED	World Commission on Environment and Development
WFEO	World Federation of Engineering Organizations

CHAPTER ONE
THE NECESSITY TO REDUCE THE CARBON EMISSIONS OF BUILDING CONSTRUCTION

1.1 Overview

The UN recognises climate change and global warming as major concerns of sustainable development. According to a past US President, Barack Obama, climate change has emerged as the greatest threat of the 21st century (Pande 2015). For example, several cities in the US, Mozambique, Bangladesh and other countries will disappear over the next hundred years; and New York, London, Rio de Janeiro and Shanghai will be among the cities that could flood in coming decades (Friedman 2009).

What mankind takes from nature cannot always be compensated, and can often only be produced by nature itself. Humans thus need to use less of the earth's natural resources to allow future generations to fulfil their own needs. The aim of the research presented in this thesis is to outline one area where it is possible to reduce the use of natural resources, that is within building construction. As will be seen in subsequent chapters, there is great potential for reduction of carbon emissions during building construction, but only where appropriate methods are used during the construction process. The focus of this study is the degree to which carbon emissions released from energy use in building construction can be reduced through use of bioclimatic principles.

The chapter is presented in seven sections. Section 1.1 introduces this study. Section 1.2 provides the background to this research. Section 1.3 considers the research problem. Section 1.4 discusses the scope and limitations of this research. Section 1.5 considers the aim of this research. Section 1.6 considers a number of questions that will be answered during conduct of the research. Section 1.7 provides an outline of the chapters in this thesis

1.2 Background to this Research

The United Nations Environment Program reports in its Sustainable Buildings and Climate Initiative (UNEP SBCI 2009) that the building sector is responsible for 40 per cent of global energy use. This sector also generates more than one third of global greenhouse gas (GHG) emissions, and is the largest emission source in most countries around the world. In Australia, the building sector is reported to be one of the largest contributors to Australian greenhouse gas emissions, and thus has the greatest potential for a significant reduction in GHG emissions as compared to other major emitting sectors (McKinsey 2008).

The UN maintains that it is necessary for countries to reduce their greenhouse gas emissions by half in the next forty years. Developed and developing countries have thus agreed to cut their emissions from between 26 to 47 per cent by 2030. To achieve this goal, there will be increasing restrictions on gasoline-powered vehicles on the streets of European countries over the next few years, and the United Nations proposes spending $100 billion per year to achieve the Paris targets. In reference to this, the UN believes that reduced emissions from the building sector will have multiple benefits for both the global economy and society (Chini 2005; UNEP SBCI 2009; United Nations Framework Convention on Climate Change UNFCCC 2015).

According to the United Nations Environment Program (UNEP), the energy consumption of buildings could be reduced by between 30 to 50 per cent by 2020 (UNEP SBCI 2009). However, Treloar (1998) maintains that construction carbon emissions in the building industry can potentially be reduced by up to six times their current levels. Related to this, the UK government has funded research planning to achieve an 80 per cent reduction in construction carbon emissions in the near future (UK Indemand 2014). It remains to be seen whether these reductions can be achieved.

1.3 The Research Problem

This study proposes that the carbon emissions of building construction can be dramatically reduced through the use of bioclimatic design principles (BDP). These are known techniques that reduce the embodied energy and generated carbon emissions of building construction, but the question remains as to how great a reduction can actually be achieved.

This research focuses on three main areas that can measure potential carbon reduction during building construction – first, carbon emission from energy consumed during the extraction and production of building materials; second, carbon emission from the energy consumed during the construction processes in building implementation; and finally, carbon emission from the energy consumed in transportation.

1.4 Scope and Limitations of this Research

The building lifecycle is considered as composed of five stages – Stage One, Extraction, covers the extraction of raw materials for the project including fuel used; Stage Two, Production, includes the production, pre-assembling and assembling of materials for the building project concerned; Stage Three, Construction, refers to activities during construction of the building; Stage Four, Operation, includes the use and maintenance activities required during operation of the building; and Stage Five, Demolition, encompasses the demolition and disposal of the building. These five stages are known as a 'cradle-to-grave' building lifecycle.

Within the building lifecycle, all energy used and carbon generated in extraction from mining (Stage One) until the construction products leave the manufacturing gate (Stage Two) are within the boundary condition known as 'cradle-to-gate' in the construction industry. A further boundary condition is termed 'cradle-to-site' which takes into consideration Stages One to Three of the building lifecycle, and includes all energy consumed and generated carbon emissions until the product has reached the point of use on the construction site (Greenspec 2015). This cradle-to-site boundary condition is the focus of this present research study.

This study thus takes as its focus construction carbon emission reductions during the first three stages of the building lifecycle, namely during extraction, production and construction. This presents one limitation of this present study in that the embodied energy and relevant carbon emission calculations will only be considered for these three stages, and not for stages four (operation) and five (demolition) of the building lifecycle. A second limitation is that the main building elements that will be examined in this study include only the floors, walls and roofs. The finishing, stairs, windows and doors will not be considered in the calculations.

1.5 Research Aims

Research is lacking on decreasing the embodied energy and carbon emissions of construction by consideration of criteria based on bioclimatic design principles. This present study proposes that consideration of bioclimatic principles during construction processes can reduce the energy consumption and carbon emissions in the pre-construction and construction stages of the building lifecycle (stages one to three).

This research aims to develop a research model with criteria identified from bioclimatic design principles; and apply that model to the floor, wall and roof construction systems of six selected case studies, and to general Australian construction systems. This will be to identify the potential reductions in carbon emission achievable in these scenarios.

1.6 Research Questions

Many organisations and legal entities that exist to control construction activities have produced a range of recommendations intended to reduce energy consumption and relevant carbon emissions during the building process. However, there are a number of problematic issues that remain unaddressed. For example, no established benchmarks exist to measure construction carbon emissions reduction. Each construction project is unique, and this limits the ability of governmental agencies to develop effective environmental regulations and incentives to control carbon emissions.

During the construction process, the amount of energy consumed and level of resulting carbon emissions are highly variable. Several concerns and questions can be raised about the construction process. These include:

1/ Is existing construction practice sustainable?

2/ What countries are the leaders in construction carbon emissions reduction?

3/ How can the construction industry assist governments to achieve the emission targets accepted in the Paris agreement?

4/ Can the building sector play a major role in an emissions reduction scheme, and would this be cost effective?

5/ What are the levels of embodied energy and associated carbon emissions of different elements of the construction process?

6/ To what extent are techniques to reduce carbon emissions of construction processes known and applied?

7/ What alternatives are available when the existing techniques for reduction of construction emissions are applied, but the results are not substantial?

8/ What percentage of current construction carbon emissions in the Australian construction sector be reduced?

These questions are answered in the research conducted for this thesis.

1.7 Outline of the Chapters in this Thesis

This research is presented in eight chapters. Chapter One presents an introduction to this thesis and sets the context for the remaining chapters. There is consideration of the research problem, background, and scope and limitations of this project.

Chapter Two reviews literature in relation to construction and sustainability, with a focus on the embodied energy of buildings and tools available for its measurement. Bioclimatic design principles are also introduced as a method to reduce the embodied energy and carbon emissions of construction.

Chapter Three reviews literature in relation to sustainable development and the environmental impact of construction. There is also consideration of the decisions and agreements made at several environmental conferences by a range of countries and agencies.

Chapter Four discusses the embodied energies of building materials in greater detail, the method for their conversion to equivalent carbon emissions, and a range of techniques for reducing the carbon emissions of construction.

Chapter Five provides greater detail on bioclimatic design principles, and their consideration in currently available green rating systems (LEED, BREEAM, Green

Star).[1] The research model based on bioclimatic design criteria is also described in this chapter.

Chapter Six outlines the research design and methodology used in this study, and identifies the sources of the embodied energy and carbon emissions data used in this research.

Chapter Seven presents the detailed results and analysis from applying the developed research model to construction elements of the floor, wall and roof in the six case studies selected for this research, and also within similar elements of general Australian construction systems.

Chapter Eight provides an overview to the conclusions made from this study, and makes associated recommendations that need consideration by the Australian construction sector. Recommendations are also made as to further research that should be undertaken to complement the findings from this project.

[1] LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Methodology) are green building assessment tools.

CHAPTER TWO

CONSTRUCTION, CLIMATE CHANGE AND SUSTAINABILITY

2.1 Overview

The energy consumption of the building sector across the world is substantial, around 40 per cent of global energy use (UNEP SBCI 2009), and this has significant related effects on the environment and climate change. It is thus imperative that the energy use and carbon emissions of the global building sector are reduced. Approaches towards achieving this are the focus of this chapter.

Section 2.1 provides the background to this chapter. Section 2.2 review relationships between the embodied energy of buildings and sustainable development. Section 2.3 considers how carbon emissions during construction may be reduced. Section 2.4 discusses tools that are available for measurement of embodied energy and carbon emissions of buildings. Section 2.5 considers Bioclimatic Design Principles and current research relating to their use. Section 2.6 summarises the content of this chapter.

2.2 Embodied Energy of buildings and Sustainable Development

In striving towards ecologically sustainable development, Lawson (1996) presents a study taking as its focus the embodied energies of common building materials and their assembly in various construction systems in the Australian context. The detail in this study presents useful and practical information, which assists in the development of a methodology for ecological sustainability in respect to building design and construction. This is achieved through the description of the manufacturing process and its environmental impact, as well as through the provision of the embodied energy ratings of Australian building materials and their assembly in a manner useful for building designers.

Lawson (1996) also provides detail on a method for assessment of the embodied energy of construction materials as combined in contemporary Australian building and construction systems. This method is useful when considering holistic evaluation of a given building, taking into account not only its embodied energies, but also the building’s various environmental impacts. Lawson’s (1996) method uses seven criteria – one relates to the siting of the building, five criteria are concerned with the choice and use of building materials, and the final criterion pertains to an estimate of the building's operational energy performance.

The original calculations in Lawson (1996) were based on a Process Energy Requirement (PER) analysis. This estimates the embodied energy directly related to the manufacture of the construction materials concerned (Milne & Reardon 2014). However, in later work on Australian construction systems, Lawson (2006) switched to the use of other calculation methods, including input-output (I-O) analysis, and hybrid methods combining PER and I-O, for embodied energy analysis. These latter methods calculate the total direct and indirect energy requirements for each output made by a construction system, and figures obtained for embodied energies are significantly higher than for PER calculations (Lawson 2006).

Mawhinney (2002) presents a consideration of sustainable development from the viewpoint of economists and environmentalists, and makes clear the impact that it may have on their workplace practice. It is noted that 'sustainable development' is an overused and sometimes misunderstood phrase. Four key questions are thus raised: these relate to whether sustainable development defines a starting point, a process, or the end-goal; whether sustainable development can provide a coherent theory of practice; whether it is a workable concept in practice; and, finally, whether sustainable development can provide a balanced solution, or whether balance forms part of the solution to sustainable development. Mawhinney (2002) strongly makes the point that ecologically sustainable construction practice must not be limited to the location of the project concerned, but consideration must also be given to environmental impacts over the entire life cycle of a project.

Craig and Ding (2001) present discussion of sustainable practice in the built environment. Various building scenarios are presented together with their proposed solutions whereby development can be undertaken in an environmentally efficient and sustainable manner. There is also consideration of the impact of environmental economics on the construction industry. These authors also stress that an assessment of environmental impact must consider not just the site location of construction, but the environmental impact of all aspects of the project concerned.

Sabnis (2012) considers the use of concrete in sustainable design and construction, relating it to best practice in today's built environment. Given the current pressure on the construction industry to reduce waste, it is noted that there is increasing refurbishing, recycling and reuse of concrete in building construction as the least-waste option. Concrete as a construction material is also justified as having significant economic green benefits (Sabnis 2012).

It is becoming increasingly apparent that to be ecologically friendly, building design must consider the entire life cycle of a building project and the associated embodied energies. This is evidenced in a study by Crowther (2015) which found that by designing buildings for disassembly, the potential for embodied energy recovery could be as high as 25 to 50 per cent of the total life cycle energy. In relation to this, Haynes (2010) believes that if buildings were designed with their future deconstruction in mind, we could re-value the materials and components in them, and also recapture the energy embodied within them. This embodied energy of the built environment has been estimated at between 10 and 20 per cent of Australia's total energy consumption (Haynes 2010).

Volz and Stovner (2010) report on embodied energy in masonry construction. Traditionally, masonry takes a considerable amount of energy to produce, and fired materials are generally used which are energy intensive in their production (e.g. clay brick, Portland cement). In contrast to this, non-fired materials and related methods offer substantial energy savings. For example, fly ash has an embodied energy which is effectively zero (provided that the fly ash is considered as a readily-available waste product), and it can be combined with mineral oxide pigments and fine aggregate to produce fly ash bricks in a non-fired process. Fly ash brick production uses 85 per cent less energy than fired clay brick production. Fly ash can also be used as a partial replacement for Portland cement in concrete masonry units. Additional reductions in energy can also be achieved by using recycled products. For example, recycled steel can be used in the steel reinforcing of concrete, which can reduce embodied energy by up to 75 per cent as compared to new steel production (Volz & Stovner 2010).

Following the passage of legislation, the British construction industry are now legally obliged to reduce their carbon emissions by 80 per cent by 2050. In relation to this, UK Indemand is an academic research centre based in the United Kingdom comprising more than 30 full-time researchers working across four universities (the University of Cambridge, the University of Leeds, Nottingham Trent University, and the University of Bath). UK Indemand is concerned with reducing the use of materials which have energy intensive production methods, this being towards trying to meet the 80 per cent reduction target (UK Indemand 2014).

UK Indemand identifies three main ways in which construction carbon emissions can be reduced. First, there is redesign which reconsiders the construction process to ensure than there is minimum material wastage. Second, there is reuse which involves construction of a new building from the components of an old building as far as is practical: this presupposes the deconstruction rather than the demolition of old buildings. Finally, there must be an intention to reduce materials usage by ensuring that, during the manufacturing and construction process, materials have been designed to last and are used for longer periods in order to slow down their rate of replacement (UK Indemand 2014).

A study by Myer, Fuller and Crawford (2012) from Deakin University found that the use of renewable materials in residential buildings can reduce their embodied energy by up to 28 per cent. However, even where renewable material alternatives could be located, there was often insufficient information available to accurately calculate their embodied energy. These authors concluded that while there is potential to reduce the embodied energy in construction by use of renewable materials, more widespread use of renewable energy in the stages of manufacturing and transportation would be required to maximise this potential reduction in embodied energy.

Thormark (2006) investigated how material choice may affect both embodied energy and recycling potential in an energy-efficient apartment-type housing project in Sweden. The calculated energy for operation was 45 kWh/m_2 of floor-area per year. The embodied energy component was 40 per cent of the total energy needed for a lifetime expectancy of 50 years. This author noted that in the design phase of buildings, it is of great importance to reduce both the overall operational energy needs and the choice of building materials in respect to their later recycling potential.

While a material may be recyclable, the forms of that recycling and how disassembly is to be achieved must also be considered. Thormark (2006) concluded that if attention is paid to such factors in the design of buildings, then the embodied energy of conventional buildings can be decreased by up to 15 per cent using relatively simple means.

Ramesh, Prakash and Shukla (2010) investigated the life cycle energy use of a range of residential and office buildings from 73 case studies in 13 countries. The life cycle energy requirement of conventional residential buildings was in the range of 150–400kWh/m^2 per year compared to that of office buildings, which was 250–550kWh/m^2 per year. They identified that the operation (80–90 per cent) and embodied (10–20 per cent) phases of energy use were significant contributors to the life cycle energy demand of a given building.

Research from the Queensland University of Technology (QUT) by Crowther (1999) was concerned with design for disassembly to recover embodied energy. It was found that designing for disassembly may require an initial extra input of direct energy during the construction phase of a building. Disassembly requires more energy than demolition, but the potential recovery of embodied energy in the materials and components salvaged for reuse can be as high as one third of the total energy use of a building, a percentage much higher than that required for disassembly. There are also other relative benefits from reuse and recycling of materials represented by the saving of natural resources and a reduction in waste generation and pollution (Crowther 1999).

2.3 Reduction of the Construction Carbon Emissions of Buildings

The carbon emissions generated during the construction of buildings has become a topic of importance given the increasing attention being paid to the reduction of the construction carbon emissions in Australia and the rest of the developed world. A range of research that pertains to this area is presented in this section.

2.3.1 A common carbon metric

The United Nations Environment Programme’s Sustainable Buildings and Climate Initiative (UNEP-SBCI) represents a partnership between the UN and public and private stakeholders in the building sector, formed to promote sustainable building practices globally. A study by the UNEP in 2009 proposed the use of a Common Carbon Metric that quantifies the weight of carbon dioxide equivalent ($kgCO_2e$) emitted per square metre per annum ($kgCO_2e/m^2/year$) by building type and by climate region. The aim of this metric is to accurately measure and quantify greenhouse gas emissions during building operations. The Common Carbon Metric would allow for the collection of consistent data in respect to reporting on the climate performance of existing buildings. Additionally, such a consistent measure would support the formation of policies aimed at the reduction of GHG emissions from buildings. However, the Common Carbon Metric covers only stage four of the building lifecycle, that is carbon emitted during the operation (use and maintenance) of a building (Bisset 2007; UNEP SBCI 2009).

2.3.2 The use of wood in building construction

Research performed by the Centre for Sustainable Architecture with Wood (CSAW) has found that the use of timber in new building construction has a lower carbon and environmental impact than comparable building materials. Timber production was found to be a low energy and low impact process, and the use of timber in construction represents an efficient and economical alternative (CSAW 2010). In support of this, Australian research at the RMIT University investigated the environmental impact of a range of building materials in standard house design using life cycle assessment. This research found that the use of wood products rather than other construction materials could reduce greenhouse gas emissions by up to 51 per cent (Carre 2015).

2.3.3 GreenSpec: A green building resource in the UK

The foremost green building resource in the UK is GreenSpec, launched in 2003 with government funding. GreenSpec provides advice on sustainable building products, materials and construction techniques, this advice being independent of the interests of companies and trading bodies. This organisation suggests several factors that need to be considered when aiming to reduce the embodied carbon in construction activities. First, building design must aim to minimise the use of materials wherever possible, thus reducing embodied carbon. Second, the building elements with the highest carbon impact need to be identified, and where possible these should be replaced with alternative materials with a lower carbon impact. For example, reduction in the use of cement in construction significantly reduces the carbon impact of the building process. Alternatives to cement include Pulverised Fuel Ash (PFA) and Ground Granulated Blast-Furnace Slag (GGBS) (Greenspec 2015).

In respect to concrete production, an investigation by Turner and Collins (2013) performed in Melbourne quantified the carbon dioxide equivalent emissions (CO_2-e) generated by all activities involved in the production of one cubic metre of concrete. This included all processes from obtaining raw materials through to the manufacturing and construction of the concrete. They compared the CO_2-e footprint generated by 100 per cent Ordinary Portland Cement (OPC) with concrete containing geopolymer binders. The CO_2-e footprint of geopolymer concrete was found to be approximately nine per cent less than comparable concrete containing 100 per cent OPC binder, a figure much less than predicted by earlier studies.

The factors that led to these higher carbon emissions for geopolymer concrete in the study by Turner and Collins (2013) were threefold. First, there was inclusion of the carbon emitted during the mining, treatment and transport of raw materials required for manufacture of the alkali activators required for geopolymers. Second, the actual manufacture of these alkali activators required a significant amount of energy use. Finally, there was a need for an elevated temperature during the curing of geopolymer concrete to achieve reasonable strength, again an energy-requiring process.

2.4 Measuring the embodied energy values of buildings

Note is made here of the Inventory of Carbon and Energy research database maintained at the University of Bath in the UK. This provides an inventory of embodied energy and carbon emissions for building materials in the UK (Inventory of Carbon & Energy 2011).

In respect to measurement of the embodied energy values of buildings, the ISO 14040:2006 and 14044:2006 Life Cycle Assessment (LCA) standards promote sustainable development, particularly in reference to embodied CO_2-eq analysis. However, it is accepted that embodied CO_2-eq values are probabilistic rather than definite. This is due to weakness in the data gathering on product-related CO_2 use and emissions. To address this weakness, research by Acquaye, Duffy and Basu (2011) presents an analysis of hybrid embodied CO_2-eq in building using stochastic analytical methods. These authors apply this stochastic analysis to a case study involving seven apartment buildings from the construction sector in Ireland. The details of this stochastic analysis are beyond the scope of this thesis. However, these authors conclude that:

> Greater methodological and informational benefits are derived from the stochastic hybrid ECO_2-eq intensity analysis of buildings compared to deterministic analysis … This can provide useful information if embodied CO_2-eq standards and regulatory measures are to be formulated … [and] provides more useful information to building designers and policy makers (Acquaye, Duffy & Basu 2011, p. 1302).

The stochastic embodied emissions methodology employed by Acquaye, Duffy and Basu (2011) can be applied to any type of building, not only in construction but also other sectors. This methodology can also be applied internationally.

2.4.1 Tools to measure embodied energy and construction emissions

There are various tools that have been developed to measure construction carbon emissions and embodied energy during the five stages of the building lifecycle (extraction, production, construction, operation and demolition). Some of these tools are applicable to the international context, but others relate only to a specific country and region or context. A discussion of some of these tools is presented in this section.

The Building Research Establishment (BRE) group in the UK developed ‘Envest’, one of the first online software packages that aimed to assist in analysis of building design towards achieving optimum environmental impact and whole life costs. The Envest design tool first appeared in 2002, and went through two revisions to the Envest 2 version. However, Envest was a commercial tool that required companies to purchase a licence for use. There was consequently little uptake by the market, and Envest was discontinued in favour of a simple and free database tool called

'IMPACT' which stands for the Integrated Material Profile and Costing Tool (Watson, Jones & Mitchell 2004; Envest 2 2016).

In 2009 in the United Kingdom, the Technology Strategy Board (TSB) and the Engineering and Physical Sciences Research Council provided £4.8 million to encourage British companies to develop new green design and decision tools (TSB 2010). However, IMPACT is currently the tool that is most commonly used. IMPACT aims to integrate Life Cycle Assessment (LCA), Life Cycle Costing and Building Information Modelling (BIM). It is a tool that is integrated into existing 3D, CAD and BIM software, in a way that "allows construction professionals to measure the embodied environmental impact and life cycle cost performance of buildings … The results generated by IMPACT can be used in whole building assessment schemes like BREEAM" (IMPACT 2016).

An Australian software provider called eTool has developed a life cycle assessment application (eToolLCD) that is compliant with IMPACT's LCA method. Consequently, use of eToolLCD can earn building designers two credits in the BREEAM New Construction UK, and up to six credits in BREEAM International. The eToolLCD application can be used for the design of all types of building projects from single houses to multi-residential buildings, to multi-billion-dollar infrastructural developments (eToolLCD 2015).

There are life cycle analysis tools available in other countries. For example, 'Elodie' is a tool developed in France to meet the demands of various French environmental declarations relating to life cycle analysis in construction. Similarly, in Germany the German Sustainable Building Council has developed the 'GaBi Build-it' tool for mandatory use in assessment of building LCA (GaBi Build-it 2010). Additionally, the Dutch government has developed several tools for use in its regulated embodied impact assessment for new housing and office buildings that covers all stages of the building lifecycle (Nationale Milieu Stichting Bouwkaliteit NMSB 2013).

In establishing the ISO-21930 International Standard, the Waste and Resources Action Programme (WRAP) in collaboration with the UK Green Building Council, launched the first embodied carbon database for UK buildings in 2007. This allows users to compare the embodied carbon results for their building with others in respect to the building life cycle and building elements, and companies and those involved in building and construction can benchmark their building designs. Such national benchmarks will assist in the assessment and measurement of the embodied carbon in building LCA, and thus identification of where reductions in carbon can be achieved during the building life cycle (ISO 21930 International Standard 2007; Brown, 2014).

In the United States, the 'Tally' application and database have been developed as a BIM plug-in to assist with building LCA. This application requires that architects and engineers use Revit software to quantify the environmental impact of building materials. Tally provides accurate life cycle analysis data for building design process in the USA, and the tool allows for comparative analyses of design options. While working on a Revit model, the user can define relationships between BIM elements and construction materials from the Tally database. The result is life cycle assessment on demand, and an important layer of decision-making information within the same period that building designs are generated. As a Revit application, Tally is easy to use and requires no special modelling practices (EPD-TALLY 2008).

2.5 Bioclimatic Design Principles

The design process that brings together the disciplines of human physiology, climatology and building physics (Olgyay 1963)

Bioclimatic design principles (BDP) were identified several decades ago in 1963 by the Olgyay brothers (Altomonte 2008). These twin brothers from Hungary defined bioclimatic design principles as those principles that bring together the disciplines of human physiology, climatology and building physics. They have been integrated into building design in the context of regionalism in architecture, and in recent years have been seen as a cornerstone for achieving more sustainable buildings (Hyde 2008).

Bioclimatic design principles have been used, investigated and analysed by different people and organisations in the construction industry. For example, the techniques and bioclimatic design principles of the Olgyay brothers provide the foundation for much of the building simulation software in use today, and they have also been used to analyse environmental factors and graphical representations of climate (Jones 2003; Hyde 2008).

The field of bioclimatic design is adding knowledge to the construction area where the flexible cooperation of several disciplines contributes to the well-being of the human and built environment. The focus of bioclimatic design principles is to develop a design method based on the integration of specialised and interconnected areas of knowledge (Altomonte 2008).

2.5.1 Background to Bioclimatic Design Principles

The Olgyay brothers published three books on bioclimatic architecture: *Application of Climatic Data to House Design* (1954); *Solar Control and Shading Devices* (1957); and in 1963 by Victor Olgyay only, the well-known *Design with Climate*: *Bioclimatic Approach to Architectural Regionalism* (1963). Although the three books share some text and illustrations, there are significant differences between them in respect to the trajectory of environmental building design. The little-known first book of the Olgyays, *Application of Climatic Data to House Design*, was used to prepare a report for the US Housing and Home Finance Agency. In that book, they suggested a new approach to house design based exclusively on environmental principles. Victor Olgyay (1910–1970) is best known today as the author of his 1963 publication, a book often referenced in the environmental building design field. (Leather & Wesley 2014).

As leaders in research in bioclimatic architecture from the early 1950s to the late 1960s, the Olgyay brothers can be considered as the fathers of contemporary environmental building design (Leather & Wesley 2014). Related to this, Pereira (2002) believes that building design should be inspired by nature, and aim to minimise environmental impact. To do this, issues that must be considered in the design include health and well-being, energy and sustainability.

2.5.2 Current research on Bioclimatic Design Principles

As noted, the research and publications of the Olgyays provided the inspiration for much of the building simulation software of today. For example, other than the difference between working on graph paper and using computer-generated graphics, Autodesk's Ecotect Analysis program (simulation and building energy analysis software) and the Olgyays' techniques for the analysis of environmental factors and graphical representation of climate are quite similar. The manner in which the Olgyays established connections between building design and climate science laid the foundation for the development of environmental simulation, one of contemporary architecture's leading methods of form generation. Victor Olgyay's teaching, however, represents another kind of thinking, a broader concern for architecture beyond energy performance.

Considerable progress in reducing the energy consumption of new buildings has been achieved through use of modern bioclimatic techniques. Attention has now turned to reducing the energy consumption of existing buildings. By use of appropriate technologies and techniques of bioclimatic retrofitting and design, it is possible to significantly reduce the energy consumption of existing buildings by a factor of five to six times as compared to a conventional building (Jones 2003; Hyde 2008).

Bioclimatic design principles have also been used for mitigation and adaptation strategies to achieve sustainable development in climate change and architecture. For example, the following is taken from a study by Altomonte (2008):

> Site & Climate Analysis; comprising the analysis of the site, exposure, climate, orientation, topographical factors, local constraints and the availability of natural resources and ecologically sustainable forms of energy considered in relation to the duration and intensity of their use (Altomonte 2008, p. 105).

More recent research at the University of Sydney has used bioclimatic design principles in retrofitting of existing buildings and urban networks. The results show that substantial improvement in energy performance can be realistically achieved through the implementation of bioclimatic design principles in retrofitting of existing buildings (Liu 2010; Architecture 2015).

Use of bioclimatic design principles has been integrated into building design in the context of regionalism in architecture, and in recent years has been seen as a cornerstone for achieving more sustainable buildings (Hyde & Yeang 2009). Research has found that appropriate bioclimatic design can significantly reduce energy consumption in a building as compared to conventional building design (Jong & Rigdon 1998). More detail and analysis of bioclimatic design principles is presented in Chapter Four.

2.6 Summary

This chapter identifies that there are numerous studies and research on embodied energy, carbon emissions and bioclimatic design principles in respect to building and construction. However, reducing embodied energy and carbon emissions through use of BDPs has received little attention in the Australian context. The focus of this research is thus on reducing embodied energy and carbon emissions during the building lifecycle through use of bioclimatic design principles in Australian construction systems.

CHAPTER THREE

SUSTAINABLE DEVELOPMENT AND INTERNATIONAL AGREEMENTS

3.1 Overview

Climate change, depletion of natural resources and the rising global population have increased international attention to the problems facing the environment, and the increasing necessity to achieve sustainability in development and construction. This is reflected in the range of international conferences which have taken place over recent decades, culminating in the signing of the Paris Agreement in 2015.

Section 3.1 provides a brief overview to this chapter. Section 3.2 considers the notional of sustainability, and its relationship to sustainable development and construction. Section 3.3 discusses the environmental impact of building. Section 3.4 considers a range of key decisions and international reaction to environmental issues as demonstrated within a range of international agreements and protocols from the 1980s to the present. Section 3.5 provides a summary of the main themes within this chapter.

3.2 Sustainability

Sustainability is at the centre of any governmental discussion or decision related to energy crises, climate change or global warming. Such considerations have several times brought world leaders together for discussion and policy formation. Examples include the oil crisis summit in 1973; the UN Geneva Convention on Air Pollution in 1979; the Montreal Protocol on the ozone layer in 1987; and the Kyoto Protocol on the reduction of greenhouse gases in 1997 (Adams 2003). More recently, there has been the Intergovernmental Panel on Climate Change (IPCC) in 2007; and the Paris Agreement on Global Warming in 2015 (UNFCCC 2015).

In the past, the word ‘sustainability’ had a simple meaning related to the act of continuing (sustaining) a given behaviour or action for an ongoing period. More recently, sustainability has assumed a new meaning related to the quality of not being environmentally harmful. Hendriks (2001) extends this and argues that any definition of sustainability should include not only the notion of environment, but also social and economic interests such as health, wellbeing, safety, care for living space, prosperity and related concepts.

The resources humanity now takes from the earth increasingly cannot be balanced and reversed by nature. The rapidly increasing world population has led to overuse and increasing depletion of global resources from the natural environment. There is also global warming and increasing environmental problems. The health and wellbeing of future generations depends on sustainable environmental policies being established as soon as possible. The aim of such policies must be to create an ecologically healthy environment based on a program of sustainability and sustainable development (Hendriks 2001).

3.2.1 Sustainable Development

The Brundtland Report of 1987 issued by the World Commission on Environment and Development (WCED) identified the urgency of progressing towards a notion of economic development that could be sustained without depletion of natural resources or harm to the environment. The report defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987, para 1).

Three obligations follow on from this definition of sustainable development. First, there must be responsible use of resources now and into the future. This implies a responsibility to leave future generations with both natural resources and enough scientific/cultural capital to allow them to meet their needs. Second, there must be efficient protection of global resources. This implies a responsibility to protect and effectively manage all environmental resources including land, water, air and biodiversity. Thirdly, there must be equal sharing of global resources. This implies a duty to share resources locally and globally based on equal access for all (Edwards 1999; Mawhinney 2002).

Following on from these obligations, in 2000, a wider definition was suggested by the UN’s National Strategies for Sustainable Development that encompasses not only sustainable development, but also the notion that there must be associated sustainable social and economic development. This allows for the needs of the present generation without threatening the ability of future generations to meet their needs. In respect to this definition, the UK Department of Environment and Transport believes that alongside sustainable social and economic development, there must also be environmental protection and wise use of natural resources (Mawhinney 2002).

The main notions within these various definitions of sustainable development are summarised in Table 3.1.

Table 3.1: Main notions within definitions of sustainable development

Definition	**Message**
Brundtland Report (WCED 1987)	• Responsible use of resources now and in the future • Efficient protection of global resources • Equal sharing of global resources
National Strategies for Sustainable Development (2000, cited by Mawhinney 2002)	• Similar to WCED definition, but with the added notion that there must be social and economic development along with sustainable development
UK Department of Environment and Transport (Mawhinney 2002)	• Promotes a definition of sustainable development that maintains social and economic growth alongside environmental protection and careful use of resources

Sources: WCED 1987; Mawhinney 2002.

3.2.2 Sustainable Construction

The Brundtland Report considers sustainable construction as part of the more general area of sustainable development. Sustainable construction may be defined as a way of designing and constructing buildings that provides a healthy, ecological environment, one that begins to address the effects of problems caused in the past, and that provides for the needs of existing and future generations. (WCED 1987). The Future Foundation in the UK extends this definition of sustainable construction to include refurbishment of existing structures. They note that sustainable construction and development promotes environmental, social and economic gains both for the present and future generations, and that our economy, environment and social well-being are interdependent (Future Foundation 2015).

Hendriks (2001) agrees that to be sustainable, construction must not only consider the impact of building on nature and the environment, but also support the physical, psychological and social aspects of human health. Additionally, this author notes that sustainable construction must also take the durability of construction materials into account, in that any materials used must serve for at least the expected lifetime of the building concerned. Edwards (1999) also argues that sustainable construction must integrate low energy design with materials that have minimal environmental impact at all points in the building lifecycle. Essentially, sustainable construction assumes careful consideration of resource efficiency, energy conservation, and environmental principles during the entire lifecycle of any building project from cradle to grave (Organization for Economic Co-operation and Development OECD 2003; Hui 2015).

The focus of this study concerns the carbon emissions generated by the construction industry in Australia, and their potential reduction through use of bioclimatic design principles. This is of increasing importance, as reducing construction carbon emissions has become a mandate for sustainable construction. The themes running through the various notions and definitions of sustainable construction discussed in this section reflect this: to be sustainable, building projects must consider conservation of resources used for construction, environmental impact, and protection of biodiversity. Sustainable construction must aim to provide an ecologically healthy environment and optimum living conditions to meet the needs of existing and future generations.

3.3 Environmental impact of building

Climate change and global warming have been recognized as major concerns of sustainable development. By 2100, sea levels are predicted to rise by two metres if current levels of carbon emissions are not reduced (DeConto & Pollard 2016). If this occurs, up to fourteen cities in the United States will disappear over the next century; and several countries including Mozambique and Bangladesh will be completely inundated by the rising ocean levels (Friedman 2009). The UN believes that humanity needs to reduce its greenhouse gas emissions by at least 50 per cent within the next forty years in order to avoid these worst-case scenarios of climate change (UNEP 2009; UNEP SBCI 2009).

The building process produces large amounts of greenhouse gas emissions during construction, demolition, reconstruction and/or restoration of buildings. These activities also produce large quantities of construction and demolition waste, and thus have a high environmental impact. They also consume large amounts of global resources, not only minerals, but also water and energy in its various forms (UNEP SBCI 2009).

A report by Naik (2008) estimates that resources are being extracted from the earth at a rate of 20 per cent greater than the earth can produce or replenish. However, it is believed that if the principles of sustainable development are followed, this unsustainable level of resource consumption will be reduced. Environmental considerations must therefore take an equal part alongside economic considerations if the construction industry is to achieve development that is sustainable (Naik 2008). This is not an impossible expectation because, based on existing technology, the energy consumption in both new and existing buildings can be cut by an estimated 30 to 50 per cent without significant increase in the cost (UNEP SBCI 2009).

A study by the UN’s Sustainable Buildings and Climate Initiative (UNEP SBCI 2009) considered the quantity of carbon emissions produced during the building lifecycle. It was found that the building sector generates more than one third of global GHG emissions, and in most countries, is the largest source of carbon emissions. Transportation of people, goods and services to and from the building site was also noted as one of the most significant ways in which energy was consumed. In global terms, the environmental impact of the construction process was considerable, being responsible for 40 per cent of energy use, 30 per cent of raw materials taken from nature, 25 per cent of total waste, 25 per cent of water use, and 12 per cent of land use (UNEP SBCI 2009)

The research in this thesis considers only the first three stages of the building lifecycle (extraction, production and construction). However, these stages produce only 10 to 20 per cent of the total carbon emissions during the entire lifecycle of a building, the remainder being produced in stages four and five (operation and demolition). In fact, most carbon emissions are produced during the operational phase (UNEP SBCI 2009). Future research will consider these last two stages of the building lifecycle as they are beyond the scope of the present research.

In Australia, buildings and their users are responsible for between 18 per cent (ClimateWorks Australia 2010) and 25 per cent (Commonwealth Scientific and

Industrial Research Organisation CSIRO 2000) of Australia's greenhouse gas emissions, depending on the source of the estimate. Residential buildings account for around 58 per cent of these emissions, and commercial buildings for around 42 percent. It is estimated that the energy embodied in existing building stock in Australia is equivalent to around ten years of the nation's energy consumption. In this respect, the choice of materials and design principles has a significant, but previously unrecognised, impact on the energy required to construct a building (CSIRO 2000).

A report by the Intergovernmental Panel on Climate Change (IPCC) suggests that the Australian building sector has the greatest potential for a significant reduction of carbon emissions as compared to other major emitting sectors. Costs to reduce GHG emissions were also noted to be relatively lower in the building sector as compared to other emitting sectors (Levine & Urge-Vorsatz 2007). In respect to this, it has been estimated that a total of 60 Mt of carbon-reduction opportunities could be found in the Australian building sector by 2030 (McKinsey 2008). A decrease in carbon emissions from Australian buildings is consequently a priority for both the Green Building Council of Australia (GBCA 2008), and the Federal Government which has announced plans to cut emissions by 26 to 28 per cent by 2030 (Hasham, Bourke & Cox 2015).

In absolute figures, it is estimated that the Australian building sector has potential to contribute to around 11 per cent of the carbon reductions to be achieved by 2020. Around three quarters (77 perc cent) of these opportunities for reduction are within the commercial sector (including 16 Mt CO_2-e for existing building retrofits, and 4 Mt CO_2-e for new builds). Such reductions offer an average net saving to society of $99 per tonne, and offer investors an average profit of A$90 per tonne (ClimateWorks Australia 2010).

Drawing these themes about the environmental impact of the construction process together, some general figures can be identified in respect to the global context. The built environment worldwide accounts for some 40 per cent of global GHG emissions, and the construction sector accounts for around 40 per cent of the world's total energy consumption. Construction is also responsible for approximately half of all resources taken from nature, and production and transport of building materials consumes up to 40 per cent of all energy used (UNEP SCBI 2009). These figures are predictably the greatest in developed countries (UNEP SBCI 2009; Technology Strategy Board 2010; Ecospecifier 2015; GreenSpec 2015).

Based on the reviewed environmental impacts of building, Table 3.2 is a summary of the environmental impacts of buildings on different levels: globally, in the UK, in the EU and in Australia.

Table 3.2: Summary of environmental impacts of global construction

Global figures

- Fourteen U.S. cities, Mozambique and Bangladesh may disappear over the next century (Huffington Post 2013).
- New York, London, Rio de Janeiro and Shanghai will be among the cities that could flood by 2100
- The built environment accounts for some 40 per cent of global GHG emissions
- Buildings are responsible for 40 per cent of global energy consumption
- Construction is responsible for nearly half of all resources taken from nature
- Resources are extracted at a rate of 20 per cent more than the earth produces (UNEP SBCI 2009)
- Production and transport of building materials consumes 25 to 40 per cent of global energy use
- In the EU, building and transport use more than 65 per cent of total energy consumption (compared to 60 and 50 per cent in the US and Japan respectively (OECD 2003)
- In the EU buildings are responsible for 50 per cent of energy use; production of 50 per cent of ozone depleting chemicals; and 50 per cent of raw materials used by industry (Edwards 1999).

UK figures

- Building accounts for around 45 per cent of the UK’s total carbon emissions
- Up to 50 per cent of ozone depleting chemicals in the UK relate to construction
- Construction materials account for 420 million tonnes of material consumption (seven tonnes per person) (UNEP SBCI, 2009; Green Spec 2015)
- From 10 to 20 per cent of total construction emissions are produced during extraction of materials
- From 80 to 90 per cent of the energy used by construction is consumed during use of a building (Ecospecifier 2015).

Australian figures

- The building sector is one of the largest contributors to Australian greenhouse gas emissions
- Buildings and their users are responsible for almost a quarter of Australia’s greenhouse emissions
- Australia spends around $4 billion per year on energy, generating 46.4 million tonnes of CO_2 in 1999, and these emissions increase by 3 to 4 per cent annually (Energy Information Administration 2013)

Source: Extracted from Chapter Three

3.4 Key decisions and international reaction to environmental issues

In recent decades, the building and construction sector have caused considerable environmental problems, as well as a significant impact on the use of vital key resources such as water, air, climate, food supplies and energy resources. The environmental problems include ozone depletion, global warming, acid rain, air pollution and greenhouse gas emissions, as well as the need for energy in the transportation and demolition of waste materials. These issues have required international attention, as evidenced in the range topics that have been discussed at various summits over the last fifty years: for example, energy supplies in the 1970s; sustainable development in the 1980s; depletion of the ozone layer and global warming in the 1990s; sustainable construction in the 2000s; and greenhouse gas reduction in recent years (Edwards 1999; IPCC 2011).

Since the advent of the world oil crisis in 1973 and the start of the green movement, several important international summits and conferences have been convened in an effort to reduce the impact of human activity on the environment and climate. These include the World Commission on Environment and Development (WCED); the Earth Summit in Rio de Janeiro; the Kyoto Protocol in Japan; the European Environmental Agency (EEA); the Intergovernmental Panel on Climate Change (IPCC); the United Nations Environmental Program Sustainable Buildings and Climate Initiative (UNEP SBCI); and the Paris Agreement in 2015. These conferences and their main themes and outcomes are briefly reviewed in this section.

3.4.1 World Commission on Environment and Development – 1987

The WCED conference in 1987 produced the well-known Brundtland Report, titled as *Our Common Future*. This conference drew attention to the urgency of making progress toward economic development that could be sustained without depleting natural resources or harming the environment. A key statement (and warning) from this conference was that sustainable development is development that must meet the needs of the present generation, but without compromising the needs of future generations (WCED 1987).

Sustainable construction based on the notion of equity and social justice was a cornerstone of the Brundtland Report. The main aim of the WCED enshrined in the Brundtland Report was to promote economic development and growth, but at the same time ensuring that such development considered environmental and social factors within any construction or related program to meet society's needs for employment, food, energy, water and sanitation (Borowy 2013).

The report also recommended a major reorientation and refocusing of programs concerning sustainable development within the various sectors of the UN. It was proposed that in such a new system-wide commitment to sustainable development, the United Nations Environmental Program (UNEP) should be the primary source providing environmental data, assessment, reporting, and related support for environmental management. Additionally, the UNEP should be the main advocate and agent for change and cooperation on critical environment and natural resource protection in any project where sustainable development was to be a priority (WCED 1987).

The Brundtland Report also highlighted several major global challenges facing humanity including preserving the quality of the environment; stabilising global population; the conservation and enhancement of natural global resources; meeting energy needs; meeting water needs and providing sanitation; and finally the survival of species and ecosystems. Reducing the impact of construction projects on the environment and natural resources assists in meeting these challenges (Borowy 2013). This, in fact, provided the impetus for this present research project on reducing the carbon emissions of construction through application of bioclimatic design principles, thus promoting sustainable construction.

3.4.2 The Earth Summit – 1992 and 2012

The United Nations Conference on Environment and Development (UNCED), also known as the Earth Summit, was held in Rio de Janeiro in 1992 (UNCED 1992). A further related summit called the United Nations Conference on Sustainable Development, *Rio+20*, was held in 2012, also in Rio (UNCSD 2012). During these summits, the environment and ecology was the prime focus, with the aim being promotion of sustainable construction and design practices. The major issues discussed at these summits were reducing resource use in construction; minimising the impact of development on the environment; and protecting global biodiversity (UNCED 1992; UNCSD 2012).

The most important outcome resulting from the Earth Summit of 1992 was a document called ‘Agenda 21’, a non-binding action plan relating to sustainable development which was agreed to by the representatives of 178 governments attending this conference. The subsequent UN Conference on Sustainable Development in 2012 saw the aims of Agenda 21 reaffirmed by 192 governments represented at this conference (UNCED 1992; UNCSD 2012).

The action plan in Agenda 21 included a range of environmental goals to be undertaken by signatories at the local, national and global level. A full consideration of Agenda 21 is beyond the scope of this thesis. Suffice to say here that Agenda 21 is a 350-page document with 40 chapters that sets out in detail how sustainable development might be achieved at every level of government. The main aims of Agenda 21 are that sustainable design is in harmony with nature, with responsible use of resources, and that design considers the needs of both the current and future generations in a socially, environmentally and economically friendly manner (UNCED 1992; UNCSD 2012).

3.4.3 The Kyoto Protocol – 1997

The Kyoto Protocol is an international agreement signed in Japan in 1997, but which did not take effect until 2005. The aim of the Protocol was to reduce global greenhouse gas emissions to reduce the impact of climate change. The Protocol also contained agreements to sustainable development within its clauses. These included that any materials produced or used for construction should be energy efficient and sustainable, with minimal impact on the environment; that new and renewable forms of energy should be developed; that there should be improved management of the products of building demolition; and that there should be associated reductions in greenhouse gases in the transport sector. Around 192 countries are currently signatories to the Kyoto Protocol, though at present these do not include the USA and China, two countries with significant greenhouse gas emissions (UNFCCC 1998).

Some of the key decisions of the Kyoto Protocol included the following.

- Enhancement of energy efficiency in relevant sectors of the national economy
- Protection and improvement of sinks and reservoirs of greenhouse gases not controlled by the Kyoto Protocol
- Promotion of sustainable forms of agriculture in light of climate change considerations

- Research into, and the promotion, development and increased use of, new and renewable forms of energy as well as research into carbon dioxide sequestration technologies
- Progressive reduction or phasing out of market imperfections, fiscal incentives, tax and duty exemptions and subsidies in all greenhouse gas emitting sectors that run counter to the objective of the convention
- Encouragement of appropriate reforms in relevant sectors aimed at promoting policies and measuring the limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol
- Measures to limit and reduce emissions of greenhouse gases not controlled by the Montreal Protocol in the transport sector

(UNFCCC 1998).

In conclusion, the Kyoto Protocol demonstrates that there have been a series of decisions relating to sustainable construction that include to use energy more efficiently; to reduce greenhouse gas emissions in all areas of the construction sector, including in transportation and waste management; and to increase use of renewable forms of energy and carbon dioxide sequestration technologies (UNFCCC 1998).

3.4.4 The European Environment Agency (EEA) – 1994

The European Environment Agency (EEA) is an office of the European Union (EU) which became operational in 1994. The Agency provides independent information on the environment to its 33-member countries in the EU. The aim is assist those countries to make informed decisions about environmental issues when considering major construction and other projects, and for sustainable environmental policies to be integrated into economic and social policy (EEA 2016).

Research has found that in the European Union, buildings and construction are responsible for around half of total energy use, with materials transport being largely responsible for the remaining component (Edwards 1999). The European Environment Agency (EEA) thus has sustainable construction as one of its major mandates, with related policies being established towards construction that has minimum environmental impact and maintains ecological diversity (EEA 2016).

EU environmental policy includes that pollution should be prevented at its source, and polluters should pay for environmental damage they cause; that environmental policy should be integrated with economic and social policy; that environmental effects of development should be taken into account in the technical planning and decision making stage; that environmental protection is a responsibility of the entire community; and that EU environmental policy should be harmonised with national policy (EEA 2016).

The European Environment Agency describes sustainable construction as a process that effectively integrates low energy design with materials which have minimum environmental impact and maintain ecological diversity. Based on this policy, the main objects of sustainable construction are to minimise non-renewable resource consumption; to reuse and recycle construction materials or waste; to enhance the natural environment through product selection; to minimise waste and prevent pollution at building sites; and to use outputs from one process as inputs to others (e.g. energy from materials) (EAA 2016).

3.4.5 The Intergovernmental Panel on Climate Change (IPCC) – 1988

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body set up by the United Nations in 1988. It aims to provide an objective scientific perspective on the effects of climate change and its global economic impacts. A report by the IPCC in 2007 identified that global construction is responsible for 40 per cent of the world’s energy consumption, and produces one third of global greenhouse gas emissions. The report also noted that most energy consumed in the construction sector was during use of a building (i.e. Stage Four, operation, of the building life cycle) at 80 to 90 per cent (Levine & Urge-Vorsatz 2007).

The report proposes that energy consumption in both new and existing buildings could be cut by 30 to 50 per cent, and that this could be done in a cost-effective manner using existing technologies, with potential to reduce construction carbon emissions by around 5.6 Gt CO_2 by 2030. However, achieving such reductions is going to require significant effort by the governments of the various countries of the United Nations (Levine & Urge-Vorsatz 2007).

The report concluded that the global construction sector has great potential to provide long-term, cost-effective reduction in greenhouse gas emissions. A significant portion of these savings could also be obtained in ways that reduce life-cycle costs, thus providing reductions in carbon emissions that have a net benefit rather than cost (Levine & Urge-Vorsatz 2007).

3.4.6 United Nations Environment Program, Sustainable Buildings and Climate Initiative – 2009

A report by the Sustainable Buildings and Climate Initiative within the United Nations Environment Program (UNEP SBCI 2009) reiterated several of the themes noted in the earlier publications of the various bodies involved in dealing with climate change. In particular, yet again there was identification of the fact that the global construction sector is one of the largest producers of greenhouse gas emissions, but that it also has the greatest potential for significant and cost-effective reductions in emissions through use of existing technologies. Such reductions have the potential to deliver both social and economic benefits to global society. However, emission reduction targets cannot be achieved without gains in energy efficiency in the building sector (UNEP SBCI 2009).

3.4.7 The Paris Agreement – 2015

In 2015, the UN Framework Convention on Climate Change (UNFCCC) brokered an agreement in Paris between 196 countries related to climate change. The agreement included action to promote low greenhouse gas and climate-resilient development, but in a fashion that will not impact on global food production. The Paris Agreement of 2015 is a legally-binding framework for a global effort to reduce the impacts of climate change. Of significant importance is that China is and the USA[2] were parties to the Paris Agreement (UNFCCC 2015).

The Paris Agreement allows the signatory countries to determine their own national contributions to meeting the aims of the document, but such contributions are expected to be ambitious and progressive over time. A specific aim is to achieve net-zero emissions in the second half of this century. This assumes profound changes to the economies of some countries, particularly those in the developed world. A non-

[2] On 2 June 2017, the USA withdrew from the Paris agreement on climate change (ABC News 2017).

legally binding part of the Agreement is for private and public entities to provide an annual US$100 billion to aid developing countries to meet their nationally determined targets (Hasham, Bourke & Cox 2015; UNFCCC 2015).

Other highlights of the Paris agreement of interest to this study include that Nationally Determined Contribution (NDC) countries can meet their targets by transferring 'mitigation outcomes' internationally, that is by sharing mitigation targets. Related to this, public and private organisations can support sustainable development projects that generate transferable emissions reductions (Hasham, Bourke & Cox 2015; UNFCCC 2015).

The Paris Agreement thus provides a common framework for individual countries to consider their own capacities for reducing climate change. The Agreement has the potential to provide a basis for long-term international action on climate change, particularly as the technologies and alternative energy systems to do this become further developed and economically more viable (UNFCCC 2015).

Emissions in 2005 were determined as the base point from which reductions would be measured. The Australian Federal Government has pledged to reduce emissions by 26 to 28 per cent by 2030, a figure which provides justification for this present research whose outcomes have potential to assist in this process. The USA has pledged to reduce emissions by 41 per cent (but has since withdrawn from the agreement), and Canada by 30 percent. The European Union has pledged a reduction of 40 percent, but relative to their emission levels in 1990 (Hasham, Bourke & Cox 2015). Details of these targets are presented in Table 3.3.

Table 3.3: Post-2020 emission reduction targets for major developed countries

Country	**Change on base year**	**Rate of reductions to achieve target**	
	2005	2010-2020	Post 2020
Australia	**-26%-28%**	**-0.8%**	**-1.6%/-1.9%**
USA	-41%	-1.4%	-2.3%
EU	-34%	-0.4%	-2.6%
United Kingdom	-48%	-1.6%	-5.1%
Germany	-46%	-2.4%	-2.6%

Source: The Climate Institute (cited in Hasham, Bourke & Cox 2015) [3]

[3] On 2 June 2017, the USA withdrew from the Paris agreement on climate change (ABC News 2017).

3.5 Summary

In the face of global environmental problems. existing construction practices are not sustainable, and it is necessary to rethink current methods and establish new building construction processes. The efficient use of natural resources (energy and construction materials), the prevention and reduction of the environmental impact of construction activities, and the protection of biodiversity must be major considerations in any move towards achieving sustainable construction practices.

This chapter has considered an extended notion of sustainability suitable for use when a focus is taken on achieving sustainability in construction practices. The major findings from a range of international conferences and agreements have also been discussed, with common themes being identified as to how reduction in greenhouse gases and carbon emissions might be achieved. The main theme that informs this present research is that the construction sector is a major site of global energy use, but one where significant reductions in carbon emissions can be achieved in a cost-effective manner using existing technologies. This is the case for the Australian construction sector, which has the greatest potential for significant reduction of greenhouse gas emissions as compared to other major emitting sectors in this country. The next chapter considers specific ways in which reduction in the carbon emissions of construction in Australia and elsewhere may be achieved.

CHAPTER FOUR
EMBODIED ENERGY AND REDUCING CARBON EMISSIONS OF CONSTRUCTION

4.1 Overview

One third of the world's energy is used by industry to make products – the buildings, infrastructure, vehicles, capital equipment and household goods that sustain our lifestyles. Most of this energy is needed in the early stages of production to convert raw materials, such as iron ore or trees, into stock materials like steel plates or reels of paper (UK Indemand 2015). The key materials with which we create modern lifestyles – steel, cement, plastic, paper and aluminium in particular – are thus the main carriers of this 'embodied energy', and if we want to make a significant reduction in this industrial energy use, we need to reduce our demand for these materials.

The purpose of this chapter is to present the concept of embodied energy in building materials, how this can be measured, and how embodied energy and carbon emissions might be reduced. Section 4.1 provides an overview to this chapter. Section 4.2 considers the embodied energy of building materials and their measurement. Section 4.3 identifies the carbon emissions within construction processes. Section 4.4 considers how embodied energy can be converted to its equivalent in carbon emission. Section 4.5 discusses various techniques that can reduce the carbon emissions from construction. Section 4.6 identifies barriers that exist to emissions reduction in construction. Finally, Section 4.7 presents a summary of this chapter's content and links to the next chapter.

4.2 The Embodied energy of building materials

Embodied energy represents the energy consumed by all processes associated with the production of a building, from the mining and processing of natural resources, to manufacturing transport and product delivery (Milne & Reardon 2014). Embodied energy can be broken down into direct and indirect energies. Direct embodied energy relates to the energy involved in transportation of construction materials, and then assembling those materials on site. Indirect embodied energy relates to the energy put 'into' the component itself, in terms of extracting it from the ground, then the energy consumed in its processing and manufacturing, together with generated carbon emissions (Bull 2012). It also includes any energy used to transport subcomponents or equipment in any of these stages.

Embodied energy varies for any given material depending upon the efficiency of the production processes. If the source of any given material and the performance of the company producing the material are known, it is possible to establish specific embodied energy and greenhouse emission factors for particular materials, considering exact fuel type, mining place, transportation and delivery consumed energy, and generated carbon emissions. For example, a material manufactured and used in Brisbane has a different embodied energy if the same material is transported by road to Perth.

The quantification of embodied energy and associated greenhouse gas emissions is thus related to process location and is company specific. Embodied energy and carbon emissions can vary from country to country – for example, embodied energy of steel in Australia is 34 MJ/kg (Lawson 2006); in Canada it is 32 MJ/kg (Canadian Architects 2015); and in the US is 40 MJ/kg (Jong & Rigdon 1998). In this regard, for this research, specifications of materials used in Australia, the UK, the US and Canada is provided together with their relevant carbon emissions.

In the case where the source of a material is known, the company can be contacted to provide the information required to calculate accurate embodied energy and carbon emissions for that building material or element. However, the embodied energy of the materials used in Australian construction systems which provide the basis for this study (Table 4.1) have been converted to carbon emissions based on the Australian Government's global average equation of 0.098 kg CO_2 eq = 1 MJ (CSIRO 2014).

4.2.1 Embodied energy and operational energy

It was thought until recently that the embodied energy content of a building was small compared to the energy used in operating the building over its life. Most effort, therefore, was put into reducing operating energy by improving the energy efficiency of the building envelope. However, this is not always the case. For example, research on office construction shows that embodied energy can approach 37 years of operational energy (Moncaster 2007). Embodied energy can therefore be the equivalent of many years of operational energy. Research by CSIRO has also found that the average house contains about 1,000GJ of energy embodied in the materials used in its construction. This is equivalent to about 15 years of normal operational energy use. For a house that lasts 100 years, this is over 10 per cent of the energy used in its life (Milne & Reardon 2014).

4.2.2 Types of embodied energy and methods of calculation

As already noted, embodied energy includes the energy consumed in mining and processing of natural resources, and then in the manufacture, transport and product delivery. Final energy calculation also depends on where boundaries are drawn in the assessment process. For example, embodied energy will vary if all possible energy use is included – for example, in transporting the materials and workers to the building site; in factory and office lighting; the energy used for the machines that make the materials; and the energy used for urban infrastructure (roads, drains, water and energy supply). Based on these considerations, there are two types of embodied energy which can be considered – the gross energy requirement (GER); and the process energy requirement (PER).

Gross energy requirement (GER) is a measure of the true embodied energy of a material, which would ideally include all the embodied energy used, directly and indirectly. However, measurement of GER is usually impractical.

Process energy requirement (PER) is a measure of the energy usage that is directly related to manufacture of the material. This is simpler to quantify. Consequently, most figures quoted for embodied energy are based on the PER. This would include the energy used in transporting the raw materials to the factory, but not the energy used to transport the final building materials and elements to the construction site.

PER has been used in this study, and accounts for 50 to 80 per cent of GER. Even within this narrower definition, arriving at a single figure for a material is impractical as it depends on the efficiency of the manufacturing process; the fuels used in the manufacture of the materials; the distance materials are transported; and the amount of recycled product used (Milne & Reardon 2014). Each of these factors varies according to product, process, manufacturer and application. They also vary depending on how the embodied energy has been calculated. Considering these factors, any improvement in the manufacturing and processing stages can cause variation in the embodied energy figures.

Embodied energy calculation can thus vary based on several factors. As a result, figures quoted for embodied energy are broad guidelines only. For example, material manufactured and used in Melbourne has a different embodied energy if the same material is transported by road to Darwin. Thus, one way to reduce relative embodied energy is to use local materials.

Tables 4.1 provides the embodied energies of common building materials in Australian construction systems; these are based on embodied energies of building materials used in British and Canadian construction systems (further detail on these is provided in Appendix A). Australian standard/basic carbon emissions are calculated using the Australian government's global average of 0.098 kg CO_2 eq = 1 MJ (CSIRO 2014), and are presented in column three of Table 4.1.

Table 4.1: Embodied energy and carbon emissions of common Australian building materials

Australian Building Materials	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions Kg/MJ
Kiln dried sawn softwood	3.4	0.333
Kiln dried sawn hardwood	2.0	0.196
Air dried sawn hardwood	0.5	0.049
Hardboard	24.2	2.372
Plywood	10.4	1.019
Stabilized earth	0.7	0.069
Plasterboard	4.4	0.431
Fibre cement	4.8	0.470
Cement	5.6, 5.4[1]	0.549, 0.82[1]
In situ concrete	1.9	0.186
Precast steam-cured concrete	2.0	0.196
Precast tilt-up concrete	1.9	0.186
Clay bricks	2.5	0.245
Concrete blocks	1.5	0.147
Aluminium	170	16.660
Galvanized steel	38	3.724
Steel	34[1]	AU 3.33, AU 2[1]

Source: Lawson 1996; 2006[1]; Sattary & Cole 2012.

Embodied energy values for materials used in Canadian construction systems have been studied for the past several decades by architectural researchers interested in the relationship between building materials and their environmental impacts. These include the embodied energy of building materials based on units of weight (MJ/kg) and volume (MJ/m^3) (Canadian Architects 2015). These are further detailed in Appendix A.

Table 4.2 presents embodied energy and relevant carbon emission values from data within the Inventory of Carbon and Energy (2011) database, provided by the Department of Mechanical Engineering in the University of Bath in the United Kingdom.

Table 4.2: Embodied energy and carbon emissions of common UK building materials

United Kingdom common building materials	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions Kg/MJ
Aggregate	0.083	0.0048
Concrete (1:1.5:3)	1.11	0.159
Bricks (common)	3	0.24
Concrete block (Medium density)	0.67	0.073
Aerated block	3.5	0.3
Limestone block	0.85	
Cement mortar (1:3)	1.33	0.208
Cement	-	1.0[1]
Steel (general, av. recycled content)	20.1	1.37
Steel	-	2.7
Stainless steel	56.7	6.15
Timber (general, excludes sequestration)	8.5	0.46
Timber		0.30[1]
Glass fibre insulation (glass wool)	28	1.35
Expanded Polystyrene insulation	88.6	2.55
Polyurethane insulation (rigid foam)	101.5	3.48
Wool (recycled) insulation	20.9	
Slate	0.1–1.0	0.006–0.058
Clay tile	6.5	0.45
Aluminium (general & incl 33% recycled)	155	8.24
Aluminium	-	11.5[1]

Source: Inventory of Carbon & Energy (2011); Wilson (2014) (figures with superscript [1] are from the latter source).

Table 4.3 presents Australian, UK and Canadian PER data (further detailed in Appendix A) relating to building materials and relevant carbon emissions. These are for items produced from ‘raw material and virgin natural resources’ and ‘recycled materials and recycled content’. Some of these embodied energy figures have been used in the carbon emissions reduction calculations of the case studies in Chapter Six of this research.

Table 4.3: Embodied energy and carbon emissions of building materials derived from ‘raw material and virgin natural resources’ and ‘recycled materials and recycled content’

Building Materials in AU, UK and Canada	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions per Kg/MJ	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions per Kg/MJ
	From raw materials & virgin natural resources		From recycled materials and recycled content	
Aggregate	AU, CA 0.1, UK 0.083	CA 0.009[2] UK 0.0048[1]		
Kiln dried sawn softwood	3.4	0.333		
Kiln dried sawn hardwood	2.0	0.196		
Particleboard	8.0	0.784		
Plywood	10.4	1.019		
Stabilized earth	0.7	0.069		
Gypsum plaster	2.9	0.284		
Plasterboard	4.4	0.431		
Fibre cement	4.8	0.470		
Cement	5.6	0.549		
In situ concrete	1.9	0.186		
Precast steam-cured concrete	2.0	0.196		
Precast tilt-up concrete	1.9	0.186		
Clay bricks	AU 2.5, UK 3	AU 0.245, UK 0.24		
Concrete blocks	AU 1.5, UK 0.67	AU 0.147, UK 0.073		
Polyethylene	US 98, AU 103		US 56, AU	
Thermal insulation			0.585[1]	
Polypropylene expanded	117			
Aluminium	US 196, AU 170, AU 191[3]	AU 16.660, UK 11.5[4]	US 27, AU 8.1, AU8.1[3] CA 8.1, UK 155,	UK8.25 (33% recycled)
Steel	AU 32[3], US40, CA32	UK2.7[4]	AU 10.1[3], US 18, CA8.9	CA0.872
Steel (general - average recycled content)	AU 32[3], US40, CA32		UK 20.7, 20.50[1]	UK 1.37
Steel (section - average recycled content)	AU 32[3], US40, CA32		UK 21.5	UK 1.42
Steel (pipe-average recycled content)	AU 32[3], US40, CA32		UK 19.8	UK 1.37
Galvanized steel	AU38	3.724	AU 10.1	
Stainless steel	UK 56.7	UK 6.15		

Sources: Australian data – Lawson 1996, 2006; O'Halloran, Fisher & Rab 2008; US data – Jong & Rigdon, 1998; Canadian data – Canadian Architects 2015 | Superscripted sources: 1. Greenspec 2015; 2. Canadian Architects 2015; 3. O'Halloran et al 2008; 4. Institution of Civil Engineers 2012

Lawson (1996) studied the embodied energies of Australian Floor, Wall and Roof construction systems. The embodied energy figures are converted using the Australian global average as previously described, and presented in column three of Tables 4.4, 4.5 and 4.6. These figures have been used in the case studies described in Chapter Six.

Table 4.4: Embodied energy and carbon emissions in Australian Floor construction systems

Australian Floor construction systems	Basic Embodied Energy MJ/m²	Basic Carbon Emissions Kg/m²
a. Elevated Timber Floor (lowest level)	293	28.7
b. Elevated Timber Floor (upper level)	147	14.4
c. 110 mm Concrete Slab on ground	645	63.21
d. 125mm Elevated Concrete Slab (temporary framework)	750	73.5
e. 110mm Elevated Concrete Slab (permanent framework)	665	65.17
f. 200mm Precast Concrete Tee Beam/Infill flooring	602	59
g. 200mm Hollow Core Precast Concrete flooring	908	88.98

Source: From Lawson (1996) and the case study analyses (Chapter Seven)

Table 4.5: Embodied energy and carbon emissions in Australian Wall construction systems

Australian Wall construction systems	Basic Embodied Energy MJ/m²	Basic Carbon Emissions Kg/m²
a. Timber Frame, Single Skin Timber Wall	151	14.8
b. Timber Frame, Timber Weatherboard Wall	188	18.4
c. Timber Frame, Reconstituted Timber W/board Wall	377	36.9
d. Timber Frame, Fibre Cement Weatherboard Wall	169	16.6
e. Timber Frame, Steel Clad Wall	336	32.9
f. Steel Frame, Steel Clad Wall	425	41.7
g. Timber Frame, Aluminium Weatherboard Wall	403	39.5
h. Timber Frame, Clay Brick Veneer Wall	561	63.8
i. Steel Frame, Clay Brick Veneer Wall	650	63.7
j. Timber Frame, Concrete Block Veneer Wall	361	35.4
k. Steel Frame, Concrete Block Veneer Wall	453	44.4
l. Steel Frame, timber weatherboard Wall	238	23.3
m. Cavity Clay Brick Wall	860	84.3
n. Cavity Concrete Block Wall	465	45.6
o. Single Skin Stabilised Rammed Earth Wall	405	39.7
p. Single Skin autoclave Aerated Concrete Block wall	440	43.1
q. Single Skin Cored Concrete Block Wall	317	31.1
r. Steel Frame, Compressed Fibre Cement Clad Wall	385	37.7
s. Hollow-Core Precast Concrete Wall	729	71.4
t. Tilt-up Precast Concrete Wall	818	80.1
u. Porcelain-Enamelled Steel Curtain Wall	865	84.8
v. Glass Curtain Wall	770	75.5
w. Steel Faced Sandwich Panel Wall	1087	106.5
x. Aluminium Curtain Wall	935	91.6

Source: From Lawson (1996) and the case study analyses (Chapter Seven)

Table 4.6: Embodied energy and carbon emissions in Australian Roof construction systems

Australian Roof construction systems	Basic Embodied Energy MJ/m²	Basic Carbon Emissions Kg/m²
a. Timber Frame, Timber Shingle Roof	151	14.8
b. Timber Frame, Fiber Cement Shingle Roof	291	28.5
c. Timber Frame, Steel Sheet Roof	330	32.3
d. Steel Frame, Steel Sheet Roof	483	47.3
e. Timber Frame, Concrete Tile Roof	240	23.5
f. Steel Frame, Concrete Tile Roof	450	44.1
g. Timber Frame, Terracotta Tile Roof	271	26.6
h. Timber Frame, Synthetic Rubber Membrane Roof	386	37.8
i. Concrete Slab, Synthetic Rubber Membrane Roof	1050	102.9
j. Steel Frame, Fibre Cement Sheet Roof	337	33
k. Steel Frame, Steel Sheet Roof (commercial)	401	39.3

Source: From Lawson (1996) and the case study analyses (Chapter Seven)

4.2.3 Input-Output embodied energy and hybrid methods

Input-Output embodied energy analysis is the main method used today, and originates from the input-output model described in Leontief (1995). This I-O analysis method was adapted for embodied energy to describe ecosystem energy flows. This adaptation tabulated the total direct and indirect energy requirements (the energy intensity) for each output made by the system. The total amount of energies, direct and indirect, for the entire amount of production was called the Input-Output embodied energy (Leontief 1995).

The I-O method calculates data obtained from industrial manufacturing processes. The Process Energy Requirement (PER) was the focus, even though this was often considered in the context of the Gross Energy Requirement (GER) – and earlier research had found that the PER was usually only 50 to 80 per cent of the GER. However, if rough comparisons of the embodied energy of different materials were required to assist designers to decide between high embodied energy and low embodied energy materials, then the I-O method gave easily comprehensible information. Nevertheless, the approach was clearly incomplete – for example, energy used in transport, a significant consideration as building materials are often heavy or bulky, was often omitted.

Today, there is an increasing need for more accurate and comprehensive analysis of embodied energy, rather than mere relativities. The input-output approach, based on gross national economic data, was initially seen as a way of achieving the completeness that the process approach lacked. However, the modelling of supply and demand, then its translation into energy requirements and greenhouse gas emissions, involves quite sophisticated mathematics, making the method difficult to understand. This has led to development of a hybrid input-output method that enables any amount of industry data to be incorporated within a consistent input-output model. The Centre for Design at RMIT believes the hybrid input-output method is now the preferred technique of assessing embodied energy (Lawson 2006).

Tables 4.7 and 4.8 present a comparison of the embodied energy of some common Australian building materials calculated using the PER approach and the hybrid input-output approach. The I-O figures for Australian building materials are obtained from Lawson (2006) where he used I-O calculations rather than PER calculations used in his earlier 1996 paper. The carbon emissions are calculated based on the Australian government's global average.

The higher accuracy of the I-O approach is indicated by the consistently higher figures, which incorporate upstream requirements for goods and services. For example, in the production of cement, limestone, shale and probably coal have to be mined, processed and transported to the cement works, and this is taken into account in I-O calculations.

This present research and the developed model is based on calculations of embodied energy using process energy requirements (PER). However, calculations using the input-output embodied energy method can also be applied within the research model. Future research using Building Information Modelling (BIM) will make it easier to replace PER with I-O embodied energies

Table 4.7: Comparison of PER and hybrid I-O methods for embodied energy and carbon emissions of common building materials

Australian Building Materia	PER		Hybrid Input-Output	
	Embodied Energy MJ/kg	**Carbon Emissions Kg/MJ**	**Embodied Energy MJ/kg**	**Carbon Emissions Kg/MJ**
Organic				
Kiln dried sawn hardwood	2	0.196	25.1	2.46
Kiln dried sawn softwood	3.4	0.333	19.9	1.95
Plastic General	90	8.82	163.4	16.01
Ceramics				
Cement	5.6	0.549	16.4	1.607
Concrete 20MPa (no reo)	1.7	1.167	4.1	0.401
Aerated Concrete	3.6	0.353	4.0	0.392
Clay Brick	2.5	0.245	2.7	0.265
Glass	12.7	1.245	160.0	15.68
Metals				
Aluminium	170.0	16.66	252.6	24.75
Cooper	100.0	9.8	378.9	37.1
Structural Steel	34.0	3.332	85.3	8.36
Stainless Steel	115.0	11.27	445.2	43.43

Source: Lawson (1996; 2006).

Table 4.8: Comparison of PER and hybrid I-O methods for some typical residential wall, floor and roof systems

Australian Floor, Wall and Roof construction systems	PER		Hybrid Input-Output	
	Embodied Energy MJ/kg	Carbon Emissions Kg/MJ	Embodied Energy MJ/kg	Carbon Emissions Kg/MJ
Floor				
Elevated timber floor (lowest level)	293	28.71	1289	126.32
Elevated timber floor (upper level)	147	14.41	873	85.55
110 mm concrete slab on ground	645	63.21	960	94.08
110 mm elevated concrete slab (permanent framework)	665	65.17	1617	158.47
Wall				
Timber frame, timber weatherboard, plasterboard lined wall	188	18.42	999	97.90
Single skin AAC block, plasterboard lined wall	472	46.26	805	7.73
Timber frame, clay brick veneer, plasterboard lined wall	561	54.98	1207	118.29
Steel frame, clay brick veneer, plasterboard lined wall	604	59.19	968	94.86
Double clay brick, plasterboard lined wall	906	88.79	1243	121.81
Roof				
Timber frame, concrete tile roof, plasterboard ceiling	251	24.6	1269	124.36
Timber frame, terracotta tile roof, plasterboard ceiling	271	26.56	2200	215.6
Timber frame, steel sheet roof, plasterboard ceiling	330	32.34	1302	127.6
Steel frame, steel sheet roof, plasterboard ceiling	483	47.33	1471	144.16

Source: Crawford and Treloar (2004); Lawson (1996; 2006).

4.2.4 Guidelines for reducing embodied energy and carbon emissions

Lightweight construction materials such as timber frames are usually lower in embodied energy than heavyweight construction materials. This may not be the case if large amounts of light but high energy materials such as steel or aluminium are used. There are many situations where a lightweight building is the most appropriate and may result in the lower lifecycle energy use (i.e. in hot, humid climates, sloping or shaded sites, or sensitive landscapes) (Milne & Reardon 2014).

In climates with greater heating and cooling requirements, and significant day/night temperature variations, embodied energy in a high level of well insulated thermal mass can significantly offset the energy used for heating and cooling. However, there is little benefit in building a house with high embodied energy in the thermal mass or other elements of the envelope in areas where heating and cooling requirements are minimal, or where other passive design principles are not applied. Each design should select the best combination for its application based on climate, transport distances, and availability of materials and budget, balanced against known embodied energy content (Milne & Reardon 2014).

The following is a summary of guidelines, tips and techniques for reducing embodied energy.

- Reduce building elements with the highest impact on embodied energy – for example, replacing the high embodied energy Portland cement component of concrete with an appropriate lower embodied energy alternative will reduce the embodied energy of concrete. As concrete is such a common building material, such energy savings may be significant (Greenspec 2015).
- Select low embodied energy construction materials (which may include materials with a high recycled content), preferably based on supplier-specific data (Greenspec 2015).
- Give preference to materials manufactured using renewable energy sources (Greenspec 2015).
- Select materials that can be reused or recycled easily at the end of their lives using existing recycling systems (Greenspec 2015), and ensure materials from demolition of existing buildings, and construction wastes, are reused or recycled (Milne & Reardon 2014).
- Use locally sourced materials (including materials salvaged on site) to reduce transport (Milne & Reardon 2014).
- Reduce material use by appropriate design, and increase the resource efficiency of materials and elements (Milne & Reardon 2014). Some very energy intensive finishes, such as paints, often have high wastage levels (Lawson 2006).

The advice, guidelines and tips provided here may result in substantial reductions in embodied energy and related carbon emissions. In respect to reuse and recycling of building materials, this can save up 95 per cent of embodied energy that would otherwise be lost (Milne & Reardon 2014).

4.3 Carbon emissions of the construction process

In the construction industry, designers and other interested parties must be aware that carbon dioxide can be emitted through a variety of mechanisms other than by simply burning fossil fuels to provide a power supply to a building. For example, carbon emissions result from burning fossil fuels in transporting construction workers and materials in both pre-construction and construction stages. Once all contributing factors to embodied energy and generated carbon emissions have been identified, the total embodied energy and relevant carbon emissions can be calculated (UK Indemand 2015).

There are two types of carbon emissions that need to be considered in construction: the operational carbon and the embodied carbon. Operational carbon is the carbon dioxide released over the lifetime use of a building, including that generated by heating, cooling, lighting, and so on. Embodied carbon refers to the carbon dioxide released from materials extraction, transport, manufacturing, and related activities, including end of life emissions (Sustain 2014; Wynn 2012).

Embodied energy has a significant impact on a building's (embodied) carbon emissions, and this proportion has been steadily increasing over recent decades as technology has developed and operational energy use has reduced. In addition, the recurring embodied energy also needs to be considered, this being defined as the energy required for maintenance, refurbishment and replacement of components during the lifetime of the building, a process which also releases (operational) carbon. The ratio of embodied carbon to operational carbon has grown to approximately 40:60 as shown in Table 4.9 (Bull 2012).

Table 4.9: The carbon life cycle of a typical building

Initial material investment 1-2 years construction	Refurbishment and Retrofit 1-2 Years Construction	Deconstruction 0-6 months	Building in use 30 years operation	Operation (increased efficiency and fabric improvements) 15-20 Years
21%	**8.5%**	**8.5%**	**45%**	**17%**
38% Total Embodied Carbon			62% Total Operational Carbon	

Source: Bull (2012)

Currently embodied carbon can be equivalent to as much as 37 years of operational carbon (Moncaster 2007). This figure will increase as operational carbon is decreased with implementation of zero carbon operational strategies (Centre for

Sustainable Development 2014). Under such circumstances, the impact of the building sector on the environment could be reduced significantly by taking into account bioclimatic design principles.

Carbon emissions generated by a specific material or construction element can vary considerably – for example, if the energy and electricity used for the processes were generated by hydro or coal generation, with a ratio of around 1/250 (Table 4.10). The type of energy resources used in production and construction processes can thus play a major role in carbon emissions reduction, a factor considered in the bioclimatic design principles of the developed model.

Table 4.10: The carbon intensity of electricity generation (all figures in g co_2eq/kwh)

Hydro	Ocean	Wind	Nuclear	Biomass	Solar CSP	Geothermal	Solar PV	Natural Gas	Oil	Coal
4	8	12	16	18	22	45	48	469	840	1001

Source: Intergovernmental Panel on Climate Change (IPCC 2011); Wilson 2014

As Table 4.10 shows, alternatives to fossil fuels are many and varied, ranging from solar energy in its various forms, to wind, geothermal, natural gas, nuclear fission and so on. It is sometimes suggested that nuclear energy is not associated with the production of greenhouse gases. This is untrue. The energy associated with mining, transport of uranium, and nuclear waste generates substantial quantities of greenhouse gases. Additionally, when the nuclear fuel cycle is examined, it is clear that considerable amounts of other potential pollutants are produced at various stages. For example, while a 1000MW nuclear power plant consumes only 36 tonnes of processed and enriched uranium fuel, this necessitates the mining of $85.5x10^3$ tonnes of ore which produces toxic tailings containing arsenic, cadmium, and mercury as well as radionuclides (Masters 1991).

4.4 Converting embodied energy to carbon emission (CO_2) equivalent

The term ‘carbon’ is frequently used as shorthand for either carbon dioxide (CO_2) or carbon dioxide equivalents (CO_2-e), which includes both CO_2 and other gases with significant global warming potential, meaning that they tend to trap heat in our atmosphere. Once each greenhouse gas is on the same carbon-equivalent scale, emissions for a specific material can be added up to get its total embodied CO_2-e. A lot of the embodied carbon of a product or building comes from energy consumption (embodied energy), but not all of it.

The embodied carbon of a product usually includes CO_2-e emitted from the extraction of raw materials through to the final manufacture of the product, sometimes referred to as 'cradle-to-gate'. The embodied carbon of new construction includes this, plus transport and installation of all products and materials that make up the building.

Some measures (gross energy requirement, input-output and hybrid method) include emissions from construction activity, such as equipment use, transportation of workers to and from the job site, and even land disturbance in construction (which causes loss of carbon stored in healthy soils). As with the more comprehensive life-cycle analysis, the definition of what is and is not included in the calculation has to be consistent to be useful. For building products, work is ongoing in defining these boundaries through product category rules, which clearly explain the types of embodied energy used.

An increasing proportion of the total energy used and carbon emissions for high-performance buildings come from its materials and products. This is not only because less energy is used in operation, but also because buildings may be using more carbon-intensive materials to achieve lower energy use. To minimise climate change, the goal is to reduce the total quantity of greenhouse gases emitted into the atmosphere, and reducing the embodied carbon of building materials has an important role (Building Green 2014).

The embodied energy of a building or building material is the simple and most convenient measure of its environmental impact. The greater the embodied energy, the greater are its carbon emissions and environmental impacts. Another reason to address embodied carbon is that reductions in carbon emissions of materials have an immediate benefit, whereas the carbon reductions through operations accrue over a long period of time. By taking embodied carbon into account, design is for carbon emissions reduction.

Embodied energy, like operational energy, can be directly related to the generation of greenhouse gases such as CO_2, although energy derived from different fossil fuel sources will vary in its associated CO_2 emissions. On average, approximately 0.1 tonnes of CO_2 are produced per gigajoule of embodied energy (Lawson 2006). Typical embodied energy units used are MJ/kg (megajoules of energy needed to make a kilogram of product), and tCO_2/kg (tonnes of carbon dioxide created by the energy needed to make a kilogram of product).

Converting MJ to tCO_2 is not straightforward because different types of energy (oil, wind, solar, nuclear, and so on) emit different amounts of carbon dioxide, so the actual amount of carbon dioxide emitted when a product is made will be dependent on the type of energy used in the manufacturing process. For example, the Australian Government gives a global average of 0.098 tCO_2 = 1 GJ. This is the same as 1 MJ = 0.098 kg CO_2 = 98 g CO_2, or 1 kg CO_2 = 10.204 MJ (CSIRO 2014).

4.5 Review of techniques to reduce construction carbon emissions

This section discusses potential ways in which carbon emission reductions can be achieved in the construction process. There are several illustrative examples given which are identified from the six case studies which are considered in this research.

4.5.1 Reuse and recycling of construction materials

The ‘throw-away’ mentality of the past needs to change in order to preserve our environment. One important facet relating to this is that reusability of building materials and elements must be implemented in global construction activities. Reusability is often misinterpreted for recycling. Recycling refers to taking the construction materials, breaking them down into their raw materials, and creating new construction products. Reuse refers to extending the life of a building material or element (Waste Watch 2004). Additionally, reuse of construction materials and elements does not require more energy like recycling, because it relies on the embodied energy present within the materials (Danciu 2012).

Construction materials have a limited life cycle before they become waste. Reuse thus extends the lifespan of a construction product. This means that through reuse, materials can last longer and pollution and waste can be reduced. Reusability has become globally prominent, and more integrated into the policies and procedures of governments, industries, and communities through advances in technology and globalisation (World Federation of Engineering Organizations 2011).

The common theme in any reusability project is to reduce waste, reduce emissions, and decrease the environmental impact of construction (World Federation of Engineering Organization 2011). In fact, up to 80 per cent of construction waste is actually made up of discarded materials which are ideal for re-use or recycling, and which represent significant potential for use in this market. This market is already developed in the United States, Germany, Britain and some European countries, but has not yet to be fully developed in Australia (UN Environmental Protection Agency UNEPA 2015).

Most of the resources used in house construction are suitable for reuse or recycling. Table 4.11 identifies materials suitable for recycling or reuse in a typical Australian house.

Table 4.11: Higher value materials typically recovered in house deconstruction

Material	Comments
Bricks and concrete	Almost all bricks and concrete – the heaviest building materials – can be recycled, making significant savings on landfill fees.
Terracotta tiles	Depending on their condition, terracotta tiles can be either sold for re-use or collected free for recycling. Like bricks and concrete, landfill fees for disposal of heavy tiles can be easily avoided.
Wood products (lumber, timber and floorboards)	Up to 75 per cent of wood products can be re-used or recycled.
Good quality fixtures and fittings	Easily accessible items of value can be resold.

Source: Environment Protection Authority NSW (EPA 2015).

Of the total building-related materials generated during construction and demolition, the United Nations Environmental Protection Agency (UNEPA) estimates that only 40 per cent are reused, recycled, or sent to waste-to-energy facilities; the remaining 60 per cent are sent to landfill (UNEPA 2015). Reuse and recycling of building materials commonly saves about 95 per cent of embodied energy that would otherwise be wasted (Milne & Reardon 2014). There is thus great potential to reduce carbon emissions through recycling and reuse of construction materials, as will be considered in the following sections of this chapter.

4.5.2 Reduce materials use in design

The Green Building Council of Australia aims to work with customers and design consultants in the design and tender stage to reduce the tons of steel and other resources used in projects through design efficiency. Both environmental improvement and project cost savings are the result. (Green Building Council of Australia GBCA 2014a).

As an example of reduced materials in design, the London Olympics stadium (Figure 4.1) was constructed using only one tenth of the steel required to build Beijing 'Bird's Nest' stadium. Additionally, the amount of carbon output of the stadium is only an eighth of the Beijing stadium (Cable News Network 2012; Craven, 2012). On a similar note, aluminium in the roofs of the London Aquatics Centre and the velodrome has a high percentage of recycled content; and leftover gas pipes make up the Olympic Stadium's ring beam, reducing the need for new steel to be produced (Inventory of Carbon & Energy 2011).

Calculating the reduction of carbon emissions achieved in the London Olympic Stadium through the decreased materials in design as follows – the basic carbon emissions level of 39.3 Kgs CO_2/m^2 was reduced to 8.02 Kgs CO_2/m^2. There was thus a 79.6 per cent reduction in released carbon emissions from the London Olympic stadium.

Figure 4.1: London Olympic Stadium
Source: London attractions information (2016)

4.5.3 Use of appropriate construction materials

There is significant potential for improving resource efficiency within the construction industry by using construction materials and elements with a high recycling and 'complete reuse' potential. On a much larger scale, complete steel buildings can be reused. An example is the British Pavilion at the Seville Expo in 1993 (Figure 4.2). This innovative, energy efficient steel building was designed to be reused after the Expo (Steel Construction Information 2014) in fact it was designed for deconstruction and use elsewhere.

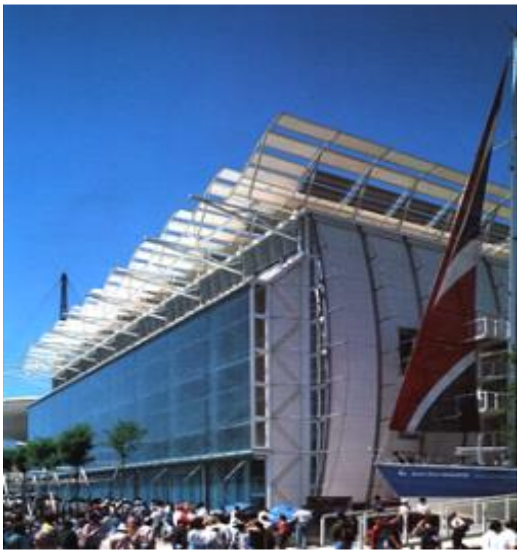


Figure 4.2: British Pavilion, Seville Expo 93
Source: Steel Construction Information (2014)

To reduce environmental impact, a system is needed that facilitates reuse through a range of mechanisms including – a reuse management model; careful demolition; establishment of storage sites; maintenance of a stock of reusable members; creation of performance evaluation and fabrication procedures for reusable members (Frangopol 2011).

A study done by Aye et al. (2012) demonstrated that use of a prefabricated steel system produces significant reductions in the consumption of raw materials of up to 50.7 per cent by weight. A further benefit of a prefabricated system is that a significant portion of the structure can be reused at the end of the building's life. This may result in a significant reduction in waste being sent to landfill, and reduced requirements for additional new materials. However, the energy embodied in the prefabricated steel buildings was up to 50 per cent greater than that for concrete buildings. This was offset by the fact that at the end of the building's useful life, up to 81.3 per cent of the embodied energy of the initial steel building can be saved by reuse of the main steel structures of the prefabricated modules and other components in further construction (Aye et al. 2012).

4.5.4 Reuse of building elements and building spaces

In the last decade, reusability has become a rising global trend and countries have been actively pursuing policies of reusability to prolong the use of construction materials and other items of what was once ‘waste’. The common theme in any reusability project is to reduce waste, reduce emissions, and decrease the environmental impact of construction (World Federation of Engineering Organizations 2011). New technologies for demolishing buildings also contribute to reducing waste because most building elements can be reused in the deconstruction materials market (Architecture & Engineering 2015). This market is already developed in the United States, Germany, Britain and some European countries, but has not yet to be fully developed in Australia (UNEPA 2015).

Reuse and recycling of structural building elements can play a significant role in reducing the depletion of natural resources, not only through compliance with new standards, but also by minimising costs through efficient use of resources, solving problems interactively within design teams, having the knowledge and skills to assess and adapt existing buildings, and bringing an open-minded and innovative approach to design (Steel Construction Information 2014).

Where a building has been designed with deconstruction in mind, much of the building material and elements can be reused. An example is provided in family housing units in Berlin which reused the complete walls, floor plates and ceilings from a demolished communist-era 11-storey tower block (Figure 4.3). The only significant energy costs arose from the transportation of the five-tonne panels and the use of a portable crane to lift them into place on site. For the residential project, the demolition firm provided the panels free of charge, which saved them the disposal cost and the architects the materials cost (CCAA 2015).

Another German example is where the prefabricated concrete walls of Stalin-era apartment buildings were upcycled into two-story villas (Figure 4.4). After deconstruction, the panels were resized or taken as designed after stripping the wallpaper (High Concrete Group 2014).

Figure 4.3: Upcycled prefabricated concrete walls – the prefabricated concrete walls of an eleven-story Stalin-era apartment buildings were upcycled into two-story villas
Source: High Concrete Group (2014).

Figure 4.4: Reused prefabricated concrete walls – designing future buildings for deconstruction is vital for facilitating higher levels of reclamation and re-use.
Source: High Concrete Group (2014).

The basic carbon emission of a square metre tilt-up precast concrete wall is 80.16 kg CO_2/m^2 – which was decreased to 16.26 kg CO_2 / m^2 by deconstructing and downsizing the prefabricated concrete walls of these Stalin-era apartment buildings. Thus, a potential reduction of 79.72 per cent in possible carbon emissions from the two-story precast concrete walls was achieved. Additionally, this program also saved 14.7 million tonnes of waste from ending up in landfill (Fischer 2006; Adaptivereuse 2015).

Research on residential case studies has shown that costs for salvaged materials are 20 to 50 per cent less than the cost of new materials. Economic benefits are mainly from salvaged materials, but also include lower landfill fees, and less future cost for replacement of materials. The cost of deconstruction was also 37 per cent lower than for demolition (Kernan et al. 2001).

According to Morgan and Stevenson (2005), economic benefits of deconstruction include increased flexible use and adaptation of property at minimal future cost; maximized value of building elements; reduced quantity of materials going to landfill; and reduced risk of financial penalties in the future through easily replaceable building elements. Deconstruction and design for deconstruction can redirect waste back into the building life cycle, thus conserving resources, energy and landfill space, as well as providing other associated environmental, economic and social benefits (Bales 2008).

4.5.5 Recycling and reuse of steel from recycled content

It is estimated that the construction industry consumes some 420mt of materials annually, and generates some 90mt of construction, demolition and excavation waste, of which 25mt ends up in landfill. A significant proportion of this are waste steel products. In construction, most steel products are large, and can be easily captured at the end of a building's life. Capture rates are on average 96 per cent (Steel Construction Information 2014) (Figure 4.5).

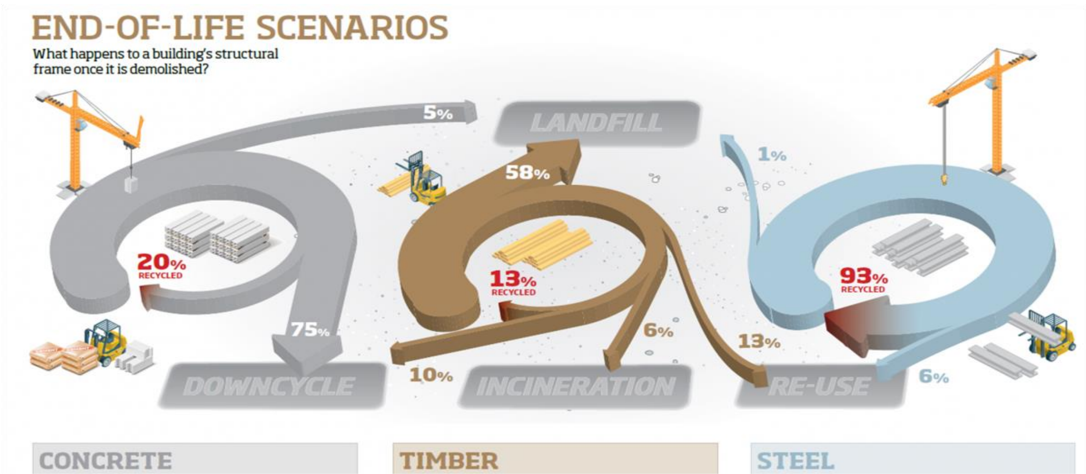


Figure 4.5: Current end-of-life outcomes for concrete, timber and steel
Resource: (Steel Construction Information 2014)

The primary method used in the production of structural steel shapes and bars is the electric arc furnace, which uses 95 to 100 per cent old steel to make new steel. In this process, producers of structural steel are able to achieve up to 97.5 per cent recycled content for beams and plates, 65 per cent for reinforcing bars, and 66 per cent for steel decks. Total recycled content varies from mill to mill. Steel for products such as soup cans, pails, drums and automotive fenders is produced using the basic oxygen furnace process which uses 25 to 35 per cent old steel to make new products (Kang & Kren 2007).

4.5.6 Reuse of structural steel

Steel buildings and steel construction products are generally deconstructable and reusable. This potential is illustrated by the large number of temporary works systems that use steel components, e.g. scaffolding, formwork, sheet piles, and so on. Provided that attention is paid to eventual deconstruction at the design stage, there is no reason why nearly all of the steel building elements should not be regarded as a vast ‘warehouse of parts’ for future use in new applications.

Research carried out by the Steel Construction Institute (SCI) has estimated that there is around 100 million tonnes of steel in buildings and infrastructure in the UK. This stock of steel is an important and valuable source for materials reuse, and there is research currently being conducted to identify how this can be done in the most effective fashion (Steel Construction Information 2014).


Figure 4.6: Steel elements from demolition in Toowong, Australia
Source: Author (2015).


Figure 4.7: Materials from house demolition in Australia
Source: EPA (2015).


Figure 4.8: Floating shipping container apartments in Denmark
Source: Stella (2016).

Figures 4.6, 4.7 and 4.8 illustrate examples of sources and uses of steel elements and products that can be reused at both the product and the building level. One innovative example is the use of old shipping containers to assist in solving the student housing shortage in Denmark (Stella 2016).

Many industries commonly reuse steel components. Steel construction products are often reusable including steel piles (sheet and bearing piles); steel structural components including hollow sections; and light gauge steel products such as purlins and rails (Steel Construction Information 2014). Structural steel reuse can occur either on an individual element level, for example in the reuse of steel beams (e.g. in the BedZED project [Bioregional n.d.]), or on a component level, (e.g. a steel trusses, as demonstrated in the construction of the Ottawa Convention Centre, which reused nine 160ft long trusses from old buildings on that site [O'Connor 2004]). Steel is particularly suited for reuse due to its durability and robustness during deconstruction (UK Indemand 2014). Figure A.1 in Appendix A presents possible structural construction systems made of reused materials.

There are three barriers to reuse of structural steel. First, although new steel is certified based on a process audit, reused steel must be re-certified by mechanical testing to confirm its grade, and this is a costly process. Second, although deconstruction rather than demolition can be profitable due to the value of reclaimed materials and components, it still takes longer, and delays to a construction project program are undesirable. Third, because reuse of components is still relatively uncommon, there is a supply problem – for example, finding the appropriate steel section sizes and lengths can be difficult and expensive (Steel Construction Information 2014). In contrast, non-structural materials can also be salvaged and re-used, and this is more common than structural steel reuse as re-certification is not required (UK Indemand 2014). Other technical and logistical barriers to reuse of structural steels are summarised in Table 4.12.

Table 4.12: Barriers to reuse of structural steel

Technical barriers

- Lack of standardisation of components
- Ensuring and warranting the performance of reused components
- Lack of detailed knowledge of a product's properties and in-use history (this may be important, for example, if the component has been subject to fatigue loading)
- Quality assurance of reused products

Logistical barriers

- Lack of commercial drivers for reuse
- Cost of storage, cataloguing, refurbished products, etc.
- Cost of testing to verify and guarantee properties
- Client expectation that 'second-hand' products should be cheaper than new ones

Source: Sattary and Thorpe (2011); Steel Construction Information (2014).

Structural engineers have an important role in respect to this process – to produce construction designs that allow for reuse of steel and other components (Bull 2012). Steps that they can take to maximise the opportunities for reusing structural steel include:

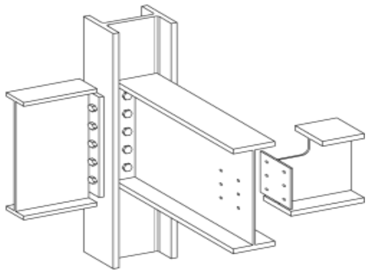


Figure 4.9: Reuse strategy, End plate beam to column, beam-to-beam connections
Source: (Steel Construction Information 2014)

- Using bolted connections in preference to welded joints to allow structures to be dismantled during deconstruction (Figure 4.9)
- Using standard connections including bolt sizes and spacing of holes
- Ensuring easy and permanent access to connections
- Where possible, ensuring that the steel is free from coatings or coverings that would prevent visual assessment of its condition
- Minimising use of fixings to structural steel elements that require welding, drilling of holes, or fixing with Hilti nails – clamped fittings are preferable where possible
- Identifying the origin and properties of components (e.g. by bar-coding, e-tagging, or stamping) and keeping an inventory of products
- Use long-span beams as they are more likely to allow flexibility of use and to be reusable (Steel Construction Information 2014).

In conclusion, reuse of steel construction elements is becoming more prominent across the world. Particular countries may implement reuse in different ways and for different reasons. However, this trend will help create a better future for everyone (World Federation of Engineering Organizations 2011).

4.5.7 Recycling and reuse of bricks

Reuse and recycling options for bricks are economically viable because costs associated with sending bricks and concrete to landfill are rising. Demolition is also more expensive than deconstruction – brick disposal costs to landfill are $115/tonne, recycling uncontaminated material costs $24/tonne. Many companies will also collect bricks free of charge and typically sell them for $0.50 each, making reuse an attractive option (Brick Development Association [UK] BDA 2014; Department of Environment, Climate Change and Water NSW 2014).

In the building of the London Olympics, 28 per cent of construction used recycled materials. Some materials were reclaimed for re-use as aesthetic and practical features in the Olympic Park – including 660 tonnes of various brick types, 176 tonnes of paving material, and 5,400 m of kerbing (Smith 2012).

Since the early days of ecologically sustainable building, most brick manufacturers have incorporated recycled materials into their brick production in different ways. Materials used as recycled content can come from either pre-consumer or post-consumer sources. For example, 'Green Leaf Bricks' are newly manufactured fired masonry bricks composed of 100 per cent recycled materials, designed and engineered especially for sustainable construction (Green Leaf Brick 2016).

Bricks may incorporate recycled materials such as overburden from mining, washings from aggregate processing, grog, sawdust and metallic oxides (BDA 2009). Research demonstrates a potential 40 per cent energy saving in brick manufacturing by using 67 per cent recycled container glass brick grog (BDA 2014; Tyrell & Goode 2014).

4.5.8 Use of fly ash in bricks and concrete

In a standard concrete mix, the cement component commonly accounts for approximately 70 to 80 per cent of the embodied energy. Fly ash, being a by-product of coal fired electricity generation, has a relatively low embodied CO_2 content related to its manufacture, estimated at 0.027kg of CO_2 emissions per tonne, 3 per cent that of Portland cement manufacture (Ash Development Association of Australia 2013).

The manufacture of Portland cement is an energy intensive process that releases approximately 0.820 tonnes of CO_2 emissions for each tonne of cement produced. A strategy to produce more sustainable concrete is to replace a portion of the cement component with one or more supplementary cementitious materials such as fly ash. The benefits of using fly ash include reduction in CO_2 emissions and embodied energy; reduction in resource use; re-use of industrial by-products as alternative raw materials; and sustainability achieved through efficient design and enhanced durability (Ash Development Association of Australia 2013).

In respect to bricks, US-made fly ash brick gains strength and durability from the chemical reaction of fly ash with water. However, 85 per cent less energy is used in fly ash brick production than in fired clay bricks. A potential 85 per cent reduction in released carbon emissions in brick manufacturing can thus be achieved (Volz & Stovner 2010; Structure Magazine 2014) (Figure 4.10).

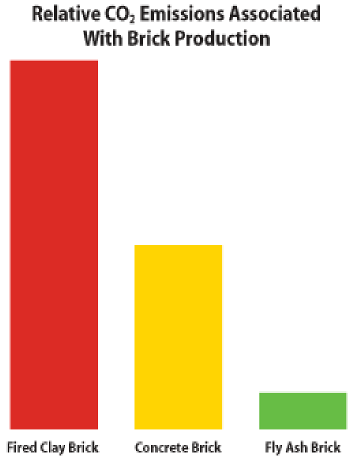


Figure 4.10: CO_2 emissions of different brick types
Source: Volz and Stovner (2010); Structure Magazine (2014);

As fly ash brick technology produces bricks without using coal, it has the potential to eliminate carbon emissions from the brick-making industry which burns huge amounts of coal and emits millions of tons of carbon dioxide annually. Additionally, the process uses fly ash, previously an unwanted residue from coal-fired power plants. The World Bank is supporting fly ash brick production by allowing entrepreneurs to earn carbon credit revenues. So far, the project has allowed 108 fly ash brick plants to earn around $3.2 million (World Bank 2012).

4.5.9 Use of recycled aggregate in concrete

Recycling concrete and using aggregates is an increasing practice at construction sites. For example, in 2006 the Brookhaven National Laboratory saved over $700,000 in construction costs by using Recycled Concrete Aggregate (RCA) from the demolition of ten structures (Craven 2012). Another example was in construction of the 2012 London Olympics Park, where over 200 buildings were dismantled, and the materials reused (Ingenia 2014; Learning Legacy 2014).

The sustainability summary of the London Olympics notes that a quarter of all materials used in the buildings were recycled – this included 400,000 tonnes of concrete which used up to 76 per cent recycled aggregate (‘stent’, a by-product of the Cornish china clay industry), and 40 per cent recycled cement substitute (granulated blast furnace slag) in the concrete. Sixty per cent of recycled content was used in the interior block work; recycled glass in the wall insulation; and recycled plastic for the seats. Additionally, the foundations of the Aquatics Centre, Handball Arena, and Olympic Stadium all used concrete containing more than 30 per cent recycled materials in place of gravel, which otherwise would have had to be mined and transported to the site. Overall, around 90 per cent of materials left over from construction, demolition and excavation works were reused or recycled on site (Ingenia 2014; Learning Legacy 2014).

The Gulf Organisation for Research and Development has found that the recycling of concrete, brick and masonry rubble as concrete aggregates is an important way to contribute to a sustainable material flow. Experimental studies were carried out on the improvement of RCA performance. Beneficial effects from polymer based treatments applied to RCA were obtained, especially lower water absorption and better fragmentation resistance (Spaeth & Tegguer 2013).

To achieve emissions reduction in construction, many countries are focusing on recycled concrete aggregates as they are proven to be practical for non-structural concrete, and to a limited extent for some structural-grade concrete. In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities, and these have potential to be used in construction. Air-cooled blast furnace slag and manufactured sand are two good examples of concrete aggregates (Cement Concrete & Aggregates Australia CCAA 2015). Additionally, the use of milled waste glass as partial replacement for cement is estimated to effectively overcome the limitations of recycled aggregate (Nassar & Soroushian 2012).

Recent research (e.g. Katz 2003; Tam, Gao & Tam 2006; Kotrayothar 2012) has demonstrated that the use of recycled aggregate in both structural and non-structural concrete applications has become technically feasible and commercially viable (Eguchi et al 2007). For example, recycled concrete aggregate has now been used in a wide range of construction projects in Germany, Hong Kong, Britain, Norway and Australia, confirming the practicality of its use. Many countries including Australia have thus established specialised standards for recycled concrete aggregates (Yiu, Tam & Kotrayothar 2009; Kotrayothar 2012; Tierney 2012). Concrete recycling is thus a method that is an attractive option to achieve greater sustainability and cost savings in construction. Using concrete waste as aggregate also solves the critical shortage of natural aggregate anticipated in the near future (Portland Cement Australia 2014)

It is generally accepted that when natural sand is used, from 30 to 80 per cent of natural crushed coarse aggregate can be replaced with coarse recycled aggregate without significantly affecting any of the mechanical properties of the concrete. As replacement amounts increase, drying, shrinkage and creep will increase, and tensile strength and modulus of elasticity will decrease. However, compressive strength and freeze-thaw resistance are not significantly affected (Uche 2008; Kwan, et al. 2012; Portland Cement Australia 2014). When the mix design method proposed by the Department of Environment in the UK was used, a target strength was achieved even when 80 per cent of the total coarse aggregate content was replaced by the RCA (Kwan et al. 2012). It is also apparent that at 75 per cent or less RCA replacement, the concrete compressive strength is well above the designed characteristic strength of grade 30 concrete, hence it can be used for structural grade concrete work (Uche 2008).

According to Tam (2009), from experience gained in Japan in recycling of concrete, Australia should develop a unified policy on concrete recycling; seek financial support from the government to implement recycled concrete use; and develop clear technical specifications and standards on the use of recycled aggregate for structural applications. Table 4.13 presents the current recycled aggregate concrete codes in the US, UK and Australia.

Table 4.13: Summary of recycled aggregate concrete codes in the US, UK and Australia

Country	Recycled Aggregate (Type/Name/Classification)	Maximum RCA Substitution	Maximum RCA 28 Day, Cylinder Strength
USA	LCA	100%	20MPa
		25%	50MPa
		60%	NS Concrete
UK	RCA	No restriction	40MPa
		20%	Designated concrete, 20 to 40 MPa
	LCA	No restriction	No restriction
	RA		16 MPa
AU	Class 1A - RCA	30%	40 MPa
	Class 1B - RCA	100%	25 MPa

Source: Chisholm (2011). LCA = Leftover Concrete Aggregate; RCA = Recycled Concrete Aggregate; RA = Recycled Aggregate; NS = Non-Structural Concrete,

4.5.10 Replacement of cement with geopolymers

Geopolymer has a history starting in the 1940s, and has attracted significant academic research, but has yet to achieve significant market use. However, the use of geopolymer concrete is increasing, in part motivated by the sustainability benefits of using a binder system composed almost entirely of recycled materials. Wagners are an Australian company supplying a proprietary geopolymer concrete for both precast and in-situ applications in the construction industry (Aldred & Day 2012).

Figure 4.11: 10.8 metre geopolymer beam with vaulted soffit being craned into position
Source: Aldred and Day (2012)

Geopolymers were first used in some concrete applications in the Soviet Union after World War Two, being known then as 'soil-cements'. Numerous structures have been constructed since then, though no commercial entities have carried this through to an industrial scale (Zeobond Group 2014). The University of Queensland’s Global Change Institute is the world’s first building to successfully use geopolymer based cement for structural purposes (Geopolymer Institute 2014); and the Wellcamp

Airport in Toowoomba is the first airport in the world where geopolymer cement has been used (Welcamp 2014).

Replacing the high embodied energy Portland cement component of concrete with an appropriate lower embodied energy alternative is a simple way of reducing the embodied energy of concrete. Because concrete is such a universal building material, such energy saving may be significant (Lawson 2006).

Fly ash geopolymer can be used as binding material for partial replacement of cement in geopolymer concrete (Lohani et al. 2012). The opportunities for using fly ash in production of sustainable concrete are extensive and will continue to increase. Related to this, Louisiana Technology University is currently working to develop a 'green' type of concrete that uses geopolymers to reduce greenhouse gases by as much as 90 per cent compared to regular Portland cement (Building industry council 2014).

Replacing some of the cement content in concrete with sustainable construction materials such as fly ash is arguably the most efficient and economical means of reducing CO_2 emissions of concrete (Ash Development Association of Australia 2013). Key elements that could be considered to result in a more sustainable outcome when using such concrete are – less resource depletion; reduced emissions in production of the material or components (embodied energy); reduced water consumption; and waste avoidance and reduction (Geiger 2015).

Geopolymer represents a sustainable and economical binding material as it is produced from industrial by-products such as fly ash (Nath & Sarker 2014). Research has shown that fly ash based geopolymer concrete cured in ambient conditions can be modified for desirable workability, setting time, and compressive strength using ground granulated blast-furnace slag as a small part of the binder (Olivia & Nikraz 2012). Full replacement of Portland cement by geopolymer can result in a 97 per cent reduction in greenhouse gas emissions. However, where Portland cement has been replaced with geopolymer concrete mixes based on typical Australian usage, there is potential only for a 44 to 64 per cent reduction in greenhouse gas emissions, with associated reductions in financial costs (McLellan et al. 2011). For instance, the released carbon emissions for a one square metre ‘200 mm concrete slab on ground Floor’ (Case Study 4: Civil Engineering Laboratory building, USQ) are 58.12 Kgs CO_2/m^2. Use of geopolymer concrete can reduce this to 29.73 Kgs CO_2/m^2, representing a potential 48.84 per cent (28.39 kg) reduction in the released carbon emissions, and reducing the total costs of cement production by up to 50 per cent (Calculation is illustrated in Table A.A.8, Appendix A).

In 2014, a project submitted to the Low Carbon Living Capital Research Centre (LCLCRC) aimed to gather field data from geopolymer real-life constructions to develop greater confidence in geopolymer use. Using field and laboratory data, a comprehensive handbook for geopolymer specification was developed and published through Standards Australia. Additionally, a pilot program developed lightweight aggregates based on fly ash to produce lightweight concrete, which reduces energy usage in buildings. Current technologies for producing lightweight aggregates using sintered fly ash involve carbon intensive processes. This project aims to develop low carbon processes based on geopolymerisation and alternative methods for producing aggregates from fly ash (LCLCRC 2015).

The project is supported by a range of partner organisations including the Ash Development Association of Australia (ADAA), the Australian Standard Associations (ASA), the University of New South Wales (UNSW), Swinburne University of Technology (SUT), and others. The project coordinators also have support from the main Australian geopolymer concrete suppliers, including Zeobond Pty Ltd and Wagners Concrete Pty Ltd, and other interested parties. The project is being funded by these various partner organisations, and this research has great potential in geopolymer concrete and high-volume applications of fly ash (Ash Development Association of Australia 2013).

An example of the use of geopolymer concrete in block wall construction is provided in the carbon emissions for a one square metre ‘cavity concrete block wall’ (Case Study 4: Civil Engineering Laboratory building, USQ). Emissions can be reduced from 37.73 Kgs CO_2/m^2 to 23.28 Kgs CO_2/m^2 by use of geopolymer cement, representing a potential 38.29 per cent (14.45 kg) reduction in released carbon emissions. The detailed calculation is presented in Table A.A.9 in Appendix A.

4.5.11 Emissions reduction in transportation

Transport activity is a major source of carbon emissions due to the use of fossil fuels. Transport produced 83.2 Mt CO_2-e or 15 per cent of Australia's net emissions in 2010. Emissions from this sector were 32 per cent higher in 2010 than in 1990. Road transport is the main source of transport emissions (Macintosh 2007; Carbon Neutral 2015). In respect to construction, environmental pollution relates to mining, logging and transportation of raw materials, and then to the manufacture and transportation of the finished products, and their installation on the construction site.

Waste and debris from demolished and dismantled buildings can be reused as an aggregate. This occurred in construction of the 2012 London Olympics Park where over 200 buildings were dismantled, and around 98.5 per cent of the debris was reclaimed and reused in production of the thousands of tonnes of concrete produced on site. Reduced use of fossil fuel was also achieved due to use of nearby waterways to transport materials and waste out of the park (Inventory of Carbon & Energy 2011; Aggregate Industries 2014). Calculations in Table A.A.10 (Appendix A) indicate that reduced transportation emissions by not carrying the waste to the landfill was 15.42 kg CO_2/m^2 for each square metre of 200 mm concrete slab laid.

4.5.12 Using sustainable types of transportation

The carbon emissions associated with construction are relatively small when compared to other aspects of construction operations. However, the use of sustainable modes of transport is still important. The energy consumption of different modes of transport is presented in Table 4.14 – thus, it is important to reduce road transport where possible. For example, the Tata Steel Group manages shipping and logistic operations. Their policies towards a shift to sustainable modes of transport for construction materials include – using water and rail in preference to road transport; road haulage weight optimisation; linking outward journeys with return journeys to minimise empty running; and improving the efficiency of the contracted and sub-contracted haulage fleet (TATA Steel 2015).

Table 4.14: Transportation energy consumption: United Kingdom and Canada

Mode	Energy Consumption (MJtonne/km) United Kingdom	Energy Consumption (MJtonne/km) Canada
Road	4.50	1.18
Rail	0.60	0.49
Ship	0.25	0.12

Source: Lawson (1996).

For reuse and recycling to become established in the Australian construction industry, several supporting initiatives will need to be enabled. Salvage markets and speciality suppliers of used building materials will have to increase in number and scope of offerings. Databases detailing the salvaged materials on offer will need to be established – providing life cycle inventory data, assembly and disassembly instructions, and warranty information on the building materials. Buyers and sellers need to know the full origin, use and impact of the materials or assemblies they are to exchange (Bales 2008).

Specifications in a building contract that demands use of recycled materials can facilitate increase in reuse. The following items are usually easy to locate and reuse – recycled steel reinforcements, recycled or plantation timber, recycled concrete and bricks. For example, there is an online initiative linking buyers and sellers of building products called Construction Connect in Sydney. Similarly, Eco Buy lists suppliers of second-hand construction and building materials. Buying recycled products increases the market for them, making it more viable for businesses to supply them (Hawkesbury City Council 2014).

4.6 Barriers to emission reduction in construction

The recovery process for deconstructing materials used in building can be time consuming and expensive. Additionally, many buildings were not constructed with future recovery of materials in mind. In this respect, recovered non-structural materials are more commonly used than structural components as certification is not required.

There are specific barriers to reuse of some construction elements. For example, reused steel must be recertified before use, and this is costly (UK Indemand 2014). Finding the appropriate steel section sizes and lengths can also be difficult and expensive (Steel Construction Information 2014). There are also barriers to use of geopolymer concretes due to lack of standard specifications and unfamiliarity of their use (Wilson & Tagaza 2006).

Asbestos contamination is also a well-documented problem, and still presents a significant issue in waste derived from demolition and renovation works. High recovery rates for materials are achieved when materials are captured closer to the source, before there is opportunity for mixing with other wastes (Edge Environment Pty Ltd 2012). A summary classification of barriers to emission reduction is presented in Table 4.15

Table 4.15**:** Barriers to emission reduction

Market barriers
- Guaranteed quality and quantities of reused materials are difficult
- Reuse today is rare, there is a supply problem
- Limit and lack of market (many cities have limited markets, though these are increasing market in the US, Germany and the UK)
Design for Deconstruction
- Design for deconstruction in new buildings is often not considered important
- Existing buildings are not generally designed to be deconstructed
Technical barriers
- Lack of standardisation of components
- Reused steel generally must be recertified by mechanical testing to confirm its grade and this is costly
- Ensuring and warranting the performance of reused components
- Lack of detailed knowledge of the product’s properties and in-use history
- Quality assurance of reused products
- Robustness of products in the deconstruction process (e.g. many lighter products do not survive the deconstruction process intact)
- Practicalities of economic deconstruction including deconstructing composite components
- Some new materials are subsidised, creating unfair competition with reused materials
- Increased use of non-reversible technology, systems, construction, chemical bonds, plastic sealants etc
- There are significant volumes of materials still being sent to landfill due to the lack of technology or equipment to sufficiently clean materials.
- Asbestos contamination is a well-documented problem
- New construction systems make recovery more difficult and less financially rewarding
Logistical and Transportation barriers
- Assured availability of supply
- Demolition programs are too short to enable contractors to deconstruct buildings
- Lack of sufficient storage space for recovered products
- Deconstruction as opposed to demolition has significant impacts on the health and safety

precautions required
Legislation and codification barriers
- Construction and demolition waste minimisation is not a priority for some councils and governments
- Inconsistent units of measurement in local waste data
- Waste management is a local council responsibility
- Lack of standard specifications for recycled products
Economic barriers
- The high cost of transport and storage of recycled components and materials
- Cost of storage, cataloguing, refurbished products, etc.
- Cost of testing to verify and guarantee properties
- Finding the appropriate section sizes and lengths can be difficult and expensive
- Additional cost of deconstruction over faster demolition
Liability barriers
- How to manage and apportion risk and liability associated with deconstruction and reuse
- Current standard specifications imply new materials should be used
-The limit and lack of a grading system for reuse components
- Liability in certification of reused components or materials is not clear
Construction and Demolition Industry barriers
- Lack of communication and networking in the construction and demolition industry with waste minimisation organisations
- There is no formal umbrella group to distribute information
- There are significant volumes of materials still being sent to landfill due the inability to identify markets for the material as it is presented.
- Demolition is generally a low profit margin industry compared with construction

Source: Storey et al. (2005); Sattary &Thorpe (2011); Steel Construction Information (2014); UK Indemand (2014).

The Institute of Public Works Engineering Australasia have developed a specifications course designed to assist project managers and engineers responsible for public works to understand the specifications for materials such as recycled aggregates and other substitute materials, and to learn how to incorporate them into projects (Edge Environment Pty Ltd 2012). As the range of recyclable and reusable products and materials increases, there will be a greater need for such courses to provide awareness of materials and, more importantly, knowledge of how to use them successfully in projects.

4.7 Summary

This chapter has reviewed the significance of embodied energy and relevant carbon emissions in the construction process, and identified the optimum methods for their measurement. Discussion also centred on how construction carbon emissions may be minimised. This sets the context for the next chapter which takes as its focus Bioclimatic Design Principles and their application to the six case studies within this research.

CHAPTER FIVE
BIOCLIMATIC DESIGN PRINCIPLES, GREEN BUILDING RATING TOOLS AND THE RESEARCH MODEL

5.1 Overview

Bioclimatic design principles (BDP) have already been introduced in Section 2.5 of Chapter Two. The purpose of this chapter is to provide more detail of the BDP criteria and their basic application to the six case studies in this research. There is also consideration of how BDPs are integrated into a range of green building rating systems. As will be seen, voluntary application of measures to reduce the carbon emissions of construction by the various stakeholders is patchy at best. Given this, it may be that legislation compelling the use of BDPs and similar measures through the building life cycle may be necessary.

This chapter is divided into nine sections. Section 5.1 provides an overview to the chapter. Section 5.2 discusses how BDPs can be applied in building design. Section 5.3 identifies how carbon emissions can be reduced through use of BDPs as exemplified in respect to aspects of the six case studies considered in this research. Section 5.4 considers bioclimatic design principles as applied in current best practice, and their current positioning with the LEED, BREEAM and Green Star green building rating systems. Section 5.5 identifies measurable criteria derived from BDPs that can be used to quantify the degree of carbon emission reduction that may be achieved through use of BDPs. Section 5.6 considers the carbon emissions achieved through use of BDPs in other research and under laboratory conditions. Section 5.7 discusses the limitations of green tool rating systems. Section 5.8 considers the role of Building Information Modelling (BIM) and how green tool rating systems may be integrated into its use. The final Section 5.9 provides a summary of this chapter's content.

5.2 Using bioclimatic design principles in building design

The term 'bioclimatic' refers to a process where savings in energy are achieved through the use of bioclimatic design principles (BDP) in building. As the energy efficiency of buildings increases, the relative contribution of embodied energy to total energy consumption becomes increasingly important, as does its reduction through bioclimatic design principles or other method. Energy saving (carbon emissions reduction) may be achieved through attention to BDPs during design. Appropriate bioclimatic design can reduce energy consumption in a building by five to six (Jones 2003). Other benefits of such energy reduction include improved health and productivity of workers, and reduction in costs of building (Birkeland 2002).

The Energy Design Partnership (EDP) company (2012) proposed use of bioclimatic design principles to improve and regulate environmental conditions in a building. As well as their use during the construction of the building, bioclimatic design principles are also taken into account during the design phase of the building in order to optimise control or use of the sun, the prevailing winds, and the ambient temperature and humidity. The Energy Design Partnership believes that exploitation of solar energy can be achieved in several ways – including through appropriate design of the building envelope (to maximise absorption of solar energy during winter, and minimise it during summer); through suitable orientation of spaces and openings in the building (a southern orientation is considered as the most appropriate); through the optimum sizing of the openings; through use of a layout of the interior spaces of the building based on thermal requirements; and finally by the adoption of passive applications that can collect sunlight and thus be considered as a 'natural' heating system (EDP 2012).

As seen in the Energy Designs Partnership example above, appropriate bioclimatic design can achieve thermal protection of a building by the suitable placement of openings to prevent the escape of heat; by use of appropriate insulation of the building envelope; and by strategic arrangement of internal spaces. Additionally, the provision of shading has as its goal the protection of the building from overheating during summer with strategically placed internal or external, vertical or horizontal blinds. Such systems and passive cooling techniques are a method of bioclimatic design that aims to control a building’s microclimate. Another technique emerging from bioclimatic design principles is the careful use of natural lighting in a direct or indirect way to optimise conditions of comfort within the building for the sake of its occupants.

In the final analysis, the crucial principle of bioclimatic design is to achieve the least possible energy consumption concurrently with provision of optimum thermal and visual comfort for the users of a building (EDP 2012). The ‘resources’ of bioclimatic design may be considered as the natural flows of energy in and around a building – created through the interplay of the sun, wind, precipitation, vegetation, temperature and humidity in the air and in the ground (Architecture 2015).

This present research is focused on construction carbon emissions reduction. This can be achieved through use of bioclimatic design principles to identify measurable criteria that have potential to reduce carbon emissions generated by building construction. There are two main aims in bioclimatic construction – first, to ensure that the constructed building is able to function satisfactorily within current and future climatic conditions; and, second, that the environmental impact of existing buildings is reduced through reduction in their energy use and greenhouse gas emissions (Clarke & Pullen 2008).

The following is a summary of the bioclimatic design principles that have been used in the model proposed in this present research. They focus on reduced and smarter use of sustainable materials to minimise carbon equivalent emissions.

- Minimise energy consumption in mining, processing, equipment use, pre-assembly and assembly in manufacturing. Criteria measured are reduced energy in mining, processing, and construction materials.
- Minimise transportation at all stages of the building process. Criteria measured are reduced energy as a result of preassembly and reduced materials transportation.
- Minimise use of resources, achieving waste reduction by facilitating reuse and recycling. Criteria measured are reduced energy by recycling and reusing of building materials and building elements.
- Maximise use of renewable energy. Criteria measured are replaced and saved energy in mining and construction (preassembly, professional worker transportation, site processing, materials transportation).

5.3 Reduction of carbon emissions by application of bioclimatic design principles to the six case studies

The following guidelines have been identified through analysis of bioclimatic design principles to measure the potential carbon emissions that can be reduced in the pre-construction and construction stages of building (lifecycle stages 1 to 3). The criteria focus on three main areas that can measure potential carbon reduction: first, carbon emission from energy consumed in ***extraction and production*** of building materials and elements; second, in ***implementation***; and finally, in ***transportation*****.** At this stage, the research model and the calculations have been applied only to the major building elements (floor, wall and roof) of Australian construction systems; and only consider stages one, two and three of the building lifecycle (Table 5.1): extraction, production, and construction.

Table 5.1: Building lifecycle stages

Stage one	Stage two	Stage three	Stage four	Stage five
Extraction	Production	Construction	Operation	Demolition

Source: Author

Measurable indicators from bioclimatic design principles that can be used to decrease the embodied energy and the associated carbon emissions of building construction – from mining and processing of natural resources to manufacturing, transport and product delivery – are delineated in Table 5.2 below, and also in Tables A.B.1 and A.B.2 in Appendix B.

The following methods and techniques based on bioclimatic design principles can reduce construction carbon emissions. They are available, but are not being consistently and properly used and applied in existing construction practices. This research proposes that if these practices were adopted, this would result in substantial reduction of construction carbon emissions. These reductions could be achieved through consideration of the bioclimatic criteria in Table 5.2; by legislation granting credits for use of environmental assessment tools (LEED, BREEAM, Green Star) to enable reuse of structural elements; by expanding and creating a warehouse of parts and reuse markets; and by expanding deconstruction techniques, machinery and facilities (Bales 2008; Steel Construction Information 2014).

Table 5.2: Measurable indicators – potential carbon emissions reduction in construction processes

Stage of construction process	Stage 1 and 2 Pre-Construction	Stage 3 Construction
Measurable carbon emissions (embodied energy) that can be reduced in extraction and production of **Building Materials**	**Saved** and **reduced** embodied energy (relevant carbon emissions) by using recycled, reprocessed, reassembled components, materials and elements	**Saved** and **reduced** carbon emissions (embodied energy) by: - Reusing buildings, spaces and building elements - Using re-treated, repaired and recycled materials - Using materials with recycled content
Measurable carbon emissions that can be reduced in **Implementation**	- **Reduced** carbon emissions in production processes	**Saved** and **reduced** carbon emissions in construction processes: - **Replaced** materials to reduce carbon emissions - **Replaced** renewable energy in construction processes - **Reduced** carbon emissions by reducing materials use
Measurable carbon emissions (embodied energy) that can be reduced in **Transportation**	- **Reduce** carbon emission in transportation and production process - **Replaced** renewable energy and reduced energy in transportation	- **Reduce** carbon emissions in transportation and construction processes by: - Reusing and recycling materials - Regionalizing and localizing suppliers - Using types of transportation that generate less carbon emissions such as ship or rail rather than road

Source: Author

The following paragraphs discuss the application of these techniques to the six case studies considered in this research. Table 5.3 presents results in three columns in respect to the case studies – the possible reduced carbon emissions achieved through use of BDPs; the standard/Basic (expected) carbon emissions without application of BDPs; and the percentage reduction achieved through use of BDPs. These are referenced in Table 5.3. by letters (a) to (o), and build on examples discussed in the previous chapter. Detailed calculations for these results (a to o) are presented in Appendix A.

(a) Potential emission reduction by use of steel from average recycled content

Carbon emission for steel from primary resources is 3.33kg CO_2/kg (Lawson 1996), but that of steel from average recycled content is 1.96 kg CO_2/kg (Greenspec 2015). Steel from average recycled content: Steel mesh +Edge beams from average recycled content = 5.148 Kg/m^2 x (embodied energy of steel from primary resources 34 MJ/Kg) (Lawson 1996, p. 13) – (embodied energy of the steel from average recycled content 20.10 MJ/Kg) (GreenSpec 2015) = 71.55MJ/m^2. By using steel from recycled content in the mesh of the concrete slab of Case Study 5 (London Olympics buildings), the basic carbon emissions of 17.14 kg CO_2/m^2 can be reduced to 10.09 kg CO_2/m^2, representing a 58.8 per cent reduction in generated carbon emission from just the concrete ground slab (see Table 5.3).

(b) Potential emission reduction by use of recycled materials in brick production

Research demonstrates a potential 40 per cent energy saving in brick manufacturing by using 67 per cent recycled container glass brick grog (BDA 2014; Tyrell and Goode 2014). If this technique was applied in Case Study 2 (ACF Green Home – a timber framed brick veneer wall system), there would be a potential 40 per cent energy savings in brick manufacturing. The relevant calculations show that the released carbon emissions could be reduced from 36.04 kg to 21.63 kg, a potential 40 per cent reduction (see Table 5.3).

(c) Potential emission reduction by use of fly ash brick

Fly ash brick gains strength and durability from the chemical reaction of fly ash with water. However, 85 per cent less energy is used in fly ash production than in fired clay brick (Volz & Stovner 2010; Structure Magazine 2014). For example, the carbon emission for a one square metre clay brick veneer wall system is 36.06 kg CO_2/m^2 (Case Study 3). Carbon emissions could be reduced to 6 kg CO_2/m^2 by using fly ash brick. This represents a potential 85 per cent reduction in released carbon emissions in brick manufacturing by using fly ash brick (see Table 5.3). Reduced energy 368 MJ/m^2 x 85% = 312.8 MJ/m^2.

(d) Potential emission reduction by use of recycled concrete aggregates

If a concrete mix uses from 30 to 80 per cent of coarse recycled aggregate, mechanical properties of the concrete are unaffected (Uche 2008; Kwan, et al. 2012; PCA 2014). In this case, the embodied energy of the aggregate is 0.083 MJ/Kg (GreenSpec 2015). If this technique was applied in Case Study 2 (ACF Green Home – a 110 mm Concrete slab on ground Floor), the following could be achieved. The released carbon emissions could be reduced from 47.13 Kg CO_2/m^2 to between 45.84

and 43.68 Kg CO_2/m^2, a potential reduction of 2.73 to 7.32 per cent (1.29 - 3.45 Kg CO_2/m^2) in released carbon emissions from a 110-mm concrete ground floor slab (see Table 5.3).

(e) Emission reduction by using unwanted gas pipelines for structural elements

An example of the reuse of structural steel is that the roof trusses of the London Olympic Stadium were made out of unwanted gas pipelines (Craven 2012; Learning Legacy 2014). In Case Study 5, this use of unwanted gas pipelines in the steel framed, fabric roof of the London Olympic Buildings reduced carbon emissions by 18.02 per cent – usual carbon emissions for this process at 27.63 kg CO_2/m^2 was decreased to 22.65 kg CO_2/m^2 (Steel Construction Information 2014) (Table 5.3).

(f) Potential emission reduction by reuse of brick

Reuse of deconstructed bricks, specifically in non-exposed locations, can achieve an emission reduction of 28.85 kg CO_2/m^2 as demonstrated in Case Study 2, the ACF Green Home. Reuse of brick in the timber-framed clay brick veneer walls reduced carbon emissions by 52.48 per cent – usual carbon emission for this process at 54.97 kg Co_2/m^2 was decreased to 26.12 kg CO_2/m^2 (see Table 5.3).

(g) Potential emission reduction by recycling and reusing concrete roof tiles

Concrete roof tiles can be used towards achieving LEED credits in several new construction or major renovation categories. For example, they can be crushed and recycled, or reused as landscaping fill (LEED 2014). Reuse of concrete roof tiles in the timber frame, concrete tile roof of Case Study 2 demonstrates reduced carbon emissions of 0.65 per cent – usual carbon emission for this process at 23.52 kg CO_2/m^2 was decreased to 21.95 kg CO_2/m^2 (see Table 5.3).

(h) Potential emission reduction by decreasing material use in design

The London Olympics stadium (Case Study 5) weighs only 4,500 tonnes, the lightest Olympic Stadium ever built. This was achieved through design that aimed for reduced materials use. Calculating the reduction of carbon emissions achieved in the London Olympic Stadium is as follows – the basic carbon emissions level of 39.3 Kgs CO_2/m^2 was reduced to 8.02 Kgs CO_2/m^2. There was thus a 79.6 per cent reduction in released carbon emissions from the London Olympic stadium (Table 5.3).

(i) Potential emission reduction by replacing Portland cement with E-Crete

According to the International Energy Agency, the manufacture of cement produces about 0.9 kilograms of CO_2 for every kilogram of cement produced. In respect to Portland cement, the CSIRO has found that for every tonne of Portland cement manufactured, one tonne of carbon dioxide is produced. As noted around 5 per cent of global CO_2 emissions result from cement manufacture, making it one of the most polluting activities undertaken by mankind (Zeobond Group 2014).

A new geopolymer cement product called E-Crete forms at room temperature, requires no kiln, and uses fly ash as the main component. Life cycle analysis studies show that E-Crete produces 80–90 per cent less carbon dioxide than traditional Portland cement. Australia is now among the world leaders in research and commercialisation of such cement (Smith et al. 2009).

For example, in Case Study 2, the energy required to construct a one square metre area of a 110-mm concrete slab with Portland cement is 47.13 kg. If this is replaced by E-Crete, the released carbon emissions for one square metre of a 110-mm concrete slab can be reduced to 40.91 kg. If there was full replacement of Portland cement with this geopolymer product in floor construction, there is a potential 47.31 per cent reduction in released carbon emissions (Zeobond Group 2014) (see Table 5.3).

(j) Potential emission reduction by replacing Portland cement with geopolymer

Significant reduction in carbon emissions can be achieved by replacement of Portland cement by geopolymer cements. For example, the carbon emissions from one square metre of a ‘125 mm elevated concrete floor’ of the Velodrome Building for the 2012 London Olympics (Case Study 5) is 48.70 Kgs CO_2 /m^2 – by replacing 40 per cent of Portland Cement with geopolymer, this can be reduced to 39.49 Kgs CO_2/m^2, representing a potential 18.9 per cent reduction in released carbon emissions (Table 5.3) (calculations are illustrated in Table A.A.6, Appendix A). Alternatively, if Portland cement were fully replaced with geopolymer based cement, the released carbon emissions for a one square metre a '125 mm elevated concrete floor' (Case Study 5) would reduce from 48.7 Kgs CO_2/m^2 25.66 Kgs CO_2/m^2, representing a potential 47.31 per cent reduction in released carbon emissions (Table 5.3) (calculations are illustrated in Table A.A.7 in Appendix A).

(k) Potential emission reduction by replacing Portland cement with geopolymer in concrete blocks

The carbon emissions for a one square metre cored concrete block wall (Case Study 4 – Civil Engineering Laboratory building, USQ) is 37.73 Kgs CO_2/m^2 which can be reduced to 23.28 Kgs CO_2/m^2, representing a potential 38.29 per cent (14.45 kg) reduction in released construction carbon emissions (see Table 5.3).

l) Potential emission reduction in transportation by rail or water

Sustainability management reports show that 63 per cent (by weight) of construction materials were transported to the London Olympic Park by rail or water (JLL 2012), with consequent reduction in carbon emissions. For instance, consider the reduced carbon emission of transportation by reuse of one square metre of a '200 mm concrete slab floor aggregate' in Case Study 5: The Olympic Velodrome building. The carbon emissions of transportation if required materials were carried by road (truck) would be 13.62 Kgs CO_2/m^2. However, when recycled aggregates were used, the carbon emissions were only 1.29 Kgs $CO_2/m^{2.}$ This represents a potential reduction of 90.52 per cent (12.33 Kgs CO_2/m^2) when recycled concrete aggregate is used (detailed calculations are illustrated in Table A.A.12, Appendix A). Similarly, for reuse of one square metre of 'Concrete Block wall's materials' (Case Study 5), there is a potential 90.57 per cent reduction in the released carbon emissions (calculations are illustrated in Table A.A.13, Appendix A) (Table 5.3).

(m) Potential emission reduction in transportation by localizing suppliers

Using locally produced building materials shortens transport distances, thus reducing air pollution produced by vehicles (Structure Magazine 2014). For example, if the construction materials in Case Study Six (Multi Sports Building USQ) were supplied from a local instead of distant supplier, the potential reduction in carbon emission for one square metre of concrete block wall would be 3.91 $kgCO_2/m^2$, an 8.6 per cent reduction in the wall-generated carbon emissions (see Table 5.3). Even products manufactured near the source of their raw materials reduce the transportation energy in the products.

(n) Potential emission reduction in transportation by decreasing material use in design

Reduced materials use in design also decreases the need for transportation, thus reducing carbon emissions. For example, the London Olympics roof (Case Study 5) used a minimum of steel due to its design, thus reducing carbon emissions to 0.37 Kg CO_2/m^2, an 0.94 per cent reduction in the roof generated carbon emissions (calculations are presented in Table A.A.11, Appendix A) (Table 5.3).

(o) Potential emission reduction by replacing energy in transportation

Construction materials can be carried by different types of transport. The energy efficiency of different means of transport is significant for construction materials (e.g. 4.5 MJtonne/km for road transport, compared to 0.60 MJtonne/km for rail, and 0.25 MJtonne/km for water) (Lawson 1996). For instance, the reduced carbon emissions in transportation (carried by water) gained by reusing one square metre of 200 mm concrete slab floor aggregates (Case Study 5 – Olympics Velodrome Building, London) is 12.33 Kgs CO_2/m^2 compared to carbon emissions generated by truck of 13.62 Kgs CO_2/m^2, representing a potential 90.52 per cent reduction in released carbon emissions (Table 5.3).

Table 5.3: Summary – Reduced carbon emissions, standard/basic carbon emissions, and percentage reduction in carbon emissions in the six case studies

Case Studies (CS	Potential carbon emission reduction	Reduced $kgCO_2/m^2$	Standard/Basic $kgCO_2/m^2$	Reduction in carbon emissions (%)
Materials production				
CS5 – London Olympic buildings (a)	Steel from average recycled content for the 200-mm concrete slab floor	7.05	17.14	58.8%
CS2 – ACF Green Home (b)	Using recycled materials in brick for the timber-framed brick wall	14.58	36.04	40%
CS3 – Display Project Home (c)	Using fly ash for clay brick veneer wall system	30.06	36.06	85%
CS2 – ACF Green Home (d)	Using recycled concrete aggregates for concrete slab floor	1.29- 3.45	47.13	2.73-7.32%
CS5 – London Olympic buildings (e)	Using unwanted gas pipelines for structure of the roof	4.98	27.63	18.02%
CS2 – ACF Green Home (f)	Reusing brick for the non-exposed locations in wall	28.85	54.97	52.48%
CS2 – ACF Green Home (g)	Reusing concrete roof tiles	0.15	23.52	0.65%
CS5 – London Olympic buildings (h)	Decreasing material use in design for London stadium	28.16	39.3	79.6%
Implementation				
CS2 – ACF Green Home (i)	E-Crete fully replacing Portland cement with geopolymer in 110 mm con. slab	20.30	47.13	47.31%
CC5 – London Olympic buildings (j)	Replacing 40% Portland cement with geopolymer in 125 mm con. slab	9.21	48.70	18.9%
CS5 – London Olympic buildings (j)	Full replacement of Portland cement with geopolymer in 125 mm con. slab	23.04	48.70	47.31%
CS4 – Civil Engineering Laboratory (k)	Use of geopolymer product in cavity concrete block wall	14.45	37.73	38.29%
Transportation				
CS5 – Olympics Velodrome (l)	Aggregate transportation for concrete slab floor	12.33	13.62	90.52%
CS5 –Olympics Velodrome (l)	Using low carbon transport for concrete block wall materials	10	11.04	90.57%
CS6 – Sports building, USQ (m)	Localizing suppliers of concrete block wall materials	3.91	45.6	8.6%
CS5 – London Olympic buildings (n)	Reducing steel use in the roof by design so reduces transport	0.37	39.3	0.94%
CS5 – London Olympic buildings (o)	Replacing renewable energy in transportation, water instead of truck	12.33	13.62	90.52

Source: Table provided by Author. Content summarised from this chapter (a-o) (for detailed information and calculations, see Appendices A and B).

In this section, as exemplified in Table 5.3, bioclimatic design principles have been applied to the construction systems in the six case studies from Australia and the UK. These BDPs include**:**

- Using recycled aggregates instead of extracting new aggregate from mining
- Using steel from recycled content instead of raw materials
- Using recycled construction materials and elements
- Replacing Portland cement with geopolymer based cement
- Using transportation that generates less carbon emissions (water or rail)
- Reducing transportation by reuse/recycling, and localisation of production

Table 5.4 summarises a number of bioclimatic design principles.
Column one, ‘Bioclimatic design parameters’, represents the BDPs applied to the case studies referred to in this chapter.

Column two, ‘Current conditions, Implemented’ are BDPs in current practice identified from the literature review. This column represents summarised data from Table A.D.1 in Appendix D where the numbered references may be found.

Column three, ‘Conditions in this research’, represent the criteria required to achieve the potential construction carbon emissions referred to in this chapter.

Table 5.4: Bioclimatic conditions – current and from this research

Bioclimatic Design Parameters	Current conditions, Implemented	Conditions in this research
Concrete from recycled aggregates	In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities. [1]	100% recycled aggregate for non-structural purposes; 80 % recycled aggregate for structural purposes [6]
Concrete block from recycled aggregates	24% recycled content of an aggregate concrete block; [8]	Aggregate for concrete block fully from recycled aggregate[13]
Brick from recycled aggregates	Current level of recycled material content in brick is 11%; [14,41]	Reuse recycled aggregate for brick, 67% [19]
Steel from average recycled content	Primary typically 10-15% of scrap steel, Secondary 100% scrap based production [25, 34]	Steel from fully post-consumer recycled content
Reuse recycled and post-consumer structural and non-structural steel	Scaffolding, formwork, sheet piles, etc., London Olympic Stadium [32, 34]	Use 40% recycled and post-consumer steel elements
Reduce material use in steel structural design 10-20%	Some of the current green projects have reduced materials use in design by10-20%[23]	Reduced materials use in structural design 10-20%
Reuse recycled timber and post-consumer FSC timber	FSC works in 80 countries, 24,000 FSC chain of custody certificates are active in 107 countries [23,]	60% of all timber products re-used, post-consumer recycled timber; FSC certified timber
Roof tile from recycled tile	In some countries, materials such as concrete roof tiles, are removed separated and recycled [44, 45]	50% roof tiles from recycled aggregate [21]
Thermal insulation from recycled content	Thermal insulation is fully recyclable, i.e. wool content [31]	Thermal insulation from fully recycled waste [25]
Portland cement replaced with geopolymer based cement	Geopolymers have been used in structural, non-structural applications e.g. University GCI Qld, Wellcamp Airport Qld [46, 47, 48]	Geopolymer based cement fully replaces Portland cement, arranged for non-structural, structural
Reduce transportation by reusing and recycled materials	National Waste Policy Australia advise to reduce waste, re-use to reduce environmental impacts [35]	Reuse has been considered in material production and building elements as well
Transportation by water or rail not truck, Reduce transportation by localizing material supply.	15% of bricks are transported to the distributor’s yard or jobsite by rail and 85% by truck[19, 30]	Localizing has been considered in detail

Source: This Table and data provided by author. References and detailed information for this table is presented in Appendix D, Table A.D.1.

5.4 Bioclimatic design principles in best practice and green tools

This section discusses the positioning and usage of BDPs in respect to current best construction practice, and then as they are currently positioned within the LEED, BREEAM, and Green Star green building tools.

5.4.1 Current best practice in use of bioclimatic design principles

The following comments are made in reference to the BDP parameters in Tables 5.4, 5.5 and 5.6. Construction materials have a limited life cycle before they become waste. Their reuse in the form of concrete from recycled aggregate extends the lifespan of the product. The construction industry realises the need to use available aggregate rather than searching for the perfect aggregate to make an ideal concrete suitable for all concrete applications. The importance of recycling aggregate has been recognised by the construction industry. Indeed, to date, hundreds of tons of aggregate concrete have been recycled and used for road-base and pavement. However, the use of recycled aggregate in concrete has become even more common practice in recent times.

In reference to 'concrete from recycled aggregate', in Australia, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) initiated one of the most significant steps in promoting the use of recycled aggregate in new concrete through publication of *Guidance on the preparation of non-structural concrete made from recycled concrete aggregate* and *Guide to the use of recycled concrete and masonry materials* were issued in 1998 and 2002 respectively. These guidelines recommend two classes of recycled aggregate (Class 1 and Class 2) for non-structural concrete applications. Despite the CSIRO guidelines, there is an urgent need to establish technical and performance standards for recycled aggregate for new concrete production (Tam 2009).

A number of manufactured and recycled aggregates are readily available on the Sydney and Melbourne market. In other construction applications such as pavement, road base and sub-base, there is limited information on the performance of each material, as assessment appears to be based on field trials, especially those by road authorities. Clean waste recycled concrete aggregate is being used at least 95 per cent by weight in Australia (CCAA 2012a).

In reference to ‘concrete block from recycled aggregate’: based on a report from Concrete Block Association (CBA), the current average recycled content of an aggregate concrete blocks is only 24 per cent (CBA 2013).

In reference to ‘brick from recycled aggregates’: recycled and secondary sources are increasingly important in the manufacture of clay bricks – the current level of recycled material content in brick is 11 per cent (Brick Industry Association [Virginia] 2009). Brick is made from abundant natural resources (clay and shale), and is readily recycled for use in the manufacturing process or other uses. Brick manufacturers address sustainability by locating plants in close proximity to mines; and by incorporating waste products and recycled materials into the brick (BDA 2009).

In reference to ‘steel from average recycled content’: steel is produced by one of two production routes – the primary or basic oxygen steelmaking route which is based primarily on the reduction of iron ore and incorporates typically 10 to 15 per cent of scrap steel; and the secondary or electric arc furnace route which is 100 per cent scrap based production (Steel Construction Information 2014).

In reference to ‘reuse recycled and post-consumer steel in structural and non-structural’ applications: steel structures and steel construction products are reusable. This potential is illustrated by the large number of temporary work systems that use steel components, including scaffolding, formwork, sheet piles, etc. Provided that attention is paid to eventual deconstruction at the design stage, there is no reason why nearly all of the steel building stock should not be regarded as a vast warehouse of parts for future use in new applications (Steel Construction Information 2014).

In reference to ‘reduce material use in steel structural design’: at present the reuse of building materials and products to reduce demand for virgin materials can be achieved, but there is no defined measure (US Green Building Council 2005).

In reference to ‘reuse recycled timber and post-consumer Forest Stewardship Council (FSC) timber’: in 2012, around 165 million hectares were certified to FSC’s

Principles and Criteria in 80 countries, and around 24,000 FSC Chain of Custody certificates were active in 107 countries (Potts et al. 2014).
In reference to ‘roof tiles from recycled tiles’: in some countries, there have been recycling rates of 65 to 80 per cent. Construction materials such as concrete roof tiles and timber are recommended to be removed separately as much as possible and sorted at the source to facilitate recycling (Tam, Gao & Tam 2005)

In reference to ‘thermal insulation from recycled content’: thermal insulation is recyclable, and some manufacturers recover and recycle this product. For example, some thermal insulation such as mineral wool content can be fully recycled (Ecospecifier 2016).

In reference to ‘Portland cement replaced with geopolymer based cement’: carbon emissions are expected to increase by 100 per cent from the current level in the next few years. Geopolymer cements are available in some areas, and have been used for structural and non-structural purposes. In Australia, geopolymer cement was used in construction of the University of Queensland’s Global Change Institute (GCI) (Geopolymer Institute 2014); and also in construction of Toowoomba’s Wellcamp Airport (Welcamp 2014).

In reference to ‘reduce transportation by reusing and recycling materials’ and, ‘transportation by water or rail not truck … localizing’: the National Waste Policy advises that the generation of waste should be avoided, but when produced, waste treatment, disposal, recovery and reuse must be undertaken in a safe and environmentally-sound manner (Department of the Environment and Energy 2012).

5.4.2 Bioclimatic design principles and the LEED green building tool

The Leadership in Energy and Environmental Design (LEED) for New Construction is a green building certification program/tool established by the US Green Building Council (USGBC) in 1993. This rating tool recognises best-in-class building strategies and practices. It is claimed that LEED rates not only the materials used in construction of buildings, but also the effect those materials have on energy consumption, human health and the environment (USGBC 2016).

To achieve LEED certification, building projects must satisfy prerequisites and earn points to obtain different levels of certification. There are four levels of LEED certification: 26–32 points for certification, 33–38 points for silver status, 39–51 points for gold status, and 52–69 points for platinum status (Azhar et al. 2011).

The calculation of recycled content begins in LEED-NC by determining the recycled content value of each building material. This is the sum of the percentage of post-consumer recycled content by weight plus one-half of the percentage of pre-consumer recycled content by weight multiplied by the total cost of the material (BDA 2009). Some of the credits that LEED grants for reusing and recycling is given in Table 5.5.

Table 5.5: LEED credits for reuse, waste management, recycled content and use of regional materials in construction

Credit	Materials and resources	Points
Credit 1.1	Building Reuse, Maintain 55%, 75%, 95% of Existing Walls, Floors, and Roof	up to 3
Credit 2	Construction Waste Management, Divert 50% or 75%	up to 2
Credit 4	Recycled Content, 10% (1) or 20% (2) (post-consumer plus ½ pre-consumer)	up to 2
Credit 5	Regional Materials, 10% or 20%	up to 2

Source: Project checklist – LEED – New construction (NC) v3 (Concrete Thinking 2014)

For example, in regard to reuse of recycled aggregate in concrete, the National Ready Mixed Concrete Association (NRMCA) provides specific guidelines as to use of returned leftover concrete. Its recommendations include the use of leftover concrete aggregate ‘as received all-in’ (coarse + fine) in non-structural applications up to 30 per cent by total weight of aggregate. This recommendation presumes that there is some sorting of the leftover concrete to use only leftover concrete 20 MPa and above. Up to 100 per cent replacement of coarse aggregate is allowed only for non-structural applications (Chisholm 2011). For structural applications, the American Society for Testing Materials (ASTM) generally allows up to 10 per cent by total weight of aggregate (equivalent to 20 to 25 per cent by weight of coarse aggregate); and 100 per cent recycled coarse aggregate replacement for concrete strengths up to 20 MPa (Chisholm 2011).

LEED grants a range of credits for local building reuse, construction waste management, resource reuse, use of recycled content, and regional materials. The use of recycled aggregate in concrete block is awarded up to two points; and in brick production up to 4.5 points (BDA 2009; Obla, Kim & Lobo 2010). LEED also grants up to one point for use of FSC certified wood (Forest Stewardship Council 2010).

Detail of credits granted in LEED is presented in Table A.B.3 in Appendix B. In respect to use of bioclimatic design principles, LEED credits awarded are summarised in Tables 5.6 and 5.7.

5.4.3 Bioclimatic design principles and the BREEAM green building tool

BREEAM – the Building Research Establishment Environmental Assessment Method – was first published in 1990 by the Building Research Establishment (BRE) in the United Kingdom. It is claimed to the world's most established and widely used environmental assessment method for buildings, with over 116,000 buildings certified, and over 714,000 buildings registered. Recent studies have shown that BREEAM has helped reduce CO_2 output by over 4.5 million tonnes since its inception (Aubree 2009).

BREEAM covers a range of building types including offices, homes, industrial units, retail units, and schools. Other building types can be assessed using the Bespoke BREEAM (a custom-made option). When a building is assessed, points are awarded for each criterion, and the points are added to a total score. The overall building performance is awarded a rating of Pass, Good, Very Good, Excellent and Outstanding based on the score (Fowler & Rauch 2006). BREEAM International schemes also use a star rating system of 1 to 5 corresponding to the above rating categories (Aubree 2009). Buildings already certified or under assessment are located in twelve countries in Europe, as well as in the US, Algeria, Dubai, Mauritius, Philippines, Qatar, Lebanon, Morocco and Malaysia (Aubree 2009).

BREEAM contains a range of items that aim to reduce construction carbon emissions through use of bioclimatic design principles. Highlights are as follows. In respect to reusing 'recycled aggregate': where there is a maximum permitted level of 50 per cent recycled aggregate, one point is awarded when the percentage of recycled aggregate used is greater than or equal to 35 per cent. Where there is no maximum regulatory level, the 50 per cent requirement must be achieved in order to gain this credit (BREEAM 2014a). In respect to ‘concrete block from recycled aggregate’: one point is awarded where at least 25 per cent of the aggregate used consists of secondary and/or recycled aggregate (Chisholm 2011). In respect to ‘Portland cement replaced with geopolymer based cement’: one point is awarded where cement and aggregate used is responsibly sourced (BREEAM 2014a).

In respect to ‘steel from average recycled content’: in the UK, almost 90 per cent of these steel products are recycled through an electric furnace process. In this process, producers of structural steel are able to achieve up to 97.5 per cent recycled content for beams and plates, 65 per cent for reinforcing bars, and 66 per cent for steel deck (Kang & Kren 2007).

In respect to ‘reuse recycled timber and post-consumer FSC timber’: up to three points are awarded where materials being assessed (including timber) are part of a pre-or post-consumer waste stream (Chisholm 2011).

In respect to ‘thermal insulation from recycled content’: one point is awarded where at least 80 per cent of the thermal insulation used in the assessed building elements is responsibly sourced (BREEAM 2014).

In respect to ‘reduce transportation by reusing and recycling materials’: one credit is awarded where at least 25 per cent of the aggregate used is obtained from a waste processing site within a 30km radius of the site (Chisholm 2011).

A summary of the credits that BREEAM grants for achieving a reduction in construction carbon emissions in the rating process is presented in Tables 5.6 and 5.7, and in Appendix D in Tables A.D.1 and A.D.2.

5.4.4 Bioclimatic design principles and the Green Star green building tool

The Green Star tool is an internationally recognised sustainability rating system launched by the Green Building Council of Australia (GBCA) in 2003. Green Star covers from individual buildings to entire communities, and is transforming the way the built environment is designed, constructed and operated in Australia. The Green

Star tool is Australia's only national, voluntary rating system for buildings and communities (GBCA 2016).

The Green Star rating system is based on the US LEED system. It represents a comprehensive approach for evaluating the environmental performance of Australian buildings based on a number of categories (Iyer-Raniga & Wasiluk 2007). The Green Star rating scale provides a tool for rating buildings and fit outs, and scores are based on how the building achieves best practice or above sustainability outcomes. Buildings assessed using the Green Star tool can achieve a rating from 1 to 6 Green Stars – with stars rating respectively as Minimum Practice, Average Practice, Good Practice, Best Practice, Australian Excellence, and World Leadership (GBCA 2016; 2017).

Bioclimatic design principles to reduce construction carbon emissions are considered in the Green Star tool, and the following commentary relates to the associated credits. In reference to reusing 'recycled aggregate': Green Star grants one point when 20 per cent of all aggregate used for structural purposes is recycled aggregate class one (i.e. with a maximum specified strength limit of 40 MPa), and no natural aggregates are used in non-structural items (GBCA 2008).

In reference to 'steel from average recycled content': Green Star recognises the reduction in carbon emissions and resource depletion associated with use of recycled steel (GBCA 2008). In reference to 'reuse recycled and post-consumer steel in structural and non-structural' elements': Green Star grants up to 2 points where 90 per cent of all steel by mass either has post-consumer recycled content greater than 50 per cent, or is reused (GBCA 2008). In reference to 'reduce material use in steel structure': Green Star grants one point where 20 per cent less steel has been used than in conventional steel framing, without changing the load path to other structural components (GBCA 2008).

In reference to 'reuse recycled timber and post-consumer FSC timber': Green Star grants up to 2 points where 95 per cent of all timber products used in building and construction works have been sourced from any combination of the following: reused timber, post-consumer recycled timber, or Forest Stewardship Council (FSC) Certified Timber (GBCA 2008).

In reference to ‘roof tiles from recycled tile or recycled content’: Green Star grants one point where at least 2 per cent of the project’s total value is represented by reused products or materials. Additionally, one point is given for concrete where no natural aggregate has been used for non-structural purposes, for example in roof tiles (GCBA 2008). In reference to ‘Portland cement replaced with geopolymer’: Green Star awards two points where Portland cement content is reduced by 40 per cent in concrete block production (CCAA 2012b). Green Star also awards up to two points where a project has reduced use of Portland cement (GBCA 2008).

In reference to ‘reduce transportation by reusing and recycling materials’: Green Star credits reusing and recycling of up to 40 per cent of materials, but only advises localising, and using water and rail instead of road (GBCA 2008).

A summary of Green Star credits for achieving carbon emissions reduction in the rating process is presented in Tables 5.6 and 5.7, and detailed information is provided in Appendix D, Tables A.D.1 and A.D.2.

Table 5.6: Bioclimatic conditions of the research considered in the green tools (Green Star, LEED and BREEAM)

Bioclimatic conditions, Parameters	**Australian Tool Green Star (GBCA)**	**US Green Tool LEED**	**UK Green Tool BREEAM**
Concrete from recycled aggregates	Green Star, one point, 20% of aggregate for structural purpose; no natural aggregate used in non-structural purposes [2]	LEED, recycled content, 10-20% of aggregate up to 3 points; [2, 24]; 20-30% of aggregate for structural 100% non-structural purposes, US [18,36]	BREEAM, 25-50% RA; no restriction in 16 MPa and 40 MPa; 20% Designated concrete 20-40 MPa [2, 36]
Concrete block from recycled aggregate	Green Star, 40% RA; no natural aggregates in non-structural [23,33]	ASTM, structural 20-25% coarse aggregate; 100% up to 20 MPa [18, 36]	BREEAM, no restriction in 16 MPa and 40 for Concrete block [36]
Brick from recycled aggregates	Green Star, no direct credit, Mat-3, 80% reused material [2,9, 16]	LEED, recycled content in brick 10-20%, MR 4, 2 points, 2 ½ points [14]	BREEAM; all waste reused; recycled content is 11% [14]
Steel from average recycled content	Green Star, Mat-6; maximum 60% post-consumer recycled content [23]	LEED, 65-97.5% post-consumer recycled content [23, 16]	BREEAM, Mat-6;60% recycled content[38];97.5% beams, plates; 65% bars; 66% steel deck [16]
Reuse recycled and post-consumer steel in structural & non-structural	95% of the joinery; 50% of the structural framing, roofing, designed to be disassembled [5]	LEED, 1-2 points to 75-100% reuse of existing walls, floors and roof [24, 3]	BREEAM, Mat-6; maximum 60% recycled content [23]
Reduce material use in steel structural design	Green Star, Mat-6, grade reduced materials in design,10-20%, [23] Mat-10, one point for 20% reduction	LEED, eliminating the need for materials in the planning and design phases [10, 7]	BREEAM, grade reduced materials in design [21] avoiding over-design, material reuse [39]
Reuse recycled timber and post-consumer FSC timber	Green Star 95% of all timber products re-used, post-consumer; FSC certified timber [22, 23]	LEED, timber products re-used, post-consumer; 50% FSC certified timber, up to 1 point [32, 29, 24]	BREEAM; up to three points where timber is part of a pre-or post-consumer waste stream [36]
Roof tiles from recycled tiles	Green Star, Mat-5 one point, where no natural aggregates are used in non-structural uses [23]	LEED credits; produced from postconsumer recycled content, from the waste, up to 3.5 points [20,21]	BREEAM; M03, roof tiles can be extracted from the waste stream [36]
Thermal insulation from recycled content	Green Star, no direct credit, but 80% recycled content advised [27,]	LEED, MR4, 20% or more recycled thermal insulation, one point [12, 7]	80% thermal insulation must be responsibly sourced 1 point [37]
Portland cement replaced with geopolymer based cement	Green Star; Maximum 60% In situ concrete 40% precast and 30% for stressed concrete; 30% for 1 point and 40% for 2 points [23, 26]	LEED Concrete consists of at least 30% fly ash; 50% recycled content or reclaimed aggregate; 90% recycled content or reclaimed aggregate [23, 12,7]	One point awarded where geopolymer cement used and supply chain process and must be responsibly sourced [40]
Reduce transportation by reusing and recycling materials	Green tools credit the reusing and recycling up to 40% of materials, not directly credited 2[, 15, 35]	Green tools credit the reusing and recycling up to 40% of materials, not directly credited 2[, 15]	One credit where obtained from waste processing site(s) within a 30km radius of the site [37]
Transportation by water or rail not truck, Reduce transportation by localizing	Green Star advise localizing, using water and rail instead of road [2,15]	LEED, Regional Materials, up to 4 points[14]; tools advise localizing, using water and rail instead of road [2,15]	Regional materials, localizing, using water and rail instead of road [2,15]

References, specifications and detailed information of this table is presented in Table A.D.2 (Appendix A)

5.5 Measurable criteria based on BDPs to reduce construction carbon emissions

The bioclimatic principles identified in this research are expressed as measurable criteria that can be applied in construction projects to reduce potential construction carbon emissions. The column labelled 'Conditions in this research' in Table 5.7 in this chapter, and in Table A.D.1 in Appendix D, represent the bioclimatic criteria that produce the highest possible carbon emission reductions when appropriately applied.

A research model has been proposed to measure embodied energy in the pre-construction and construction phases of building that takes into account decreased and replaced renewable energy in preconstruction and construction processes; saved energy in transportation by localisation; and reduced energy from reusing and recycling of materials. The detailed model format is illustrated in Appendix B.

The three areas examined in this study with reference to reduction of carbon emissions (CO_2-e) are – energy consumed during extraction/production of construction materials and building elements; energy consumed during implementation; and energy consumed during transportation.

The measurable criteria summarised below and in Tables 5.6 and 5.7 are derived from bioclimatic design principles and have been applied to the construction systems of the six case studies in this research.

Bioclimatic principles applied in this research to the six case studies	**Application**
Reusing recycled aggregates in materials production instead of extracting new aggregate from mining	This includes replacing concrete with 80 per cent recycled aggregate. and 100 per cent for non-structural purposes (Uche 2008); and brick with 67 per cent recycled aggregate (BDA 2014; Tyrell & Goode 2014).
Using steel from recycled content instead of steel from raw mining	This includes the use of steel mesh, edge beams, and steel sheets, aiming towards 100 per cent replacement from recycled content (Greenspec 2015; Steel Construction Information 2014).
Reusing recycled construction materials and elements	This includes reusing post-consumer recycled timber or certified timber from the Forest Stewardship Council (FSC) (Design Coalition 2013; GBCA 2008,); use of insulation from recycled materials (Greenspec 2015); use of concrete tiles from recycled roof tiles (LEED 2014); and reuse of structural elements (Karven 2012).
Replacing Portland cement with geopolymer based cement	This includes full replacement of Portland cement with cement substitute, 80 per cent for concrete for structural purposes, and 100 per cent for non-structural purposes (McLellan 2011; Nath & Sarker 2014).
Using types of transportation that generate less carbon emissions	This refers to use of ship and rail instead of trucks, i.e. use of sustainable modes of transportation (Learning Legacy 2014).
Reducing transportation	This is done by reusing recycled aggregate, recycled materials, localizing and similar approaches.

5.6 Bioclimatic principles considered in other research and under laboratory conditions

Following is a summary of the bioclimatic design principles applied in research elsewhere and the laboratory, but which are more stringent than have been considered in this study.

Concrete from recycled aggregate: The CSIRO guide gives contamination limits for various classes of RCA. The binder content for Grade 1 RC concrete with 30 per cent partial replacement with coarse Class 1A RCA is comparable to that required for concrete containing 100 per cent natural aggregate. For Grade 2 RC mixes containing up to 100 per cent coarse Class 1A RCA, extra binder loading may be required to achieve the specified compressive strength (CCAA 2015).

Brick and concrete block from recycled aggregate: Using recycled aggregate as the replacement for natural aggregates of up to 100 percent, concrete paving blocks with a compressive strength of not less than 49 MPa can be produced without the incorporation of fly ash, while paving blocks for footway uses with a lower compressive strength of 30 MPa and masonry bricks can be produced with the incorporation of fly ash (Poon, Kou & Lam 2002).

National Green Building Standard 4RE 604.1: Brickwork can help meet requirements of many certification rating systems in the areas of development density, storm water management, the heat island effect, improved energy performance, building reuse, waste management, materials reuse, recycled content and regional materials (BDA 2009).

Reuse recycled and post-consumer steel from average recycled content in structural and non-structural applications: In the production of structural shapes and bars, 95-100 per cent old steel can be used to make new products. In this process, producers of structural steel are able to achieve high percentages of recycled content (Kang & Kren 2007). Most steel construction material and elements are highly reusable such as for sheet and bearing piles; and structural members, including hollow sections and light gauge products such as purlins and rails (Steel Construction Information 2014) (Craven 2012; Learning Legacy 2014).

Reduce material use in steel structural design: In practice, the most noteworthy cases using an integrated design process or linear design process have achieved a considerable reduction in material use (Ecospecifier 2016). For example, the London Olympics stadium was constructed using only a tenth of the steel required to build Beijing's ‘Bird's Nest’ stadium (Craven 2012).

Reuse recycled timber and post-consumer FSC timber: This includes the complete re-use of timber products post-consumer, reusing recycled products, or the use of FSC-certified timber. FSC in Australia surpasses 1 million hectares of certified forests. with Forico, a Tasmanian forestry management company, awarded full FSC certification (FSC 2015).

Roof tiles from recycled tiles: Demolition and debris from land clearing can be recycled and reused. For example, roof tiles are reusable, with concrete roof tiles being less prone to waste. Concrete roof tiles can be crushed and recycled or reused as landscaping fill (LEED 2014).

Thermal insulation from recycled content: Thermal insulation can contain high levels of post-consumer recycled content, being ultra-low to zero in content of volatile organic compound (VOC) products, as well not being associated with health concerns. For example, some thermal insulation such as mineral wool batts contain 100 per cent recycled blast furnace slag (Ecospecifier 2016).

Portland cement replaced with Geopolymer based cement: The outcomes of the current research show that geopolymer based cement which is a relatively new binder can be a sustainable and economical binding material, as it is produced from industrial by-products such as fly ash. Geopolymer cements can replace 100 per cent of the Portland cement in concrete. here is increasing interest in geopolymer based cement due to its low level of carbon emissions compared to Portland cement (Nath & Sarker 2014).

Reduce transportation by reusing and recycling materials, localizing, and use sustainable modes of transport: In the future, construction design must ensure that there is minimum wastage, maximum recycling, and (thus) reduction in transportation.

A summary of the items detailed in this section is given in Table 5.7.

Column one, ‘Bioclimatic principles/criteria’ are identified from the present research into bioclimatic design principles.

Column 2, ‘Current conditions, implemented’, are design principles already in current practice (full references are in the legend at the base of Table A.D.3 in Appendix D).

Column 3, ‘Conditions with green tools’, detail the credits in the LEED, BREEAM, and Green Star rating tools that relate to the bioclimatic criteria being used in this research (i.e. in Column 1).

Column 4, ‘Conditions in this research’, refers to the bioclimatic criteria as applied in the case studies in this research.

Table 5.7: Bioclimatic conditions – current; from best practice with green tools (Green Star, LEED and BREEAM); and from this research model

Bioclimatic principles/criteria	Current conditions, Implemented	Conditions with Green tools (Green Star., LEED, BREEAM)	Conditions in this research
Concrete from recycled aggregates	In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities. [1]	G.S. and LEED 1-3 points 20-30% RA for structural purposes; BRE 25- 50 % in 20-40 MPa - no restriction, 100% non-structural [2, 18, 36]	Fully RA for non-structural purpose; 100% RA for non-structural; 80 % RA for structural purpose [6]
Concrete block from recycled aggregates	24% recycled content of an aggregate concrete block [8]	G.S., BRE, 40%; US 25% RA structural; 100%, or no natural aggregates in non-structural [18,23,36]	Aggregate for concrete block fully from recycled aggregate [13]
Brick from recycled aggregates	Current level of recycled material content in brick is 11% 14[,41]	G.S., 30%;[16, 23]; LEED 20%; BRE 11% ISO, up to 10 points for 10% Recycled aggregate [14,16,36]	Reuse recycled aggregate for brick, 67% [19]
Steel from average recycled content	Primary typically 10-15% of scrap steel Secondary 100% scrap based production [25, 34]	G.S. Mat-6, 60%; LEED 65-97.5%; BRE, Mat-6, 60%; -97.5% beams, plates; 65% bars; 66% steel deck post-consumer recycled content [23,16,38]	Steel from fully post-consumer recycled contents
Reuse recycled and post-consumer structural and non-structural steel	Scaffolding, formwork, sheet piles, etc., London Olympic Stadium [32, 34]	G.S., 95% Joinery, 50% structural framing, roofing; LEED 75-100% existing wall, floor, roof; BRE, Mat-6, 60% recycled content [3,5,23,24]	Use 40% recycled and post-consumer steel elements
Reduce material use in steel structural design 10-20%	Some of the current green projects have reduced materials use in design 10-20%[23]	G.S., Mat-6, 10-20% one point; LEED, eliminating need for materials in the design stage; BRE reduced, avoiding over-design [23,21,10,7,32]	Reduced materials use in structural design 10-20%
Reuse recycled timber and post-consumer FSC timber	FSC works in 80 countries, 24,000 FSC chain of custody certificates are active in 107 countries.[23,]	G.S. 95% re-used, post-consumer; FSC certified timber; up to 3 points; LEED, 50% FSC; BRE, 3 points, post-consumer waste stream [22, 23, 32,24,29]	60% of all timber products re-used, post-consumer recycled timber; FSC certified timber
Roof tile from recycled tile	In some countries materials such as concrete roof tiles, removed separated and recycled[44, 45]	G.S. Mat-5, 1 point, no natural aggregates are used; LEED, from the waste, up to3.5 points, BRE, M03, from the waste stream [20,21,23,36]	50% Roof tile from recycled aggregate [21]
Thermal insulation from recycled content	Thermal insulation is fully recyclable, i.e. wool content[31]	G.S. 80% advised; LEED MR4 20%, ½ point, BRE 80%, 1 point, responsibly sourced [12.7,27,37]	Thermal insulation from fully recycled waste [25]
Portland cement replaced with geopolymer based cement	Geopolymers have been used in structural, non-structural, Zeobond group, University GCI in Qld, Wellcamp Airport, Qld[46,47,48]	G.S. 60% In situ concrete; 40% precast 30% stressed concrete; LEED, 30% structural; no limit others, BRE, responsibly sourced cement [23,26,7]	Geopolymer based cement, fully replaced with Portland cement, arranged for non-structural, structural
Reduce transportation by reusing and recycled materials	National Waste Policy Australia advise to reduce waste, re-use to reduce environmental impacts [35]	Green tools credit the reusing and recycling up to 40% of materials, not directly credited; obtained from30km radius of the site [2,15,35,37]	Reusing has been considered in material production and building elements
Transportation by water or rail not truck, Reduce transportation by localizing	15% of brick are transported to the distributor's yard or jobsite by rail and 85% by truck [19, 30]	LEED, regional materials, up to 2 points;[14]tools advise localizing, using water and rail instead of road [2,15]	Localizing has been considered

Source This Table and data provided by Author. References and detailed information of this table is presented in Table A.D.1 (Appendix D)

5.7 Limitations of green tool rating systems

Following investigation of the bioclimatic conditions within the green tools, it is noted that their focus is on energy use and the environment. All contain numerous requirements and credits intended to reduce building operational energy use. However, what is often lacking in these green rating systems is a means by which to promote and measure the avoidance of negative consequences. For example, only one of these tools (LEED) currently contains methods to measure the avoidance of construction waste. All measure the diversion of waste from landfills, but only the National Association of Home Builders (NAHB) green tool (not considered in this present research) recognises that some materials have little or no on-site waste to begin with. In addition, the efficient use of materials is not properly recognised in the green tools. Materials such as brickwork perform multiple functions and construction can thus avoid the use of other materials, such as paints, sound insulation etc. (BDA 2009). In short, LEED, BREEAM and Green Star can still be further improved.

Another issue is that at this point in time, green building rating tools are simply not being consistently factored into building design. Added to this, even when a construction project is assessed against a green building tool such as LEED, BREEEAM or Green Star, those tools do not, in fact, adequately integrate BDPs into the criteria they rate. This can be seen in reference to Table 5.8 which compares the relative use of green tools in current practice, Green Star, LEED and BREEAM, and in the model proposed in this research. As can been seen from Table 5.8, the integration of bioclimatic design principles is consistently higher in all categories in the research model as compared to current practice and the green building rating systems being considered.

Table 5.8: Relative use of bioclimatic criteria in current practice, Green Tools and for this Research

					Research model
Bioclimatic conditions	**Current practice**	**Green Star**	**LEED**	**BREEAM**	**Codes/Standards**
Concrete from recycled aggregates, structural purposes	Poor	20%	30%	40%	80%
Concrete block from recycled aggregate, non-structural	24%	40%	25%	40%	100%
Brick from recycled aggregates	11% UK	-	10-20%	11%	67%
Steel from average recycled content	10-15%	60%	65-97%	65-66%	100%
Reuse recycled and post-consumer non-structural steel	10%<	-	75%	60%	60%
Reuse recycled and post-consumer structural steel	-	-	-	-	40%
Reduce material use in steel design	Poor	10-20%	-	-	10-20%
Reuse recycled timber and post-consumer FSC timber	Poor	95% NS	50%	-	60%
Roof tile from recycled content	Poor	-	20%+	-	50%
Thermal insulation from recycled content	Poor	80%	20%+	80% RS	100%
Portland cement replaced with geopolymer cement, non-structural purposes	Poor	60%	50%	-	100%
Portland cement replaced with geopolymer cement, structural purposes	Poor	40%	30%	-	80%

Source: Table and data provided by Author (derived from data in Chapter Five)
Poor = Less than 25% availability | Fair = 25-50% availability | Good = 50-75 availability | Excellent = 75-100% availability, | NS = Non-structural | RS =Responsible Sourced

5.8 Building Information Modelling (BIM) and green design

Building Information Modelling (BIM) software provides a three-dimensional digital representation of a building or construction project (Eastman et al. 2011). BIM has applications in the engineering, architecture and construction industries, particularly as it provides a basis for life cycle analysis of a building or construction project, including energy usage analysis at various (conceptual) points of the building life cycle. This analysis of a building's energy consumption at the conceptual design stage allows for decisions to be made about the most suitable design that will provide an energy efficient building. BIM thus allows for greater sustainability and low energy performance to be more easily factored into any construction project (Jalaei & Jrade 2014).

BIM can estimate embodied energy and equivalent carbon emissions data. This information can be used to assess and calculate potential construction carbon emissions reduction in Australian construction systems at all points in the building life cycle (Eastman et al. 2011). BIM plugins for life cycle analysis tools such as Tally and IMPACT are already available (EPD-Tally 2008; IMPACT 2016). There is also work currently being conducted to link BIM and energy analysis tools with green building certification systems. This will allow building designers to identify the most energy efficient construction alternatives, and thus to calculate the potential green tool points they might gain for a given design using LEED, BREEAM, Green Star, or other green rating system (Jalaei & Jrade 2014).

5.9 Summary

This chapter has identified a range of criteria derived from bioclimatic design principles which can be used to reduce the carbon emissions from construction projects. As has been seen, the current use of BDPs and green rating tools in construction projects is inconsistent, and the green tools themselves also fail to integrate BDPs adequately into their rating criteria. Additionally, the bioclimatic design criteria in the research model have been demonstrated to potentially achieve higher levels of carbon emission reduction than in any of the rating tools considered, or even in current best practice. The levels of carbon emission reduction may improve even further as Building Information Modelling with integrated life cycle analysis becomes more widely applied in construction design and building projects.

CHAPTER SIX

RESEARCH METHODOLOGY AND RESEARCH DESIGN

6.1 Overview

It is generally accepted that the construction, demolition, reconstruction and restoration of buildings result in intensive energy consumption and generated carbon emissions with considerable environmental impact. It is thus imperative to reduce the energy consumption and carbon emissions of the construction process. There are existing techniques to do this, but these are inconsistently applied and lacking in depth of criteria for application.

There are no recognised benchmarks defining acceptable levels of embodied energy and relevant carbon emissions of the construction process. There is also a lack of knowledge and research with a focus on reducing the carbon emissions of construction through the application of bioclimatic design principles. This present research contributes knowledge to these areas, and proposes a green tool based on consideration of bioclimatic design principles whose application has the potential to reduce the carbon emissions of the construction process. The purpose of this chapter is to discuss the type of research and process used to achieve these aims.

This chapter is divided into seven sections. Section 6.1 provides an overview to this chapter. Section 6.2 discusses the research type and case study method. Section 6.3 considers the procedure (methodology) used to achieve the research aims. Section 6.4 identifies the sources providing the embodied energy and carbon emissions data analysed in this research. Section 6.5 delineates the limitations of this study. Section 6.6 identifies how the results from the study may be generalisable to other construction contexts. Section 6.7 provides a summary of this chapter.

6.2 Research type and the case study method

In any discussion of research methods, there is always debate regarding the scholarly nature, contributions, merits and limitations of quantitative as compared to qualitative research (Gan 2006). This present research is based on quantitative methods that use objective measurements to analyse the numerical data collected in the research. In respect to this, the aim of quantitative research is to gather numerical data and generalise it to explain a particular phenomenon (Giesbrecht 1996).

Quantitative research requires the use of structured and objective data, where the response options have been predetermined. The objective data for this research is gathered from a range of sources relating to the six case studies examined in this research, and to Australian construction systems (detailed in Section 6.3).

Six case studies were selected as a number that provide for a stronger research design, greater validity of the findings, and for more confidence in results that are generalisable to other contexts. In this respect, multiple case studies also allow the researcher to verify that findings are not just the result of the characteristics of the research setting (Gan 2006).

This research investigates the potential construction carbon emissions that can be reduced by application of bioclimatic design principles. The bioclimatic conditions depend on where that building and its construction site is located. Accordingly, the six cases studies were selected from a range of different locations in order to provide different construction contexts for application of the research model, enhancing its validity.

6.3 Research methodology

This study has been conducted through a range of stages. Stage one involved identifying and detailing the embodied energy and carbon emissions inherent within the construction process, and how they might be measured (Chapter Four). Stage two identified specific measurable bioclimatic criteria within bioclimatic design principles that could be applied in the green model/tool developed for this research (Chapter Five).

Stage three involved application of this model to specific elements of the floor, wall and roof construction systems used within the six case studies, and analysis of the potential reductions in carbon emissions that could be achieved (Chapter Seven). Stage four involved application of the model to emissions and embodied energy data available for elements of general floor, wall and roof construction systems in Australia, and analysis of the potential reductions in carbon emissions that could be achieved (Chapters Seven).

6.4 Sources of embodied energy and carbon emission data used in this research

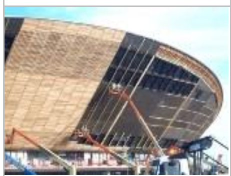
The Australian construction data used in this research has been obtained from Lawson's publications in 1996 and 2006. The analysis and detail of Australian floor, wall and roof construction systems supplied by Lawson (1996), and the embodied energy of building materials data supplied in Lawson (2006), have been applied within the research model, this to demonstrate how construction carbon emissions may have been reduced in the selected Australian case studies.

One international case study was also considered in this research, namely the velodrome building constructed for the London Olympics in 2012. Extensive data from this construction was detailed in various sources (e.g. Rodway 2010; Inventory of Carbon & Energy 2011; Bull 2012; Smith 2012). A sample of the developed model format is illustrated in Appendix B. A summary of the six case studies is provided in Table 6.1.

Other supporting data concerning the embodied energy and carbon emissions of specific elements of the construction process were obtained from a variety of sources. These include the Australian Your Home technical manual (Milne & Reardon 2014); the Building Research Establishment Environmental Assessment Method (BREEAM 2014b); Ecospecifier (2015; 2016); the Environmental Design Guide (EDG 2014); the Green Building Council of Australia (2008; 2014a; 2014b; 2016; 2017); GreenSpec (2015); the Inventory of Carbon and Energy (2011); and the US Green Building Council's Leadership in Energy and Environmental Design (LEED 2015; 2016).

Ecospecifier is a database of independently vetted eco-preferable products and materials including product descriptions. It is not a rating tool. It was developed initially by the Centre for Design at RMIT, and is now managed by Natural Integrated Living. It provides an understanding of the upstream and downstream implications of decisions in an economic, legal and ecological sense. It helps the user to identify eco-preferable products and materials, and to understand associated environmental and health issues that need to be considered in the use of a product (Iyer-Raniga & Wasiluk 2007).

Table 6.1: Case Studies – Construction systems of the main elements (floors, walls and roofs)

Case studies in this research		Construction Systems		
		Floors	**Walls**	**Roofs**
 Source: Trip Advisor (2014)	1. Friendly Beaches Lodge, 1991; accommodation for guests completing a guided three-day bushwalk Architect: Latona Masterman Freycinet Peninsula, Tasmania, Australia	Timber frame floor	Single skin timber walls	Timber frame, steel sheet roof
 Source: Environmental Design Guide (EDG 2014)	2. ACF Green Home, 1992. This display home was constructed for VDPH in accordance with environmental guidelines prepared for the Australian Conservation Foundation (ACF) Architect: Taylor Oppenheim Architects Roxburgh Park, Victoria, Australia	110 mm Concrete slab on ground floor; Timber-framed upper floor	Timber-framed brick veneer walls	Timber frame, concrete tile roof
 Source: Lawson (1996)	3. Display Project Home, 1994. This Canberra Display Project House was sponsored by Energy Research Development Corporation (ERDC) to demonstrate the application of energy-saving design measures. Architect: Jen-Vue Homes Ginninderra, Australian Capital Territory	110 mm Concrete slab floor	Timber-framed brick veneer walls	Timber frame, steel sheet roof
 Source: This author	4. Civil Engineering Laboratory, USQ, 2013; This is a one-level 350 m^2 building commissioned by the University of Southern Queensland (USQ) Nairn Construction; Architect: Wilson Architects Springfield Central, 4300, Brisbane, Australia	200 mm Concrete slab on ground floor	Cored Concrete block walls	Steel frame, steel sheet roof
 Source: London Olympics (2012)	5. The London Olympic Velodrome Building. The design brief asked for a lightweight construction. All parties in the construction supply chain co-operated to deliver the project to minimise excess material usage. Principal architects: Jonathan Watts, George Oates, Hopkins, Olympic Park London	Concrete slab floor Concrete upper floor	Cored Concrete block walls; Steel frame timber wall	Steel frame, fabric roof
 Source: This author	6. Multi Sports Building, USQ, 2013. This two-story 302 m^2 building was commissioned by USQ which as a multi sports building. Nairn Construction; Architect: Reid Design Springfield Central, 4300, Brisbane, Australia	Concrete slab floor Concrete upper floor	Cored Concrete block walls	Steel frame, steel sheet roof commercial

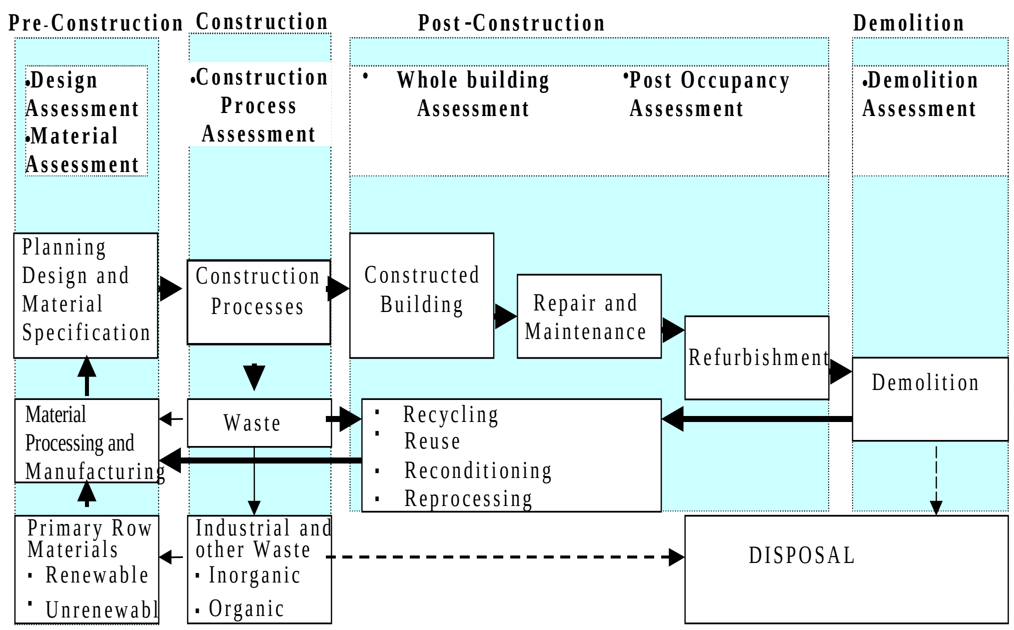
The Inventory of Carbon and Energy (2011) is a research database located at the University of Bath in the UK. It provides an inventory of embodied energy and carbon emissions for building materials in the UK. Other specific data was also collected from various suppliers and manufacturers of construction materials in the UK and Australia (e.g. Steel Construction Information 2014).

Some of the original data and information about the case studies was also obtained directly from the designers – for example, data and information about two of the case studies at USQ was obtained directly from their building manager. Finally, the latest findings and data about the currently accepted and used percentages for recycled and reused construction materials was obtained from the World Federation of Engineering Organizations (2011).

6.5 Limitations of this study

As noted in Section 1.4 of Chapter One, this study is limited to stages one to three of the building lifecycle. These stages of the building life cycle are summarised in Figure 6.1.

Stages of Life Cycle Model of Building. Stages within this study (1-3)



Stage 1,2 **Stage 3** **Stage 4** **Stage 5**

Figure 6.1: Life cycle model of building. Stages 1 to 3 are within this study.
Source: Derived from Lawson (1996) and UNEP SBCI (2009)

6.6 Generalising the outcomes from this study

The major outcome from this study is identification of a model to reduce the carbon emissions of construction during the first three stages of the building life cycle. This model has been applied to the six case studies within this research. The findings are considered as generalisable to other Australian construction projects where the model is appropriately applied.

6.7 Summary

This chapter has outlined and justified the research type and methodology used for this study, and identified the sources of the embodied energy and emissions data analysed within the research model. The limitations of this research have also been described. Results from the application of the research tool/model developed for this study are described in Chapters Seven.

CHAPTER SEVEN

RESULTS AND ANALYSIS OF APPLYING THE RESEARCH MODEL TO CASE STUDIES AND GENERAL AUSTRALIAN CONSTRUCTION SYSTEMS

7.1 Overview

The purpose of this chapter is to present the results and analysis of this research project. The bioclimatic criteria of the research model are first applied to the floor, wall, roof and then whole construction systems of the six case studies considered in this research. The research model criteria are then applied to elements of general Australian floor, wall and roof construction systems. The carbon reductions achieved, and the associated emissions generated, from application of the research model are then compared with results obtained from similar standard building system elements, implementation (completion) of building projects, and application of the Green Star rating tool. Results are presented in four ways for each construction system studied – as tables of numerical data for the reductions in emissions achieved, and the carbon emissions generated; the emissions generated are then displayed in a comparative bar graph; the final table available for each construction system considered presents the carbon emission reductions achieved as comparative percentages for each type of building element. An overall analysis of each section's results is also presented.

The chapter is divided into seven sections. Section 7.1 provides the background to this chapter. Section 7.2 details the six case studies selected for this research. Section 7.3 presents the data and analysis of results obtained following application of the research model to elements of floor, wall and roof construction systems in the case studies. Section 7.4 presents the data and analysis of results obtained following application of the research model to elements of general Australian floor, wall and roof systems. Section 5 summarises the content of this chapter.

7.2 Selected case studies

The model developed reviews six case studies, five from Australia and one from the United Kingdom. The Australian case studies use the general construction systems in Australia as identified by Lawson (1996). These can include any project from any classification (residential, public, and commercial). For example, the first three case studies are taken from a paper written by Lawson (1996) – all detail and information for these are provided, together with embodied energy and implemented embodied energy (Lawson 1996). The fourth and sixth case studies focus on buildings recently completed on the Springfield campus of the University of Southern Queensland (USQ). All drawings and detailed information were accessible. The Olympic Velodrome Building from the London Olympics in 2012 is the focus of the fifth case study – these Olympics achieved high sustainability levels from a range of different environmental tools (e.g. CEEQUAL, ISCA, and BREEAM). In case study five, the data was obtained from four main sources – Rodway (2010); Inventory of Carbon & Energy (2011); Bull (2012); and Smith (2012).

Table 7.1 presents the results from application of the bioclimatic criteria within the research model to the six case studies that could potentially result in significant carbon emissions reduction.

This section details information about the floor, wall and roof construction systems used in the six case studies. Tabulated data of their embodied energies and carbon emissions are presented in the following sections, with detailed calculations presented in Appendix C.

Table 7.1: Research model (bioclimatic criteria) applied to the six case studies (data extracted from Tables 5.4 and 5.6)

Bioclimatic criteria	1. Friendly Beaches Lodge, 1991	2. ACF Green Home, 1992	3. Display Project Home, 1994	4. Civil Engineering Laboratory, USQ 2013	5. Olympic Velodrome Building, London 2012	6. Multi Sports Building, USQ, 2013
Concrete from recycled aggregates	80 % RA for fixing posts in the ground 1, 6,	80 % RA for concrete slab on ground [1, 6,]	80 % RA for concrete slab on ground [1, 6,]	80 % RA for concrete slab on ground, structural [1, 6,]	80 % RA for concrete slab on ground, structural [1, 6,] 100% RA for non-structural	80 % RA for concrete slab on ground, structural [1, 6,]
Concrete block from recycled aggregate	N/A	N/A	N/A	Concrete block wall from full RA [13]	Concrete block wall from full RA [13]	Concrete block wall from full RA [13]
Brick from recycled aggregate	Brick from 67% RA for posts Use recycled bricks 60% [19]	Brick wall from 67% RA [19]	Brick wall from 67% RA[19]	N/A	N/A	N/A
Steel from average recycled content	Steel sheets of roof from recycled content 100% [25, 34]	Use steel mesh produced with 100% recycled content in concrete slab floor [25, 34]	Use steel mesh produced with 100% recycled content, floor and steel sheets of roof [25, 34]	Use steel mesh produced with 100% recycled content, floor and steel sheets of roof [25, 34]	Use steel mesh produced with 100% recycled content, floor and steel sheets of roof [25, 34]	Use steel mesh produced with 100% recycled content, floor and steel sheets of roof [25, 34]
Reuse recycled and post-consumer structural and non-structural steel	N/A	N/A	N/A	Use 40% recycled steel in trusses [24]	Use 40% recycled steel in trusses [24]	Use 40% recycled steel in trusses [24]
Reduce material (steel) use in design	N/A	N/A	N/A	Reduced 20% steel use in design [23]	Reduced 20% steel use in design [23]	Reduced 20% steel use in design [23]
Reuse recycled timber and post-consumer FSC timber	Use 60%, recycled timber or FSC certified timber for wall and roof [23]	Use 60%, recycled timber or FSC certified timber for wall and roof [23]	Use 60%, recycled timber or FSC certified timber for wall and roof [23]	N/A	Use 60%, recycled timber or FSC certified timber for wall and roof [23]	N/A
Roof tile from recycled tile	N/A	Use 13% recycled tile, tiles with 45% with recycled content [21]	N/A	N/A	N/A	N/A
Thermal insulation from recycled content	Thermal insulation 100% from recycled content in the wall and roof [25]	Thermal insulation 100% from recycled content in the wall and roof [25]	Thermal insulation 100% from recycled content in the wall and roof [25]	Thermal insulation 100% from recycled content in the wall and roof [25]	N/A	Thermal insulation 100% from recycled contents in the wall and roof [25]
Geopolymer cement replacement for Portland cement	100% replacing PC with GC for fixing timber posts [26]	100% replacing PC with GC in concrete slab on ground floor [26]	100% replacing PC with GC in concrete slab on ground floor [26]	100% replacing PC with GC in concrete slab on ground floor, concrete block wall [26]	100% replacing PC with GC in concrete slab, floor, first floor, concrete block wall [26]	100% replacing PC with GC in concrete slab on ground floor, concrete block wall [26]
Reduce transportation by reusing and recycled materials	Transportation reduced by reuse of recycled materials; [32, 35]	Transportation reduced by reuse of recycled materials; [32, 35]	Transportation reduced by reuse of recycled materials; [32, 35]	Transportation reduced by Transportation reduced by reuse of recycled materials; [32, 35]	Transportation reduced by reuse of recycled materials; [32, 35 35]	Transportation reduced by reuse of recycled materials; [32, 35]
Transportation by water or rail not truck, Reduce transportation by localizing	Transportation reduced by using local supplier and materials [19, 30]	Transportation reduced by using local suppliers and materials [19, 30]	Transportation reduced by using local suppliers and materials [19, 30]	Transportation reduced by using local suppliers and materials [19, 30]	Transportation by water; reduced by using local suppliers and materials [19, 30]	Transportation reduced by using local suppliers and materials [19, 30]

Sources:: 1-(CCAA 2015; Gonzalez-Fonteboa 2005)**; 2**-(GBCA 2008); **6**-Chapter Seven; **13**-(Portland Cement Australia 2014; Uche 2008; **19**-(BDA 2014; Tyrell & Goode 2014); **21**-(LEED 2014); **23**-(GBCA 2008; US Green Building Council 2011); **24**-(US Green Building Council 2005); **25**-(Greenspec 2015; Steel Construction Information 2014); **26**-(Ash Development Association of Australia 2013); **30**-(Benn, Dunphy &Griffiths 2014; Learning Legacy 2014); **32**-(Allwood et al. 2012; UK Indemand 2014, 2015); **34**-(Inhabitat 2014; Steel Construction Information 2014), **35**- (DEE 2012)) RA = Recycled Aggregate, PC = Portland cement, GC = Geopolymer Cement.

This Table and data provided by Author.

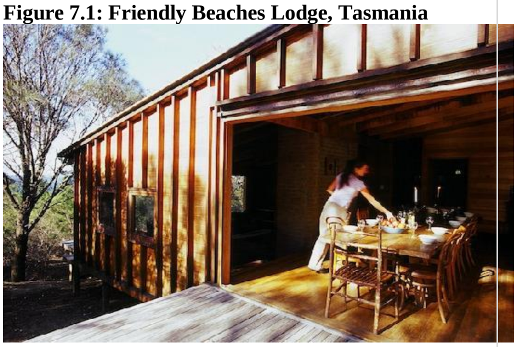
7.2.1 Case study one – Friendly Beaches Lodge

The Friendly Beaches Lodge is an environmentally well-known project that was designed by Latona Masterman Pty Ltd (Australia), and built in the Freycinet Peninsula of Tasmania in Australia in 1991. This is a private development on an isolated parcel of freehold costal woodland and heath within a national park. The architect sought to provide a basic standard of accommodation for guests completing a guided three-day bushwalk. Traditional domestic timber floor framing is comprised of hardwood beaters and dried hardwood joists. External decks are elevated and constructed from treated pine decking boards. Walls generally are single-skin timber from air-dried hardwoods and plates with kiln hardwood internal lining boards. The roof is timber framed and covered with single sheet steel (see Figure 7.1).

The embodied energy of the floor, wall and roof elements in this construction project were calculated by Lawson (1996). The floor construction system (timber floor) had an implemented embodied energy of 72 MJ/m^2 of floor area. The wall construction system (single skin timber wall) had an implemented embodied energy of 32 MJ/m^2 of wall area. The roof construction system (timber frame with single steel sheet covering) had an implemented embodied energy of 230 MJ/m^2 of roof area (Lawson 1996).

Using this basic data, the research model was applied to this case study, and calculations made of potential reductions in carbon emissions. Detailed calculations are presented in Appendix C, and a summary of potential and generated (i.e. actual) carbon emissions of construction are presented in Tables 7.2 and 7.3 respectively for the floor systems; in Tables 7.4 and 7.5 respectively for the wall construction systems; and Tables 7.6 and 7.7 respectively for the roof construction systems.

Figure 7.1: Friendly Beaches Lodge, Tasmania



Source: Trip Advisor (2014)

Location: Battery Point, Freycinet Peninsula National Park, Tasmania 7215

Floor construction system: Timber floor

Wall construction system: Single skin timber wall

Roof construction system: Timber frame, steel sheet roof

Principal architects: Latona Masterman Pty Ltd. Australia
Construction completed 1991

Bioclimatic conditions of Case Study One	
Reuse, recycle, material resources, suppliers, transport	
Recycled aggregates in material production	80% recycled aggregate assumed to be used for concrete Recycled aggregate assumed to be used for brick
Steel from recycled contents	Steel and steel mesh assumed to be used from average recycled content (Steel Construction Information 2014)
Reuse construction materials	Reuse recycled bricks Use recycled softwood Use recycled thermal insulation Use roof tiles from recycled tiles (LEED 2014)
Geopolymer, fly ash and cement substitute	Geopolymer cement replaces Portland cement
Transportation reduction	Reduce transportation by (re)using recycled materials
Material resources and suppliers	Construction material resources are inside the park, the saved distance is 80km, supplier is 237 km and local supplier is 157km (Devonport, Tasmania)

7.2.2 Case Study Two – ACF Green Home

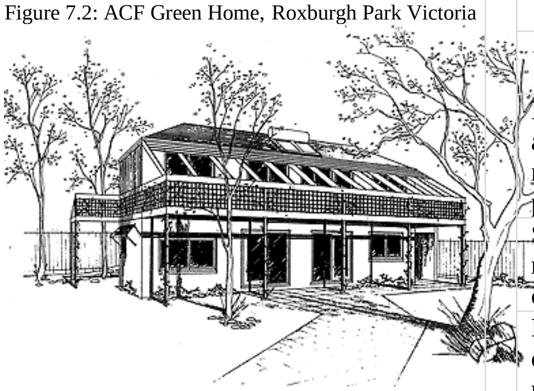
The Australian Conservation Foundation (ACF) Green Home is a well-known project designed by Taylor Oppenheim Architects, and built in Roxburgh Park in Victoria in 1992. This display home was constructed for the Victorian Department of Planning and Housing in accordance with environmental guidelines prepared by the ACF. The objectives were to create a building for the home market which demonstrated various ways of conserving energy in the day-to-day running of a house, as well as the use of materials selected on the basis of minimum embodied energy.

The ground floor is a concrete slab. Fly ash was incorporated in the concrete mix as a partial cement substitute. The slab was poured over a waterproof membrane manufactured from 70 per cent recycled material. The reinforcing steel was made entirely from recycled materials. The upper floor is constructed in pine framing with a timber floor. External walls are constructed with planation pine timber framing and a clay brick veneer. The roofs are framed in Radiata pine, and concrete tiles are fixed over aluminium foil sarking.

The embodied energy of the floor, wall and roof elements in this construction project were calculated by Lawson (1996). The floor construction system (concrete slab ground floor, timber framed upper floor) had an implemented embodied energy of 537 MJ/m^2 of floor area. The wall construction system (timber framed brick veneer wall) had an implemented embodied energy of 595 MJ/m^2 of wall area. The roof construction system (timber frame, concrete tile roof) had an implemented embodied energy of 226 MJ/m^2 of roof area (Lawson 1996).

Using this basic data, the research model was applied to this case study, and calculations made of potential reductions in carbon emissions. Detailed calculations are presented in Appendix C, and a summary of potential and generated (i.e. actual) carbon emissions of construction are presented in Tables 7.2 and 7.3 respectively for the floor systems; in Tables 7.4 and 7.5 respectively for the wall construction systems; and Tables 7.6 and 7.7 respectively for the roof construction systems.

Figure 7.2: ACF Green Home, Roxburgh Park Victoria



Source: Environmental Design Guide (EDG 2014)

Location: ACF Green Home, Roxburgh Park Victoria 3064
Floor construction system: Concrete slab floor, timber framed upper floor
Wall construction system: timber framed brick veneer walls
Roof construction system: timber Frame, concrete tile roof
Principal architects: Taylor Oppenheim Architects, Pty Ltd, Australia Construction completed 1992

Bioclimatic conditions of Case Study Two	
Reuse, recycle, materials resources, suppliers, transport	
Recycled aggregate in materials production	80% recycled aggregate assumed to be used for concrete Recycled aggregate assumed to be used for brick
Steel from recycled content	Steel and steel mesh assumed to be used from average recycled content
Reuse construction materials	Reuse recycled bricks Use recycled softwood Use recycled thermal insulation Use roof tiles from recycled tiles
Geopolymer fly ash	Geopolymer cement replaces Portland cement
Transportation reduction	Reduce transportation by (re)using recycled materials
Material resources and suppliers)	Construction materials resources are local, then the saved distance is 54.2 km (Melbourne Building Supplies 2014), and local supplier is Boral concrete Somerton (Boral 2014)

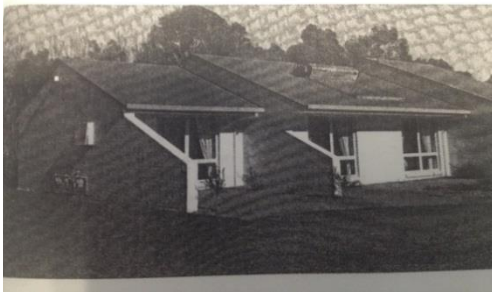
7.2.3 Case Study Three – Display Project Home

The Display Project House in Canberra was commissioned by the Energy Research and Development Corporation (ERDC) to demonstrate the application of energy-saving design measures within a house design which successfully conforms to project home style. The home was designed by Jen-Vue Homes in Ginninderra in the Australian Capital Territory, and construction completed in 1993. The external envelope of the house deliberately used conventional materials and technologies, including a concrete ground slab, brick veneer external walls, and a metal deck roof.

The embodied energy of the floor, wall and roof elements in this construction project were calculated by Lawson (1996). The floor construction system (concrete slab) had an implemented embodied energy of 841 MJ/m^2 of floor area. The wall construction system (timber framed brick veneer) had an implemented embodied energy of 570 MJ/m^2 of wall area. The roof construction system (timber frame steel sheet roof) had an implemented embodied energy of 474 MJ/m^2 of roof area (Lawson 1996).

Using this basic data, the research model was applied to this case study, and calculations made of potential reductions in carbon emissions. Detailed calculations are presented in Appendix C, and a summary of potential and generated (i.e. actual) carbon emissions of construction are presented in Tables 7.2 and 7.3 respectively for the floor systems; in Tables 7.4 and 7.5 respectively for the wall construction systems; and Tables 7.6 and 7.7 respectively for the roof construction systems.

Figure 7.3: Display Project Home, Ginninderra, ACT



Source: Lawson (1996)

Location: Ginninderra, 2913 ACT

Floor construction system: Concrete slab

Wall construction system: timber framed brick veneer walls

Roof construction system: timber frame steel sheet roof

Principal architects: Jen-Vue Homes Pty Ltd, Australia
Construction completed 1994

Bioclimatic conditions of Case Study Three	
Reuse, recycle, materials resources, suppliers, transport	
Recycled aggregate in materials production	80% recycled aggregate assumed to be used for concrete Recycled aggregate assumed to be used for brick
Steel from recycled content	100% steel and steel mesh assumed to be used from average recycled content
Reuse construction materials	Reuse recycled bricks Use recycled hardwood bearers and joists Use recycled thermal insulation
Geopolymer, fly ash	Geopolymer cement replaces Portland cement
Transportation reduction	Reduced transportation by reusing/recycling, and transportation by rail or water when required.
Material resources and suppliers	Construction materials from interstate (Thylacine 2014) and local supplier is Skyline, the saved distance is 25.2 for local, but the main supplier is over 100km (Port Jackson 2014)

7.2.4 Case Study Four – Civil Engineering Laboratory, USQ

The Civil Engineering Laboratory building at the University of Southern Queensland’s Springfield campus was designed by Wilson Architects in Brisbane, and was completed in 2013. The floor construction system uses a concrete slab on ground. The wall construction system uses cored concrete blocks. The roof construction system is steel framed with steel roof Colorbond sheeting.

Data for this building was obtained directly from the USQ campus services management section. Using this basic data, the research model was applied to this case study, and calculations made of potential reductions in carbon emissions. Detailed calculations are presented in Appendix C, and a summary of potential and generated (i.e. actual) carbon emissions of construction are presented in Tables 7.2 and 7.3 respectively for the floor systems; in Tables 7.4 and 7.5 respectively for the wall construction systems; and Tables 7.6 and 7.7 respectively for the roof construction systems.

Figure 7.4: Civil Engineering Laboratory USQ

Source: Author

Location: Civil Engineering Laboratory, Springfield Central 4300

Floor construction system: concrete slab

Wall construction system: concrete block walls

Roof construction system: steel frame, steel sheet Roof (Stramit Speed Deck; 0.48 BMT Colorbond steel sheet roof)

Principal architects: Wilson Architects, Brisbane
Construction completed in 2013

Bioclimatic conditions of Case Study Four	
Reuse, recycle, materials resources, suppliers, transport	
Recycled aggregates in material production	80% recycled aggregate assumed to be used for concrete Recycled aggregate assumed to be used for concrete block
Steel from recycled content	100% steel and steel mesh assumed to be used from average recycled content
Reduce material use in design	Reduced materials in structural design 20%
Reuse construction materials	Reuse recycled trusses Use recycled thermal insulation or with recycled content
Geopolymer, fly ash and cement substitute	Geopolymer cement replaces Portland cement
Transportation reduction by reuse, recycle, sustainable transportation mode	By reusing and recycling, transportation was reduced Transported when necessary by rail or water
Material resources and suppliers	Construction material resources are inside of state, saved distance is 44.9 km (Global 2014), for local supplier is 32.3km (BIG Mate 2014; Nuway 2014)

7.2.5 Case Study Five – London Olympic Velodrome Building

This project was constructed on 246 hectares of previously heavily contaminated industrial land – thus, around 700,000 cubic metres of soil was cleaned and reclaimed. Additionally, around 98 per cent of construction materials were recycled from the site's demolished buildings, including a glue factory, a chemical works, and an oil refinery. Final implementation achieved 38 per cent lower carbon emissions than in the original design (CNN 2012; Smith, 2012).

Using construction data from a variety of sources (Rodway 2010; Inventory of Carbon & Energy 2011; Bull 2012; Smith 2012), the research model was applied to this case study, and calculations made of potential reductions in carbon emissions. Detailed calculations are presented in Appendix C, and a summary of potential and generated (i.e. actual) carbon emissions of construction are presented in Tables 7.2 and 7.3 respectively for the floor systems; in Tables 7.4 and 7.5 respectively for the wall construction systems; and Tables 7.6 and 7.7 respectively for the roof construction systems.

Figure 7.5: Olympic Velodrome Building, London

Source: London Olympics (2012)

Location: Olympic Park, London

Floor construction system: Concrete slab floor, concrete upper floor

Wall construction system: concrete block walls, steel frame timber wall

Roof construction system: steel frame, fabric roof (commercial)

Principal architects: Jonathan Watts, George Oates, Hopkins, Olympic Park London
Construction completed in 2012

Bioclimatic conditions of Case Study Five	
Reuse, recycle, materials resources, suppliers and transport	
Aggregates for concrete	80% recycled aggregate was used in the concrete (Ingenia 2014)
Steel and steel mesh	100% steel and steel mesh was used from average recycled content (Steel Construction Information 2014)
Reduce material use in design	Reduced materials in structural design 20%
Reuse construction materials	Reuse of leftover gas pipes for construction of the Olympic stadium's ring beam (Karven 2012) Reuse softwood from local salvage/re-use centre (JLL 2012)
Geopolymer, fly ash and cement substitute	Geopolymer cement replaces Portland cement
Transportation reduction by reuse, recycle, sustainable transportation mode	By reusing and recycling, transportation was reduced Transported when necessary was by rail or water (London Olympics 2012)
Material resources and suppliers	Construction material suppliers are outside London, thus distance is more than 100km (Aggregate Industries 2014)

7.2.6 Case Study Six – Multi Sports Building, USQ

The multi sports building at the University of Southern Queensland's Springfield campus was designed by Reid Design in Brisbane, and construction was completed in 2013. The floor construction uses a concrete ground slab and a concrete upper floor. The wall systems are cored concrete blocks. The roof construction is steel framed with a trussed, steel sheet roof.

Data for this building was obtained directly from the USQ campus services management section. Using this basic data, the research model was applied to this case study, and calculations made of potential reductions in carbon emissions. Detailed calculations are presented in Appendix C, and a summary of potential and generated (i.e. actual) carbon emissions of construction are presented in Tables 7.2

and 7.3 respectively for the floor systems; in Tables 7.4 and 7.5 respectively for the wall construction systems; and Tables 7.6 and 7.7 respectively for the roof construction systems.

Figure 7.6: Multi Sports Building, Springfield

Source: Author

Location: Multi Sports Building, Springfield Central, 4300
Floor construction system: concrete slab floor, concrete upper floor
Wall construction system: concrete block
Roof construction system: steel parallel cord trussed roof
Principal architects: Reid Design Brisbane Construction completed in 2013

Bioclimatic conditions of case study six	
Reuse, recycle, materials resources, suppliers and transport	
Recycled aggregates in material production	80% recycled aggregate assumed to be used for concrete 100% recycled aggregate assumed to be used for concrete block
Steel from recycled content	Steel and steel mesh assumed to be used from average recycled content
Reduce material use in design	Reduced materials in structural design 20%
Reuse construction materials	Reuse recycled trusses Use recycled thermal insulation or with recycled content
Geopolymer, fly ash and cement substitute	Geopolymer cement replaces Portland cement
Transportation reduction by reuse, recycle, sustainable transportation mode	By reusing and recycling, transportation was reduced Transported when necessary by rail or water
Material resources and suppliers	Construction material resources are within the state, saved distance is 44.9 km (Global 2014) and for local supplier is 32.3km (BIG Mate 2014)

7.3 Case studies – Potential carbon emission reductions in floor, wall and roof construction systems

This section identifies the carbon emissions related to the floor, wall and roof construction systems of the case studies during the extraction, materials production and construction processes (stages one to three of the building life cycle), both for each construction system, and then as a whole.

The **potential carbon emission reductions** that could be achieved by application of bioclimatic criteria are presented in Tables 7.2, 7.5 and 7.8 for floor, wall and roof respectively, and for the whole/combined construction systems of the case studies in Table 7.11. There are also percentage calculations of the (potential) carbon emission reductions for the floor, wall and roof construction systems presented in Tables 7.4, 7.7, 7.10 respectively, and for the whole/combined construction systems of the case studies in Table 7.13.

This contrasts with Tables 7.3, 7.6 and 7.9 which present the **generated carbon emissions** of the case studies for floor, wall and roof respectively, and for the whole/combined construction systems of the case studies in Table 7.12. There are also bar graphs that provide a graphical representation of the carbon emissions and results for each construction system of the case studies in Figures 7.7, 7.8 and 7.9 for floor, wall and roof respectively, and one for the whole/combined (floor, wall and roof) construction systems of the case studies in Figure 7.10.

These emission generation figures are obtained by subtracting the emission reduction figure for the item concerned from the standard/basic figure in column one of the corresponding table, the result being the generated carbon emission for the item concerned. Figures in each table are compared for Implementation, the Green Star tool, and the research model. Detailed calculations relating to these tables are presented in Appendix C.

The tables and figures presented in this section compare data from four sources:

- **Standard/Basic carbon emissions**: Carbon emissions to be expected with no application of green or bioclimatic criteria to the building process.

- **Implemented**: The carbon reductions/emissions calculated from implementation (i.e. completion) of the construction element or project concerned
- **Green Star**: The potential carbon reductions/emissions predicted if the criteria of the Green Star tool is applied to a construction system of a given case study.
- **This research**: The potential carbon reductions/emissions predicted if the bioclimatic criteria of the research model are applied to a construction system of a given case study

An analysis of the findings is presented in Section 7.3.5.

7.3.1 Case studies – Floor construction systems emissions reduction

Tables 7.2 and 7.3 present comparative carbon emission reduction and generation figures for the floor construction systems used in the case studies.

Table 7.2: Potential carbon emission (embodied energy) **reductions** for the **floor** construction systems of the case studies

Floor construction systems of the case studies	**Standard/Basic**		**Potential Reduction**					
			Implementation		**Green Star**		**This Research**	
			Reduced or Increased		Potential reduction		Potential reduction	
	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2
1-Elevated Timber Floor (lowest level)	293	28.71	221	21.65	55.29	5.41	168.82	16.54
2-Elevated Timber Floor (upper level)	147	14.40	-34	-3.33	86.26	8.45	88.92	8.71
110 mm Concrete Slab on ground	645	**63.21**	108	10.58	209.74	20.55	347.30	34.03
3- 110 mm Concrete Slab on ground	645	**63.21**	- 196	- 19.2	157.21	15.40	415.06	40.67
4-200mm Concrete Slab on ground	908	**88.98**	-	-	262.35	25.71	492.39	48.25
5-200mm Hollow Core Precast Concrete Slab	908	**88.98**	600.70	58.86	283.53	27.49	608.10	59.59
125mm Elevated Concrete Slab temporary frame work	750	73.50	515.60	50.52	259.31	25.41	521.35	51.09
6-110 mm Concrete Slab on ground	645	**63.21**	-	-	206.68	20.25	382.03	37.44
125mm Elevated Concrete Slab temporary frame work	750	**73.50**	-	-	247.27	24.23	438.98	43.02

Sources: 'Standard/Basic' column represents construction carbon emissions (embodied energy) from values given in Chapter Four; the 'Implementation', 'Green Star' and 'This research' columns are the potential construction carbon emission (embodied energy) reductions as calculated in Appendix C (Tables A.C.-1 ,8, 9, 17, 24, 30, 32, 33, 42, 43, 44, 52, 53).

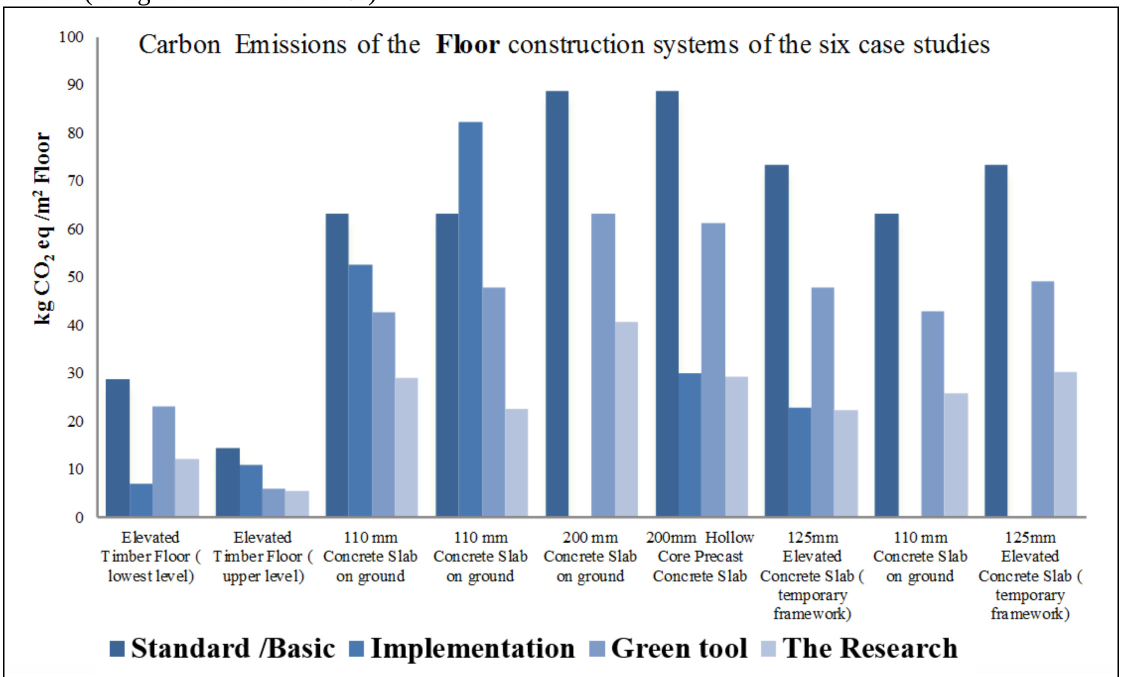
Table 7.3: Carbon emissions (embodied energy) **generated** in the **floor** construction systems of the case studies

Floor construction systems of the case studies of the research	**Standard/Basic**		**Implemented**		**Green Star**		**This research**	
	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2
1-Elevated Timber Floor (lowest level)	293	28.71	72	7.06	237.71	23.29	124.18	12.17
2- Elevated Timber Floor (upper level)	147	14.40	113	11.07	60.74	5.95	58.08	5.69
110 mm Concrete Slab on ground	645	**63.21**	537	52.62	435.26	42.65	297.70	29.17
3-110 mm Concrete Slab on ground	645	**63.21**	841	82.41	487.79	47.80	229.94	22.53
4-200mm Concrete Slab on ground	908	**88.98**	-	-	645.65	63.27	415.61	40.73
5-200mm Hollow Core Precast Concrete Slab	908	**88.98**	307.3	30.11	624.47	61.49	299.90	29.39
125mm Elevated Concrete Slab temporary frame work	750	73.50	234.4	22.97	490.69	48.08	228.65	22.40
6-110 mm Concrete Slab on ground	645	**63.21**	-	-	438.32	42.95	262.97	25.77
125mm Elevated Concrete Slab temporary frame work	750	**73.50**	-	-	502.73	49.26	311.02	30.48

Source: ‘Standard/Basic’ column is from values given in Chapter Four; ‘Implementation’, ‘Green Star’ and ‘This Research’ columns are the generated construction carbon emissions (embodied energy) obtained from Table 7.2 (subtract reduction figures from standard/basic figures)

The bar graph in Figure 7.7 provides a comparative representation of the generated carbon emissions data for the floor systems of the case studies (as given in Table 7.3).

Figure 7.7: Bar graph of carbon emissions generated for the **floor** construction systems of the case studies (using data from Table 7.3)



Source: Generated carbon emissions data from Table 7.3

Table 7.4 provides a percentage representation of the potential carbon emission reductions for the case studies using the data from Table 7.2.

Table 7.4: Potential carbon emission (embodied energy) **reductions** for the **floor** construction systems of the case studies expressed as percentages (using data from Table 7.2)

Floor construction systems of the case studies	Implemented	Green Star	This Research
	Reduction	Reduction	Reduction
1-Elevated Timber Floor (lowest level)	75.4%	18.8%	57.6%
2-Elevated Timber Floor (upper level)	Increase -23.1%	58.6%	60.4%
110 mm Concrete Slab on ground	16.7 %	32.5%	53.8%
3- 110 mm Concrete Slab on ground	Increase- 30.3%	24.3%	64.3%
4-200mm Concrete Slab on ground	-	28.8%	54.2%
5-200mm Hollow Core Precast Concrete Slab	66.1%	30.8%	66.9%
125mm Elevated Concrete Slab temporary frame work	68.7%	34.5%	69.5%
6-110 mm Concrete Slab on ground	-	32%	59.2%
125mm Elevated Concrete Slab temporary frame work	-	32.9%	58.5%

Source: Data from Table 7.2 expressed in percentage form. Highlighting indicates reference to figures in the discussion in Section 7.3.5.

7.3.2 Case studies – Wall construction systems emissions reduction

Tables 7.5 and 7.6 present comparative carbon emission reduction and generation figures for the wall construction systems used in the case studies.

Table 7.5: Potential carbon emission (embodied energy) **reductions** for the **wall** construction systems of the case studies

Wall construction systems of the case studies	Standard/Basic		Potential Reduction					
			Implementation		Green Star		This Research	
			Reduced or Increased		Potential reduction		Potential reduction	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²
1-Timber Frame, Single Skin Timber Wall	151	14.79	119	11.66	25.17	2.47	72.71	7.12
2-Timber Frame, Clay Brick Veneer Wall	561	54.97	-34	- 3.33	21.77	2.13	256.48	25.13
3-Timber Frame, Clay Brick Veneer Wall	561	54.97	- 9	- 0.88	23.44	2.29	257.47	25.23
4-Cavity Concrete Block Wall	511	50.07	-	-	96.48	9.46	248.34	24.34
5-Cavity Concrete Block Wall	511	50.07	336.81	33.01	106.77	10.46	336.81	33.01
Steel Frame, timber w/board Wall	238	23.32	134.01	13.13	125.44	12.29	134.01	13.13
6-Cavity Concrete Block Wall	511	50.07	-	-	96.48	9.45	248.34	24.34

Sources: 'Standard/Basic' column represents construction carbon emissions (embodied energy) from values given in Chapter Four; the 'Implementation', 'Green Star' and 'This research' columns are the potential construction carbon emission (embodied energy) reductions as calculated in Appendix C (Tables A.C. – 3, 4, 12, 13, 19, 20, 25, 26, 34, 35, 36, 37, 46, 47, 48, 54, 55)

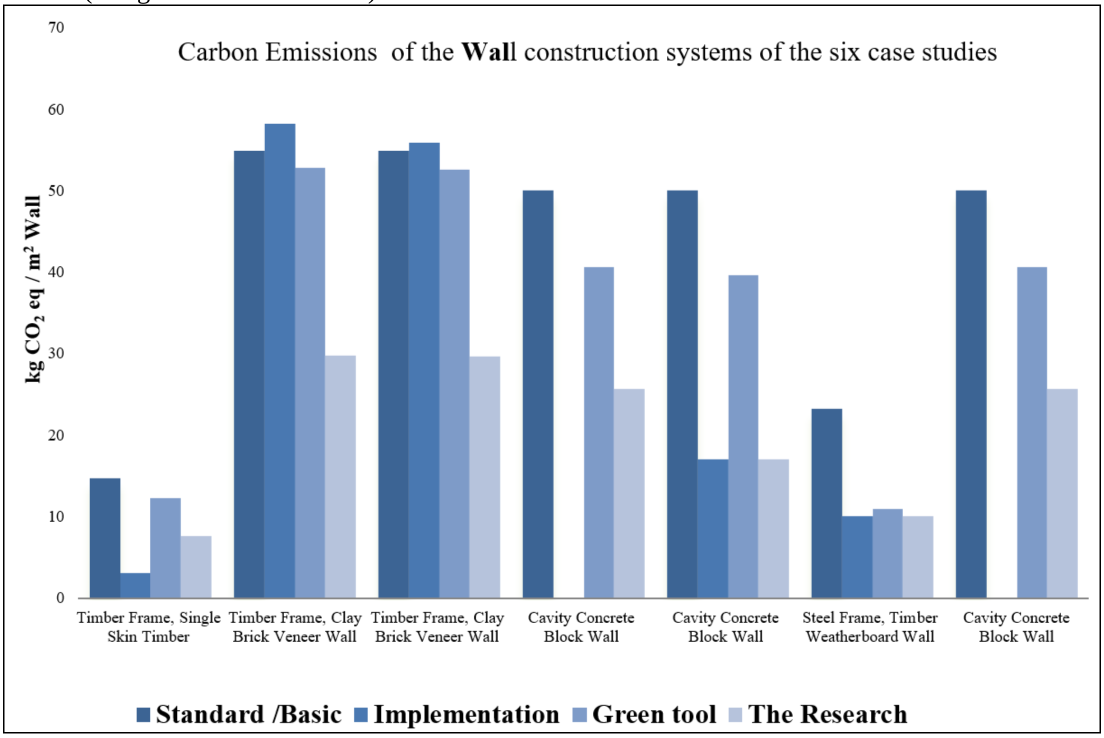
Table 7.6: Carbon emissions (embodied energy) **generated** in the **wall** construction systems of the case studies

Wall construction systems of the case studies	Standard/Basic		Implemented		Green Star		This research	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²
1-Timber Frame, Single Skin Timber Wall	151	14.79	32	3.1	125.83	12.33	78.29	7.67
2-Timber Frame, Clay Brick Veneer Wall	561	54.97	595	58.3	539.23	52.84	304.52	29.84
3-Timber Frame, Clay Brick Veneer Wall	561	54.97	570	55.9	537.56	52.68	303.53	29.74
4-Cavity Concrete Block Wall	511	50.07	-	-	414.52	40.62	262.66	25.74
5-Cavity Concrete Block Wall	511	50.07	174.19	17.07	404.23	39.61	174.19	17.07
Steel Frame, timber w/board Wall	238	23.32	103.99	10.19	112.56	11.03	103.99	10.19
6-Cavity Concrete Block Wall	511	50.07	-	-	414.52	40.62	262.66	25.74

Source: 'Standard/Basic' column is from values given in Chapter Four; 'Implementation', 'Green Star' and 'This Research' columns are the generated construction carbon emissions (embodied energy) obtained from Table 7.4 (subtract reduction figures from standard/basic figures)

The bar graph in Figure 7.8 provides a comparative representation of the generated carbon emissions data for the wall systems of the case studies (as given in Table 7.6).

Figure 7.8: Bar graph of carbon emissions generated for the **wall** construction systems of the case studies (using data from Table 7.6)



Source: Generated carbon emissions data from Table 7.6

Table 7.7 provides a percentage representation of the potential carbon emission reductions for the case studies using the data from Table 7.2.

Table 7.7: Potential carbon emission (embodied energy) **reductions** for the **wall** construction systems of the case studies expressed as percentages (using data from Table 7.5)

Wall construction systems of the case studies	Implemented	Green Star	This Research
	Reduction	Reduction	Reduction
1-Timber Frame, Single Skin Timber Wall	78.8%	17.7%	48.1%
2-Timber Frame, Clay Brick Veneer Wall	Increase - 6%	3.8%	45.7%
3-Timber Frame, Clay Brick Veneer Wall	Increase - 1.6%	4.1%	45.8%
4-Cavity Concrete Block Wall	-	18.8%	48.6%
5-Cavity Concrete Block Wall	65.9%	20.8%	65.9%
Steel Frame, timber w/board Wall	56.3%	52.7%	56.3%
6-Cavity Concrete Block Wall	-	18.8%	48.6 %

Source: Data from Table 7.5 expressed in percentage form. Yellow highlighting indicates reference to figures in the discussion in Section 7.3.5.

7.3.3 Case studies – Roof construction systems emissions reduction

Tables 7.8 and 7.9 present comparative carbon emission reduction and generation figures for the roof construction systems used in the case studies.

Table 7.8: Potential carbon emission (embodied energy) **reductions** for the **roof** construction systems of the case studies

Roof construction systems of the case studies	Standard/Basic		Potential Reduction: Implementation (Reduced or Increased)		Potential Reduction: Green Star (Potential reduction)		Potential Reduction: This Research (Potential reduction)	
	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2
1-Timber Frame, Steel Sheet Roof	330	32.34	100	9.80	114.48	11.22	144.59	14.17
2-Timber Frame, Concrete Tile Roof	240	23.52	14	1.37	45.16	4.42	91.51	8.97
3-Timber Frame, Steel Sheet Roof	330	32.34	-144	-14.11	114.48	11.22	144.59	14.17
4-Steel Frame, Steel Sheet Roof	401	39.29	-	-	145.65	14.28	231.85	22.72
5-Steel Frame, Fabric Roof (commercial)	282	27.63	182.82	17.91	84.49	8.28	144.72	14.18
6-Steel parallel chord trussed sheet roof	401	39.29	-	-	145.65	14.27	231.85	22.72

Sources: 'Standard/Basic' column represents construction carbon emissions (embodied energy) from values given in Chapter Four; the 'Implementation', 'Green Star' and 'This research' columns are the potential construction carbon emission (embodied energy) reductions as calculated in Appendix C (Tables A.C. – 5, 6, 14, 15, 21, 22, 27, 28, 39, 40, 48, 49, 56)

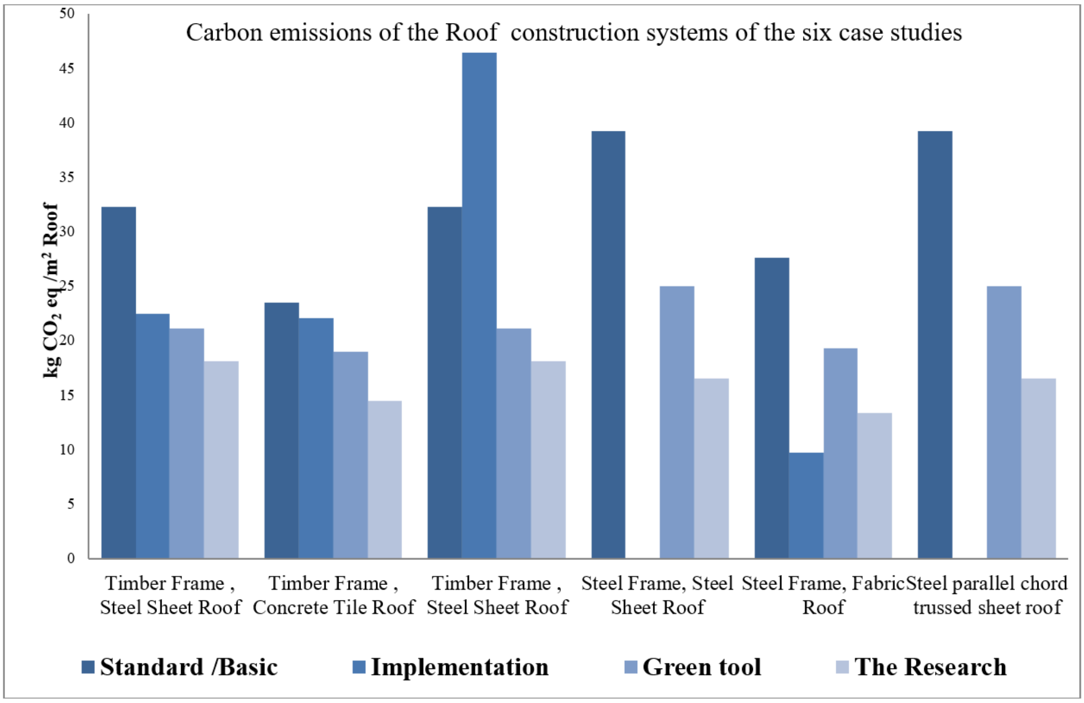
Table 7.9: Carbon emissions (embodied energy) **generated** in the **roof** construction systems of the case studies

Roof construction systems of the case studies	Standard/Basic		Implemented		Green Star		This research	
	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2
1-Timber Frame, Steel Sheet Roof	330	32.34	230	22.54	215.52	21.12	185.41	18.17
2-Timber Frame, Concrete Tile Roof	240	23.52	226	22.15	194.84	19.09	148.49	14.55
3-Timber Frame, Steel Sheet Roof	330	32.34	474	46.45	215.52	21.12	185.41	18.17
4-Steel Frame, Steel Sheet Roof	401	39.29	-	-	255.35	25.02	169.15	16.57
5-Steel Frame, Fabric Roof (commercial)	282	27.63	99.18	9.72	197.51	19.35	137.28	13.45
6-Steel parallel chord trussed sheet roof	401	39.29	-	-	255.35	25.02	169.15	16.57

Sources: Standard/Basic' column is from values given in Chapter Four; 'Implementation', 'Green Star' and 'This Research' columns are the generated construction carbon emissions (embodied energy) obtained from Table 7.6 (subtract reduction figures from standard/basic figures)

The bar graph in Figure 7.9 provides a comparative representation of the generated carbon emissions data for the roof systems of the case studies (as given in Table 7.9).

Figure 7.9: Bar graph of carbon emissions generated for the **roof** construction systems of the case studies (using data from Table 7.9)



Source: Generated carbon emissions data from Table 7.9

Table 7.10 provides a percentage representation of the potential carbon emission reductions for the case studies using the data from Table 7.8

Table 7.10: Potential carbon emission (embodied energy) **reductions** for the **roof** construction systems of the case studies expressed as percentages (using data from Table 7.8)

Roof construction systems of the case studies	**Implemented**	**Green tool**	**This Research**
	Reduction	Reduction	Reduction
1-Timber Frame, Steel Sheet Roof	30.3%	34.6%	43.8%
2-Timber Frame, Concrete Tile Roof	5.8%	18.7%	38.1%
3-Timber Frame, Steel Sheet Roof	Increase - 43.6%	34.6%	43.8%
4-Steel Frame, Steel Sheet Roof	-	36.3%	57.8%
5-Steel Frame, Fabric Roof (commercial)	64.8%	29.9%	51.3%
6-Steel parallel chord trussed sheet roof	-	36.3%	57.8%

Source: Data from Table 7.8 expressed in percentage form. Yellow highlighting indicates reference to figures in the discussion in Section 7.3.5.

7.3.4 Case studies – Whole construction systems emissions reduction

The final summary table presented in this section is for the whole construction system of each case study which collates the figures for the floor, wall and roof construction systems presented in Tables 7.2 to 7.7. The comparative data for potential carbon emission reductions in the six case studies is presented in Table 7.8, and the comparative data for generated carbon emissions is presented in Table 7.9.

Table 7.11: Potential construction carbon emission (embodied energy) **reductions** for the **whole** (floor, wall and roof) construction systems of the six case studies

Case studies of the research	Standard/Basic		Potential Reduction					
			Implementation		Green Star		This Research	
			Reduced or Increased		Potential reduction		Potential reduction	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²
1. Friendly Beaches Lodge	774	75.85	440	43.12	194.94	19.10	386.12	37.84
2. ACF Green Home	1623	159.05	122	11.95	276.67	27.11	783.86	76.81
3. Display Project Home	1536	150.52	347	34	295.13	28.92	817.12	80.07
4. Civil Engineering Lab.	1820	178.36	-	-	504.48	49.45	972.58	95.31
5. Velodrome Building	2689	263.52	1769.9	173.4	856.54	83.94	1744.99	170.98
6. Multi Sports Building	2307	226.08	-	-	696.08	68.21	1301.20	127.51

Sources: 'Standard/Basic' column represents construction carbon emissions (embodied energy) from values given in Chapter Four; the 'Implementation', 'Green Star' and 'This research' columns are the potential construction carbon emission (embodied energy) reductions as calculated in Appendix C (Tables A.C. – 7, 16, 23, 29, 40, 50, 57)

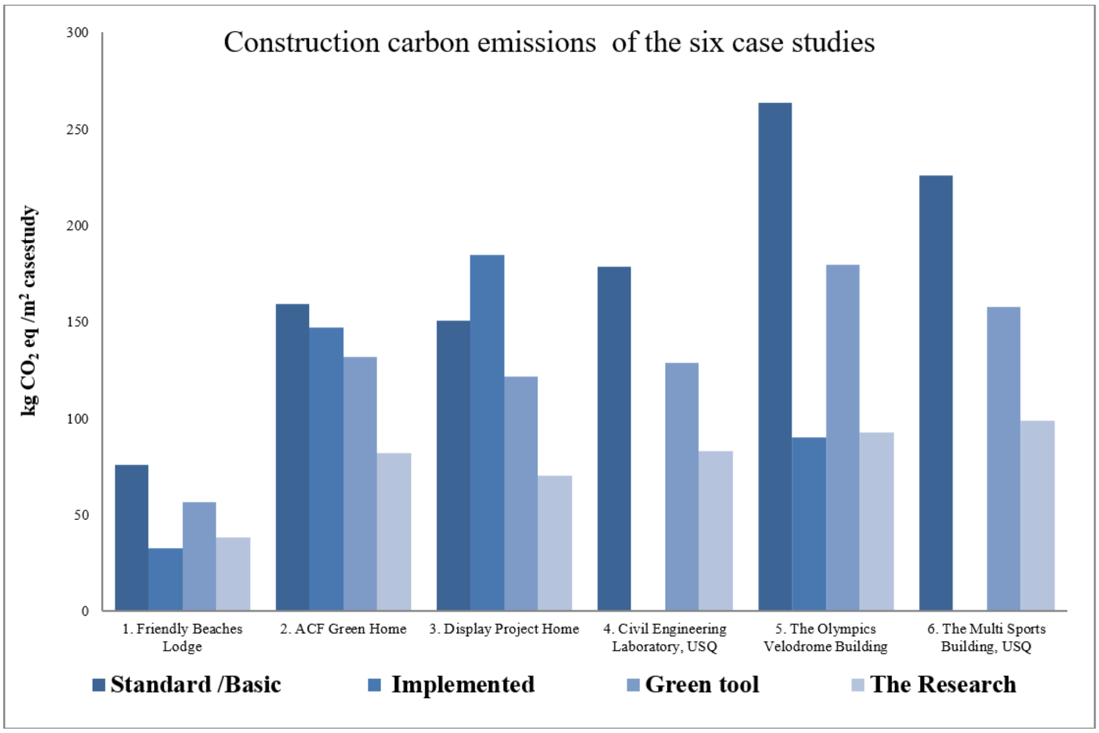
Table 7.12: Carbon emissions (embodied energy) **generated** in the **whole** (floor, wall and roof) construction systems of the case studies

Case studies of the research	Standard or Basic		Implemented		Green Star		This research	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²
1. Friendly Beaches Lodge	774	75.85	334	32.73	579.06	56.75	387.88	38.01
2. ACF Green Home	1623	159.05	1501	147.10	1346.33	131.94	839.14	82.23
3. Display Project Home	1536	150.52	1883	184.53	1240.87	121.60	718.88	70.45
4. Civil Engineering Lab.	1820	178.36	-	-	1315.52	128.92	847.42	83.04
5. Velodrome Building	2689	263.52	919.1	90.07	1832.46	179.58	944.01	92.51
6. Multi Sports Building	2307	226.08	-	-	1610.92	157.87	1005.80	98.57

Sources: 'Standard/Basic' column is from values given in Chapter Four; 'Implementation', 'Green Star' and 'This Research' columns are the generated construction carbon emissions (embodied energy) obtained from Table 7.8 (subtract reduction figures from standard/basic figures)

The bar graph in Figure 7.10 provides a comparative representation of the generated carbon emissions data for the whole construction systems of the case studies (as given in Table 7.12).

Figure 7.10: Bar graph of carbon emissions generated for the whole construction systems of the case studies (using data from Table 7.12)



Source: Generated carbon emissions data from Table 7.12

Table 7.13 provides a percentage representation of the potential carbon emission reductions for the whole construction systems of the case studies (using the data from Table 7.11).

Table 7.13: Potential carbon emission (embodied energy) **reductions** for the **whole** construction systems of the case studies expressed as percentages (using data from Table 7.11)

Case studies of the research	**Implemented**	**Green tool**	**This Research**
	Reduction	Reduction	Reduction
1. Friendly Beaches Lodge	56.7%	25.2%	49.8%
2. ACF Green Home	7.5%	17%	48.3%
3. Display Project Home	- 22.6%	19.2%	53.2%
4. Civil Engineering Lab	-	30%	53.4%
5. The Velodrome Building	65.8%	31.9%	64.9%
6. The Multi Sports Building	-	30.2%	56.4%

Source: Data from Table 7.11 expressed in percentage form. Yellow highlighting indicates reference to figures in the discussion in Section 7.3.5.

7.3.5 Analysis of data from the floor, wall and roof systems of the case studies

In respect to the floor construction systems of the case studies, the bar graph of carbon emissions generated (Figure 7.7) indicates that emissions following application of the research model to the floor systems are consistently lower than for the other three scenarios (standard building practice, at implementation/completion of a floor construction project, and following application of the Green Star tool). Similar trends are seen when the bar graph of generated carbon emissions of the wall and roof construction systems are considered (Figures 7.8 and 7.9). The generated carbon emissions for wall and roof systems are generally lower following application of the bioclimatic criteria in the research model as compared to the standard building practice, on completion of a building, and following application of the Green Star tool. This is also the case for generated emissions for the whole construction systems of the case studies as shown in Figure 7.10.

This trend is also seen when carbon reductions are considered. Potential carbon emission reductions data for the floor, wall and roof construction systems of the case studies are presented in Tables 7.4, 7.7 and 7.10 respectively as percentage reductions. There is a similar presentation of percentage data for the combined/whole construction systems of the case studies in Table 7.13. Analysis of these figures indicates that, in all cases, the potential carbon emission reductions are generally higher with application of the research model as compared to the implemented and Green Star results.

In analysis of the data presented in the tables and figures in this section, as compared to the carbon emissions from standard building practice, there are generally considerable reductions in construction carbon emissions that can be achieved through use of environmentally-friendly building practices. The highest overall reduction was achieved in the whole construction system of the 2012 Olympics Velodrome building (Case Study 5), at 65.8 per cent (Table 7.13). This was at implementation of the building and presumably reflects the focus on sustainable material usage in the construction of the Velodrome.

Application of the criteria in the Green Star tool to the construction process (Table 7.13) again shows significant reductions across all buildings considered in the case studies, with the highest at 31.9 percent, again for the Olympic Velodrome (Case Study 5). The figures for the Olympic Velodrome (Case Study 5) are about equal for the implemented and research model reductions (65.8 per cent and 64.9 percent respectively). This Velodrome building was, in fact, implemented by the London Olympic builders to achieve maximum emission reduction during construction, and it obviously has achieved this.

It is also noted that the potential carbon emission reduction for the Friendly Beaches Lodge (Case Study 1) as implemented (constructed) is higher than achieved through application of the research model (56.7 per cent compared to 49.8 percent – Table 7.13). This is presumably due to the environmental considerations applied at implementation of the project in this particular case study.

Overall, however, the research model using bioclimatic criteria clearly shows the greatest potential for reduction in construction carbon emissions across the six case studies as compared to standard construction carbon emissions and those achievable following application of the Green Star tool. The lowest carbon reduction was 48.3 per cent for the ACF Green Home (Case Study 2), and the highest for the Olympic Velodrome at 64.9 percent for their whole construction systems (Table 7.13). In fact, in many cases, reductions in construction carbon emissions could be approximately doubled by use of the criteria in the research model tool as compared with Green Star and current best practice.

In respect to application of the research model's bioclimatic criteria to the construction systems of the case studies, it is noted that:

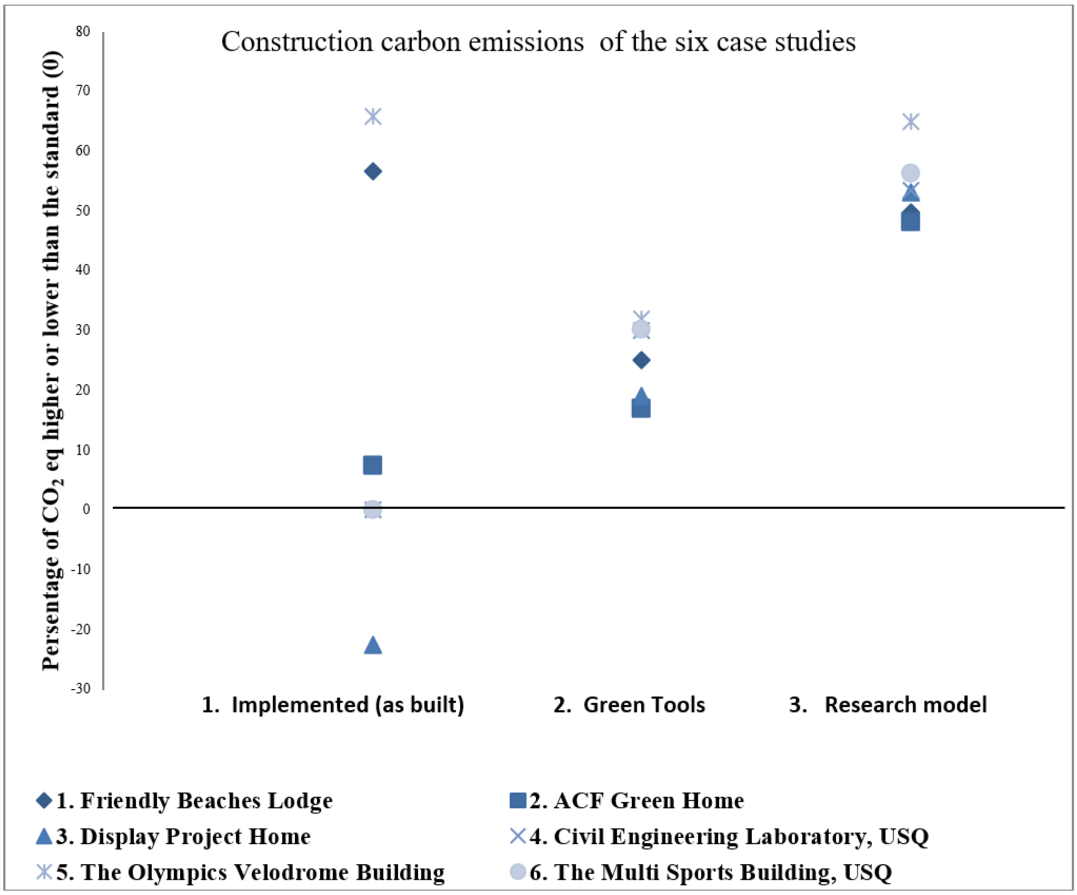
- For the floor construction systems (Table 7.4), the potential reductions in carbon emissions are between 53.8 and 69.5 per cent, the highest percentage being for the Olympics Velodrome Building's concrete slab floor (Case Study 5).
- For the wall construction systems (Table 7.7), the potential reductions in carbon emissions are between 45.7 and 65.9 per cent, the highest being for the Velodrome Building's concrete block wall (Case Study 5).
- For the roof systems (Table 7.10), the potential reductions in carbon emissions are between 38.1 and 57.8 per cent, the highest being in the Civil

Engineering Lab and the Multi Sports building roof construction systems (Case Studies 4 and 6).

- For the combined/whole construction systems (Table 7.13), the potential reductions in carbon emissions are between 48.3 and 64.9 per cent, the highest being for the Velodrome building (Case Study 5).

These results are displayed graphically in Figure 7.11 which compares the carbon emission reductions achieved in the case studies at implementation, and then through application of the Green Star tool and the research model tool. From these results, the conclusion can be made that application of the research model to the construction systems of the case studies can achieve potential reduction in carbon emissions of from 50 to 65 per cent.

Figure 7.11: Carbon emission reductions in the whole construction systems of the case studies achieved at Implementation, and then by application of the Green Star and the research model tools



Source: Data from Table 7.13

A summary table of the bioclimatic design principles used in the research model, and the percentage potential reductions in carbon emissions of the research compared to those from implantation and green tools is presented in Table 7.14.

Table 7.14: Bioclimatic conditions – current; from best practice with green tools (Green Star, LEED and BREEAM); from this research model (BDP)

Bioclimatic Design Principles (BDP)	Current conditions, Implemented	Conditions with Green tools G.S., LEED, BRE	Through Bioclimatic Principles Conditions in this research
Concrete from recycled aggregates	In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities [1]	G.S. and LEED 1-3 points 20-30% RA for structural purpose; BRE 20% in 20-40 MPa - no restriction, 100% non-structural [2, 18, 36]	Fully RA for non-structural purposes; 100% RA for non-structural; 80 % RA for structural purpose [6]
Concrete block from recycled aggregate	24% recycled content of an aggregate concrete block [8]	G.S., BRE, 40%; US 25% RA structural; 100%, or no natural aggregates in non-structural [18,23,36]	Aggregate for concrete block fully from recycled aggregate [13]
Brick from recycled aggregates	Current level of recycled material content in brick is 11% 14[,41]	G.S. 30% [16, 23]; LEED 20%; BRE 11% ISO, up to 10 points for 10% Recycled aggregate [14,16,36]	Reuse recycled aggregate for brick, 67% 19
Steel from average recycled content	Primary typically 10-15% of scrap steel Secondary 100% scrap based production [25, 34]	G.S. Mat-6, 60%; LEED 65-97.5%; BRE, Mat-6, 60%; -97.5% beams, plates; 65% bars; 66% steel deck post-consumer recycled content [23,16,38]	Steel from fully post-consumer recycled content
Reuse recycled and post-consumer structural and non-structural steel	Scaffolding, formwork, sheet piles, etc., London Olympic Stadium[32, 34]	G.S., 95% Joinery, 50% structural framing, roofing; LEED 75-100% existing wall, floor, roof; BRE, Mat-6, 60% recycled content [3,5,23,24]	Use 40% recycled and post-consumer steel elements
Reduce material use in steel structural design 10-20%	Some of the current green projects have reduced materials use in design 10-20% [23]	G.S., Mat-6, 10-20% one point; LEED, eliminating need for materials in the design stage; BRE reduced, avoiding over-design [23,21,10,7,32]	Reduced materials use in structural design 10-20%
Reuse the recycled timber and post-consumer FSC timber	FSC works in 80 countries, 24000 FSC chain of custody certificates are active in 107 countrie.[23,]	G.S. 95% re-used, post-consumer; FSC certified timber; up to 3 points; LEED, 50% FSC; BRE, 3 points, post-consumer waste stream [22, 23, 32,24,29]	60% of all timber products re-used, post-consumer recycled timber; FSC certified timber
Roof tile from recycled tile	In some countries materials such as concrete roof tiles, are removed separated and recycled [44, 45]	G.S. Mat-5, 1 point, no natural aggregates are used; LEED, from the waste, up to3.5 points, BRE, M03, from the waste stream;[20,21,23,36]	50% Roof tile from recycled aggregate [21]
Thermal insulation from recycled content	Thermal insulation is fully recyclable, i.e. wool content[31]	G.S. 80% advised; LEED MR4 20%, ½ point, BRE 80%, 1 point, responsibly sourced [12,7,27,37]	Thermal insulation from fully recycled waste [25]
Portland cement replaced with Geopolymer based cement	Geopolymer has been used structural, non-structural, University GCI in Qld, Wellcamp Airport, Qld [46,47,48]	G.S. 60% In situ concrete; 40% precast 30% stressed concrete; LEED, 30% structural; no limit others, BRE, responsibly sourced cement [23,26,7]	Geopolymer based cement fully replaces Portland cement, arranged for non-structural, structural
Reduce transportation by reusing and recycled materials	National Waste Policy Australia advice to reduce waste, re-use to reduce environmental impacts [35]	Green tools credit the reusing and recycling of up to 40% of materials, not directly credited; obtained from30km radius of the site [2,15,35,37]	Reuse considered in material production and building elements
Transportation by water or rail not truck, reduce transportation by localizing	15% of bricks are transported to the distributor's yard or jobsite by rail and 85% by truck [19, 30]	LEED, Regional Materials, up to 2 points [14] Tools advise localizing, using water and rail instead of road 2[15]	Localizing has been considered
CONSTRUCTION CARBON EMISSIONS REDUCTION	**CASE STUDIES: IMPLEMENTATION → BETWEEN -23% AND 57%**	**CASE STUDIES: GREEN TOOL → POTENTIAL BETWEEN 17 TO 32 %**	**CASE STUDIES: RESEARCH MODEL POTENTIAL BETWEEN 50 AND 65 %**

References and detailed information of this table is presented in Table A.D.3 \| RA = Recycled Aggregate, From Author

7.4 General Australian floor, wall and roof construction systems – Potential carbon emission reductions

In this section, the research model and Green Star criteria are applied to the general Australian construction systems of floor, wall and roof (i.e. construction systems unrelated to the case studies). The bioclimatic criteria applied are summarised in Table 7.15.

The **potential carbon emission reductions** achievable by application of bioclimatic criteria to the floor, wall and roof of general Australian construction systems are presented in Tables 7.16, 7.19 and 7.22 respectively. There are also percentage calculations of the potential carbon emission reductions for the floor, wall and roof construction systems presented in Tables 7.18, 7.21 and 7.24 respectively for floor, wall and roof systems.

This contrasts with Tables 7.17, 7.20 and 7.23 which present the **generated construction carbon emissions** for floor, wall and roof respectively. These figures are obtained by subtracting the emission reduction figure for the item concerned from the standard/basic figure in column one of the corresponding table, the result being the generated carbon emission for the item concerned. Figures in each table are compared for the Green Star tool and the research model. Detailed calculations relating to these tables are presented in Appendix C.

The tables and figures presented in this section compare data from three sources:

- **Standard/Basic carbon emissions**: Carbon emissions to be expected with no application of green or bioclimatic criteria to the building process.
- **Green Star**: The potential carbon reductions/emissions predicted if the criteria of the Green Star tool is applied to a given construction system.
- **This research**: The potential carbon reductions/emissions predicted if the bioclimatic criteria of the research model are applied

An analysis of the findings is presented in Section 7.4.4.

Table 7.15: Bioclimatic criteria examined in general Australian floor, wall and roof construction systems using the research model and the Green Star rating tool

Bioclimatic criteria		A.1 Floor construction systems	A.2. Wall construction systems	A.3. Roof construction systems
Concrete from recycled aggregates	Study	80% RA for fixing posts in the ground [1]	80 % RA for concrete slab on ground [1]	80 % RA for concrete slab on ground [1]
	Green Star	20% RA for fixing posts in the ground [2]	20 % RA for fixing posts in the ground [2]	20 % RA for fixing posts in the ground [2]
Concrete block and brick from recycled aggregate	Study	-	Concrete block wall from (67-100%) RA [3]	-
	Green Star	-	Concrete block wall from 20% RA [3]	-
Brick from recycled aggregate	Study	Brick from 67% RA for posts Use recycled bricks %60 [4]	Brick wall from 67% RA [4]	-
	Green Star	-	-	-
Steel from average recycled content	Study	Use steel produced with 100% recycled content [8,13]	Use steel produced with 100% recycled content [8,13]	Use steel produced with 100% recycled content [8,13]
	Green Star	Use steel produced with 90% recycled content [6,7]	Use steel produced with 90% recycled content [6,7]	Use steel produced with 90% recycled content [6,7]
Reuse recycled and post-consumer structural and non-structural steel	Study	Reuse 40% recycled steel in structural and non-structural elements [31,32]	Reuse 40% recycled steel in structural and non-structural elements [31,32]	Reuse 40% recycled steel in the structural and non-structural elements [31,32]
	Green Star	-	-	-
Reduce material (steel) use in design 10-20%	Study	Reduced 20% steel use in design [12, 14]	Reduced 20% steel use in design [12, 14]	Reduced 20% steel use in design [12, 14]
	Green Star	Reduced 20% steel use in design, [15,16, 5, 6, 12]	Reduced 20% steel use in design, [15,16, 5, 6, 12]	Reduced 20% steel use in design, [15,16, 5, 6, 12]
Reuse recycled timber and post-consumer FSC certified timber	Study	Use 100%, recycled timber or FSC certified timber, reuse [6, 17]	Use 100%, recycled timber or FSC certified timber, reuse [6, 17]	Use 100%, recycled timber or FSC certified timber, reuse [6, 17]
	Green Star	Use 100%, recycled timber or FSC certified timber, reuse [6, 7, 12, 18, 19]	Use 100%, recycled timber or FSC certified timber, reuse [6, 7, 12, 18, 19]	Use 100%, recycled timber or FSC certified timber, reuse [6, 7, 12, 18, 19]
Roof tile from recycled tiles	Study	-	-	Use 13% recycled tile, tiles with 45% recycled content [5, 20]
	Green Star	-	-	-
Thermal insulation from recycled content	Study	-	Thermal insulation 100% from recycled content [8]	Thermal insulation 100% from recycled content [8]
	Green Star	-	-	-
Replaced Portland cement with geopolymer cement	Study	Replace 100% of Portland cement with geopolymer [12, 21]	Replace 100% of Portland cement with geopolymer [12, 21]	Replace 100% of Portland cement with geopolymer [12, 21]
	Green Star	Replace 60% of Portland cement with geopolymer [6 ,9, 22]	Replace 60% of Portland cement with geopolymer [6 ,9, 22]	Replace 60% of Portland cement with geopolymer [6 ,9, 22]

References, specifications and detailed information relating to this table are presented in Table A.D.4 (Appendix D). (RA = Recycled Aggregates)

7.4.1 Potential emission reductions in general Australian floor construction systems

Tables 7.16 and 7.17 present comparative carbon emission reduction and generation figures for general Australian floor construction systems.

Table 7.16: Potential carbon emission (embodied energy) r**eductions** for general Australian **floor** construction systems

General Australian floor construction systems	Standard /Basic		Potential Reduction: Green Star		Potential Reduction: This research	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²
a-Elevated Timber Floor (lowest level)	293	28.7	45.6	4.46	146.58	14.36
b-Elevated Timber Floor (upper level)	147	14.4	84.60	8.29	84.60	8.29
c-110 mm Concrete Slab on ground	645	63.21	194.70	19.08	291.46	28.56
d-125mm Elevated Concrete Slab (temporary framework)	750	**73.5**	234.76	23.01	344.72	**33.78**
e-110mm Elevated Concrete Slab (permanent framework)	665	65.17	218.14	21.37	292.3	28.64
f- 200mm Precast Concrete Tee Beam/Infill flooring	602	**59**	238.46	23.36	273.50	**26.80**
g-200mm Hollow Core Precast Concrete flooring	908	88.98	249.05	24.40	383.07	37.54

Sources: 'Standard/Basic' column represents construction carbon emissions (embodied energy) from values given in Chapter Four; the 'Green Star' and 'This research' columns are the potential construction carbon emission (embodied energy) reductions as calculated in Appendix C (Tables A.C.58-A.C.69)

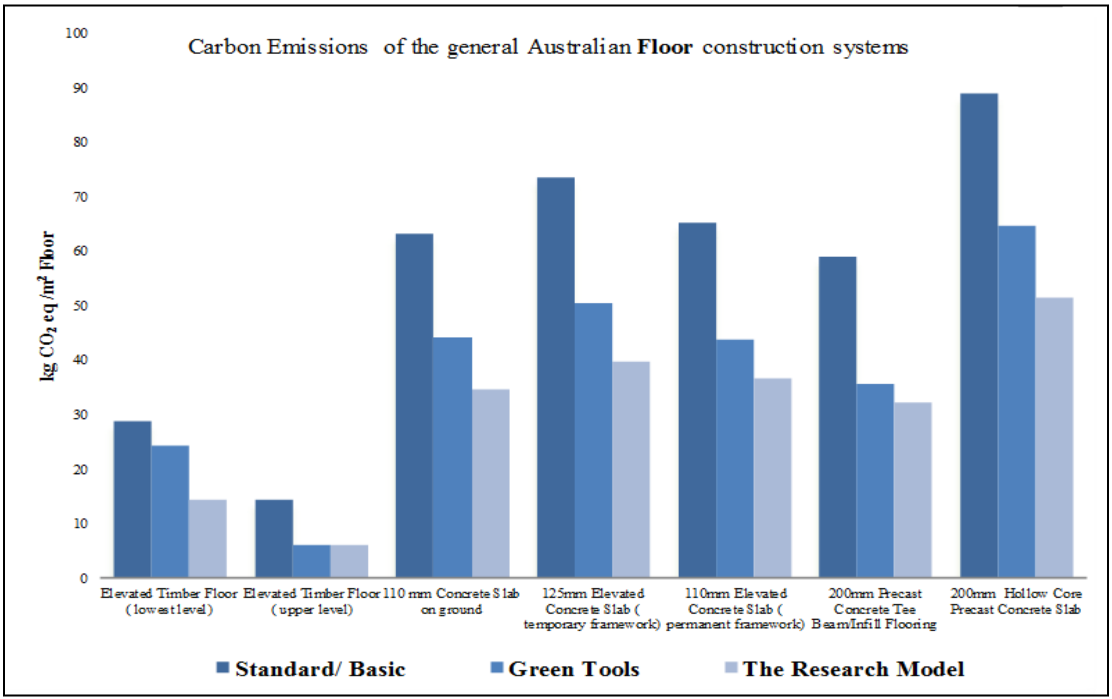
Table 7.17: Carbon emissions (embodied energy) **generated** in the general Australian **floor** construction systems

General Australian floor construction systems	Standard /Basic		Green Star		This research	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²
a-Elevated Timber Floor (lowest level)	293	28.7	247.4	24.24	146.42	14.34
b-Elevated Timber Floor (upper level)	147	14.4	62.4	6.11	62.4	6.11
c-110 mm Concrete Slab on ground	645	63.21	450.30	44.12	353.54	34.64
d-125mm Elevated Concrete Slab (temporary framework)	750	73.5	515.24	50.49	405.28	39.71
e-110mm Elevated Concrete Slab (permanent framework)	665	65.17	446.86	43.79	373	36.55
f- 200mm Precast Concrete Tee Beam/Infill flooring	602	**59**	363.54	35.62	328.5	32.19
g-200mm Hollow Core Precast Concrete flooring	908	88.98	658.95	64.57	524.91	51.44

Sources: 'Standard/Basic' column is from values given in Chapter Four; the 'Green Star' and 'This Research' columns are the generated construction carbon emissions (embodied energy) obtained from Table 7.16 (subtract reduction figures from standard/basic figures)

The bar graph in Figure 7.12 provides a comparative representation of the generated carbon emissions data for general Australian floor systems (as given in Table 7.17).

Figure 7.12: Bar graph of carbon emissions generated for general Australian floor construction systems (using data from Table 7.17)



Source: Generated carbon emissions data from Table 7.17

Table 7.18 provides a percentage representation of the potential carbon emission reductions that can be achieved in general Australian floor construction systems by application of the Green star and research model tools (using data from Table 7.16).

Table 7.18: Potential carbon emission **reductions** in general Australian **floor** construction systems expressed as percentages (using data from Table 7.16)

General Australian floor construction systems	Green Star	This research
	Carbon Emissions Kg/m²	Carbon Emissions Kg/m²
a-Elevated Timber Floor (lowest level)	15.56%	50.02%
b-Elevated Timber Floor (upper level)	57.55%	57.55%
c-110 mm Concrete Slab on ground	30.18%	45.17%
d-125mm Elevated Concrete Slab (temporary framework)	31.30%	45.96%
e-110mm Elevated Concrete Slab (permanent framework)	32.80%	43.95%
f- 200mm Precast Concrete Tee Beam/Infill flooring	39.61%	45.43%
g-200mm Hollow Core Precast Concrete flooring	27.42%	33.37%

Sources: Data from Table 7.16 expressed in percentage form. Yellow highlighting indicates reference to figures in the discussion in Section 7.4.4.

7.4.2 Potential emission reductions in general Australian wall construction systems

Tables 7.19 and 7.20 present comparative carbon emission reduction and generation figures for general Australian wall construction systems.

Table 7.19: Potential carbon emission (embodied energy) **reductions** for general Australian **wall** construction systems

General Australian wall construction systems	Standard /Basic		Potential Reduction			
			Green Star		This research	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²	Carbon Emissions Kg/m²
a-Timber Frame, Single Skin Timber Wall	151	14.8	40.36	3.95	41.36	4.05
b-Timber Frame, Timber Weatherboard Wall	188	18.4	71.06	6.96	107.01	10.48
c-Timber Frame, Reconstituted Timber Weatherboard Wall	377	36.9	287.73	28.19	320.03	31.36
d-Timber Frame, Fiber Cement W/board Wall	169	16.6	35.53	3.48	70.60	6.91
e-Timber Frame, Steel Clad Wall	336	32.9	114.46	11.21	157.32	15.41
f-Steel Frame, Steel Clad Wall	425	41.7	143.45	14.05	234.53	22.98
g-Timber Frame, Aluminium W/board Wall	403	39.5	266.10	26.07	310.03	30.38
h-Timber Frame, Clay Brick Veneer Wall	561	63.8	19.80	1.94	191.60	18.77
i-Steel Frame, Clay Brick Veneer Wall	650	63.7	78.72	7.71	154.99	15.18
j-Timber Frame, Concrete Block Veneer Wall	361	35.4	76.69	7.51	131.95	12.93
k-Steel Frame, Concrete Block Veneer Wall	453	44.4	121.41	11.89	228.58	22.40
l-Steel Frame, timber weatherboard Wall	238	23.3	134.82	13.21	222.64	21.81
m-Cavity Clay Brick Wall	860	84.3	29.15	2.85	340.07	33.32
n-Cavity Concrete Block Wall	465	45.6	145.15	14.22	256.18	25.10
o-Single Skin Stabilised Rammed Earth Wall	405	39.7	95.76	9.38	273.72	26.82
p-Single Skin Aerated Concrete Block(AAC)wal	440	43.1	40.55	3.97	74.10	7.26
q-Single Skin Cored Concrete Block Wall	317	31.1	56.30	5.51	103.71	10.16
r-Steel Frame, Compressed Fibre Cement Clad Wall	385	37.7	158.70	15.55	282.34	27.67
s-Hollow-Core Precast Concrete Wall	729	71.4	187.60	18.38	298.76	28.2
t-Tilt-up Precast Concrete Wall	818	80.1	224.02	21.95	356.95	34.98
u-Porcelain-Enamelled Steel Curtain Wall	865	84.8	480.92	47.11	523.09	51.26
v-Glass Curtain Wall	770	75.5	451.42	44.23	492.09	48.22
w-Steel Faced Sandwich Panel Wall	1087	106.5	197.05	19.31	218.24	21.38
x-Aluminium Curtain Wall	935	91.6	722.19	70.77	802.44	78.63

Sources: 'Standard/Basic' column represents construction carbon emissions (embodied energy) from values given in Chapter Four; the 'Green Star' and 'This research' columns are the potential construction carbon emission (embodied energy) reductions as calculated in Appendix C (Tables A.C.71-A.C.118)

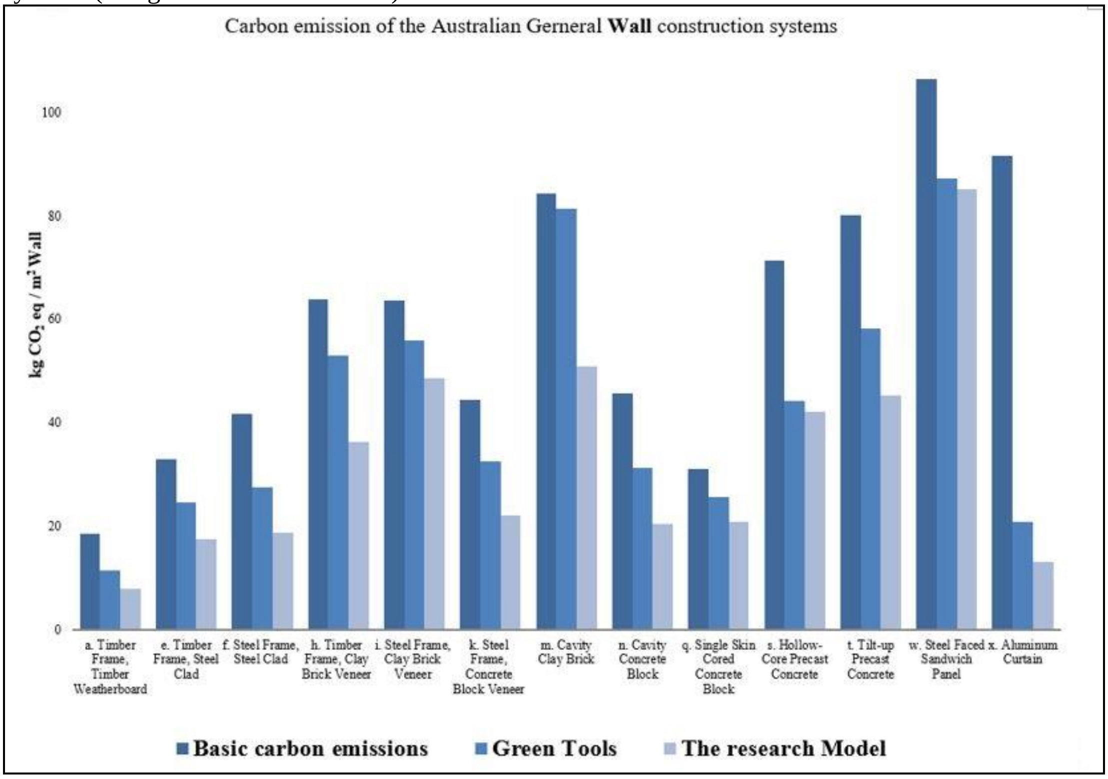
Table 7.20: Carbon emissions (embodied energy) **generated** in general Australian **wall** construction systems

General Australian Wall construction systems	Standard /Basic			Green Star			This research	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²		Embodied Energy MJ/m²	Carbon Emissions Kg/m²		Embodied Energy MJ/m²	Carbon Emissions Kg/m²
a-Timber Frame, Single Skin Timber Wall	151	14.8		110.64	10.84		109.64	10.74
b-Timber Frame, Timber Weatherboard Wall	188	18.4		116.94	11.46		80.99	7.93
c-Timber Frame, Reconstituted Timber Weatherboard Wall	377	36.9		89.27	8.74		56.97	5.58
d-Timber Frame, Fiber Cement W/board Wall	169	16.6		133.47	13.08		98.40	9.64
e-Timber Frame, Steel Clad Wall	336	32.9		251.54	24.65		178.68	17.51
f-Steel Frame, Steel Clad Wall	425	41.7		281.55	27.53		190.47	18.66
g-Timber Frame, Aluminium W/board Wall	403	39.5		136.90	13.41		92.97	9.11
h-Timber Frame, Clay Brick Veneer Wall	561	63.8		541.20	53.03		369.40	36.20
i-Steel Frame, Clay Brick Veneer Wall	650	63.7		571.28	55.98		495.01	48.51
j-Timber Frame, Concrete Block Veneer Wall	361	35.4		284.31	27.86		229.05	22.44
k-Steel Frame, Concrete Block Veneer Wall	453	44.4		331.59	32.49		224.42	21.99
l-Steel Frame, timber weatherboard Wall	238	23.3		103.18	10.09		15.36	1.50
m-Cavity Clay Brick Wall	860	84.3		830.85	81.42		519.93	50.95
n-Cavity Concrete Block Wall	465	45.6		319.85	31.34		208.82	20.46
o-Single Skin Stabilised Rammed Earth Wall	405	39.7		309.24	30.30		131.28	12.86
p-Single Skin Aerated Concrete Block(AAC)wall	440	43.1		399.45	39.14		365.90	35.85
q-Single Skin Cored Concrete Block Wall	317	31.1		260.70	25.54		213.29	20.89
r-Steel Frame, Compressed Fibre Cement Clad Wall	385	37.7		226.30	26.09		101.66	9.96
s-Hollow-Core Precast Concrete Wall	729	71.4		541.40	44.23		430.24	42.16
t-Tilt-up Precast Concrete Wall	818	80.1		593.98	58.21		461.05	45.18
u-Porcelain-Enamelled Steel Curtain Wall	865	84.8		384.08	37.63		431.91	42.32
v-Glass Curtain Wall	770	75.5		318.58	31.22		277.91	27.23
w-Steel Faced Sandwich Panel Wall	1087	106.5		889.95	87.21		868.76	85.13
x-Aluminium Curtain Wall	935	91.6		212.81	20.85		132.56	12.98

Sources: 'Standard/Basic' column is from values given in Chapter Four; the 'Green Star' and 'This Research' columns are the generated construction carbon emissions (embodied energy) obtained from Table 7.20 (subtract reduction figures from standard/basic figures)

The bar graph in Figure 7.13 provides a comparative representation of the generated carbon emissions data for general Australian wall construction systems (as given in Table 7.17).

Figure 7.13: Bar graph of carbon emissions generated for general Australian wall construction systems (using data from Table 7.20)



Source: Generated carbon emissions using data from Table 7.20

Table 7.21 provides a percentage representation of the potential carbon emission reductions that can be achieved in general Australian wall construction systems by application of the Green star and research model tools (using data from Table 7.19).

Table 7.21: Potential carbon emission **reductions** in general Australian **wall** construction systems expressed as percentages (using data from Table 7.19)

General Australian wall construction systems		Green Star		This research
		Carbon Emissions Kg/m^2		Carbon Emissions Kg/m^2
a-Timber Frame, Single Skin Timber Wall		26.72%		27.39%
b-Timber Frame, Timber Weatherboard Wall		37.79%		56.92%
c-Timber Frame, Reconstituted Timber Weatherboard Wall		76.32%		84.88%
d-Timber Frame, Fiber Cement W/board Wall		21.02%		41.77%
e-Timber Frame, Steel Clad Wall		34.06%		46.82 %
f-Steel Frame, Steel Clad Wall		33.75%		55.18%
g-Timber Frame, Aluminium W/board Wall		66.02%		76.39%
h-Timber Frame, Clay Brick Veneer Wall		3.52%		34.15%
i-Steel Frame, Clay Brick Veneer Wall		12.11%		23.84%
j-Timber Frame, Concrete Block Veneer Wall		21.24%		36.55%
k-Steel Frame, Concrete Block Veneer Wall		26.80%		50.45%
l-Steel Frame, timber weatherboard Wall		56.64%		93.54%
m-Cavity Clay Brick Wall		3.38%		39.54%
n-Cavity Concrete Block Wall		31.23%		55.09%
o-Single Skin Stabilised Rammed Earth Wall		23.64%		67.58%
p-Single Skin Aerated Concrete Block(AAC)wall		9.21%		16.84%
q-Single Skin Cored Concrete Block Wall		17.76%		32.71%
r-Steel Frame, Compressed Fibre Cement Clad Wall		41.22%		73.33%
s-Hollow-Core Precast Concrete Wall		25.73%		40.98%
t-Tilt-up Precast Concrete Wall		27.38%		43.63%
u-Porcelain-Enamelled Steel Curtain Wall		55.59%		60.74%
v-Glass Curtain Wall		58.62%		63.90%
w-Steel Faced Sandwich Panel Wall		18.12%		20.07%
x-Aluminium Curtain Wall		72.23%		85.82%

Sources: Data from Table 7.19 expressed in percentage form. Yellow highlighting indicates reference to figures in the discussion in Section 7.4.4.

7.4.3 Potential emission reductions in general Australian roof construction systems

Tables 7.22 and 7.23 present comparative carbon emission reduction and generation figures for general Australian roof construction systems.

Table 7.22: Potential carbon emission (embodied energy) **reductions** for general Australian **roof** construction systems

General Australian roof construction systems	Standard /Basic		Potential Reduction			
			Green Star		This research	
	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2	Embodied Energy MJ/m^2	Carbon Emissions Kg/m^2
a-Timber Frame, Timber Shingle Roof	151	14.8	48.45	4.74	68.57	6.71
b-Timber Frame, Fiber Cement Shingle Roof	291	28.5	40.85	4.00	74.10	7.26
c-Timber Frame, Steel Sheet Roof	330	32.3	109.47	10.72	137.32	13.46
d-Steel Frame, Steel Sheet Roof	483	47.3	178.57	17.49	232.29	31.68
e-Timber Frame, Concrete Tile Roof	240	23.5	**45.16**	4.42	74.10	7.26
f-Steel Frame, Concrete Tile Roof	450	44.1	97.64	9.56	191.49	18.76
g-Timber Frame, Terracotta Tile Roof	271	26.6	**45.16**	4.42	78.59	7.70
h-Timber Frame, Synthetic Rubber Membrane Roof	386	37.8	**45.16**	4.42	60.57	5.93
i-Concrete Slab, Synthetic Rubber Membrane Roof	1050	102.9	258.71	25.35	393.11	38.52
j-Steel Frame, Fibre Cement Sheet Roof	337	33	55.44	5.43	149.55	14.65
k-Steel Frame, Steel Sheet Roof (commercial)	401	39.3	145.65	14.27	230.20	22.56

Sources: 'Standard/Basic' column represents construction carbon emissions (embodied energy) from values given in Chapter Four; the 'Green Star' and 'This research' columns are the potential construction carbon emission (embodied energy) reductions as calculated in Appendix C (Tables A.C.119 – A.C.140).

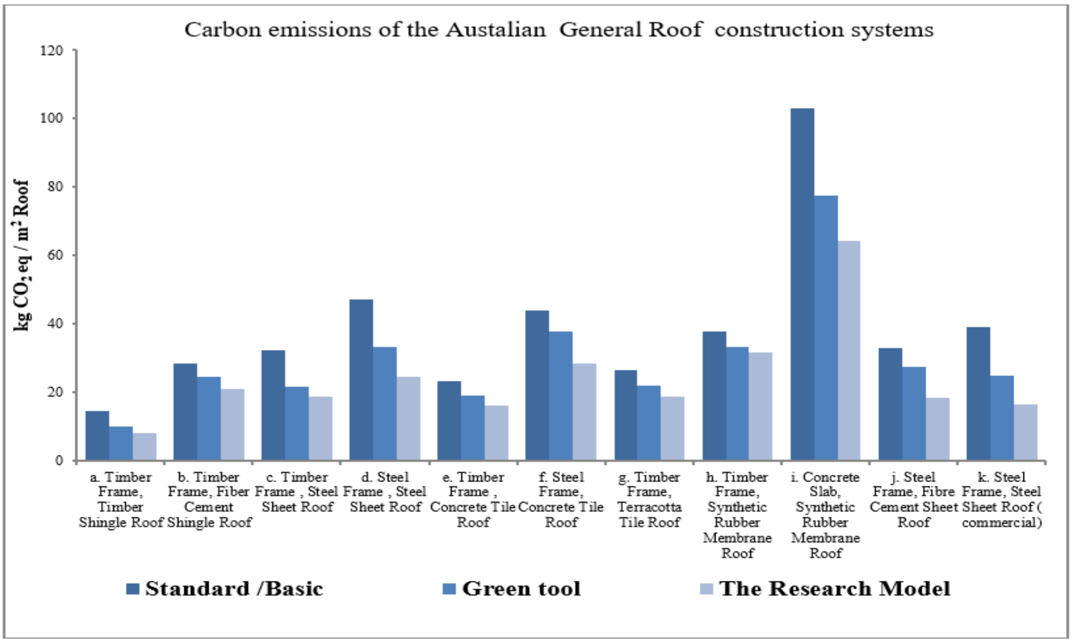
Table 7.23: Carbon emissions (embodied energy) **generated** in general Australian **roof** construction systems

General Australian roof construction systems	Standard /Basic			Green Star			This research	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²		Embodied Energy MJ/m²	Carbon Emissions Kg/m²		Embodied Energy MJ/m²	Carbon Emissions Kg/m²
a-Timber Frame, Timber Shingle Roof	151	14.8		102.55	10.04		82.43	8.08
b-Timber Frame, Fiber Cement Shingle Roof	291	28.5		250.15	24.51		216.9	21.25
c-Timber Frame, Steel Sheet Roof	330	32.3		220.53	21.61		192.68	18.88
d-Steel Frame, Steel Sheet Roof	483	47.3		339.75	33.29		250.71	24.56
e-Timber Frame, Concrete Tile Roof	240	23.5		194.84	19.09		165.90	16.25
f-Steel Frame, Concrete Tile Roof	450	44.1		385.68	37.79		291.89	28.60
g-Timber Frame, Terracotta Tile Roof	271	26.6		225.84	22.13		192.41	18.85
h-Timber Frame, Synthetic Rubber Membrane Roof	386	37.8		340.84	33.40		325.46	31.89
i-Concrete Slab, Synthetic Rubber Membrane Roof	1050	102.9		791.29	77.54		656.89	64.37
j-Steel Frame, Fibre Cement Sheet Roof	337	33		281.56	27.59		187.45	18.37
k-Steel Frame, Steel Sheet Roof (commercial)	401	39.3		255.35	25.02		170.80	16.73

Sources: 'Standard/Basic' column is from values given in Chapter Four; the 'Green Star' and 'This Research' columns are the generated construction carbon emissions (embodied energy) obtained from Table 7.24 (subtract reduction figures from standard/basic figures)

The bar graph in Figure 7.14 provides a comparative representation of the generated carbon emissions data for general Australian roof systems (as given in Table 7.23).

Figure 7.14: Bar graph of carbon emissions generated for general Australian roof construction systems (using data from Table 7.23)



Source: Generated carbon emissions using data from Table 7.23

Table 7.24 provides a percentage representation of the potential carbon emission reductions that can be achieved in general floor construction systems by application of the Green star and research model tools (using data from Table 7.22).

Table 7.24: Potential carbon emission **reductions** in general Australian **roof** construction systems expressed as percentages (using data from Table 7.22)

General Australian roof construction systems	**Green Star** Carbon emissions KgCo$_2$/m^{2}eq.	**This Research** Carbon emissions KgCo$_2$/m^{2}eq.
a-Timber Frame, Timber Shingle Roof	32.08%	45.41%
b-Timber Frame, Fiber Cement Shingle Roof	14.03%	25.46%
c-Timber Frame, Steel Sheet Roof	33.17%	41.61%
d-Steel Frame, Steel Sheet Roof	36.97%	48.09%
e-Timber Frame, Concrete Tile Roof	18.81%	30.87%
f-Steel Frame, Concrete Tile Roof	21.69%	42.55%
g-Timber Frame, Terracotta Tile Roof	16.66%	29.00%
h-Timber Frame, Synthetic Rubber Membrane	11.69%	15.69%
i-Concrete Slab, Synthetic Rubber Membrane	24.63%	37.43%
j-Steel Frame, Fibre Cement Sheet Roof	16.45%	44.37%
k-Steel Frame, Steel Sheet Roof (commercial)	36.32%	57.40%

Sources: Data from Table 7.22 expressed in percentage form. Yellow highlighting indicates reference to figures in the discussion in Section 7.4.4.

7.4.4 Analysis of data from general Australian floor, wall and roof systems

In respect to general Australian floor construction systems, the bar graph (Figure 7.12) of carbon emissions generated indicates that, following application of the research model to the floor systems, generated carbon emissions are consistently lower in comparison to standard building practice and use of the Green Star tool.

This trend is also seen when percentage carbon reductions are considered for floor systems as in Table 7.18. The potential carbon emission reductions achieved by application of the Green Star tool ranged from 15.56 to 57.55 per cent. In comparison, the potential carbon emission reductions achieved by application of the bioclimatic criteria of the research tool were higher for all floor systems, ranging from 33.37 to 57.55 per cent. Overall, the research model criteria clearly show the greater potential reduction in carbon emissions for Australian floor construction systems.

In respect to general Australian wall construction systems, the bar graph (Figure 7.13) of carbon emissions generated indicates again that the research model consistently produces the lowest emissions. This is confirmed in consideration of percentage emission reductions as shown in Table 7.21, where Green Star emission reductions range from 3.52 to 76.23 per cent, in comparison to application of the research model where the reductions range from 16.84 to 93.54 per cent, and again potential emission reductions are higher for all Australian wall construction systems.

Finally, in the case of general Australian roof construction systems, the bar graph (Figure 7.14) confirms that the carbon emissions generated after application of the research model tool are consistently lower than in the other scenarios (standard/basic building practice and the Green Star tool). This trend is confirmed in reference to the percentage emission reductions in Table 7.24. Reductions for use of the Green Star tool range from 11.69 to 36.97 per cent, in comparison to the research model tool where the range is from 15.60 to 57.40 per cent, and again potential emission reductions are higher for all Australian roof construction systems.

Overall, application of the research model criteria to an Australian floor, wall or roof construction system consistently produces the potential for the lowest carbon generation, and thus the highest reductions in carbon emissions when compared to standard building practice (standard/basic) or application of the Green Star tool. This is the case for all items considered within general Australian floor, wall and roof construction systems.

7.5 Summary

This chapter has presented and analysed the results of applying the research model's bioclimatic criteria, first, to elements of the floor, wall and roof construction systems of six selected case studies; and, second, to elements of general Australian floor, wall and roof construction systems. The results have been presented for all systems in numerical, graphical and percentage form, and compared to emissions expected in standard building systems, implemented building systems, and from application of the Australian Green Star rating tool.

Analysis of results from all construction systems clearly shows that appropriate application of the bioclimatic criteria of the research model will generally result in reduction of carbon emissions of around 50 to 65 per cent (Table 7.13) in the Case Studies, and 57 to 93 per cent (Tables 7.18, 7.21 and 7.24) in general Australian construction systems, levels which are consistently higher in achievement than current best practice or through use of a green rating tool.

CHAPTER EIGHT

CONCLUSIONS

BIOCLIMATIC DESIGN PRINCIPLES IN CONSTRUCTION

8.1 Overview

The Australian building sector is reported to be one of the largest contributors to Australian greenhouse gas emissions (McKinsey 2008), and thus has the greatest potential for a significant reduction of greenhouse gases as compared to other major emitting sectors (IPCC 2011). This is now of immediate importance given that the Australian Federal Government has agreed to reduce greenhouse gas emissions 26 to 28 per cent by 2030 (Hasham, Bourke & Cox 2015). The application of bioclimatic design principles within the building life cycle has been explored in this research as one way to achieve this.

This final chapter is divided into six sections. Section 8.1 provides the context for this chapter. Section 8.2 presents a discussion on the significance of this study. Section 8.3 details recommendations for the Australian construction sector following on from this research. Section 8.4 makes recommendations for further research. Section 8.5 discusses the limitations of this research project. Finally, Section 8.6 offers some concluding remarks and brings this thesis to a close.

8.2 Significance of this study

The use of green rating tools such as the Australian Green Star tool to assist in reduction of the carbon emissions from buildings is well known. However, from personal experience of using this tool, I can attest to the fact that the Green Star tool can be applied to only 5 to 10 per cent of a given building under limited conditions. This is because green tools do not assess and apply the range of criteria inherent in bioclimatic design principles and the research model. With the Green Star tool, it may thus not be possible to include evaluation of all the sustainability features present in a given construction project. The sustainability credits offered to the construction industry for use of a green tool rating system for a given project are also limited

The particular significance of this present research lies in the fact that the green tool developed for this project is based on generic bioclimatic sustainability criteria that can be applied to single cases or all areas of the construction industry and its activities. This research has produced a bioclimatic green tool that can be applied to reducing carbon emissions from any single building element in an Australian construction system independently of their building class or typology. Furthermore, the effectiveness of the developed model tool has been demonstrated in this research.

For whole construction systems, the maximum reductions achieved using the Green Star tool were from 17 to 32 per cent, as compared to the higher reductions achieved in the research model tool of 48 to 65 per cent (Table 7.13). When the research tool is applied to building elements of the floor, wall and roof of general Australian construction systems, reduction in carbon emissions ranged from 57 to 93 per cent (Tables 7.18, 7.21 and 7.24). However, a more significant finding is that application of the research tool to these elements of general construction systems consistently achieved significantly higher reductions in carbon emissions than in current building practice or through application of a currently-used green rating system (i.e. Green Star tool) to building elements (Tables 7.18, 7.21 and 7.24).

The significance of this study thus lies in the fact that it clearly demonstrates that consideration of bioclimatic principles in construction projects has potential to significantly reduce the environmental impact of the construction process. Reduction of construction carbon emissions is becoming of vital importance if an ecologically healthy environment based on a program of sustainability and sustainable development is to be achieved in Australia and elsewhere.

8.3 Recommendations for the Australian construction sector based on this research

Consideration of bioclimatic design principles in the construction industry must be of high priority in order to reduce carbon emissions resulting from the building construction process. Research needs to be funded and commenced on how these principles can best be implemented, as has been done in the United Kingdom (Allwood et al. 2012; UK Indemand 2014) and Germany (World Federation of Engineering Organizations 2011). It is also important to establish criteria that would allow for grant of credits where use of environmental assessment tools is incorporated into the building design process.

Reuse and recycling of construction and demolition materials also needs to be facilitated and mandated through legislation. Related to this, there also needs to be the creation and expansion of a warehouse of parts, reuse markets, and construction guidelines, as well as the expansion of deconstruction techniques, machinery and facilities (Bales 2008; Steel Construction Information 2014). This would increase the use of recycled construction materials, and reduce the impact of transportation. If such were established in the Australian context, this would significantly reduce embodied energy and carbon emissions in the building sector, and assist the Federal Government in their aim to reduce the total carbon emissions generated by Australian society.

8.4 Recommendations for further research

The green model developed for this research considers only the main elements of the buildings in the case studies and general Australian construction systems (i.e. floors, walls and roofs), and then only within the first three stages of the building lifecycle. Extension of this research to include calculation of embodied energies and potential carbon emission reductions for all building elements in construction (e.g. finishing, stairs, windows, doors) needs to be performed. Additionally, this future research should encompass the entire building lifecycle.

The use of 3D digital modelling in BIM (Eastman et al. 2011), with other software such as IMPACT (eToolLCD 2015) and Tally (EPD-Tally 2008), are able to collate and analyse data through applications such as AutoCAD or Revit (Eastman et al. 2011). Such applications have been used in environmental assessment, materials selection, and calculation of embodied energies and potential carbon emission reduction levels. Furthermore, such software can be used for sustainability assessment at any point during the building life cycle. Overall, use of such software facilitates a more integrated materials selection, design and construction process management that results in better quality and more sustainable buildings with lower carbon emissions, and even has potential to reduce the project duration (Drogemuller 2009; Jalaei & Jrade 2014).

Extension of this research can thus most easily be achieved through use of software tools such as these. This will remove the limitations of the current research model, and facilitate the application of bioclimatic design principles to any Australian construction project.

8.5 Limitations of this research

As noted, the model in this present study has been applied only to the main building elements in the first three stages of the building lifecycle. In the next stage of this research, Building Information Modelling (BIM) or other software will be used. This will allow for calculation of embodied energy and relevant construction carbon emissions throughout the building lifecycle, and for all elements of the building concerned. It will then be possible for the research model to be applied to any case study with any classification in any location in Australia.

The Process Energy Requirement (PER) method was used to calculate embodied energies in this research. An alternative calculation technique for embodied energies is the Input-Output method which is based on the sum of all energy inputs into a product system through all stages of the life cycle (Lawson 2006). However, calculations using the Input-Output method produce figures for embodied energy that are two to three times higher than the PER method. Such discrepancies will be solved through the use of Building Information Modelling and other software.

Typical embodied energy units are measured using MJ/kg (megajoules of energy needed to make a kilogram of product), and these have to be converted to equivalent kilograms of carbon emissions. However, such conversion is not straightforward because different types of energy (oil, wind, solar, etc.) emit different amounts of carbon dioxide, thus the actual amount of carbon dioxide emitted when a product is made will depend on the type of energy used in the manufacturing process. To facilitate this conversion, the standard Australian Government equation (1 MJ = 0.098 $kgCO_2$) has been used to convert embodied energy to equivalent carbon emissions.

This study proposes geopolymer cement as a replacement for Portland cement for structural and non-structural building purposes. Geopolymer cement was chosen as the cement for reference in this thesis rather than other green cements for two reasons. First, while there are other options available, geopolymer cement is currently by far the most common and widely used green cement in Australian construction, and its use is increasing. Second, geopolymer cement emerged in the literature review as the most appropriate green cement to consider from the viewpoint of reducing carbon emissions of construction.

In respect to this, when used as a replacement for Portland cement, geopolymer cement produces a range of potentially high reductions in carbon emissions (75 to 90 per cent). This is because GC can be slag-based, rock-based or fly-ash-based. Geopolymer cements made from fly ash or granulated blast furnace slag require less sodium silicate solution in order to be activated. They consequently have a lower environmental impact than geopolymer concrete made from metakaolin rock (i.e. rock-based geopolymer cement). However, the type of geopolymer cement that might be used to replace Portland cement in building construction ultimately depends on the particular type available in the area concerned (Habert, d'Espinose de Lacaillerie & Roussel 2011). In turn, this will affect the outcomes where the research model is used, and this must be taken into account when the research model is applied.

8.6 Concluding Remarks

Our world is changing, and our construction industry needs to adapt to these changes. The Australian building sector has the largest potential for achieving a significant reduction in greenhouse gas emissions. This could be through the simple application of bioclimatic design and construction principles.

The outcomes of this research demonstrate that use of bioclimatic criteria can achieve reductions in carbon emissions from 48 to 65 per cent for whole building systems (Table 7.13), and from 57 to 93 per cent when applied to building elements of general Australian construction systems (Tables, 7.18, 7.21 and 7.24). However, a more significant finding is that application of the research tool to elements of general Australian construction systems consistently achieved significantly higher reductions in carbon emissions than in current building practice, or through application of a currently-used green rating system (i.e. Green Star tool) to building elements. The future of the green construction industry should thus include consideration of bioclimatic design principles.

The UK government has funded the UK-Indemand plan to achieve an 80 per cent reduction in construction carbon emissions by 2050. This is considered as an achievable target providing that future design and construction of buildings take into account bioclimatic principles and criteria (Allwood et al. 2012). If the Australian construction sector is to follow this lead, then some form of Australian Indemand scheme has to be funded and established. The outcomes of this research based on bioclimatic design support this proposal. Such a scheme would enable the government to achieve significant reductions in greenhouse gas emissions, and thus to reduce the impact of the building sector on the Australian environment.

Current green tool rating systems are voluntary, do not apply the range of bioclimatic criteria inherent in the research model, and can be used only in 5 to 10 per cent of buildings. Full development of the research model will allow for its application to all building elements throughout the building lifecycle, and to any construction project of any classification in any location in Australia.

One of the main objectives of this study is to assist the Australian Federal Government to meet the agreed targets from the 2015 Paris conference. Reducing the carbon emissions of the building sector is one of the most cost-effective ways of doing this. The application of green criteria and bioclimatic principles in building design and construction is currently not mandatory for the Australian construction sector, and thus sustainable practice is not routinely followed in this country. This must change if the Australian Federal Government are serious about meeting their carbon emission reduction targets of 26 to 28 per cent by 2030.

In concluding this thesis, I would like to mention a quote attributed to the famous physicist, Albert Einstein:

> *Problems cannot be solved at the same level of awareness that created them* (Albert Einstein)

For the last century, humankind has had an increasingly negative impact on the resources and environment of this planet through unsustainable population growth and development, seemingly without great awareness of the problems we are now facing. Urgent measures are now required to address these environmental and other problems.

Awareness of bioclimatic principles in building design to reduce carbon emissions may provide a small step along the way to achieving sustainable construction as part of the solution to our global problems.

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PAPERS AND BOOK CHAPTERS FROM THIS RESEARCH

Papers published as a consequence of this reseach have received much attention – for example, Sattary and Thorpe (2016) has received the highest read rating for the University of Southern Queensland (USQ) papers on the ResearchGate website.

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Sustainable Construction

APPENDICES

Potential Carbon Emissions Reduction (PCER) in Australian Construction Systems through the Use of Bioclimatic Design Principles

A Thesis submitted by

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B.Sc. (Architectural Engineering)
M.Sc. (Architectural Engineering)

For the award of

Doctor of Philosophy

2017

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APPENDIX A

DATA RELATING TO CHAPTERS TWO, THREE AND FOUR

In respect to Table A.A.1 Embodied energy figures for the materials of Canadian construction systems have been studied over several decades by researchers interested in the relationship between building materials, construction processes, and their environmental impact. These figures include the embodied energy of building materials based on units of weight (MJ/kg) and volume (MJ/m^3) (Canadian Architects 2015).

Table A.A.1: Embodied energy of common Canadian building materials)

The Canadian common Building Materials	Standard/Basic Embodied Energy	
	MJ/kg	MJ/m^3
Aggregate	0.10	150
Straw bale	0.24	31
Soil-cement	0.42	819
Stone (local)	0.79	2030
Concrete block	0.94	2350
Concrete (30 Mpa)	1.3	3180
Concrete precast	2.0	2780
Lumber	2.5	1380
Brick	2.5	5170
Cellulose insulation	3.3	112
Gypsum wallboard	6.1	5890
Particle board	8.0	4400
Aluminium (recycled)	8.1	21870
Steel (recycled)	8.9	37210
Shingles (asphalt)	9.0	4930
Plywood	10.4	5720
Mineral wool insulation	14.6	139
Glass	15.9	37550
Fiberglass insulation	30.3	970
Steel	32.0	251200
Zinc	51.0	371280
Brass	62.0	519560
PVC	70.0	93620
Copper	70.6	631164
Paint	93.3	117500
Linoleum	116	150930
Polystyrene insulation	117	3770
Carpet (synthetic)	148	84900
Aluminium	227	515700

Source: Canadian Architects (2015)

Table A.A.2: Embodied energy and carbon emissions of common Australian building materials

Australian Building Materials	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions per Kg/MJ
Kiln dried sawn softwood	3.4	0.333
Kiln dried sawn hardwood	2.0	0.196
Air dried sawn hardwood	0.5	0.049
Hardboard	24.2	2.372
Particleboard	8.0	0.784
MDF	11.3	1.107
Plywood	10.4	1.019
Glue-laminated timber	11.0	1.078
Laminated veneer lumber	11.0	1.078
Plastics – general	90.0	8.820
PVC	80.0	7.840
Synthetic rubber	110.0	10.780
Acrylic paint	61.5	6.027
Stabilized earth	0.7	0.069
Imported dimension granite	13.9	1.362
Local dimension granite	5.9	0.578
Gypsum plaster	2.9	0.284
Plasterboard	4.4	0.431
Fiber cement	4.8	0.470
Cement	5.6, 5.4[1]	0.549, 0.82[1]
In situ concrete	1.9	0.186
Precast steam-cured concrete	2.0	0.196
Precast tilt-up concrete	1.9	0.186
Clay bricks	2.5	0.245
Concrete blocks	1.5	0.147
AAC	3.6	0.353
Glass	12.7, 12.8[1]	1.245, 1.5[1]
Aluminium	170	16.660
Copper	100	9.800
Galvanized steel	38	3.724
Steel	34[1]	AU 3.33, AU 2[1]

Source: Superscript data – 1: from Lawson (1996); remaining figures are from Lawson (2006); and Sattary and Cole (2012)

Table A.A.3: Embodied energy in common building materials

Common Building Materials	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions per Kg/MJ
Aggregate	0.083	0.0048
Concrete (1:1.5:3)	1.11	0.159
Bricks (common)	3	0.24
Concrete block (Medium density)	0.67	0.073
Aerated block	3.5	0.3
Limestone block	0.85	
Stone	-	0.1[1]
Marble	2	0.116
Cement mortar (1:3)	1.33	0.208
Cement	-	1.0[1]
Steel (general, av. recycled content)	20.1	1.37
Steel	-	2.7
Stainless steel	56.7	6.15
Timber (general, excludes sequestration)	8.5	0.46
Timber		0.30[1]
Glue laminated timber	12	0.87
Cellulose insulation (loose fill)	0.94–3.3	
Cork insulation	26	
Glass fibre insulation (glass wool)	28	1.35
Flax insulation	39.5	1.7
Rockwool (slab)	16.8	1.05
Expanded Polystyrene insulation	88.6	2.55
Polyurethane insulation (rigid foam)	101.5	3.48
Plastic	-	1.9[1]
Wool (recycled) insulation	20.9	
Straw bale	0.91	0.1[1]
Mineral fibre roofing tile	37	2.7
Slate	0.1–1.0	0.006–0.058
Clay tile	6.5	0.45
Aluminium (general & incl 33% recycled)	155	8.24
Aluminium	-	11.5[1]
Bitumen (general)	51	0.38–0.43
Medium-density fibreboard	11	0.72
Plywood	15	1.07
Plasterboard	6.75	0.38
Gypsum plaster	1.8	0.12
Glass	15	0.85
Fiber glass	-	8.1[1]
PVC (general)	77.2	2.41
Vinyl flooring	65.64	2.92
Terrazzo tiles	1.4	0.12
Ceramic tiles	12	0.74
Wool carpet	106	5.53
Wallpaper	36.4	1.93
Vitrified clay pipe (DN 500)	7.9	0.52
Iron (general)	25	1.91
Copper (average incl. 37% recycled)	42	2.6
Brass	-	4.5[1]
Lead (incl 61% recycled)	25.21	1.57
Lead	-	3.2[1]
Zinc	-	2.9[1]
Ceramic sanitary ware	29	1.51
Paint - Water-borne	59	2.12
Paint - Solvent-borne	97	3.13
Photovoltaic (PV) Cells Type	**Energy MJ per m^2**	**Carbon kg CO_2 per m^2**
Monocrystalline (average)	4750	242
Polycrystalline (average)	4070	208
Thin film (average)	1305	67

Source: Superscript data – 1: Wilson (2015); remaining figures are from the Inventory of Carbon & Energy (2011); and the Institution of Civil Engineers (Bull 2012).

Table A.A.4: Embodied Energy and carbon emission of building materials (AU, UK, US, CA)

Building Materials in AU, UK and CA	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions per Kg/MJ	Standard/Basic Embodied Energy MJ/kg	Standard/ Basic Carbon Emissions per Kg/MJ
	From Raw materials, Virgin natural resources		From recycled materials and recycled contents	
Aggregate	AU--, CA 0.1 UK 0.083	CA 0.009[2] UK 0.0048[1]		
Kiln dried sawn softwood	3.4	0.333		
Kiln dried sawn hardwood	2.0	0.196		
Air dried sawn hardwood	0.5	0.049		
Hardboard	24.2	2.372		
Paper	36.4		23.4	
Particleboard	8.0	0.784		
MDF	11.3	1.107		
Plywood	10.4	1.019		
Glue-laminated timber	11.0	1.078		
Laminated veneer lumbe	11.0	1.078		
PVC	US 65, AU 80.0	7.840	US 29, AU --	
Synthetic rubber	110.0	10.780		
Acrylic paint	61.5	6.027		
Stabilized earth	0.7	0.069		
Imported dimension granite	13.9	1.362		
Local dimension granite	5.9	0.578		
Gypsum plaster	2.9	0.284		
Plasterboard	4.4	0.431		
Fiber cement	4.8*	0.470		
Cement	5.6	0.549		
In situ concrete	1.9	0.186		
Precast steam-cured concrete	2.0	0.196		
Precast tilt-up concrete	1.9	0.186		
Clay bricks	AU 2.5, UK 3	AU 0.245, UK 0.24		
Concrete block	AU 1.5, UK 0.67	AU 0.147, UK 0.073		
AAC	3.6	0.353		
Glass	AU12.7, UK15, AU 15.6[3]	AU 1.245, UK 0.85	12.5[3]	
Plastics – general	AU 90, AU 98[3]	8.820	AU 12, AU12[3]	
Polyethylene	US 98, AU 103		US 56, AU -	
Polyester	53.7			
Polypropylene expanded	117			
Aluminium	US 196, AU 170, AU 191[3]	AU 16.660, UK 11.5[4]	US 27, AU 8.1, AU8.1[3] CA 8.1, UK 155	UK8.25 (33%recycled)
Copper	AU100	AU9.800	UK 42 (average incl. 37% recycled)	UK 2.6 (average incl. 37% recycled)
Steel	AU 32[3], US40, CA32	UK2.7[4]	AU 10.1[3], US 18, CA8.9	CA0.872
Steel (general - average recycled content)	AU 32[3], US40, CA32		UK 20.7	UK 1.37
Steel (section - average recycled content)	AU 32[3], US40, CA32		UK 21.5	UK 1.42
Steel (pipe-average recycled content)	AU 32[3], US40, CA32		UK 19.8	UK 1.37
Galvanized Steel	AU38	3.724	AU 10.1	
Stainless Steel	UK 56.7	UK 6.15		

Sources: Superscript data – 1: Greenspec (2015); 2: Canadian Architects (2015); 3: O'Halloran, Fisher and Rab (2008); 4: Institution of Civil Engineers (Bull 2012).
Remaining Australian data from Lawson (1996; 2006), and O'Halloran, Fisher and Rab (2008); US data from Jong and Rigdon (1998); and Canadian data from Canadian Architects (2015).

Table A.A.5: LEED Points for concrete roof tiles

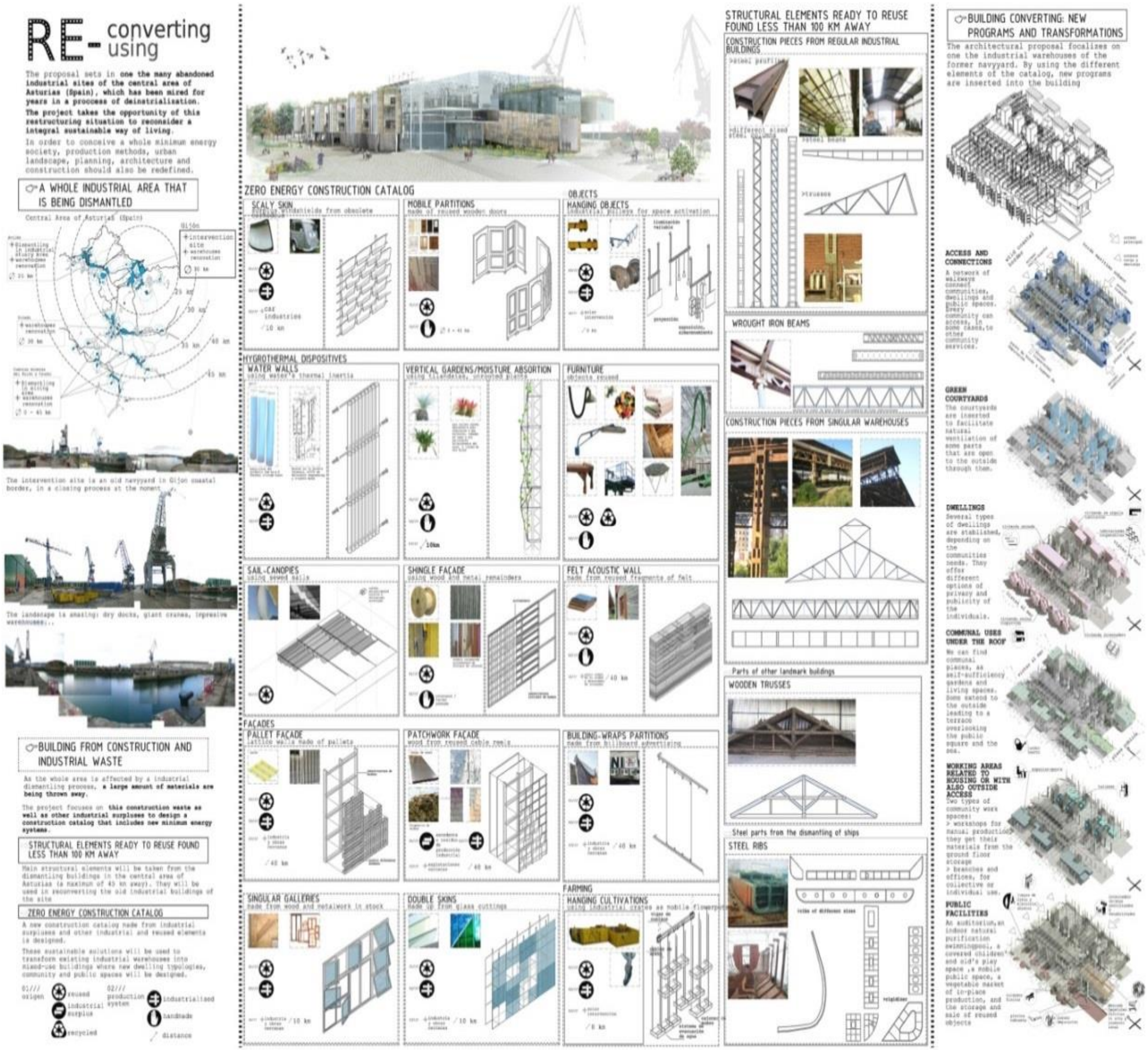
LEED NC Category	US Green Building Council Requirements	Concrete Roof Tile	Points
Local Heat Island Effects LEED for Homes			
SS 3	Material with a solar reflectance (SRI) > 29	Roof Tile offers product with SRI > 29	1
Energy Performance			
EA 1	Improve the overall energy performance of a home by meeting or exceeding the performance of an ENERGY STAR labelled home	Roof Tiles with SRI > 29 help to reduce cooling loads in homes	Up to 4
Environmentally Preferable Products			
MR 2	Local production. Use products that were extracted, processed and manufactured within 500 miles of the home	Roof tile manufacturers can provide information to identify production facilities within 500 miles of a project.	1/2
Environmentally Preferable Products			

Source: Hanson Roof Tiles (LEED 2014)

Table A.A.5: LEED credits for reuse of roof tiles

Use recycled roof tiles, 92 MJ/m^2 x 13% (LEED 2014) = 11.96 MJ/m^2 Use recycled roof tiles (Herbudiman & Saptaji 2013) from 45% recycled content Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg (Greenspec 2015) x (44 concrete – 6.16 cement) Kg/m^2 (Lawson 1996, p.134) x 45% = 0.083 x 37.84 kg/m2 x 50% (Herbudiman & Saptaji 2014) =1.57 MJ/m^2 Therefore, total released carbon from concrete roof tile (Lawson 1996, p. 127) is 240 MJ/m^2 x 0.098 kg CO_2 = 23.52 Kg CO_2/m^2 The reduced carbon emission from use of recycled concrete roofs: 1.57 MJ/m^2 x 0.098 kg CO_2 = 0.15 Kg CO_2/m^2

Figure A.A.1: Reuse strategy: Catalogue of construction systems made of reused materials



Source: Holcim (2011).

Table A.A.6: Replacement 40% Portland cement with geopolymer cement: carbon emissions for a one square metre of 125 mm elevated concrete floor

300kg/m^2 concrete (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 42 kg replaced cement/ m^2 in concrete; therefore the reduced embodied energy will be:

42 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 40% = 94.08 MJ/ m^2

Generated carbon emission 1 MJ = 0.098 kg CO_2 (CSIRO 2014)

Therefore, the total reduced carbon emission of 125 mm elevated concrete floor will be: 94.08MJ/m^2 x 0.098 kg CO_2 = 9.21 Kg CO_2 /m^2

Total carbon emission of 125 mm elevated concrete floor will be: 497 MJ/m^2 x 0.098 kg CO_2 = 48.7 Kg CO_2 /m^2.

Table A.A.7: Full replacement of Portland cement with geopolymer cement: carbon emissions for one square metre of 125 mm elevated concrete floor

300kg/m^2 concrete (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 42 kg replaced cement/ m^2 in concrete; therefore the reduced embodied energy will be:

42 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) = 235.2 MJ/ m^2

Generated carbon emission 1 MJ = 0.098 kg CO_2 (CSIRO 2014)

Therefore, total reduced carbon emission of 125 mm elevated concrete will be: 235.2MJ/m^2 x 0.098 kg CO_2 = 23.04 Kg CO_2 /m^2

The total carbon emission of 125 mm elevated concrete floor will be: 497 MJ/m^2 x 0.098 kg CO_2 = 48.7 KgCo$_2$/m^2.

Table A.A.8: Full replacement of Portland cement with geopolymer concrete: carbon emissions for a one square metre 200 mm concrete slab on ground floor

381 kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 97% = 51.73 kg replaced cement/ m^2 in concrete
51.73 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p.13) = 289.74 MJ/ m^2 Reduced Embodied Energy
289.74 MJ/ m^2 Reduced Embodied Energy
594 MJ/ m^2 Total Embodied Energy of the 200mm Concrete Slab (Lawson 1996, p. 125)
Embodied energy 1 MJ = 0.098 kg CO_2) Generated carbon emission (CSIRO 2014)
The total carbon emission of 200 mm concrete slab floor will be: 594MJ/m^2 x 0.098 kg CO_2 = 58.12 Kg CO_2/m^2
Therefore, total reduced carbon emission of 200 mm concrete slab floor will be: 289.74 MJ/m^2 x 0.098 kg CO_2 = 28.39 Kg CO_2/m^2 – shows 48.84% reduction in the generated carbon emissions of 200mm concrete slab on ground floor

Table A.A.9: Reduced carbon emissions in concrete block with full replacement by geopolymer cement

Geopolymer based cement = 89Kgs/tonne (CBA 2013) / 1000 x 275 = 24.47 Kg/ m^2 reduced Portland cement in concrete block
Reduced cement 24.47 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) = 137.03 MJ/ m^2 reduced embodied energy
Embodied energy 1 MJ = 0.098 kg CO_2 Generated carbon emission (CSIRO 2014)
Embodied Energy of the concrete Block with Portland cement 385 MJ/m^2
Reduced carbon emissions 137.03 MJ/ m^2
Generated carbon emissions of the concrete block with Portland cement is 385 MJ/m^2 (Lawson 1996, p. 129) x 0.098 kg CO_2 = 37.73 Kgs CO_2/m^2
Reduced carbon emissions by replacing Portland cement with geopolymer cement is 137.03 MJ/ m^2 x 0.098 kg CO_2 = 14.45 Kgs CO_2/m^2
That shows 38.29 per cent reduction in carbon emissions.

Table A.A.10: Reduced transportation emissions for each square metre of 200 mm concrete slab from recycled aggregate

Reuse aggregate (275 concrete – 24.47 cement) kg.m^2 /1000 T/m^2 x 100 km x 4.5 – {(0.6 +0.25) / 2} MJtonne/km (Lawson 1996, p. 12) = 102.09 MJ/ m^2

Generated carbon emission 1 MJ = 0.098 kg CO_2 (CSIRO 2014)

Reduced carbon emission is: 102.09 MJ/ m^2 x 0.098 kg CO_2 = 10.00 Kgs CO_2/m^2

The Standard/Basic carbon emission by truck is:

Reuse aggregate (275 concrete – 24.47 cement) kg/m^2 /1000 T/m^2 x 100 km x 4.5 MJ/ton/km (Lawson p. 12**)** = 112.73 MJ/ m^2

139.01 MJ/ m^2 x 0.098 kg CO_2 = 11.04 Kgs CO_2/m^2

Table A.A.11: Emission reduction in transportation by decreasing steel use in design (London Olympics stadium roof, Case Study 5)

9.33 kg/m^2 steel (Lawson 1996, p. 135) /1000 T/m^2 x 100 km x 4.5 MJtonne/km (Lawson 1996, p. 12) x 90% = 3.77 MJ/ m^2 decreased embodied Energy

Generated carbon emission 1 MJ = 0.098 kg CO_2 (CSIRO 2014)

3.77 MJ/ m^2 x 0.098 kg CO_2 = 0.37 Kgs CO_2/m^2

Embodied Energy of the roof is 282 MJ/ m^2 (Lawson 1996, p. 129)

Generated carbon emissions from the roof is 401 MJ/ m^2 x 0.098 kg CO_2 = 39.3 Kgs CO_2/m^2

Table A.A.12: Reduced carbon emissions in transportation from reuse of one square metre of 200 mm concrete slab floor's aggregates (Case Study 5)

Reduced embodied energy in transportation

(297 + 5.148 + 84) = 386.14 kg/m^2

386.14 kg/m^2 /1000 T/m^2 x 100 km x {4.5 – (0.6 +0.25) /2} MJ/ton/km (Lawson 1996, p. 12**)** = 125.87 MJ/ m^2

Generated carbon emission 1 MJ = 0.098 kg CO_2 (CSIRO 2014)

The reduced carbon emission is:

125.87 MJ/ m^2 x 0.098 kg CO_2 = 12.33 Kgs CO_2/m^2

The Standard/Basic carbon emission by truck is:

386.14 kg/m^2 /1000 T/m^2 x 100 km x 4.5 MJ/ton/km (Lawson 1996, p. 12**)** = 139.01 MJ/ m^2

139.01 MJ/ m^2 x 0.098 kg CO_2 = 13.62 Kgs CO_2/m^2

Table A.A.13: Reduced carbon emissions in transportation (carried by ship or rail) from reuse of one square metre of concrete block wall materials

Reduced embodied energy in transportation:
Reuse aggregate (275 concrete – 24.47 cement) kg.m^2 /1000 T/m^2 x 100 km x 4.5 – {(0.6 +0.25) / 2} MJtonne/km (Lawson 1996, p. 12) = 102.09 MJ/ m^2
Generated carbon emission 1 MJ = 0.098 kg CO_2 (CSIRO 2014)
Reduced carbon emission is: 102.09 MJ/ m^2 x 0.098 kg CO_2 = 10.00 Kgs CO_2/m^2
The Standard/Basic carbon emission by truck is:
Reuse aggregate (275 concrete – 24.47 cement) kg/m^2 /1000 T/m^2 x 100 km x 4.5 MJ/ton/km (Lawson 1996, p. 12**)** = 112.73 MJ/ m^2
139.01 MJ/ m^2 x 0.098 kg CO_2 = 11.04 Kgs CO_2/m^2

APPENDIX B

DATA RELATING TO CHAPTER FIVE

Table A.B.1: Technical guide – Potential embodied energy reductions in building life cycle

Building Life Cycle Stages	Stage I, II	Stage III	Stage IV	Stage V
	Pre-Construction	Construction	Post-Construction	Demolition
Bioclimatic criteria	Produce, reprocess, assemble and re-assemble	Construct, retrofit and reuse	Repair, maintain, refurbish and retrofit	Demolish, deconstruct and recycle
Reduce, save and replace energy use in **extraction and Production of Building materials**	**Reduce**, **save** and **replace** energy use in building by using renewable materials - Use organic materials - Reprocess materials and elements - Use recycled materials	**Reduce**, **save** and **replace** energy use in buildings by: - Reusing building materials - Using organic materials - Retreating materials - Repairing materials - Using recycled materials - Using materials with recycled content - Recycling waste materials	**Reduce**, **save** and **replace** energy use in building by: - Reusing building materials - Reconditioning buildings - Retrofitting and repairing (reusing, retreating, repairing, recycling materials) - Recycling construction waste	- **Reduce**, **save** and **replace** energy use in building by using easily-demolished systems - Using deconstructible systems - Use fully recyclable materials
Reduce, save and replace energy use in **Implementation**	- **Save** and **reduce** energy use in production processes - **Replaced** renewable energy in production processes	- **Save** and **reduce** energy use in construction processes, reusing ... - **Replaced** renewable energy in production processes, reusing ...	- **Save** and **reduce** energy use in repair, maintenance, refurbishment, retrofitting ... **- Replace** renewable energy in repair, maintenance, refurbishment and retrofitting ...	- **Save** and **reduce** energy use in demolishing, deconstructing and recycling ... - **Replace** renewable energy in demolishing, deconstructing and recycling...
Reduce, save and replace energy use in **Transportation**	- **Save** and **reduce** energy use in transportation of materials and elements - **Replace** renewable energy in transportation of materials and elements	- **Save** and **reduce** energy use in transportation of construction processes by using locally resourced materials, local professionals - **Replace** renewable energy in transportation by using materials carried with renewable energy	- **Save** and **reduce** energy use in transportation of repair, maintenance, refurbishment and retrofitting … **- Replace** renewable energy in transportation for repair, maintenance, refurbishment and retrofitting	- **Save** and **reduce** energy use in transportation for demolishing, deconstructing and recycling - **Replace** renewable energy in transportation for demolishing, deconstructing and recycling

Table A.B.2: Measurable indicators – Potential embodied energy that can be saved during building lifecycle

Building Life Cycle Stages	Stage I, II	Stage III	Stage IV	Stage V
	Pre-Construction	Construction	Post-Construction	Demolition
Bioclimatic criteria	Produce, reprocess, assemble and reassemble	Construct, retrofit and reuse	Repair, maintain, refurbish and retrofit	Demolish, recycle and deconstruct
Measurable energy that can be reduced and saved in **extraction and Production of Building materials**	- Saved and reduced embodied energy by using recycled, reprocessed, reassembled components, materials and elements	Saved and reduced embodied energy by: - Reusing buildings - Reusing materials and elements - Retreating & repairing materials - Using recycled material - Using material with recycled content - Using fully recycled material - Using recycled materials from waste	Saved and reduced embodied energy by: - Reusing buildings - Reusing material - Reconditioning, repairing and retrofitting (reusing, retreat, repair, recycled material)	Saved and reduced embodied energy by: - Using de-constructible elements and building materials - Using recyclable materials
Measurable energy that can be replaced and saved in Implementation	- Saved and reduced energy use in production processes - Replaced renewable energy in production processes	Saved and reduced energy use in construction processes by; - Reusing building, spaces, elements, materials - Replaced renewable energy in construction processes	Saved and reduced energy use in repair, maintenance, refurbishment and retrofitting processes - Replaced renewable energy in repair, maintenance	- Saved and reduced energy use in demolition processes - Replaced renewable energy in demolition processes
Measurable energy that can be replaced and saved in Transportation	- Saved and reduced energy use in transportation, and production processes - Replaced renewable energy in transportation of materials	- Saved and reduced energy use in transportation and construction processes - Reused buildings, spaces, elements, materials - Replaced renewable energy in transportation and construction processes - Reused buildings, spaces, elements, materials	- Saved and reduced energy use in transportation of production processes - Reused building, spaces, elements, materials - Replaced renewable energy in transportation	- Saved and reduced energy use in transportation for demolition processes - Replaced renewable energy in transportation

Table A.B.3: Credits in LEED

Credit 1 - Building Reuse
The intent of this credit is to extend the life cycle of existing building stock, conserve resources, retain cultural resources, reduce waste and reduce the environmental impacts of new buildings.
Credit 1.1 awards one point for 75 per cent reuse of existing walls, floors and roof. Credit 1.2 gives one additional point for maintaining 100 per cent of the existing walls, floors and roof.
Changes proposed for LEED version 2.2 lower these thresholds to 40 per cent and 80 percent, respectively, making it easier to qualify.
Credit 1.3 awards one additional point for the reuse of 50% of interior non-structural elements. Non-structural masonry walls and floors can contribute to this point.

Credit 2 - Construction Waste Management
The intent of this credit is to divert construction, demolition and land clearing debris from landfill disposal. Scraps and broken pieces of concrete masonry can be crushed and used for aggregate or fill. Clay brick scraps can be crushed and used for landscaping as brick chips. Intact, unused masonry units can be saved to use on another project, or donated to Habitat for Humanity or other charitable organizations. One point is awarded for the diversion of 50 per cent of the construction, demolition and land clearing waste (Credit 2.1). One additional point is awarded for diverting 75 per cent (Credit 2.2). Calculations can be done on a weight or volume basis.

Credit 3 - Resource Reuse
This credit is intended for the reuse of salvaged materials and products to reduce the demand for virgin products. Materials salvaged on site do not apply to this credit, but do count toward Credit 1 — Building Reuse. Masonry materials such as brick can be salvaged, but the Brick Industry Association warns against their use. Used brick may not meet the requirements of present-day specifications and may not bond properly. Paver brick that is salvaged and used for interior applications on a new building meet the intent of this credit. Up to two points can be earned for the use of salvaged building materials for 5 and 10 per cent of building materials (Credits 3.1 and 3.2).

Credit 4 -Recycled Content
This credit is intended to increase demand for building products that incorporate recycled content materials, therefore reducing the impacts resulting from extraction and processing of new and virgin materials. This credit award up to two points for using building products that incorporate recycled content materials. Because of the inert nature of masonry products, they are ideal candidates for incorporating recycled materials. The requirement for one point is that materials with the sum of post-consumer recycled content plus half the post-industrial content constitutes at least 5 per cent of the total value of materials in the project (Credit 4.1). If the sum of post-consumer recycled content plus half the post-industrial content equals 10% or more,

one additional point is awarded (Credit 4.2).
Concrete masonry units often incorporate recycled materials. According to the NCMA, supplementary cementitious materials such as fly ash, silica fume and slag cement are considered post-industrial materials. Concrete masonry that incorporates recycled concrete masonry, glass, slag or other recycled materials such as aggregate qualify as post-consumer.

Clay brick often incorporates recycled brick ground and used as grog (i.e. crushed unglazed pottery or brick used as an additive in plaster or clay). If reclaimed from a job site, this material can qualify as post-consumer recycled content. Some manufacturers use bottom ash, a post-industrial waste, for 10 to 12 per cent (by weight) of the clay body. Other post-industrial materials used include fly ash and even sludge. Because of the inert properties of brick, even contaminated soil and sawdust is used. One company uses waste from a nearby ceramic white ware manufacturer as grog.

Mortar may contain recycled materials such as fly ash. Steel reinforcing bars used in reinforced masonry may contain post-consumer or post-industrial materials.

Credit 5 - Regional Materials

This credit encourages the use of building materials that are extracted and manufactured within the region, thereby supporting the regional economy and reducing the environmental impacts resulting from transportation. Masonry products can contribute up to one point when 20 per cent of the building materials and products are manufactured within a 500-mile radius of the project site (Credit 5.1). One additional point is earned if the regionally manufactured materials use a minimum of 50 per cent of building materials that are extracted, harvested or recovered within 500 miles of the project site (Credit 5.2). Changes to the specifics of this credit are proposed for LEED 2.2 (Subasic 2016).

Sample of the research model developed for assessment of potential construction carbon emissions reduction

The research model developed reviews six case studies from Australia and the United Kingdom. The selected case studies and their construction systems represent the general construction systems used in Australia as identified by Lawson (1996). These can include any project from any classification (residential, public, and commercial). For example, the first three case studies are taken from a paper written by Lawson (1996) – all details and information for these are provided, together with embodied energy and implemented embodied energy (Lawson 1996). The fourth and sixth case studies focus on buildings recently completed on the Springfield campus of the University of Southern Queensland (USQ). All drawings and detailed information were accessible. The Olympic Velodrome Building from the London Olympics in 2012 is the focus of the fifth case study – these Olympics achieved high sustainability levels from a range of different environmental tools (e.g. CEEQUAL, ISCA, and BREEAM).

Table A.B.1: Case Study <number>

Figure <number>
Location:
Floor construction system
Wall construction system
Roof construction system
Principal architects

Bioclimatic Conditions	
Reuse, recycle, materials resources, suppliers and transport	
Recycled aggregates in material production	
Steel from recycled contents	
Reduce material use in design	
Reuse construction materials	
Geopolymer, fly ash and cement substitute	
Transportation reduction by reuse, recycle sustainable transportation mode	
Material resources and suppliers, Global Building Resources	

Table A.B.2: Potential carbon emission (embodied energy) reductions in <name> ground floor construction system

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	Reused recycled aggregate for concrete Steel from average recycled content
	Green Star Reused recycled aggregate for concrete Steel from average recycled content
Implementation	Decreased and Replaced energy in process Replaced cement
	Green Star Decreased and Replaced energy in process Replaced cement
Transportation	Decreased transportation of waste by reusing and recycling
	Green Star
	Decreased transportation by localizing the suppliers

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**			**---MJ/m²**
Measurable energy to reduce in **Implementation**			
Measurable energy to reduce in **Transportation**			
Total Floor	**--- MJ/m²**	**--- MJ/m²**	**--- MJ/** m²
	--- MJ/m²		

Table. A.B.3: Green Star, potential carbon emission (embodied energy) reductions in <name> ground floor construction system. Case Study <number>. Based on Green Star Technical Manual.

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	**--- MJ/m²**	**--- MJ/m²**	**--- MJ/m²**
Measurable energy to reduce in **Implementation**	**--- MJ/m²**	**--- MJ/m²**	
Measurable energy to reduce in **Transportation**	**--- MJ/ m²**	**--- MJ/ m²**	
Green Star, Total Floor	**---- MJ/m²**	**--- MJ/m²**	**--- MJ/ m²**
	--- MJ/m²		

Table A.B.4: Potential carbon emission (embodied energy) reduction in construction stages of <name> upper floor construction system

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	Reused recycled aggregate for concrete Steel from average recycled content
	Green Star Reused recycled aggregate for concrete Steel from average recycled content
Implementation	Decreased and Replaced energy in process Replaced cement
	Green Star
Transportation	Decreased transportation of waste by reusing and recycling
	Green Star
	Decreased transportation by localizing the suppliers

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) reduction		
Measurable energy to reduce in **Building materials and elements**	**--- MJ/m^2**	**--- MJ/m^2**	**--- MJ/m^2**
Measurable energy to reduce in **Implementation**	**--- MJ/m^2**	**--- MJ/m^2**	
Measurable energy to reduce in **Transportation**	**--- MJ/ m^2**	**--- MJ/ m^2**	
Total Floor	**--- MJ/m^2**	**--- MJ/m^2**	**--- MJ/m^2**
	--- MJ/m^2		

Table A.B.5: Green Star, potential carbon emission (embodied energy) reduction in <name> upper floor construction system. Case Study <number>. Based on Green Star Technical Manual.

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	**--- MJ/m^2**	**--- MJ/m^2**	**--- MJ/m^2**
Measurable energy to reduce in **Implementation**	**--- MJ/ m^2**	**--- MJ/m^2**	
Measurable energy to reduce in **Transportation**	**--- MJ/ m^2**	**--- MJ/ m^2**	
Green Star, Total elevated Floor	**--- MJ/m^2**	**--- MJ/m^2**	**--- MJ/ m^2**
	--- MJ/m^2		

Table A.B.6: Potential carbon emission (embodied energy) reduction in construction stages of the <name> wall construction system.

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled materials as aggregate for concrete block**
	Green Star **Reused recycled materials for -----------**
Implementation	**Decreased and Replaced energy in process**
	Green Star
Transportation	**Decreased transportation of waste by reusing and recycling**
	Green Star
	Decreased transportation by localizing the suppliers

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) to reduce		
Measurable energy to reduce in **Building materials and elements**	**--- MJ/ m^2**	**--- MJ/ m^2**	**---MJ/ m^2**
Measurable energy to reduce in **Implementation**		**--- MJ/m^2**	
Measurable energy to reduce in **Transportation**	**--- MJ/ m^2**	**--- MJ/m^2**	
Total Walls	**--- MJ/ m^2**	**--- MJ/ m^2**	**---MJ/ m^2**
	--- MJ/m^2		

Table A.B.7: Green Star, potential carbon emission (embodied energy) reductions in <name> construction system. Case Study <number>. Based on Green Star Technical Manual.

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	**--- MJ/m^2**		**--- MJ/m^2**
Measurable energy to reduce in **Implementation**		**--- MJ/m^2**	
Measurable energy to reduce in **Transportation**	**--- MJ/ m^2**		
Green Star, Total Wall	**---- MJ/m^2**	**--- MJ/m^2**	**--- MJ/ m^2**
	--- MJ/m^2		

Table A.B.8: Green Star, potential carbon emission (embodied energy) reduction in <name> construction system. Case Study <number>. Based on Green Star Technical Manual.

ife Cycle Stages of building	Construction		nbodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
asurable energy to reduce in **lementation**	**--- MJ/m^2**	**--- MJ/m^2**	**--- MJ/m^2**
Green Star, Total Roof	**---- MJ/m^2**		**--- MJ/ m^2**
	---- MJ/m^2		

Table A.B.9: Total potential carbon emission (embodied energy) reductions in construction stages of floor, wall and roof systems

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emissions (Embodied Energy) to reduce		
Measurable replaced and saved energy in **Building materials and elements** (Tables <numbers>)	**---- MJ/m²**	**---- MJ/m²**	**---- MJ/m²**
Measurable replaced and saved energy in **Implementation** (Tables <numbers>)	**----- MJ/m²**	**----- MJ/m²**	
Measurable replaced and saved energy in **Transportation** (Tables <numbers?)	**----- MJ/ m²**	**---- MJ/m²**	
Total, building system	**----- MJ/m²**	**----- MJ/m²**	**---- MJ/m²**
	------ MJ/m²		

Table A.B.10: Comparison of basic carbon emissions (embodied energy) from different sources (implemented, this research, Green Star and basic/standard) for each building system

	Implemented carbon emission (embodied energy)		**CO^2 Emission (embodied energy) reductions**				**Basic** carbon emission (embodied energy)	
	Embodied Energy MJ/m²	Carbon Emissions Kg/m²	Embodied Energy MJ/m²		Carbon Emissions Kg/m²		Embodied Energy MJ/m²	Carbon Emissions Kg/m²
Floor/s	-	-	--	--	--	--	--	--
External walls	-	-	--	--	--	--	--	--
Roof/ceiling	-	-	--	--	--	--	--	--
Total	-	-	--	--	--	--	--	--
			This Research	**Green Star**	**This Research**	**Green Star**		

Sources
Columns 2 and 3 data are the embodied energy and reduced carbon emissions in implementation (i.e. completed construction)
Columns 3 and 5 data are the potential reductions in embodied energy and carbon emissions from this research
Columns 4 and 6 data are the potential reductions in carbon emissions through application of the Green Star tool
Columns 7 and 8 data are the (expected) standard or basic embodied energy and carbon emissions

APPENDIX C
DATA RELATING TO CHAPTER SEVEN
APPLICATION OF RESEARCH MODEL

A.C.1.1 Case Study One – Friendly Beaches Lodge

Table A.C.1: Potential reduction in carbon emissions (embodied energy) in an **elevated timber floor** (lower level) construction system. Case Study One (see Lawson 1996, p. 124)

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reuse the recycled aggregate in concrete** - Concrete from 80 % Recycled aggregate (Uche 2008; PCA2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (26.4 kg concrete – 3.69 cement) Kg x 80% (Lawson 1996, p. 135) =**1.52 MJ/m²** Reuse the recycled aggregate for brick, 67% (BDA 2014; Tyrell and Goode 2014), 36 kg/m² (Lawson 1996, p. 124) x 67% x 0.083 MJ/kg = **2 MJ/ m²**
	Reuse materials and elements - Use recycled bricks 60% x 90 **= 54MJ/m²** -Timber products re-used, post-consumer recycled timber or FSC certified timber, use recycled hardwood joist, flooring, 54 MJ/m² x 60% = **32.4 MJ/m²**
	Green Star **Reused recycled aggregate for concrete** In Green Star technical manual, considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (26.4 concrete – 3.69 cement) Kg (Lawson 1996, p. 125) x 20% = **0 .38 MJ/m²** Material-8 Timber, Green Star Technical Manual, Materials p. 275, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber 60% Recycled hardwood joints use recycled hardwood joist, flooring, 54 MJ/m² x (p.124, L.1), 60% = **32.4 MJ/m²**

Implementation	**Decrease and replace energy in the process, Replaced cement** Geopolymer concrete or 100% replacing Portland with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011; Kotrayothar 2012) 26.4 kg/m² (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 97% = 3.69 kg replaced cement/ m² in concrete 3.69 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 20.66 MJ/ m²** Potential 40 per cent energy savings in brick manufacturing using 67% recycled container glass brick grog (BDA 2014; Tyrell & Goode 2014). Reduced energy 90 MJ/m² x 40% = **36 MJ/m²**
	Green Star, Replaced cement Geopolymer concrete or 60% replacing Portland cement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 26.4 kg/m² (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = 2.29 kg replaced cement/ m² in concrete 2.29 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 12.82 MJ/ m²**

Transportation	**Decreased transportation of waste by reusing and use recycled materials** There are construction material suppliers if the materials come from the inside of state, the distance will be over 50 km (60% x 36 kg/m² Brick + 60% x 14.7 kg/m2 Hardwood and Joist) 36.3 kg/m2 /1000 T/m² x 50 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) **= 8.16 MJ/ m²** Concrete from recycled aggregate (26.4 kg concrete – 3.69 cement) Kg x80% (Lawson 1996, p.125) /1000 T/m² x 50 km x 4.50 MJ/tonne/km (Lawson 1996, p. 12) = **4.08 MJ/ m²**
	Green Star, Decreased transportation of waste by reusing and use recycled materials There are construction material suppliers if the materials come from the inside of estate the distance will be over 50 km (60% x 36 kg/m² Brick + 60% x 14.7 kg/m2 Hardwood and Joist) 36.3 kg/m2 /1000 T/m² x 50 km x 4.5 MJ/tonne/km (Lawson p. 12) **= 8.16 MJ/ m²** Concrete from recycled aggregate (26.4 kg concrete – 3.69 cement) Kg x2% (Lawson 1996, p.125, Legend 2) /1000 T/m² x 50 km x 4.50 MJ/tonne/km (Lawson 1996, p. 12) = **1.02 MJ/ m²**
	Decreased transportation by localizing the suppliers There are three construction material suppliers, (Devonport TAS 2014), the materials come from the interstate from Devonport of Tasmania. The decreased distance will be 237 Devonport - 157 Launceston km = 80 km 27.78 kg/m² (Lawson 1996, p. 124) /1000 T/m² x 80 km x 4.5 MJtonne/km (Lawson 1996, p. 12 = **10 MJ/ m²**

Life cycle stages of building	Construction		Embodied Energy Standard
	Pre-Construction	Construction	
	Potential Embodied Energy to Replace and Save		
Measurable energy to reduce in **Building materials and elements**	Concrete from recycled aggregate **1.52 MJ/m²** 67% Use recycled aggregate for brick **2KJ/m²**	Use recycled brick **54MJ/m²** Use recycled Hardwood **32.4 MJ/m²**	**293MJ/m²**
Measurable energy to reduce in **Implementation**	40% saving energy in production **36** MJ/m²	Geopolymer concrete **20.66 MJ/ m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **8.16 MJ/ m²** Decreased transportation by reusing **4.08 MJ/ m²**	Decreased transportation by localizing **10 MJ/ m²**	
Total Floor	**51.76 MJ/m²**	**117.06 MJ/m²**	**293MJ/** m²
	168.82 MJ/m²		

Table A.C.2: Green Star. Potential reduction in carbon emission (embodied energy) in an elevated timber floor (lower level) construction system. Case Study One (see Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic	
	Pre-Construction	Construction		
	Potential Carbon Emission (Embodied Energy) Reduction			
Measurable energy to reduce in **Implementation**	Concrete from recycled aggregate **0 0.38 MJ/m²**	Use recycled Hardwood **32.4 MJ/m²**	**293 MJ/m²**	
Implementation		Geopolymer concrete **12.82 MJ/ m²**		
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **8.16 MJ/ m²** Decreased transportation by reusing **1.53 MJ/ m²**			
Green Star, Total Floor	**10.07 MJ/ m²**	**45.22 MJ/m²**	**293 MJ/ m²**	
	55.29 MJ/m²			

Table A.C.3: Potential reduction in carbon emissions (embodied energy) in timber frame, single skin timber wall construction system. Case Study One (see Lawson 1996, p. 125)

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reuse the recycled materials** Use timber products re-used, post-consumer recycled timber or FSC certified timber (GBCA 2008) Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm, p.127, 60% x 37 MJ/m² (Lawson 1996, p.125) = **22.2 MJ/m²** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m² = **16.43 MJ/m²**
	Green Star **Reuse the recycled materials** Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm =, 60% x 37 MJ/m² (p.125, L. 7) = **22.2 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** There are construction material suppliers if the materials come from the inside of state, the distance will be over 50 km 7.15 kg/m2 Softwood + Softwood plate + …… = 22 kg/m² 22 x 60% kg/m2 /1000 T/m2 x 50 km x 4.5 MJ/tonne/km (Lawson p. 12) = **2.97 MJ/ m²**
	Green Star **Decreased transportation of waste by reusing and recycling** There are construction material suppliers if the materials come from the inside of estate. The distance will be over 50 km 7.15 kg/m2 Softwood + Softwood plate + …… = 22 kg/m² 22 x 60% kg/m2 /1000 T/m2 x 50 km x 4.5 MJ/tonne/km (Lawson p. 12) = **2.97 MJ/ m²**
	Decreased transportation by localizing the suppliers There are three construction material suppliers, (Devonport TAS 2014), the materials come from interstate from Devonport of Tasmania. The decreased distance will be 237 Devonport - 157 Launceston km = 80 km 22 kg/m² /1000 T/m2 x 80 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **7.91 MJ/ m²**

Areas that Embodied Energy can be reduced	Construction			Embodied Energy
	Pre-Construction	Construction		
	Potential Embodied Energy to Replace and Save			Standard
Measurable energy to reduce in **Building materials and elements**	Use thermal insulation with recycled aggregates **23.2 MJ/m²**	60% softwood stud + softwood plates **22.2 MJ/m²** Use Recycle thermal insulation **16.43 MJ/m²**		**151MJ/ m²**
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **2.97MJ/ m²**	Decreased transportation by localizing **7.91 MJ/ m²**		
Total Walls	**26.17 MJ/m²**	**46.54 MJ/m²**		**151MJ/ m²**
	72.71 MJ/m²			
General Construction system	**61.83 MJ/m²**			**151MJ/ m²**

Table A.C.4: Green Star. Potential reduction in carbon emissions (embodied energy) in timber frame, single skin timber wall construction system. Case Study One (see Lawson, 1996. p. 125).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		60% softwood stud + softwood plates **22.2 MJ/m²**	**151 MJ/m²**
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **2.97MJ/ m²**		
Green Star, Total Wall	**2.97 MJ/ m²**	**22.2 MJ/m²**	**151 MJ/ m²**
	25.17 MJ/m²		

Table A.C.5: Potential reduction in carbon emissions (embodied energy) in a timber frame, steel sheet roof. Case Study One (see Lawson 1996, p. 133).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Steel from average recycled content** - **Steel sheet** from recycled contents {38 MJ/Kg (Lawson 1996) – 20.50 MJ/Kg} = 17.5 MJ/Kg x 4.9 kg/ **m²** = **85.75 MJ/m²** **Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 34 MJ/m² P. 133 L.2 (Design Coalition 2013) = **13.6 MJ/m²** - Using recycled trusses = 60% x 34 MJ/m² (Lawson 1996, p. 133) **20.4 MJ/m²** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.825kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014)
	Green Star **Steel from average recycled content** Material-6 Steel (Green Star Technical Manual, Materials) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (GBCA 2008) is: - **Steel sheet** from recycled contents {38 MJ/Kg, P. 133 l.2 (Lawson 1996) – 20.50 MJ/Kg} = 17.5 MJ/Kg x 4.9 kg/m² x 90% = **77.17 MJ/m²** **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber (Green Star Technical Manual, Materials), 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 34 (Design Coalition 2013) = **13.6 MJ/m²** - Using recycled trusses = 55% x 34 MJ/m² (Lawson, 1996, p. 133) = **18.7 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** There are construction material suppliers if the materials come from the outside of state, the distance will be Port Jackson (Port Jackson 2014) 297 - Thylacine (Thylacine 2014) 25.2 km = over 100 km Reuse softwood trusses 11.15 (trusses 8.25, battens 2.9) kg/m² /1000 T/m² x 100km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **5.01 MJ/ m²**
	Green Star There are construction material suppliers if the materials come from the outside of state: the distance will be (Port Jackson (Port Jackson 2014) 297 - Thylacine (Thylacine 2014) 25.2 km) = over 100 km Reuse softwood trusses 11.15 (trusses 8.25, battens 2.9) kg/m² /1000 T/m² x 100 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **5.01 MJ/ m²**
	Decreased transportation by localizing the suppliers There are construction material suppliers if the materials come from the inside of state: Local supplier is Skyline (2014) The saved distance will be (Thylacine 2014) 25.2 km 19.99 kg/m² (whole roof materials) /1000 T/m2 x 25.2 km x 4.5 MJtonne/km (Lawson 1996, p. 12 = **2.26 MJ/ m²**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled timber 40% **13.6 MJ/m²** Steel sheet from recycled content **85.75 MJ/m²**	Use recycled trusses 60% **20.4 MJ/m²** Use recycled thermal insulation **17.57 MJ/m²**	**330MJ/** m²
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing trusses **5.01 MJ/ m²**	Decreased transportation by localizing **2.26 MJ/ m²**	
Total Roof, Research	**104.36 MJ/m²**	**40.23 MJ/m²**	**330MJ/ m²**
	144.59 MJ/m²		

Table A.C.6: Green Star, potential reduction in carbon emissions (embodied energy) in timber frame, steel sheet roof construction system. Case Study One (see Lawson 1996, p. 133)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel sheet from 90% Recycled contents = **77.17 MJ/m²** Trusses from recycled timber 40% **13.6 MJ/m²**	Use recycled trusses 55% **18.7 MJ/m²**	**330 MJ/m²**
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing trusses **5.01 MJ/ m²**		
Green Star, Total Roof	**95.78 MJ/m²**	**18.7 MJ/m²**	**330 MJ/ m²**
	114.48 MJ/m²		

Table A.C.7: Potential reduction in carbon emissions (embodied energy) in timber floor, timber walls, steel roof construction system. Case Study One.

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions to reduce		Basic
Measurable energy to reduce in **Building materials and elements**	**126.07 MJ/m²**	**163 MJ/m²**	**774 MJ/m²**
Measurable energy to reduce in **Implementation**	**36 MJ/m²**	**20.66 MJ/m²**	
Measurable energy to reduce in **Transportation**	**20.22 MJ/m²**	**20.17 MJ/m²**	
Total, building system	**182.29 MJ/m²**	**203.83 MJ/m²**	**774 MJ/m²**
	386.12 MJ/m²		

A.C.1.2 Case Study Two – ACF Green Home

Table A.C.8: Potential reduction in carbon emissions (embodied energy) in a concrete slab on ground floor construction system. Case Study Two (see Lawson 1996, p. 124).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80 % Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (290.4 concrete –39.43 cement) Kg (Lawson 1996, p.125) x 80% =**16.67 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 3.882 Kg x {34 MJ/Kg (Lawson 1996, p13) - 20.10 MJ/Kg} = **53.96MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 (Green Star Technical Manual, Materials) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: embodied energy by this credit (Concrete from 20% Recycled aggregate) (GCBA 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA) 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (290.4 concrete –39.43 cement) Kg (Lawson 1996, p. 125) x 20% = **4.16 MJ/m^2** **Steel from average recycled content** Material-6 (Green Star Technical Manual, Steel) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (GBCA 2008) is: 3.882 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **53.95 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete or 100% replacement Portland cement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 290.4 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 97% = 39.43 kg replaced cement/ m^2 in concrete 39.43 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 220.83 MJ/ m^2**
	Green Star Replacing maximum 60% of cement 290.4 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = 24.38 kg replaced cement/ m^2 in concrete 24.38 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 136.59 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** There are three construction material suppliers, (Melbourne Building Supplies 2014), If the materials come from the interstate somewhere in Melbourne, (Boral 2014). The decreased distance will be 54.2 k Reduced transportation by Reusing aggregate, (290.4 kg/m^2- 39.43 kg/m^2) x 80% /1000 T/m^2 x 54.2 km x 4.5 MJ/ton/km (Lawson p. 12) =**40.80 MJ/ m^2**
	Green Star There are three construction material suppliers, (Melbourne Building Supplies 2014). If the materials come from somewhere in Melbourne, (Boral 2014), the decreased distance will be 54.2 k Reduced transportation by reusing aggregate, (290.4 kg/m^2- 39.43 kg/m^2) /1000 T/m^2 x 45.2 km x 4.5 MJ/ton/km (Lawson 1996, p. 12) x 20% = **10.20 MJ/ m^2**
	Decreased transportation by localizing the suppliers There are three construction material suppliers, (Melbourne Building Supplies 2014), If the materials come from somewhere in Melbourne, (Boral 2014), the decreased distance will be 54.2 k (290.4kg aggregate + mesh 3.12kg) = 293.52 kg/m^2 /1000 T/m2 x 54.2 km x 4.5 MJtonne/km (Lawson 1006, p. 12) = **15.04 MJ/ m^2**

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**	Concrete from 30% recycled aggregate = **16.67 MJ/m^2**	Steel mesh, beams from average recycled content = **53.96 MJ/m**	**645MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **220.83 MJ/ m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **40.80 MJ/m^2**	Decreased transportation by localizing **15.04 MJ/ m^2**	
Total Floor	**57.47 MJ/m^2**	**289.83 MJ/m^2**	**645MJ/** m^2
	347.30 MJ/m^2		

Table A.C.9: Green Star. Potential reduction in carbon emissions (embodied energy) in a 110 mm concrete slab on ground floor construction system. Case Study Two (see Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete = **4.16 MJ/m²**	90%Steel mesh from average recycled content **53.95MJ/m²**	**645 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **136.59 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **15.04 MJ/m²**		
Green Star, Total Floor	**19.20 MJ/m²**	**190.54 MJ/m²**	**645MJ/ m²**
	209.74 MJ/m²		

Table A.C.10: Potential reduction in carbon emissions (embodied energy) in timber framed timber upper floor construction system. Case Study Two (see Lawson 1996, p. 124).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused materials and elements** 60% Recycled softwood joints (Design Coalition 2013) @ (600 c-c) 300x 500 mm + Timber flooring @ 18 mm particleboard 50 MJ/m² + 91 MJ/m² = 60% x 141 MJ/m² (Lawson 1996, p. 124) = **84.6 MJ/m² (Steel Construction Information 2014)**
	Material-8 Timber Materials (Green Star Technical Manual) 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber (GBCA 2008) 60% Recycled softwood joints (Design Coalition 2013) @ (600 c-c) 300x 500 mm + Timber flooring @ 18 mm particleboard 50 MJ/m² + 91 MJ/m²= %60 x 141 MJ/m² (Lawson 1996, p. 124 = **84.6 MJ/m² (**Steel Construction Information 2014)
Transportation	**Decreased transportation of waste by reusing and recycling** There are three construction material suppliers, (Melbourne Building Supplies 2014), If the materials come from somewhere in Melbourne, (Boral 2014), the decreased distance will be 54.2 k 11.4 kg/m²x 60% /1000 T/m2 x 54.2 k x 4.5 MJtonne/km (Lawson 1996, p. 12) = **1.66 MJ/ m²**
	Green Star There are three construction material suppliers (Melbourne Building Supplies 2014). If the materials come somewhere in Melbourne (Boral 2014), the decreased distance will be 54.2 k 11.4 kg/m²x 60% /1000 T/m2 x 54.2 k x 4.5 MJtonne/km (Lawson 1996, p. 12) = **1.66 MJ/ m²**
	Decreased transportation by localizing the suppliers There are three construction material suppliers, (Melbourne Building Supplies 2014). If the materials come from somewhere in Melbourne, (Boral 2014), the decreased distance will be 54.2km 18.2 kg/m² x 60% /1000 T/m2 x 54.2 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **2.66 MJ/ m²**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		
Measurable energy to reduce in **Building materials and elements**		60% recycled timber floor **84.6 MJ/m²**	**147MJ/m²**
Measurable energy to reduce in **Transportation**	Saved energy in transportation by reusing **1.66 MJ/ m²**	Decreased transportation by localizing **2.66 MJ/ m²**	
Total Floor	**1.66 MJ/m²**	**87.26 MJ/m²**	**147MJ/ m²**
	88.92 MJ/m²		

Table A.C.11: Green Star. Potential reduction in carbon emissions (embodied energy) in timber framed timber floor upper floor construction system. Case Study Two (see Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		60% recycled timber floor **84.6 MJ/m^2**	**147 MJ/m^2**
Measurable energy to reduce in **Transportation**	Saved energy in transportation by reusing **1.66 MJ/ m^2**		
Green Star, Total Floor	**1.66 MJ/m^2**	**84.6 MJ/m^2**	**147 MJ/ m^2**
	86.26 MJ/m^2		

Table A.C.12: Potential reduction in carbon emissions (embodied energy) in timber framed, clay brick veneer wall construction system. Case Study Two (see Lawson 1996, p. 127).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused recycled aggregates** Reuse recycled aggregate for brick, 67% (BDA 2014; Tyrell and Goode 2014), 147 kg/m^2 (Lawson 1996, p.127) x 67% x 0.083 MJ/kg = **8.17 MJ/ m^2** **Reused materials and elements** Use recycled softwood stud, 60% reuse softwood stud@100x50mm+ softwood plates@100x50 mm = 60% x 33 MJ/m^2= **19.8 MJ/m^2** Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014). Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Reused materials and elements** Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm = 60% x 33 MJ/m^2= **19.8 MJ/m^2**
Implementation	**Decreased and replaced energy** **Decrease energy** US-made fly ash brick gains strength and durability from the chemical reaction of fly ash with water. However, 85 per cent less energy is used in production than in fired clay brick (Volz & Stovner 2010). Potential 40 per cent energy saving in brick manufacturing using 67% recycled container glass brick grog (BrDA2014; Tyrell & Goode 2014). Reduced energy 368 MJ/m^2 x 40% = **147.2** MJ/m^2
Transportation	**Decreased transportation of waste by reusing and recycling** There are three construction material suppliers, (Melbourne Building Supplies 2014). If the materials come somewhere in Melbourne, (Boral 2014), the decreased distance will be 54.2km Reuse and Recycled aggregate for brick 147 kg/m^2 x 67% /1000 T/m^2 x 54.2 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **24.02 MJ/ m^2** Reused the recycled softwood 8.1 kg/m^2 /1000 T/m^2 x 54.2 km x 4.5 MJ/tonne/km = **1.97 MJ/ m^2**
	Green Star There are three construction material suppliers (Melbourne Building Supplies 2014). If the materials come from somewhere in Melbourne, (Boral 2014), the decreased distance will be 54.2km Reused the recycled softwood 8.1 kg/m^2 /1000 T/m^2 x 54.2 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **1.97 MJ/ m^2**
	Decreased transportation by localizing suppliers There are three construction material suppliers, (Melbourne Building Supplies 2014). If the materials come from somewhere in Melbourne, (Boral 2014), the decreased distance will be 54.2km 158 kg/m^2 (brick +wood) /1000 T/m2 x 54.2 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **38.53 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	76% Use recycled aggregate for brick **8.17 KJ/m^2**	60% softwood stud + softwood plates **19.8 MJ/m^2** Use Recycled thermal insulation **16.43 MJ/m^2**	**5**61**MJ/ m^2**
Implementation	40% saving energy in production **147.2** MJ/m^2		
Measurable energy to reduce in **Transportation**	Saved energy in transportation Reuse of aggregate **24.02 MJ/ m^2**	Reuse of softwood **1.97 MJ/ m^2** Decreased transportation by localizing **38.53 MJ/ m^2**	
Total Walls	**179.39 KJ/m^2**	**77.09 MJ/m^2**	**561MJ/ m^2**
	256.48 MJ/m^2		

Table A.C.13: Green Star. Potential reduction in carbon emissions (embodied energy) in timber framed, clay brick veneer wall. Case Study Two (see Lawson 1996, p. 127).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		60% softwood stud + softwood plates **19.8 MJ/m^2**	**561 MJ/m^2**
Measurable energy to reduce in **Transportation**		Reuse of softwood **1.97 MJ/ m^2**	
Green Star, Total Wall		**242.57 MJ/m^2**	**561 MJ/ m^2**
	21.77 MJ/m^2		

Table A.C.14: Potential reduction in carbon emissions (embodied energy) in timber framed, concrete tile roof construction system. Case Study Two (see Lawson 1996, p. 134).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses = 60% x 43 MJ/m² = **25.8 MJ/m²** - Use insulation from recycled materials, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.6255kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014) Being small and modular in nature, concrete roof tile is less prone to waste. Roof tiles can be crushed and recycled (LEED 2014) Use tiles from recycled roof tiles, 92 MJ/m² x 13% (LEED 2014) **= 11.96 MJ/m²** Use tiles from recycled roof tiles (Herbudiman & Saptaji 2013) from 45% recycled content Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (44 concrete – 6.16 cement) Kg/m² (Lawson 1996, p. 134) x 45% = 0.083 x 37.84 kg/m2 x 50% (Herbudiman & Saptaji 2013) =**1.57 MJ/m²**
	Green Star **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber (Green Star Technical Manual) Materials 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses, 55% x 43 MJ/m² = **23.65 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** There are three construction material suppliers, (Melbourne Building Supplies 2014). If the materials come from somewhere in Melbourne (Boral 2014), the decreased distance will be 54.2km. Decreased transportation by reusing of trusses 18.25 kg/m² (Lawson 1996, p.134) /1000 T/m² x 54.2 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **4.45 MJ/ m²**
	Green Star There are three construction material suppliers, (Melbourne Building Supplies 2014). If the materials come from somewhere in Melbourne (Boral 2014), the decreased distance will be 54.2km. Reuse of trusses, 18.25 kg/m² /1000 T/m² x 54.2 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **4.45 MJ/ m²**
	Decreased transportation by localizing suppliers There are three construction material suppliers, (Melbourne Building Supplies 2014). If the materials come from somewhere in Melbourne (Boral 2014), the decreased distance will be 54.2km. 59.6 kg/m² /1000 T/m² x 54.2 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **14.53 MJ/ m²**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions to reduce		Basic
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **25.8 MJ/m²** Use recycled thermal insulation **17.57MJ/m** Use recycled roof tiles 13%, **11.96 MJ/m²**	**240MJ**/m²
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing trusses. **4.45 MJ/ m²**	Decreased transportation by localizing **14.53 MJ/ m²**	
Total Roof	**21.65 MJ/m²**	**69.86 MJ/m²**	**240MJ/ m²**
	91.51 MJ/m²		

Table A.C.15: Green Star. Potential reduction in carbon emissions (embodied energy) in timber framed, concrete tile roof construction system. Case Study Two (see Lawson 1996, p. 134).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	Softwood Trusses from recycled trusses **17.2 MJ/m^2**	Using recycled trusses **23.65 MJ/m^2**	**240 MJ/m^2**
Measurable energy to reduce in **Transportation**	Decreased transportation by Reuse of truss **4.45 MJ/ m^2**		
Green Star, Total Roof	**21.51 MJ/ m^2**	**23.65 MJ/m^2**	**240 MJ/ m^2**
	45.16 MJ/m^2		

Table A.C.16: Potential reduction in carbon emissions (embodied energy) in concrete slab floor, timber framed brick veneer walls, timber framed concrete tile roof. Case Study Two.

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions to Reduce		Basic
Measurable energy to reduce in **Building materials and elements** (Tables 1,2,3,)	**42.04 MJ/m^2**	**230.12 MJ/m^2**	**1623 MJ/m^2**
Measurable energy to reduce in **Implementation** (Tables 1,2 and 3)	**147.2 MJ/m^2**	**220.83 MJ/ m^2**	
Measurable energy to reduce in **Transportation** (Tables 1,2 and 3)	**49.42 MJ/m^2**	**94.25 MJ/m^2**	
Total, building system	**238.66 MJ/m^2**	**545.20 MJ/m^2**	**1623 MJ/m^2**
	783.86 MJ/m^2		

A.C.1.3 Case Study – Three Display Project Home

Table A.C.17: Potential reduction in carbon emissions (embodied energy) in a 110 mm concrete slab on ground floor. Case Study Three (see Lawson 1996, p. 124).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014) embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (290.4 concrete –39.43 cement) Kg (Lawson 1996, p.125) x 80% = **16.67 MJ/m^2** **Steel from average recycled content** - Steel mesh + Edge beams from average recycled content = 3.882 Kg x {34 MJ/Kg (Lawson 1996, p13) - 20.10 MJ/Kg} = **53.96MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 (Green Star Technical Manual) Materials is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GCBA 2008) is: - Concrete from 30% Recycled aggregate embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (290.4 concrete –39.43 cement) Kg (Lawson 1996, p. 125) x 20% = **4.16 MJ/m^2** **Steel from average recycled content** Material-6 (Green Star Technical Manual) steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (GBCA 2008) is: 3.882 Kg x 90% {34 MJ/Kg (Lawson 1996, p13) - 20.10 MJ/Kg} = **48.56 MJ/m^2**

Implementation	**Decreased and Replaced energy** **Replaced cement** Geopolymer concrete or 100% replacement by recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 290.4 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 97% = 39.43 kg replaced cement/ m^2 in concrete 39.43 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 220.83 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (GBCA 2008) 290.4 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = 24.38 kg replaced cement/ m^2 in concrete 24.38 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) x 60% **= 81.91 MJ/ m^2**

Transportation	**Decreased transportation of waste by reusing and recycling** There are construction material suppliers, if the materials come from the outside of stat, the distance will be (Port Jackson 2014) 297 - (Thylacine 2014) 25.2 km = over 100km Reduced transportation by reusing aggregate, (290.4 kg/m^2- 39.43 kg/m^2) x80% /1000 T/m^2 x 100 km x 4.5 MJ/ton/km (Lawson 1996, p. 12) = **90.32 MJ/ m^2**
	Green Star There are construction material suppliers, if the materials come from the outside of stat, the distance will be (Port Jackson 2014) 297 - (Thylacine 2014) 25.2 km = over 100km Reduced transportation by reusing aggregate, (290.4 kg/m^2- 39.43 kg/m^2) /1000 T/m^2 x 100 km x 4.5 MJ/ton/km (Lawson 1996, p. 12) x 20% = **22.58 MJ/ m^2**
	Decreased transportation by localizing the suppliers There is construction material supplier: If the materials come from a local supplier (Skyline 2014), the decreased distance will be 25.2 = km (290.4kg aggregate + mesh 3.12kg) = 293.52 kg/m^2 /1000 T/m2 x 25.2 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **33.28 MJ/ m^2**

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**	30 % Concrete from recycled aggregate = **16.67 MJ/m^2**	Steel mesh, beams from average recycled content = **53.96 MJ/m**	**645MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **220.83 MJ/ m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **90.32 MJ/m^2**	Decreased transportation by localizing **33.28 MJ/ m^2**	
Total Floor	**106.99 MJ/m^2**	**308.07 MJ/m^2**	**645MJ/** m^2
	415.06 MJ/m^2		

Table A.C.18: Green Star. Potential reduction in carbon emissions (embodied energy) in a 110 mm concrete slab on ground floor. Case Study Three (see Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete = **4.16 MJ/m²**	90%Steel mesh from average recycled content **48.56 MJ/m²**	**645 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **81.91 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **22.58 MJ/m²**		
Green Star, Total Floor	**26.74 MJ/m²**	**130.47 MJ/m²**	**645MJ/ m²**
	157.21 MJ/m²		

Table A.C.19: Potential reduction in carbon emissions in a timber framed, clay brick veneer wall (Lawson 1996, p. 127).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused the recycled aggregates** Reuse recycled aggregate for brick, 67% (BDA 2014; Tyrell & Goode 2014), 147 kg/m^2 (p.127, L 6) x 67% x 0.083 MJ/kg = **8.17 MJ/ m^2** **Reused materials and elements** Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm = 60% x 33 MJ/m^2= **19.8 MJ/m^2** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Reused materials and elements** Material-3 (Green Star Technical Manual) Materials is considered maximum 80% reused materials, therefore reduced embodied energy by this credit (Concrete from 80% reused material) (GCBA 2014) Material-8 Timber (Green Star Technical Manual) Materials, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm = 60% x 33 MJ/m^2= **19.8 MJ/m^2**
Implementation	Potential 40 per cent energy savings in brick manufacturing using 67% recycled container glass brick grog (BCA 2014, Tyrell & Goode 2014). Reduced energy 368 MJ/m^2 x 40% = **147.2** MJ/m^2
Transportation	**Decreased transportation of the waste by reusing and recycling** If materials come from the outside of state, distance will be (Port Jackson (Port Jackson 2014) 297 - (Thylacine 2014) 25.2 km = over 100 km Reuse and Recycled aggregate for brick 147 kg/m^2 x 67% /1000 T/m^2 x 100 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **44.32 MJ/ m^2** Reused recycled softwood 8.1 kg/m^2 /1000 T/m^2 x 100 km x 4.5 MJ/tonne/km (Lawson 1996. p.12) = **3.64 MJ/ m^2**
	Green Star If materials come from the outside of state, distance will be (Port Jackson (Port Jackson 2014) 297 - (Thylacine 2014) 25.2 km = over 100 km Reused recycled softwood 8.1 kg/m^2 /1000 T/m^2 x100 km x 4.5 MJ/tonne/km (Lawson p.12) = **3.64 MJ/ m^2**
	Decreased transportation by localizing suppliers If materials come from the inside of state, local supplier is Skyline (2014), the saved distance will be (Thylacine 2014) 25.2 km 158 kg/m^2 (brick +wood) /1000 T/m2 x 25.2 km x4.5 MJtonne/km (Lawson 1996, p. 12) = **17.91 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	20% Use recycled contents brick **8.17 KJ/m^2**	60% softwood stud + softwood plates **19.8 MJ/m^2** Use Recycle thermal insulation **16.43 MJ/m^2**	**561MJ/ m^2**
Implementation	40% saving energy in production **147.2** MJ/m^2		
Measurable energy to reduce in **Transportation**	Saved energy in transportation Reuse of aggregate **44.32 MJ/ m^2**	Reuse of softwood **3.64 MJ/ m^2** Decreased transportation by localizing **17.91 MJ/ m^2**	
Total Walls	**199.69 KJ/m^2**	**57.78 MJ/m^2**	**561MJ/ m^2**
	257.47 MJ/m^2		

Table A.C.20: Green Star. Potential reduction in carbon emissions (embodied energy) in a timber framed, clay brick veneer wall. Case Study Three (see Lawson 1996, p. 127).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		60% softwood stud + softwood plates **19.8 MJ/m^2**	**561 MJ/m^2**
Measurable energy to reduce in **Transportation**		Reuse of softwood **3.64 MJ/ m^2**	
Green Star, Total Wall		**23.44 MJ/m^2**	**561 MJ/ m^2**
	23.44 MJ/m^2		

Table A.C.21: Potential reduction in carbon emissions (embodied energy) in a timber framed, steel sheet roof. Case Study Three (see Lawson 1996, p. 133).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Steel from average recycled content** - **Steel sheet** from recycled contents {38 MJ/Kg – 20.50 MJ/Kg} = 17.5 MJ/Kg x 4.9 kg/ **m²** = **85.75 MJ/m²** **Reused materials and elements** - Softwood trusses from recycled trusses 40% x 34 MJ/m² P. 133 L.2 (Design Coalition 2013) = **13.6 MJ/m²** - Using recycled trusses = 60% x 34 MJ/m² = **20.4 MJ/m²** - Use recycled thermal insulation, 49MJ/kg - 20.90 MJ/kg x 0.825kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014) - Use recycled thermal insulation = **40 MJ/m²** (Steel Construction Information 2014)
	Green Star **Steel from average recycled content** Material-6 Steel (Green Star Technical Manual) Materials is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (GBCA 2008) is: - **Steel sheet** from recycled contents {8 MJ/Kg – 20.50 MJ/Kg} = 17.5 MJ/Kg x 4.9 kg/ **m²** x 90% = **77.17 MJ/m²** **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber (Green Star Technical Manual) 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 34 (Design Coalition 2013) = **13.6 MJ/m²** - Using recycled trusses = 55% x 34 MJ/m² = **18.7 MJ/m²**

Transportation	**Decreased transportation of waste by reusing and recycling** If the materials come from outside the state, the distance will be (Port Jackson 2014) 297 - (Thylacine 2014) 25.2 km) = over 100 km Reuse softwood trusses 11.15(trusses 8.25, battens 2.9,) kg/m² /1000 T/m² x 100km x 4.5 MJ/tonne/km = **5.01 MJ/ m²**
	Green Star If the materials come from outside the state, the distance will be (Port Jackson 2014) 297 - (Thylacine 2014) 25.2 km) = over 100 km Reuse softwood trusses 11.15 (trusses 8.25, battens 2.9) kg/m² /1000 T/m² x 100 km x 4.5 MJ/tonne/km = **5.01 MJ/ m²**
	Decreased transportation by localizing the suppliers If materials come from the inside of state, local supplier is Skyline (2014). The saved distance will be (Thylacine 2014) 25.2 km 19.99 kg/m² (whole roof materials) /1000 T/m2 x 25.2 km x 4.5 MJtonne/km = **2.26 MJ/ m²**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Basic
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled timber 40% **13.6 MJ/m²** Steel sheet from recycled content **85.75 MJ/m²**	Use recycled trusses 60% **20.4 MJ/m²** Use recycled thermal insulation = **17.57 MJ/m²**	**330MJ/** m²
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing trusses **5.01 MJ/ m²**	Decreased transportation by localizing **2.26 MJ/ m²**	
Total Roof	**104.36 MJ/m²**	**40.23 MJ/m²**	**330MJ/ m²**
	144.59 MJ/m²		

Table A.C.22: Green Star. Potential reduction in carbon emissions (embodied energy) in timber framed, steel sheet roof. Case Study Three (see Lawson 1996, p. 133).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel sheet from 90% Recycled contents = **77.17 MJ/m^2** Trusses from recycled timber 40% **13.6 MJ/m^2**	Use recycled trusses 55% **18.7 MJ/m^2**	**330 MJ/m^2**
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing trusses **5.01 MJ/ m^2**		
Green Star, Total Roof	**95.78 MJ/m^2**	**18.7 MJ/m^2**	**330 MJ/ m^2**
	114.48 MJ/m^2		

Table A.C.23: Potential reduction in carbon emissions (embodied energy) in building system: concrete slab floor, timber framed brick veneer walls, timber framed steel sheet roof. Case Study Three (see Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions to Reduce		Basic
Measurable energy to reduce in building materials and elements	**124.19 MJ/m^2**	**128.16 MJ/m^2**	**1536 MJ/m^2**
Measurable energy to reduce in **Implementation**	**147.2** MJ/m^2	**220.83 MJ/m^2**	
Measurable energy to reduce in **Transportation**	**139.65 MJ/m^2**	**57.09 MJ/m^2**	
Total, building system	**411.04 MJ/m^2**	**406.08 MJ/m^2**	**1536 MJ/m^2**
	817.12 MJ/m2		

A.C.1.4 Case Study Four – Civil Engineering Laboratory, USQ 2013

Table A.C.24: Potential reduction in carbon emissions (embodied energy) in a 200 mm concrete slab on ground floor. Case Study Four (see Lawson 1996, p. 125).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused the recycled aggregates for concrete** - Concrete from 80% recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083MJ/Kg x (381 kg/m^2concrete – 51.73 kg/m^2 cement) x 80% = **21.84 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 5.148 Kg x {34 MJ/Kg - 20.10 MJ/Kg} = **71.55 MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 (Green Star Technical Manual) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: - Concrete from 30% recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (381 kg/m^2concrete – 51.73kg/m^2 cement) x 20% = **5.46 MJ/m^2** **Steel from average recycled content** Material-6 (Green Star Technical Manual) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (GBCA 2008) is: 5.148 Kg x 90% {34 MJ/Kg - 20.10 MJ/Kg} = **64.39 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete or 100% replacement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 381kg/m^2 x 14% cement (Lawson 1996) 97% = 51.73 kg replaced cement/ m^2 in concrete 51.73 kg cement/m2 x 5.6 MJ/kg **= 289.68 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (GBCA 2008) 381kg/m^2 x 14% cement 60% = 32 kg replaced cement/ m^2 in concrete 32 kg cement/m^2 x 5.6 MJ/kg **= 179.2 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** Reduced transportation by reusing aggregate (381concrete -51.73 cement) kg/m^2 x 80% /1000 T/m^2 x 44.9 km x 4.5 MJ/ton/km (Lawson 1996, p. 12) = **53.2 MJ/ m^2**
	Green Star Reduced transportation by reusing aggregate, (381concrete -51.73 cement) kg/m^2 /1000 T/m^2 x 44.9 km x 4.5 MJ/ton/km (Lawson 1996, p. 12) x 20% = **13.3 MJ/ m^2**
	Decreased transportation by localizing suppliers Construction material supplier: BIG Mate Projects, Springfield QLD (BIG Mate 2014) If the materials come somewhere in Brisbane: Landscape Supplies, 488 Loganlea Rd, Slacks Creek QLD 4127 (Nuway 2014) The hypothetically decreased distance will be 32.3 km 381kg/m^2 concrete +5.148 Kg/m^2 steel) /1000 T/m^2 x32.3 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **56.12 MJ/m^2**

Life Cycle Stages of building	Construction			Embodied Energy Standard
	Pre-Construction	Construction		
	Potential reduction in carbon emissions			
Measurable energy to reduce in **Building materials and elements**	30 % Concrete from recycled aggregate = **21.84 MJ/m^2**	100%Steel mesh, beams from average recycled content = **71.55 MJ/m^2**		**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **289.68 MJ/ m^2**		
Measurable energy to reduce in **Transportation**	Decreased Energy in transportation by reuse aggregate **53.2 MJ/m^2**	Decreased transportation by localizing **56.12 MJ/ m^2**		
Total Floor	**75.04 MJ/m^2**	**417.35 MJ/m^2**		**908MJ/** m^2
	492.39 MJ/m^2			

Table A.C.25: Green Star. Potential reduction in carbon emissions (embodied energy) in a 200 mm concrete slab on ground floor. Case Study Four (see Lawson 1996, p. 125).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	%20Recycled aggregate for concrete =**5.46 MJ/m^2**	90%Steel mesh from average recycled content **64.39 MJ/m^2**	**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **179.2 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **13.3 MJ/m^2**		
Green Star, Total Floor	**18.76 MJ/m^2**	**243.59 MJ/m^2**	**908 MJ/ m^2**
	262.35 MJ/m^2		

Table A.C.26: Potential reduction in carbon emissions (embodied energy) in a cored concrete block wall. Case Study Four (Lawson 1996, p. 129)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled materials as aggregate for concrete block** - Concrete from 100% recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (275 Kg concrete – 24.47 kg cement) = **20.79 MJ/m^2**
	Green Star **Reused recycled materials for concrete block** Material-5 (Green Star Technical Manual) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (275 Kg concrete – 24.47 kg cement) x 20% = **4.15 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete block or 100% replacement with recycled cement substitute results 80% reduction in GHG (Geiger 2010) Reduced Cement = 89Kgs/tonne (Concrete Block Association 2013) / 1000 x 275 = 24.47 Kg/ m^2 Reduced cement 24.47 Kg/ m^2 x 5.6 MJ/kg **= 137.03 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 24.47 kg Cement/m2 x 60% x 5.6 MJ/kg **= 82.21 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** If the materials come from inside of state from local supplier, Big Mate Projects, Springfield QLD (BIG Mate 2014), the saved distance will be 44.9 km Reduced transport for recycled materials for reuse aggregate (275 concrete – 24.47 cement) kg.m^2 /1000 T/m2 x 44.9 km x 4.5 MJ/tonne/km = **50.62 MJ/ m^2**
	Green Star Reduced transport for Recycled materials for Reuse aggregate (275 concrete – 24.47 cement) kg/m^2 /1000 T/m2 x 44.9 km x 4.5 MJ/tonne/km (Lawson p. 12) x 20% =**10.12 MJ/ m^2**
	Decreased transportation by localizing the suppliers Landscape Supplies, 488 Loganlea Rd, Slacks Creek QLD 4127 (Nuway 2014) The hypothetically decreased distance will be 32.3km 275 kg/m^2 /1000 T/m2 x 32.3 km x 4.5 MJtonne/km = **39.9 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) reduction		
Measurable energy to reduce in **Building materials and elements**	Use recycled materials as aggregate **20.79 MJ/ m^2**		**511MJ/ m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement **137.03 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **50.62 MJ/ m^2**	Decreased transportation by localizing **39.9 MJ/m^2**	
Total Walls	**71.41 MJ/ m^2**	**176.93 MJ/ m2**	**511MJ/ m^2**
	248.34 MJ/m2		

Table A.C.27: Green Star. Potential reduction in carbon emissions (embodied energy) in a cored concrete block wall. Case Study Four (see Lawson 1996, p. 129).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	%20Recycled aggregate for concrete block = **4.15 MJ/m²**		**511 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **82.21 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **10.12 MJ/ m²**		
Green Star, Total Wall	**14.27 MJ/m²**	**82.21 MJ/m²**	**511 MJ/ m²**
	96.48 MJ/m²		

Table A.C.28: Potential reduction in carbon emissions (embodied energy) in a steel framed, steel sheet roof. Case Study Four. (Lawson 1996, p. 135).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Steel from average recycled content** - Steel sheet from average recycled content = 5.6 Kg x {38 MJ/Kg (Lawson 1996, p.135) - 20.10 MJ/Kg} = **100.24 MJ/m²** - Steel frame roofing from recycled content {38 MJ/Kg – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ m² = **61.61 MJ/m²** **Reuse materials and elements** - Use 40% recycled trusses (UK Indemand 2014)**,** 40% x 3.734 kg/m2 x 34 MJ/Kg = **50.78 MJ/m²** - Use recycled thermal insulation, 49MJ/kg - 20.90 MJ/kg x 0.55kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014)
	Green Star **Steel from average recycled content** Material-6 steel (Green Star Technical Manual) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (GBCA 2008) is: - Steel sheet from average recycled content = 5.6 Kg x {38 MJ/Kg - 20.10 MJ/Kg} x 90% = **90.21 MJ/m²** - Steel frame roofing from recycled content {38 MJ/Kg – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ m² x 90% = **55.44 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** If the materials come from inside state (BIG Mate 2014), the saved distance will be 44/9 km Reuse recycled trusses 40% x 3.734 kg/m² /1000 T/m² x 44.9 km x 4.5 MJ/tonne/km = **0.30 MJ/ m²**
	Decreased transportation by localizing suppliers Landscape Supplies, 488 Loganlea Rd, Slacks Creek QLD 4127 (Nuway 2014) considering the local supplier (BIG Mate 2014), the hypothetically decreased distance will be 32.3 = km 9.334 kg/m² /1000 T/m2 x 32.3 km x 4.5 MJtonne/km (Lawson p. 12) = **1.35 MJ/ m²**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) reduction		
Measurable energy to reduce in **Building materials and elements**	Steel frame from average recycled contents **61.61 MJ/m²** Steel Sheet from recycled contents **100.24 MJ/m²**	Use recycled trusses **= 50.78 MJ/m²** Use Recycled insulation = **17.57 MJ/m²**	**401 MJ/** m²
Measurable energy to reduce in **Transportation**		Decreased transportation by reusing **0.30 MJ/ m²** Decreased transportation by localizing**1.35 MJ/m²**	
Total Roof	**161.85 MJ/m²**	**70 MJ/m²**	**401MJ/ m²**
	231.85 MJ/m²		

Table A.C.29. Green Star. Potential reduction in carbon emissions (embodied energy) in a steel parallel chord trussed sheet roof. Case Study Four (see Lawson 1996, p. 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel sheet from 90% Recycled contents = **90.21 MJ/m²** Steel frame from 90% Recycled contents = **55.44 MJ/m²**		**401 MJ/m²**
Green Star, Total Roof	**145.65 MJ/m²**		**401 MJ/ m²**
	145.65 MJ/m²		

Table A.C.30: Potential reduction in carbon emissions (embodied energy) in concrete slab floor, concrete upper floor, concrete block walls, steel framed, steel sheet roof. Case Study Four.

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions to Reduce		Basic
Measurable energy to reduce in **building materials and elements**	**204.48 MJ/m²**	**139.9 MJ/m²**	**2570 MJ/m²**
Measurable energy to reduce in **Implementation**		**426.71 MJ/m²**	
Measurable energy to reduce in **Transportation**	**103.82 MJ/m²**	**97.67 MJ/m²**	
Total, building system	**308.30 MJ/m²**	**664.28 MJ/m²**	**2570 MJ/m²**
	972.58 MJ/m²		

A.C.1.5 Case Study Five – Olympics Velodrome Building, London 2012

Table A.C.31: Potential reduction in carbon emissions (embodied energy) in a 200 mm hollow core precast concrete slab floor. Case Study Five (Lawson 1996, p. 125).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused the recycled aggregates for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014) embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (297 + 84) x (381 kg/m^2concrete – 51.73kg/m^2 cement) x 80% **= 21.84 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 5.148 Kg x {34 MJ/Kg - 20.10 MJ/Kg} = **71.55MJ/m^2**
	Green Star, reused recycled aggregates for concrete Material-5 (Green Star Technical Manual, Materials) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: - Concrete from 20% recycled aggregate (Uche 2008PCA) 2014) embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (381kg/m^2concrete – 51.73kg/m^2 cement) x 20% = **5.46 MJ/m^2** **Steel from average recycled content** Material-6 (Green Star Technical Manual) Steel is considered maximum 60%, therefore reduced embodied energy by this credit (Steel from Recycled content) (GBCA 2008) is: 5.148 Kg x 90% {34 MJ/Kg - 20.10 MJ/Kg} = **64.40 MJ/m^2**

Implementation	**Decreased and replaced energy in reduced cement** Geopolymer concrete or 100% replacement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 381 kg/m2 x 14% cement (Lawson 1996, p. 41) 97% = 51.73 kg replaced cement/ m^2 in concrete 51.73 kg cement/m2 x 5.6 MJ/kg **= 289.74 MJ/ m^2** Reduced Embodied Energy
	Green Star Replacing maximum 60% of cement (GBCA 2008) 381kg/m2 x 14% Cement x 60% = 32 kg replaced cement/ m^2 in concrete 32 kg Cement/m2 x 5.6 MJ/kg **= 179.2 MJ/ m^2**

Transportation	**Decreased transportation of waste by reusing and recycling** Transport of material, one stop supplier. If the materials come from London, the saved distance will be over 100 km (Aggregate Industries 2014) (297 + 5.148 + 84) 386.14 kg/m^2x 80% /1000 T/m^2 x 100 km x 4.5 – (0.6 +0.25) /2} MJ/ton/km **= 125.87 MJ/ m^2**
	Green Star (297 + 5.148 + 84) 386.14 kg/m^2 x 20% /1000 T/m^2 x 100 km x 4.5 – (0.6 +0.25) /2} MJ/ton/km **= 31.47 MJ/ m^2**
	Improved and Replaced Renewable energy in transportation 63% transported by rail or water (London Olympics 2012) 386.148 kg/m2 /1000 T/m2 x 100 km = 157.3 MJ/ton/km x 63% = **99.1 MJ/M2 Transportation Energy consumption**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25
Source: Lawson (1996, p. 12)	

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	%30Recycled aggregate for concrete **21.84 MJ/m^2**	100% Steel from average recycled content **71.55MJ/m^2**	**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer 100% Cement Replacement **289.74 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse **125.87 MJ/ m^2**	Replaced Energy in transportation **99.1 MJ/M^2**	
Total Floor	**147.71MJ/m^2**	**460.39 MJ/m^2**	**908MJ/** m^2
	608.10 MJ/m^2		

Table A.C.32: Green Star. Potential reduction in carbon emissions (embodied energy) in a 200 mm hollow core precast concrete slab floor. Case Study Five (Lawson 1996, p. 125).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in Carbon Emissions (Embodied Energy)		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete = **5.46 MJ/m²**	90% Steel mesh from average recycled content **64.4 MJ/m²**	**908 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacement **179.2 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **31.47 MJ/m²**		
Green Star, Total Floor	**36.93 MJ/m²**	**243.6 MJ/m²**	**908 MJ/ m²**
	280.53 MJ/m²		

Table A.C.33: Potential reduction in carbon emissions (embodied energy) in a 125 mm elevated concrete upper floor. Case Study Five (see Lawson 1996, p. 124).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80% recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (300 Kg concrete – 40.74 kg cement) x 80% =**17.20 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 7.15 Kg x {34 MJ/Kg - 20.10 MJ/Kg} = **99.38 MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 (Green Star Technical Manual) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: Concrete from 20% recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg, saved embodied energy = 0.083 MJ/Kg x (300 Kg concrete – 40.74 kg cement) x 20% **= 4.30 MJ/m^2** **Steel from average recycled content** Material-6 (Green Star Technical Manual, Steel) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (GBCA 2008) is: 7.15 Kg x 90% {34 MJ/Kg - 20.10 MJ/Kg} = **89.44 MJ/m^2**
Implementation	**Decreased and replaced energy in process** **Replaced cement** Geopolymer concrete or 100% replacement by recycled cement substitute (Nath & Sarker 2014) results in 97% reduction in GHG (McLellan et al. 2011) 300kg/m2 x 14% Cement x 97% = 40.74 kg replaced cement/ m^2 in concrete 40.74 kg cement/m2 x 5.6 MJ/kg **= 228.14 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (GBCA 2008) 300kg/m2 x 14% Cement x 60% = 25.2 kg replaced cement/ m^2 in concrete 25.2 kg cement/m2 x 5.6 MJ/kg **= 141.12 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** Waste materials have been brought from inside of state, therefore the saved energy is at least: Aggregate 300kg/m^2 x 80% /1000 T/m^{2}x100 km x {(4.5– (0.6 +0.25) /2} MJ/ton/km = **97.78 MJ/ m^2**
	Green Star Waste materials have been brought from inside of state, therefore the saved energy is at least: Aggregate 300 kg/m^2 x 20% /1000 T/m^2 x 100 km x {(4.5 – (0.6 +0.25) /2} MJ/ton/km = **24.45 MJ/ m^2**
	Improved and Replaced Renewable energy in transportation 63% transported by rail or water (London Olympics 2012) 307.153 kg/m^2 /1000 T/m^2 x 100 km {4.5 – (0.6 +0.25) /2} MJton/km x 63% = **78.85 MJ/m2 Reduced Transportation Energy consumption by type of transportation**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (1996, p. 12)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions (Embodied Energy) to Reduce		Standard
Measurable energy to reduce in **Building materials and elements**	30% Recycled aggregate for concrete **17.20 MJ/m^2**	Steel mesh from average recycled content **99.38MJ/m^2**	**750MJ/m^2**
Measurable energy to reduce in **Implementation**		Use of 40% Fly ash mix = **228.14 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **97.78 MJ/m^2**	Replaced Energy in transportation **78.85 MJ/m^2**	
Total Floor	**114.98 MJ/m^2**	**406.37 MJ/m^2**	**750MJ/m^2**
	521.35 MJ/m^2		

Table A.C.34: Green Star. Potential reduction in carbon emissions (embodied energy) in 125 mm elevated concrete upper floor. Case Study Five (see Lawson 1996, p. 124)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete = **4.30 MJ/m²**	90% Steel mesh from average recycled content **89.44 MJ/m²**	**750 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacement **141.12 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **24,45MJ/m²**		
Green Star, Total Floor	**28.75 MJ/m²**	**230.56 MJ/m²**	**750 MJ/ m²**
	259.31 MJ/m²		

Table A.C.35: Potential reduction in carbon emissions (embodied energy) in a cored concrete block wall. Case Study Five (see Lawson 1996, p. 129).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused recycled materials as aggregate for concrete block** - Concrete from 100% recycled aggregate (Uche 2008; PCA) 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (275 Kg concrete – 24.47 kg cement) = **20.79 MJ/m^2**
	Green Star **Reused recycled materials for concrete block** Material-5 (Green Star Technical Manual) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (275 Kg concrete – 24.47 kg cement) x 20% = **4.15 MJ/m^2**
Implementation	**Decreased and replaced energy in process** **Replaced cement** Geopolymer concrete block or 100% replacement recycled cement substitute results in 80% reduction in GHG (Geiger 2010) Reduced Portland cement = 89Kgs/tonne (Concrete Block Association 2013) /1000 x 275 = 24.47 Kg/m^2 Reduced Portland cement 24.47 Kg/ m^2 x 5.6 MJ/kg **= 137.03 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (GBCA 2008) 24.47 kg cement/m2 x 60% x 5.6 MJ/kg **= 82.21 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** If materials come from London, the saved distance will be over 100 km Reuse aggregate (275 concrete – 24.47 cement) kg.m^2 /1000 T/m^2 x 100 km x 4.5 – {(0.6 +0.25) / 2} MJtonne/km = **102.09 MJ/ m^2**
	Green Star **Decreased transportation of waste by reusing and recycling** If materials come from London, the saved distance will be over 100 km Reuse aggregate (275 concrete – 24.47 cement) kg.m^2 x 20% /1000 T/m^2 x 100 km x 4.5 – {(0.6 +0.25) / 2} MJtonne/km **= 20 41 MJ/ m^2**
	Improved and replaced renewable energy in transportation 63% transported by rail or water (London Olympics 2012) 299.57 kg/m^2 /1000 T/m^2 x 100 km {4.5 – (0.6 +0.25) /2} MJton/km x %63 = **76.90 MJ/m^2** **Reduced Transportation Energy consumption by type of transportation**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (1996, p. 12)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Use 100% recycled aggregates **20.79 MJ/ m^2**		**5**11**MJ/ m^2**
Measurable energy to reduce in Implementation		Geopolymer, replacing 100% of cement **137.03** MJ/m2	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **102.09 MJ/m^2**	Replaced Energy in transportation **76.90 MJ/m^2**	
Total Walls	**122.88 MJ/ m^2**	**213.93 MJ/ m^2**	**511MJ/ m^2**
	336.81 MJ/ m^2		

Table A.C.36: Potential reduction in carbon emissions (embodied energy) in a cored concrete block wall. Case Study Five (see Lawson 1996, p. 129).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate and 60% replaced cement for concrete block = **4.15 MJ/m²**		**511 MJ/m²**
Measurable energy to reduce in Implementation		Geopolymer, replacing 60% of cement **82.21** MJ/m²	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **20 41 MJ/ m²**		
Green Star, Total Wall	**24.56 MJ/m²**	**82.21** MJ/m²	**511 MJ/ m²**
	106.77 MJ/m²		

Table A.C.37: Potential reduction in carbon emissions (embodied energy) in a steel framed timber weatherboard wall. Case Study Five (see Lawson 1996, p. 129).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Steel from average recycled content** - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg - 20.10 MJ/Kg = 3.342 KJ/Kg X 13.9 Kg/ m2 = **46.45 MJ/m2**
	Reused materials and elements (local salvage/re-use centre) Reuse softwood + softwood plates + softwood weatherboard = **74 MJ/m²** (JLL 2012)
	Green Star **Steel from average recycled content** Material-6 Steel (Green Star Technical Manual) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (GBCA 2008) is: - Steel frame roofing from recycled content {38 MJ/Kg – 21.5 MJ/Kg} = 17.5 MJ/Kg x 3.342 kg/ m² x 90% = **55.14 MJ/m²** **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber (Green Star Technical Manual) 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber Reuse softwood + softwood plates + softwood weatherboard = **74 MJ/m²** x 95% = **70.3 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** If materials come from London, the saved distance will be over 100 km 22kg.m² /1000 T/m² x 100 km x 4.5 MJtonne/km = **9.89 MJ/ m²**
	Improved and Replaced Renewable energy in transportation 63% Transported by rail or water (London Olympics 2012) 14.32 kg/m2 /1000 T/m2 x 100 km {4.5 – (0.6 +0.25) /2} MJton/km x %63 = **3.67 MJ/m2** **Reduced Transportation Energy consumption by type of transportation**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson p. 12 (Lawson 1996)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Steel frame from recycled content **46.45 MJ/m²**	Use recycled softwood + weatherboard **74 MJ/m²**	**238 MJ/ m²**
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse= **9.89 MJ/ m²**	Replaced Energy in transportation **3.67 MJ/m²**	
Total Walls	**56.34 MJ/m²**	**77.67 MJ/m²**	**238 MJ/ m²**
	134.01 MJ/m²		

Table A.C.38: Green Star. Potential reduction in carbon emissions (embodied energy) in a steel framed timber weatherboard wall. Case Study Five (Lawson 1996).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel frame from 90% Recycled contents = **55.14 MJ/m²**	Use recycled softwood + weatherboard **70.3 MJ/m²**	**238 MJ/m²**
Green Star, Total Wall	**55.14 MJ/m²**	**70.3 MJ/m²**	**238 MJ/ m²**
	125.44 MJ/m²		

Table A.C.39: Potential reduction in carbon emissions (embodied energy) in a steel framed fabric roof (hemp wrap). Case Study Five (Lawson 1996).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Steel from average recycled content** - **Steel frame roofing** from recycled content {38 MJ/Kg – 20.50 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ m² = **65.34 MJ/m²** **Reused materials and elements** - Use of recycled frame and pipes - Velodrome has high percentage of recycled content and leftover gas pipes make up the Olympic Stadium's ring beam (Karven 2012). The structure involved the use of 28% recycled materials (Ingenia 2014). - Use 40% recycled trusses (UK Indemand 2014) 40% x 3.734 kg/m² x 34 MJ/Kg (Lawson 1996) = **50.78 MJ/m²** **Reduce Materials use in design** The Velodrome is 50% lighter than Beijing stadium (New Steel Construction 2010). A materially efficient double-curved cable net design reduced the embodied carbon by 27% compared to a steel arch option (UK Indemand 2014). - 20% reduction in design x 3.734 kg/m² x 34 MJ/Kg (Lawson 1996) = **25.39 MJ/m²**
	Green Star **Steel from average recycled content** Material-6 Steel (Green Star Technical Manual) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (GBCA 2008) is: - **Steel frame roofing** from recycled content {38 MJ/Kg – 20.50 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ m² x 90% = **58.8 MJ/m²** **Reduce Materials use in design** Material-10 dematerialisation (Green Star Technical Manual) is considered using 20% less steel - 20% reduction in design x 3.734 kg/m² x 34 MJ/Kg = **25.39 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** If materials come from London, the saved distance will be over 100 km (3.384 kg/m² steel frame + 3.384 x 20% kg/m²) /1000 T/m² x 100 km x 4.5 MJtonne/km = **0.82 MJ/ m²**
	Green Star **Decreased transportation of waste by reusing and recycling** If materials come from London, the saved distance will be over 100 km 3.384 x 20% kg/m² /1000 T/m² x 100 km x 4.5 MJtonne/km = **0.30 MJ/ m²**
	Improved and Replaced Renewable energy in transportation 63% Transported by rail or water (London Olympics 2012) 14.32 kg/m² /1000 T/m² x 100 km {4.5 – (0.6 + 0.25) /2} MJton/km x %63 = **2.39 MJ/m² Reduced** **Transportation Energy consumption by type of transportation** Mode / Energy Consumption (MJtonne/km) UK: Road 4.50; Rail 0.60; Ship 0.25 Source: Lawson (1996, p. 12)

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (1996, p. 12)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	100% Steel frame from average recycled contents **65.34 MJ/m²**	Use recycled elements = **50.78 MJ/m²** 20% reduce steel in design **25.39 MJ/m²**	**282MJ**/m²
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse **0.82 MJ/ m²**	Decreased energy by replacing **2.39 MJ/m²**	
Total Roof	**66.16MJ/m²**	**78.56 MJ/m²**	**282MJ/ m²**
	144.72 MJ/m²		

Table A.C.40: Green Star. Potential reduction in carbon emissions (embodied energy) in a steel framed fabric roof (hemp wrap). Case Study Five (see Lawson 1996).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	90% Steel from recycled contents **58.8 MJ/m²**	20% reduce steel in design **25.39 MJ/m²**	**282 MJ/m²**
Measurable energy to reduce in **Transportation**	Decreased transportation by reduce in design **0.3 MJ/ m²**		
Green Star, Total Roof	**59.1 MJ/m²**	**25.39 MJ/m²**	**282 MJ/ m²**
	84.49 MJ/m²		

Table A.C.41: Potential reduction in carbon emissions (embodied energy) in concrete slab floor, concrete upper floor, concrete block walls, steel framed, fabric roof. Case Study Five.

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions (Embodied Energy) to Reduce		Basic
Measurable energy to reduce in **Building materials and elements**	**171.62 MJ/m²**	**321.10 358.72 MJ/m²**	**2689 MJ/m²**
Measurable energy to reduce in **Implementation**	-	**654.91 MJ/m²**	
Measurable energy to reduce in **Transportation**	**336.45 MJ/m²**	**260.91 MJ/m²**	
Total, building system	**508.07 MJ/m²**	**1236.92 MJ/m²**	**2689 MJ/m²**
	1744.99 MJ/m²		

A.C.1.6 Case Study Six – Multi Sports Building, USQ 2013

Table A.C.42: Potential reduction in carbon emissions (embodied energy) in a 110 mm concrete slab on ground floor. Case Study Six (Lawson 1996).

Potential carbon reduction by this research and Green tool	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80% recycled aggregate (Uche 2008; PCA 2014) embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = 0.083 MJ/Kg x (290.4 Kg concrete – 24.38 kg cement) x 80% = **17.65 MJ/m²** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 3.882 Kg x {34 MJ/Kg - 20.10 MJ/Kg} = **53.96MJ/m²**
	Green Star **Reused recycled aggregate for concrete** Material-5 (Green Star Technical Manual) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: - Concrete from 20% recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = 0.083 MJ/Kg x (290.4 Kg concrete – 24.38 kg cement) x 20% = **4.41 MJ/m²** **Steel from average recycled content** Material-6 Steel (Green Star Technical Manual) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (GBCA 2008) is: 3.882 Kg x 90% {34 MJ/Kg - 20.10 MJ/Kg} = **53.95 MJ/m²**

Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete or 100% replacement by recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 290.4 kg/m x 14% Cement x 97% = 39.43 kg replaced cement/ m² in concrete 39.43 kg cement/m2 x 5.6 MJ/kg **= 220.83 MJ/ m²**
	Green Star Replacing maximum 60% of cement (GBCA 2008) 290.4 kg/m2 x 14% cement x 60% = 24.38 kg replaced cement/ m² in concrete 24.38 kg cement/m2 x 5.6 MJ/kg **= 136.59 MJ/ m²**

Transportation	**Decreased transportation of waste by reusing and recycling** If the materials come from local supplier Big Mate Projects, Springfield QLD (BIG Mate 2014), the saved distance will be 44.9 km Reduced transportation by reusing aggregate, 80% x 290.4 kg/m² /1000 T/m² x 44.9 km x 4.5 MJ/ton/km = **46.93 MJ/ m²**
	Green Star Reduced transportation by reusing aggregate, 290.4 kg/m² /1000 T/m² x 44.9 km x 4.5 MJ/ton/km x 20% = **11.73 MJ/ m²**
	Decreased transportation by localizing suppliers Local construction material supplier is Big Mate Projects, Springfield QLD (BIG Mate 2014) If the materials come from somewhere in Brisbane: Landscape Supplies, 488 Loganlea Rd, Slacks Creek QLD 4127 (Nuway 2014) The hypothetically decreased distance will be 32.3 = km (290.4kg aggregate, mesh 3.12kg) = 293.52 kg/m² /1000 T/m2 x 32.3 km x 4.5 MJtonne/km = **42.66 MJ/ m²**

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**	30% Concrete from recycled aggregate = **17.65 MJ/m²**	Steel mesh, beams from average recycled content = **53.96 MJ/m**	**645MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 97% of cement = **220.83 MJ/ m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **46.93 MJ/m²**	Decreased transportation by localizing **42.66 MJ/ m²**	
Total Floor	**64.58 MJ/m²**	**317.45 MJ/m²**	**645MJ**/ m²
	382.03 MJ/m²		

Table A.C.43: Green Star. Potential reduction in carbon emissions (embodied energy) in a 110 mm concrete slab on ground floor. Case Study Six (see Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	%20 Recycled aggregate for concrete = **4.41 MJ/m²**	90%Steel mesh from average recycled content **53.95MJ/m²**	**645 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **136.59 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse aggregate **11.73 MJ/m²**		
Green Star, Total Floor	**16.14 MJ/m²**	**190.54 MJ/m²**	**645MJ/ m²**
	206.68 MJ/m²		

Table A.C.44: Potential reduction in carbon emissions (embodied energy) in a 125 mm elevated concrete upper floor. Case Study Six (see Lawson 1996, p. 124).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80% recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = 0.083 MJ/Kg x (300 Kg concrete – 40.74kg) (Lawson 1996, p. 125) x 80% = **17.20 MJ/m^2** ------ Embodied energy of the floor = 497 **MJ/m^2**, Carbon emission = 497 **MJ/m^2** x 0.098 kg CO^2/ kg = 48.70 kg CO^2/ m^2 The reduced embodied energy = **17.20 MJ/m^2** Reduced carbon emission = **17.20 MJ/m^2** x 0.098 kg CO^2/ kg = 1.68 kg CO^2/ m^2 **Therefore 4.06% emissions reduction** --------------------- **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 7.15 Kg x {34 MJ/Kg (Lawson 1996, p13) - 20.10 MJ/Kg (GreenSpec 201)} = **99.38 MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 (Green Star Technical Manual) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GBCA 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008: PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = 0.083 MJ/Kg (Lawson 1996, p. 13) x (300 Kg concrete – 40.74kg) (Lawson 1996, p.125) x 20% = **4.30 MJ/m^2** **Steel from average recycled content** Material-6 (Green Star Technical Manual) Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (GBCA 2008) is: 7.15 Kg x 90% {34 MJ/Kg (Lawson 1996, p 13) - 20.10 MJ/Kg (GreenSpec 2015)} = **89.44 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete or 100% replacement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 300kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 97% = 40.74 kg replaced cement/ m^2 in concrete 40.74 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 228.14 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (GBCA 2008) 300kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) x 60% = 25.2 kg replaced cement/ m^2 in concrete 25.2 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 141.12 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** If the materials come from locally, the saved distance will be 44.9 km Reduced transportation by reusing 80% x 307.12 kg/m^2 /1000 T/m2 x 44.9 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **49.63 MJ/ m^2**
	Green Star If the materials come from locally, the saved distance will be 44.9 km Reduced transportation by reusing 307.12 kg/m^2 /1000 T/m2 x 44.9 km x 4.5 MJtonne/km (Lawson 1996, p. 12) 20% = **12.41 MJ/ m^2**
	Decreased transportation by localizing the suppliers Landscape Supplies, 488 Loganlea Rd, Slacks Creek QLD 4127 (Nuway 2014) The hypothetically decreased distance will be 32.3 = km (Nuway 2014) 307.12 kg/m^2 /1000 T/m2 x 32.3 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **44.63 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) reduction		
Measurable energy to reduce in **Building materials and elements**	30% Recycled aggregate for concrete **17.20 MJ/m^2**	Steel mesh from average recycled content **99.38MJ/m^2**	**750MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement **228.14 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **49.63 MJ/ m^2**	Decreased transportation by localizing **44.63 MJ/ m^2**	
Total Floor	**66.83 MJ/m^2**	**372.15 MJ/m^2**	**750MJ/m^2**
	438.98 MJ/m^2		

Table A.C.45: Green Star. Potential reduction in carbon emissions (embodied energy) in 125 mm elevated concrete upper floor. Case Study Six (Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete **4.30 MJ/m^2**	90%Steel mesh from average recycled content **89.44MJ/m^2**	**750 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacement **141.12 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **12.41 MJ/ m^2**		
Green Star, Total elevated Floor	**16.71 MJ/m^2**	**230.56 MJ/m^2**	**750MJ/ m^2**
	247.27 MJ/m^2		

Table A.C.46: Potential reduction in carbon emissions (embodied energy) in a cored concrete block wall. Case Study Six (Lawson 1996, p. 129)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled materials as aggregate for concrete block** - Concrete from 100% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (275 Kg concrete – 24.47 kg cement) (Lawson 1996, p.129) = **20.79 MJ/m^2**
	Green Star **Reused recycled materials for concrete block** Material-5 (Green Star Technical Manual) is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (GCBA 2008) is: Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (275 Kg concrete – 24.47 kg cement) (Lawson 1996, p. 129) x 20% = **4.15 MJ/m^2**
Implementation	**Decreased and replaced energy** **Replaced cement** Geopolymer concrete block or 100% replacement recycled cement substitute results in 80% reduction in GHG (Geiger 2010) Reduced Cement = 89Kgs/tonne (Concrete Block Association 2013) / 1000 x 275 = 24.47 Kg/ m^2 Reduced cement 24.47 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 137.03 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (GBCA 2008) 24.47 kg Cement/m2 x 60% x 5.6 MJ/kg (Lawson 1996, p. 13) **= 82.21 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** If the materials come from local supplier, Big Mate Projects, Springfield QLD (BIG Mate 2014), the saved distance will be 44/9 km Reduced transport for Recycled materials for Reuse aggregate (275 concrete – 24.47 cement) kg.m^2 /1000 T/m2 x 44.9 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) = **50.62 MJ/ m^2**
	Green Star Reduced transport for Recycled materials for Reuse aggregate (275 concrete – 24.47 cement) kg.m^2 /1000 T/m2 x 44.9 km x 4.5 MJ/tonne/km (Lawson 1996, p. 12) x 20% = **10.12 MJ/ m^2**
	Decreased transportation by localizing the suppliers Landscape Supplies, 488 Loganlea Rd, Slacks Creek QLD 4127 (Nuway 2014) The hypothetically decreased distance will be 32.3 km (Nuway 2014) 275 kg/m^2 /1000 T/m2 x 32.3 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **39.9 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) to reduce		
Measurable energy to reduce in **Building materials and elements**	Use recycled materials as aggregate **20.79 MJ/ m^2**		**511MJ/ m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement **137.03 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **50.62 MJ/ m^2**	Decreased transportation by localizing **39.9 MJ/m^2**	
Total Walls	**71.41 MJ/ m^2**	**176.93 MJ/ m2**	**511MJ/ m^2**
	248.34 MJ/m2		

Table A.C.47: Green Star. Potential reduction in carbon emissions (embodied energy) in a cored concrete block wall. Case Study Six (Lawson 1996, p. 129).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete block **4.15 MJ/m²**		**511 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer 60% Cement Replacements **82.21 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **10.12 MJ/ m²**		
Green Star, Total Wall	**14.27 MJ/m²**	**82.21 MJ/m²**	**511 MJ/ m²**
	96.48 MJ/m²		

Table A.C.48: Potential reduction in carbon emissions (embodied energy) in a steel parallel chord trussed sheet roof. Case Study Six (Lawson 1996, p. 135).

	Processes where carbon emissions (embodied energy) can be reduced
Building materials and elements	**Steel from average recycled content** **-** Steel sheet from average recycled content = 5.6 Kg x {38 MJ/Kg (Lawson 1996, p.135) - 20.10 MJ/Kg} = 100.24 MJ/m² - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ **m² = 61.61 MJ/m²** **Reuse materials and elements** - Use 40% recycled trusses (UK Indemand 2014)**,** 40% x 3.734 kg/m2 x 34 MJ/Kg = **50.78 MJ/m²** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.55kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014) - Use thermal insulation with recycled contents = **40 MJ/m2** (Steel Construction Information 2014)
	Green Star **Steel from average recycled content** Material-6 Steel (Green Star Technical Manual) is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (GBCA 2008) is: **-** Steel sheet from average recycled content = 5.6 Kg x {38 MJ/Kg (Lawson 1996, p.135) - 20.10 MJ/Kg} x 90% = **90.21 MJ/m²** - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ m² x 90% = **55.44 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** If the materials come from local supplier Big Mate Projects (BIG Mate 2014), the saved distance will be 44/9 km Reuse recycled trusses 40% x 3.734 kg/m² /1000 T/m² x 44.9 km x 4.5 MJ/tonne/km (Lawson 1886, p. 12) = **0.30 MJ/ m²**
	Decreased transportation by localizing suppliers Landscape Supplies, 488 Loganlea Rd, Slacks Creek QLD 4127 (Nuway 2014), considering the local supplier (BIG Mate 2014), the hypothetically decreased distance will be 32.3km 9.334 kg/m² /1000 T/m2 x 32.3 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = 1.35 MJ/ m²

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) to reduce		
Measurable energy to reduce in **Building materials and elements**	Steel frame from average recycled content **61.61 MJ/m²** Steel Sheet from recycled content **100.24 MJ/m²**	Use recycled trusses **= 50.78 MJ/m²** Use Recycled insulation = **17.57 MJ/m²**	**401 MJ/** m²
Measurable energy to reduce in **Transportation**		Decreased transportation by reusing **0.30 MJ/ m²** Decreased transportation by localizing**1.35 MJ/m²**	
Total Roof	**161.85 MJ/m²**	**70 MJ/m²**	**401MJ/ m²**
	231.85 MJ/m²		

Table A.C.49: Green Star. Potential reduction in carbon emissions (embodied energy) in a steel parallel chord trussed sheet roof. Case Study Six (Lawson 1996, p. 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel sheet from 90% Recycled contents = **90.21 MJ/m^2** Steel frame from 90% Recycled contents = **55.44 MJ/m^2**		**401 MJ/m^2**
Green Star, Total Roof	**145.65 MJ/m^2**		**401 MJ/ m^2**
	145.65 MJ/m^2		

Table A.C.50: Potential reduction in carbon emissions (embodied energy) in concrete slab floor, concrete upper floor; concrete block walls, steel parallel chord trussed roof. Case Study Six.

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emissions (Embodied Energy) reduction		
Measurable replaced and saved energy in **Building materials and elements**	**217.49 MJ/m^2**	**221.69 MJ/m^2**	**2307 MJ/m^2**
Measurable replaced and saved energy in **Implementation**		**586 MJ/m^2**	
Measurable replaced and saved energy in **Transportation**	**147.18 MJ/ m^2**	**128.84 MJ/m^2**	
Total, building system	**364.67 MJ/m^2**	**936.53 MJ/m^2**	**2307 MJ/m^2**
	1301.20 MJ/m^2		

A.C.1.7 Implemented Calculations (example)

Olympic Velodrome Building, London 2012. Case Study Five

The following are calculations of the implemented embodied energy and generated carbon emissions for the main building elements (floor, wall and roof) of Case Study Five. These are based on the actual bioclimatic conditions achieved during the construction process, as presented in the following table.

Table A.C.51: Bioclimatic conditions in the London Olympic Velodrome.

Olympic Velodrome Building, London 2012
 Source: London Olympics (2012)
Location: Olympic Park, London
Floor construction system: Concrete slab floor, concrete upper floor
Wall construction system: Concrete block walls, steel frame timber wall
Roof construction system: Steel frame, fabric roof (commercial)
Principal architects: Jonathan Watts, George Oates, Olympic Park London Construction completed in 2012

Bioclimatic conditions	
Reuse, recycle material resources; Localise suppliers and reduce transport	
Aggregates for concrete	80 per cent recycled aggregate was used in the concrete (Ingenia 2014)
Steel and steel mesh	100 per cent steel and steel mesh was used from average recycled content (Steel Construction Information 2014)
Reduce material use in design	Reduced materials in structural design 50 per cent
Reuse construction materials	Reuse of leftover gas pipes for construction of the Olympic stadium's ring beam (Karven 2012) Reuse softwood from local salvage/re-use centre (JLL 2012)
Geopolymer, fly ash and cement substitute	Geopolymer cement replaces Portland cement
Transportation reduction by reuse, recycle, and sustainable transportation mode	By reusing and recycling, transportation was reduced. Transport when necessary was by rail or water (London Olympics 2012)
Material resources and suppliers	Construction material suppliers are outside London; thus, distance is more than 100km (Aggregate Industries 2014)

The Velodrome is 50 per cent lighter than Beijing's stadium (New Steel Construction 2010). It achieved 34 per cent use of recycled materials, well above its target of 20 per cent; and 63 per cent (by weight) of construction materials were transported to the Olympic Park by rail or water (London Olympics 2012). A quarter of all materials used in the building are recycled, including up to 76 per cent recycled aggregate (using stent, a by-product of the Cornish china clay industry), and 40 per cent recycled cement substitute (ground granulated blast furnace slag) in the concrete; 60 per cent recycled content in the interior block work (Ingenia 2014).

The velodrome has a high percentage of recycled content, and leftover gas pipes make up the Olympic Stadium's ring beam, reducing the need for new steel to be produced (Institution of Civil Engineers 2012). The roof design for the stadium is a fabric 'wrap' made of hemp (London Olympics 2012). The cable-net design reduced the embodied carbon by 27 per cent compared to a steel arch option (UK Indemand 2014).

Table A.C.52: Potential reduction in carbon emissions (embodied energy) in a 200mm hollow core precast concrete slab floor (see Lawson 1996, p 125).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled aggregates for concrete** - Concrete from 76% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (297 + 84) x (381 kg/m^{2}concrete – 51.73kg/m^2 cement) (Lawson 1996, p. 125) x 76% **= 20.74 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 5.148 Kg x {34 MJ/Kg (Lawson 1996, p13) - 20.10 MJ/Kg} = **71.55MJ/m^2**
Implementation	**Decreased and replaced energy** **Reduced Cement** Geopolymer concrete or 100% replacement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 381 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 97% = 51.73 kg replaced cement/ m^2 in concrete 51.73 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 289.74 MJ/ m^2** Reduced Embodied Energy
Transportation	**Decreased transportation of waste by reusing and recycling** Transport of material, one stop supplier, Great sustainability rating for products and transport, Bespoke products. If the materials come from London, the saved distance will be over 100 km (Aggregate Industries 2014) (297 + 5.148 + 84) 386.14 kg/m^{2}x 76 % /1000 T/m^2 x 100 km x 4.5 – (0.6 +0.25) /2} MJ/ton/km (Lawson 1996, p. 12**) = 119.57 MJ/ m^2**
	Improved and Replaced Renewable energy in transportation 63% Transported by rail or water 386.148 kg/m2 /1000 T/m2 x 100 km {4.5 – (0.6 +0.25) /2} = 157.3 MJ/ton/km (Lawson 1996, p. 12) x %63 = **99.1 MJ/M2 Transportation Energy consumption**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (1996, p.12)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	76% Recycled aggregate for concrete **20.74 MJ/m^2**	100% Steel from average recycled content **71.55MJ/m^2**	**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer 100% Cement Replacement **289.74 MJ/m^2**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse **119.57 MJ/ m^2**	Replaced Energy in transportation **99.1 MJ/M^2**	
Total Floor	**140.31 MJ/m^2**	**460.39 MJ/m^2**	**908MJ/** m^2
	600.70 MJ/m^2		

Table A.C.53: Potential reduction in carbon emissions (embodied energy) in a 125-mm elevated concrete upper floor (Lawson 1996, P. 124).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 76% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (300 Kg concrete – 40.74 kg cement) (Lawson 1996,125, Legend 3) x 76% =**16.34 MJ/m²** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 7.15 Kg x {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **99.38 MJ/m²**

Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete or 100% replacement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 300kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 97% = 40.74 kg replaced cement/ m² in concrete 40.74 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 228.14 MJ/ m²**

Transportation	**Decreased transportation of waste by reuse and recycling** If materials come from outside London, the distance would be over 100 km, but the waste materials have been reused, therefore the saved energy is at least: Aggregate300 kg/m² x76% /1000T/m²x100 km x {(4.5 – (0.6 +0.25) /2} MJ/ton/km (Lawson 1996, p.12) = **92.89MJ/ m²**
	Improved and Replaced Renewable energy in transportation 63% Transported by rail or water 307.153 kg/m² /1000 T/m² x 100 km {4.5 – (0.6 +0.25) /2} MJton/km (Lawson 1996, p. 12) x %63 = **78.85 MJ/m2 Reduced Transportation Energy consumption by type of transportation**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (1996, p. 12)

Life Cycle Stages of building	Construction		Embodied Energy Standard
	Pre-Construction	Construction	
	Potential Carbon Emissions (Embodied Energy) to Reduce		
Measurable energy to reduce in **Building materials and elements**	30% Recycled aggregate for concrete **16.34 MJ/m²**	Steel mesh from average recycled content **99.38MJ/m²**	**750MJ/m²**
Measurable energy to reduce in **Implementation**		Use of 40% Fly ash mix = **228.14 MJ/m²**	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **92.89 MJ/ m²**	Replaced Energy in transportation **78.85 MJ/m²**	
Total Floor	**109.23 MJ/m²**	**406.37 MJ/m²**	**750MJ/m²**
	515.60 MJ/m²		

Table AC.54: Potential reduction in carbon emissions (embodied energy) in a cored concrete block wall (Lawson 1996, p. 129).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled materials as aggregate for concrete block** - Concrete from100% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (275 Kg concrete – 24.47 kg cement) (Lawson 1996, p. 129) = **20.79 MJ/m^2**
Implementation	**Decreased and Replaced energy** **Replaced cement** Geopolymer concrete block or 100% replacement with recycled cement substitute results 80% reduction in GHG (Geiger 2010) Reduced Portland Cement= 89Kgs/tonne (Concrete Block Association 2013) /1000 x 275 =24.47 Kg/m^2 Reduced Portland cement 24.47 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 137.03 MJ/ m^2**
Transportation	**Decreased transportation of waste by reusing and recycling** Materials are from London, thus saved distance will be over 100 km Reuse aggregate (275 concrete – 24.47 cement) kg.m^2 /1000 T/m^2 x 100 km x 4.5 – {(0.6 +0.25) / 2} MJtonne/km (Lawson 1996, p. 12) = **102.09 MJ/ m^2**
	Improved and Replaced Renewable energy in transportation 63% Transported by rail or water 299.57 kg/m^2 /1000 T/m^2 x 100 km {4.5 – (0.6 +0.25) /2} MJton/km (Lawson 1996, p. 12) x 63% = **76.90 MJ/m^2 Reduced Transportation Energy consumption by type of transportation**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (1996, p.12)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Use 100% recycled aggregates **20.79 MJ/ m^2**		**511MJ/ m^2**
Measurable energy to reduce in Implementation		Geopolymer, replacing 100% of cement **137.03** MJ/m2	
Measurable energy to reduce in **Transportation**	Decreased transportation by reusing **102.09 MJ/m^2**	Replaced Energy in transportation **76.90 MJ/m^2**	
Total Walls	**122.88 MJ/ m^2**	**213.93 MJ/ m^2**	**511MJ/ m^2**
	336.81 MJ/ m^2		

Table A.C.55: Potential reduction in carbon emissions (embodied energy) in a steel framed timber weatherboard wall (Lawson 1996, p. 125).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Steel from average recycled content** - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13 - 20.10 MJ/Kg GreenSpec = 3.342 KJ/Kg X 13.9 Kg/ m2 = **46.45 MJ/m2**
	Reused materials and elements (local salvage/re-use centre) Reuse softwood + softwood plates + softwood weatherboard = **74 MJ/m²** (Lawson 1996, p. 125; JLL 2012)

Transportation	**Decreased transportation of waste by reusing and recycling** Construction materials from London, thus saved distance will be over 100 km 22kg.m²/1000 T/m² x 100 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **9.89 MJ/ m²**
	Improved and Replaced Renewable energy in transportation 63% Transported by rail or water 14.32 kg/m2 /1000 T/m2 x 100 km {4.5 – (0.6 +0.25) /2} MJton/km (Lawson 1996, p. 12) x 63% = **3.67 MJ/m2 Reduced Transportation Energy consumption by type of transportation**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (Lawson 1996, p. 12)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Steel frame from recycled content **46.45 MJ/m²**	Use recycled softwood + weatherboard **74 MJ/m²**	**238 MJ/ m²**
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse= **9.89 MJ/ m²**	Replaced Energy in transportation **3.67 MJ/m²**	
Total Walls	**56.34 MJ/m²**	**77.67 MJ/m²**	**238 MJ/ m²**
	134.01 MJ/m²		

Table A.C.56: Potential reduction in carbon emissions (embodied energy) in a steel framed, fabric roof (hemp wrap) (Lawson 1996, p. 133).

	Processes where carbon emissions (embodied energy) can be reduced
Building materials and elements	**Steel from average recycled content** - **Steel frame roofing** from recycled content {38 MJ/Kg (Lawson 1996) – 20.50 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ **m²** = **65.34 MJ/m²** **Reused materials and elements** - Use recycled frame and pipes - Velodrome has a high percentage of recycled content and leftover gas pipes make up the Olympic Stadium's ring beam (Karven 2012) The structure involved the use of 28% recycled materials (Ingenia 2014). - Use 40% recycled trusses (UK Indemand 2014) 40% x 3.734 kg/m² x 34 MJ/Kg (Lawson 1996, p. 13) = **50.78 MJ/m²** **Reduce Materials use in design** A materially efficient double-curved cable net design reduced the embodied carbon by 27% compared to a steel arch option (UK Indemand 2014). - 50% reduce in design x 3.734 kg/m² x 34 MJ/Kg (Lawson 1996, p. 13) = **63.47 MJ/m²**
Transportation	**Decreased transportation of waste by reusing and recycling** Materials from London, thus saved distance will be over 100 km 3.734 kg/m² steel frame x 50% kg/m² /1000 T/m² x 100 km x 4.5 MJtonne/km (Lawson 1996, p. 12) = **0.84 MJ/ m²**
	Improved and Replaced Renewable energy in transportation 63% Transported by rail or water 14.32 kg/m² /1000 T/m² x 100 km {4.5 – (0.6 +0.25) /2} MJton/km (Lawson 1996, p. 12) x 63% = **2.39 MJ/m²** **Reduced Transportation Energy consumption by type of transportation**

Mode	Energy Consumption (MJtonne/km) UK
Road	4.50
Rail	0.60
Ship	0.25

Source: Lawson (1996, p. 12)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	100% Steel frame from average recycled contents **65.34 MJ/m²**	Use recycled elements = **50.78 MJ/m²** 50% reduce steel in design **63.47 MJ/m²**	**282MJ**/m²
Measurable energy to reduce in **Transportation**	Decreased transportation by reuse **0.84 MJ/ m²**	Decreased energy by replacing **2.39 MJ/m²**	
Total Roof	**66.18MJ/m²**	**116.64 MJ/m²**	**282MJ/ m²**
	182.82 MJ/m²		

Table A.C.57: Case Study 5. Potential reduction in carbon emissions (embodied energy) in a concrete slab floor, concrete upper floor; concrete block walls, steel framed, fabric roof construction system

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emissions (Embodied Energy) to Reduce		Basic
Measurable energy to reduce in **Building materials and elements**	**169.66 MJ/m²**	**359.18 MJ/m²**	**2689 MJ/m²**
Measurable energy to reduce in **Implementation**	-	**654.91 MJ/m²**	
Measurable energy to reduce in **Transportation**	**325.28 MJ/m²**	**260.91 MJ/m²**	
Total, building system	**494.94 MJ/m²**	**1275 MJ/m²**	**2689 MJ/m²**

A.C.2 RESEARCH MODEL APPLIED TO GENERAL AUSTRALIAN FLOOR, WALL AND ROOF CONSTRUCTION SYSTEMS

A.C.2.1 Potential carbon emission reductions in general Australian floor construction systems

a. Elevated Timber Floor (lowest level)

Table A.C.58: Potential reduction in carbon emissions in an elevated timber floor (lowest level) (see Lawson 1996, p. 124),

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse the recycled aggregate for concrete** - Concrete from 80 % Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (26.4 kg concrete – 3.69 cement) Kg x 80% (Lawson, 1996, p.125) =**1.52 MJ/m²** Reuse the recycled aggregate for brick, 67% (Brick Development Association 2014; Tyrell & Goode 2014) 36 kg/m² (Lawson, 1996, p.124, L 1) x 67% x 0.083 MJ/kg = **2 MJ/ m²**
	Reuse materials and elements - Use recycled bricks 60% x 90 **= 54MJ/m²** -Timber products re-used, post-consumer recycled timber or FSC certified timber, use recycled hardwood joist, flooring, 54 MJ/m² x (Lawson 1996, p.124), 60% = **32.4 MJ/m²**
	Green Star **Reused recycled aggregate for concrete** Material-5 Green Star Technical Manual is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (26.4 concrete – 3.69 cement) Kg (Lawson 1996, p.125) x 20% = **0 .38 MJ/m²** Material-8 Timber, Green Star Technical Manual 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber 60% Recycled hardwood joints use recycled hardwood joist, flooring ,54 MJ/m² x (Lawson 1996, p.124), 60% = **32.4 MJ/m²**

Implementation	**Decrease and replace energy in process** **Replaced cement** Geopolymer concrete or 100% replacement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011; Kotrayothar 2012) 26.4 kg/m² (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 3.69 kg replaced cement/ m² in concrete 3.69 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 20.66 MJ/ m²** Potential 40 per cent energy savings in brick manufacturing using 67% recycled container glass brick grog (Brick Development Association 2014; Tyrell & Goode 2014). Reduced energy 90 MJ/m² x 40% = **36 MJ/m²**
	Green Star **Replaced cement** Geopolymer concrete or 60% replacement with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 26.4 kg/m² (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = 2.29 kg replaced cement/ m² in concrete 2.29 kg Cement/m2 x 5.6 MJ/kg (Lawson1996, p.13) **= 12.82 MJ/ m²**

Life cycle stages of building	Construction		Embodied Energy Standard
	Pre-Construction	Construction	
	Potential Embodied Energy to Replace and Save		
Measurable energy to reduce in **Building materials and elements**	Concrete from recycled aggregate **1.52 MJ/m²** 67% Use recycled aggregate for brick **2KJ/m²**	Use recycled brick **54MJ/m²** Use recycled Hardwood **32.4 MJ/m²**	**293MJ/m²**
Measurable energy to reduce in **Implementation**	40% saving energy in production **36** MJ/m²	Geopolymer concrete **20.66 MJ/ m²**	
Total Floor	**39.52 MJ/m²**	**107.06 MJ/m²**	**293MJ/** m²
	146.58 MJ/m²		

Table A.C.59: Green Star. Potential reduction in carbon emissions in an elevated timber floor (lowest level) (Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Concrete from recycled aggregate **0.38 MJ/m²**	Use recycled Hardwood **32.4 MJ/m²**	**293 MJ/m²**
Implementation		Geopolymer concrete **12.82 MJ/ m²**	
Green Star, Total Floor	**0.38 MJ/ m²**	**45.22 MJ/m²**	**293 MJ/ m²**
	45.60 MJ/m²		

b. Elevated Timber Floor (upper level)

Table A.C.60: Potential reduction in carbon emissions in a timber framed timber floor upper floor (Lawson 1996, p. 124).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused materials and elements** 60% Recycled softwood joints (Design Coalition 2013) @ (600 c-c) 300x 500 mm + Timber flooring @ 18 mm particleboard 50 MJ/m² + 91 MJ/m²= 60% x 141 MJ/m² P. 124, L.1 = **84.6 MJ/m²** (Steel Construction Information 2014)
	Material-8 Timber, Green Star Technical manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber (Green building Council of Australia 2008) 60% Recycled softwood joints (Design Coalition 2013) @ (600 c-c) 300x 500 mm + Timber flooring @ 18 mm particleboard 50 MJ/m² + 91 MJ/m²= %60 x 141 MJ/m² P. 124 = **84.6 MJ/m²** (Steel Construction Information 2014)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		
Measurable energy to reduce in **Building materials and elements**		60% Recycled timber floor **84.6 MJ/m²**	**147MJ/m²**
Total Floor		**84.60 MJ/m²**	**147MJ/ m²**
	84.60 MJ/m²		

Table A.C.61: Green Star. Potential reduction in carbon emissions in a timber framed timber floor upper floor (Lawson 1996, p. 124)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		60% Recycled timber floor **84.6 MJ/m²**	**147 MJ/m²**
Green Star, Total Floor		**84.6 MJ/m²**	**147 MJ/ m²**
	84.60 MJ/m²		

c. 110 mm Concrete Slab on ground

Table A.C.62: Potential reduction in carbon emissions in a 110-mm concrete slab on ground floor (Lawson 1996, p. 124).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (290.4 concrete –39.43 cement) Kg (Lawson 1996, p.125) x 80% =**16.67 MJ/m²** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 3.882 Kg x {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **53.96MJ/m²**
	Green Star **Reused recycled aggregate for concrete** Material-5 Green Star Technical Manual is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (290.4 concrete –39.43 cement) Kg (Lawson 1996, p.125) x 20% = **4.16 MJ/m²** **Steel from average recycled content** Material-6 Green Star Technical Manual, steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: 3.882 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **53.95 MJ/m²**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer Concrete or 100% replacing with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 290.4 kg/m2 (Lawson1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 39.43 kg replaced cement/ m² in concrete 39.43 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 220.83 MJ/ m²**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 290.4 kg/m2 (Lawson1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = 24.38 kg replaced cement/ m² in concrete 24.38 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 60% **= 81.91 MJ/ m²**

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**	Concrete from 80% recycled aggregate = **16.67 MJ/m²**	Steel mesh, beams from average recycled content = **53.96 MJ/m**	**645MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **220.83 MJ/ m²**	
Total Floor	**16.67 MJ/m²**	**274.79 MJ/m²**	**645MJ/** m²
	291.46 MJ/m²		

Table A.C.63: Green Star. Potential reduction in carbon emissions in a 110-mm concrete slab on ground floor (Lawson 1996, p. 124)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete = **4.16 MJ/m²**	90%Steel mesh from average recycled content **53.95MJ/m²**	**645 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **136.59 MJ/m²**	
Green Star, Total Floor	**4.16 MJ/m²**	**190.54 MJ/m²**	**645MJ/ m²**
	194.70 MJ/m²		

d. 125mm Elevated Concrete Slab (temporary framework)

Table A.C.64: Potential reduction in carbon emissions in a 125-mm elevated concrete upper floor (Lawson 1996, p. 124-6)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	Reused recycled aggregate for concrete - Concrete from 80% Recycled aggregate (Uche 2008: PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (300 Kg concrete – 40.74 kg cement) (Lawson 1996, p. 125) x 80% =17.20 MJ/m^2 Steel from average recycled content - Steel mesh +Edge beams from average recycled content = 7.15 Kg x {34 MJ/Kg (Lawson 1996, p13) - 20.10 MJ/Kg} = 99.38 MJ/m^2
	Green Star Reused recycled aggregate for concrete Material-5 Green Star Technical manual is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg saved embodied energy = 0.083 MJ/Kg x (300 Kg concrete – 40.74 kg cement) (Lawson 1996, p.125) x 20% = 4.30 MJ/m^2 Steel from average recycled content Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: 7.15 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = 89.44 MJ/m^2
Implementation	Decreased and Replaced energy in process Replaced cement Geopolymer concrete or 100% replacing with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 300kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996. p. 41) = 40.74 kg replaced cement/ m^2 in concrete 40.74 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) = 228.14 MJ/ m^2
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 300kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = 25.2 kg replaced cement/ m^2 in concrete 25.2 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) = 141.12 MJ/ m^2

Life Cycle Stages of building	**Construction**		**Embodied Energy Standard**
	Pre-Construction	**Construction**	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in Building materials and elements	**80% Recycled aggregate for concrete 17.20 MJ/m^2**	**Steel mesh from average recycled content 99.38MJ/m^2**	**750MJ/m^2**
Measurable energy to reduce in Implementation		**Use of 40% Fly ash mix = 228.14 MJ/m^2**	
Total Floor	**17.20 MJ/m^2**	**327.52 MJ/m^2**	**750MJ/m^2**
	344.72 MJ/m^2		

Table A.C.65: Green Star. Potential reduction in carbon emissions in a 125-mm elevated concrete upper floor (Lawson 1996, p. 124-6).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete = **4.30 MJ/m^2**	90%Steel mesh from average recycled content **89.44 MJ/m^2**	**750 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **141.12 MJ/m^2**	
Green Star, Total Floor	**4.30 MJ/m^2**	**230.56 MJ/m^2**	**750 MJ/ m^2**
	234.76 MJ/m^2		

e. 110mm elevated concrete slab (permanent frame work)

Table A.C.66: Potential reduction in carbon emissions in a 110-mm concrete slab (permanent framework) **(**Lawson 1996, p. 125)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80 % Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (264 concrete –36.96 cement) Kg (Lawson 1996, p.125) x 80% =**15.07 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 2.5 Kg x {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **34.75MJ/m^2** Steel formwork from average recycled content = 3.66 Kg x {38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **65.51MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 Green Star Technical manual is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (264 concrete –36.96 cement) Kg (Lawson 1996, p.125) x 20% = **3.76 MJ/m^2** **Steel from average recycled content** Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: Steel mesh, 2.5 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **31.27 MJ/m^2** Steel formwork 3.66 Kg x 90% {38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **58.96 MJ/m^2**

Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer Concrete or 100% replacing with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 264 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 36.96 kg replaced cement/ m^2 in concrete 36.96 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 206.97 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 264 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = **22.17** kg replaced cement/ m^2 in concrete 22.17 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 124.15 MJ/ m^2**

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**	Concrete from 80% recycled aggregate = **15.07 MJ/m^2**	Steel mesh, beams from average recycled content = **34.75MJ/m^2** Steel formwork from average recycled content = **65.51 MJ/m**	**665MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **206.97 MJ/ m^2**	
Total Floor	**15.07 MJ/m^2**	**277.23 MJ/m^2**	**665MJ/** m^2
	292.3 MJ/m^2		

Table A.C.66-1: Green Star. Potential reduction in carbon emissions in a 110-mm concrete slab (permanent framework) (Lawson 1996, p. 124)

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete = **3.76 MJ/m^2**	90%Steel mesh from average recycled content **31.27MJ/m^2** Steel formwork from average recycled content = **58.96 MJ/m**	**665 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacement **124.15 MJ/m^2**	
Green Star, Total Floor	**3.76 MJ/m^2**	**214.38 MJ/m^2**	**665MJ/ m^2**
	218.14 MJ/m^2		

f. 200mm Precast Concrete Tee Beam/Infill flooring

Table A.C.67: Potential reduction in carbon emissions in a 200-mm precast concrete tee beam/infill floor (Lawson 1996, p. 125).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (182.88 concrete – 25.60 cement) Kg (Lawson 1996, p. 125) x 80% =**10.44 MJ/m²** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 4.216 Kg x {34 MJ/Kg (Lawson 1996, p.13) - 20.10 MJ/Kg} = **58.51 MJ/m²** Steel formwork from average recycled content = 3.66 Kg x {38 MJ/Kg (Lawson 1996, p.13) - 20.10 MJ/Kg} = **65.51MJ/m²**
	Green Star **Reused recycled aggregate for concrete** Material-5 Green Star Technical Manual, considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (182.88 concrete – 25.60 cement) Kg (Lawson 1996, p. 125) x 20% = **2.61 MJ/m²** **Steel from average recycled content** Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: Steel mesh, 4.216 Kg x 90% {34 MJ/Kg (Lawson 1996, p.13) - 20.10 MJ/Kg} = **52.74 MJ/m²** Steel formwork 3.66 Kg x 90% {38 MJ/Kg (Lawson 1996, p.13) - 20.10 MJ/Kg} = **58.96 MJ/m²**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer Concrete or 100% replacing with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 182.88 kg/m2 (Lawson p. 124) x 14% Cement (Lawson 1996, p. 41) = 24.83 kg replaced cement/ m² in concrete 24.83 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 139.04 MJ/ m²**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 182.88 kg/m2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = **15.36** kg replaced cement/ m² in concrete 15.36 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 86.01 MJ/ m²**

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**	Concrete from 80% recycled aggregate = **10.44 MJ/m²**	Steel mesh, beams from average recycled content = **58.51MJ/m²** Steel formwork from average recycled content = **65.51 MJ/m**	**665MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **139.04 MJ/ m²**	
Total Floor	**10.44 MJ/m²**	**263.06 MJ/m²**	**665MJ/** m²
	273.50 MJ/m²		

Table A.C.68: Green Star Potential reduction in carbon emissions in a 200-mm precast concrete tee beam/infill floor (Lawson 1996, p. 124).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	%20 Recycled aggregate for concrete = **2.61 MJ/m²**	90%Steel mesh from average recycled content **52.74MJ/m²** Steel formwork from average recycled content = **58.96 MJ/m**	**665 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **124.15 MJ/m²**	
Green Star, Total Floor	**2.61 MJ/m²**	**235.85 MJ/m²**	**665MJ/ m²**
	238.46 MJ/m²		

g. 200mm Hollow Core Precast Concrete flooring

Table A.C.69: Potential reduction in carbon emissions in a 200-mm hollow core precast concrete slab floor (Lawson 1996, p. 125).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused the recycled aggregates for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083MJ/Kg x (381 kg/m^{2}concrete – 51.73kg/m^2 cement) (Lawson, 1996, p.125) x 80% = **21.84 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 5.148 Kg x {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **71.55 MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 Green Star Technical Manual, considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (381 kg/m^{2}concrete – 51.73kg/m^2 cement) (Lawson 1996, p. 125) x 20% = **5.46 MJ/m^2** **Steel from average recycled content** Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: 5.148 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **64.39 MJ/m^2**
Implementation	**Decreased and Replaced energy** **Replaced cement** Geopolymer Concrete or 100% replacing with recycled cement substitute (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 381kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 51.73 kg replaced cement/ m^2 in concrete 51.73 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 289.68 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 381kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = 32 kg replaced cement/ m^2 in concrete 1996, 32 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **=179.2 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	30 % Concrete from recycled aggregate = **21.84 MJ/m^2**	100%Steel mesh, beams from average recycled content = **71.55 MJ/m^2**	**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **289.68 MJ/ m^2**	
Total Floor	**21.84 MJ/m^2**	**361.23 MJ/m^2**	**908MJ/** m^2
	383.07 MJ/m^2		

Table A.C.70: Green Star. Potential reduction in carbon emissions in a 200-mm hollow core precast concrete slab floor (Lawson 1996, p. 125)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete =**5.46 MJ/m^2**	90%Steel mesh from average recycled content **64.39 MJ/m^2**	**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **179.2 MJ/m^2**	
Green Star, Total Floor	**5.46 MJ/m^2**	**243.59 MJ/m^2**	**908 MJ/ m^2**
	249.05 MJ/m^2		

A.C.2.2 Potential carbon emission reduction in general Australian wall construction systems

a. Timber Framed, Single Skin Timber Wall

Table A.C.71: Potential reduction in carbon emissions in a timber framed, single skin timber wall (Lawson 1996, p. 125).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled materials** Reuse recycled timber and post-consumer 60% FSC timber + Reuse the recycled timber 40% (7.15+2.75+1.1) X 3.4 = **24.93 MJ/m²** (Lawson 1996, p. 125; JLL 2012) Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m² = **16.43 MJ/m²**
	Green Star **Reuse recycled materials** Use recycled softwood studs, 95% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm =, 95% x 11 MJ/m² (Lawson 1996, p.125, L. 7) 3.4 = **23.68 MJ/m²**

Areas that Embodied Energy can be reduced	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Embodied Energy to Replace and Save		Standard
Measurable energy to reduce in **Building materials and elements**		softwood studs + softwood plates **24.93 MJ/m²** Use Recycle thermal insulation **16.43 MJ/m²**	**151MJ/ m²**
Total Walls		**41.36 MJ/m²**	**151MJ/ m²**
	41.36 MJ/m²		

Table A.C.72: Green Star. Potential reduction in carbon emissions in a timber frame, single skin timber wall (Lawson 1996, p. 125).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		95% softwood studs + softwood plates **23.68MJ/m²** Use Recycle thermal insulation **16.43 MJ/m²**	**151 MJ/m²**
Green Star, Total Wall		**36.43 MJ/m²**	**151 MJ/ m²**
	40.11 MJ/m²		

b. Timber Frame, Timber Weatherboard Wall

Table A.C.73: Potential reduction in carbon emissions in a timber framed timber weatherboard wall (Lawson 1996, p. 125-127).

Processes where carbon emissions (embodied energy) can be reduced

Steel (Aluminium) from average recycled content

Use Aluminium from recycled content 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m²**

Reused materials and elements (local salvage/re-use centre)

Reuse recycled timber and post-consumer 60% FSC timber + Reuse the recycled timber 40% (7.15+2.75+1.1+11) x 3.4 Mj/kg = **74.80 MJ/m²** (Lawson 1996, p. 125; JLL 2012)

Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m² = **16.43 MJ/m²** (Steel Construction Information 2014)

Green Star

Reused materials and elements (local salvage/re-use centre)

Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber

Reuse softwood + softwood plates + softwood weatherboard = 22 MJ/m² **(**Lawson 1996, p. 125) x 3.4 Mj/kg x 95% = **71.06 MJ/m²**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled contents **= 15.78 MJ/m2**	Use recycled softwood + weatherboard **74.80 MJ/m²** Recycled thermal insulation**16.43 MJ/m²**	188 MJ/ m²
Total Walls	**15.78 MJ/m2**	**91.23 MJ/m²**	**188MJ/ m²**
	107.01 MJ/m²		

Table A.C.74: Green Star, Potential reduction in carbon emissions in a timber framed timber weatherboard wall (Lawson 1996, p. 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		Use recycled softwood + weatherboard **71.06 MJ/m²**	188 MJ/ m²
Green Star, Total Wall		**71.06 MJ/m²**	**188 MJ/ m²**
	71.06 MJ/m²		

c. Timber Frame, Reconstituted Timber Weatherboard Wall

Table A.C.75: Potential reduction in carbon emissions in a timber framed reconstituted timber weatherboard wall (Lawson 1996, p. 126).

Processes where carbon emissions (embodied energy) can be reduced			
	Steel (Aluminium) from average recycled content Use Aluminium from recycled content 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m²** **Reused materials and elements** (local salvage/re-use centre, FSC) Reuse recycled timber and post-consumer 60% FSC timber + Reuse the recycled timber 40% (7.15+2.75+1.1) x 3.4 Mj/kg = **37.4 MJ/m²** (Lawson 1996, p. 125; JLL 2012) 11 kg/m2 x 24.2 Mj/kg = **266.20 MJ/m²** Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m² = **16.43 MJ/m²** (Steel Construction Information 2014) **Green Star** **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber Reuse recycled timber and post-consumer, FSC timber + Reuse the recycled timber 95%(7.15+2.75+1.1) x 3.4 Mj/kg = **35.53 MJ/m²** 11 kg/m2 x 24.2 Mj/kg x 95% = **252.89 MJ/m²**		
Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled contents **= 15.78 MJ/m2**	Use recycled softwood + weatherboard **37.4 MJ/m²** Weatherboard **266.20 MJ/m²** Thermal insulation = **16.43 MJ/m²**	377 MJ/ m²
Total Walls	**15.78 MJ/m²**	**320.03 MJ/m²**	**377MJ/ m²**
	335.81 MJ/m²		

Table A.C.76: Green Star. Potential reduction in carbon emissions in a timber frame, reconstituted timber weatherboard wall (Lawson 1996, p. 126)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		Use recycled softwood + weatherboard **35.53 MJ/m²** Weatherboard **252.20 MJ/m²**	377 MJ/ m²
Green Star, Total Wall		**287.73 MJ/m²**	**377 MJ/ m²**
	287.73 MJ/m²		

d. Timber Frame, Fiber Cement Weatherboard Wall

Table A.C.77: Potential reduction in carbon emissions in a timber framed fibre cement weatherboard wall (Lawson 1996, p. 126).

Processes where carbon emissions (embodied energy) can be reduced	
	Steel (Aluminium) from average recycled content Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m^2** **Reused materials and elements** (local salvage/re-use centre, FSC) Reuse the recycled timber and post-consumer 60% FSC timber + Reuse the recycled timber 40% (7.15+2.75+1.1) x 3.4 Mj/kg = **37.4 MJ/m^2** (Lawson 1996, p. 125; JLL 2012) 11 kg/m2 x 24.2 Mj/kg = **266.20 MJ/m^2** Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014) Use FC weatherboard from recycled 50%aggregate (Herbudiman & Saptaji 2013) Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (2.5 concrete – 0.35 cement) Kg/m^2 (Lawson 1996, p. 134) = 0.083 x 2.15 kg/m2 x 50% (Herbudiman & Saptaji 2013) = **0.018 MJ/m^2** Geopolymer 50% replacing Portland cement with geopolymer (McLellan et al. 2011; Nath and Sarker 2014) 2.5 kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 50% = 0.175 kg replaced cement/ m^2 0.175 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 0.98 MJ/ m^2**
	Green Star **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber Reuse recycled timber and post-consumer, FSC timber + Reuse the recycled timber 95% (7.15+2.75+1.1) x 3.4 Mj/kg = **35.53 MJ/m^2** 11 kg/m2 x 24.2 Mj/kg x 95% = **252.89 MJ/m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled contents **= 15.78 MJ/m2**	Use recycled softwood + weatherboard **37.4 MJ/m^2** FC Weatherboard **0.018 MJ/m^2** Geopolymer **0.98 MJ/ m^2** Thermal insulation = **16.43 MJ/m^2**	169 MJ/ m^2
Total Walls	**15.78 MJ/m2**	**58.82 MJ/m^2**	**169 MJ/ m^2**
	70.60 MJ/m^2		

Table A.C.78: Green Star. Potential reduction in carbon emissions in a timber framed fibre cement weatherboard wall (Lawson 1996, p. 126)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		Use recycled softwood + weatherboard **35.53 MJ/m^2**	169 MJ/ m^2
Green Star, Total Wall		**35.53 MJ/m^2**	**169 MJ/ m^2**
	35.53 MJ/m^2		

e. Timber Frame, Steel Clad Wall

Table A.C.79: Potential reduction in carbon emissions in a timber framed steel clad wall (Lawson 1996, p. 126)

Processes where carbon emissions (embodied energy) can be reduced	
	Steel (Aluminium) from average recycled content Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m^2** - Steel cladding from average recycled content = 4.9 Kg x {38 MJ/Kg (Lawson 1996, p13) - 20.10 MJ/Kg} = **87.71MJ/m^2** **Reused materials and elements** (local salvage/re-use centre) Reuse recycled timber and post-consumer 60% FSC timber + Reuse the recycled timber 40% (7.15+2.75+1.1) x 3.4 Mj/kg = **37.40 MJ/m^2** (Lawson 1996, p. 125; JLL 2012) Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber Reuse softwood + softwood plates + softwood weatherboard = 11 MJ/m^2 **(**Lawson 1996, p. 125) x 3.4 Mj/kg x 95% = **35.53 MJ/m^2** Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is - Steel cladding from average recycled content = 4.9 Kg x {38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg 90% = **78.93 MJ/m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled contents **= 15.78 MJ/m^2** Steel cladding from recycled content **87.71MJ/m^2**	Use recycled softwood + weatherboard **37.40 MJ/m^2** Recycled thermal insulation**16.43 MJ/m^2**	336 MJ/ m^2
Total Walls	**103.49 MJ/m2**	**53.83 MJ/m^2**	**336MJ/ m^2**
	157.32 MJ/m^2		

Table A.C.80: Green Star. Potential reduction in carbon emissions in a timber framed steel clad wall (Lawson 1996, p. 126)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel cladding from recycled content **78.93 MJ/m^2**	Use recycled softwood + weatherboard **35.53 MJ/m^2**	336 MJ/ m^2
Green Star, Total Wall	**78.93 MJ/m^2**	**35.53 MJ/m^2**	**336 MJ/ m^2**
	114.46 MJ/m^2		

f. Steel Frame, Steel Clad Wall

Table A.C.81: Potential reduction in carbon emissions in a steel framed steel clad wall (Lawson 1996, p. 127)

Processes where carbon emissions (embodied energy) can be reduced	
	Steel from average recycled content - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 3.342 KJ/Kg X 13.9 Kg/ m2 = **46.45 MJ/m2** - Steel cladding from average recycled content = 4.9 Kg x {38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **87.71MJ/m^2** **Aluminium from average recycled content** Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m^2** **Reused materials and elements** (local salvage/re-use centre) Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014) Reuse 40% recycled steel 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 40% = **45.44 MJ/m2** **Reuse materials in design** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 20% = **22.72 MJ/m2**
	Green Star **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 3.342 KJ/Kg X 13.9 Kg/ m2 x 90% = **41.80 MJ/m2** - Steel cladding from average recycled content = 4.9 Kg x {38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg 90% = **78.93 MJ/m^2** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson 11996, p. 13) x 20% = **22.72 MJ/m2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled contents **= 15.78 MJ/m^2** Steel frame from recycled content **46.45 MJ/m2** Steel cladding from recycled content **87.71MJ/m^2**	Recycled thermal insulation **16.43 MJ/m^2** Reuse steel = **45.44 MJ/m2** Reduce in design **22.72 MJ/m2**	425 MJ/ m^2
Total Walls	**149.94 MJ/m2**	**84.59 MJ/m^2**	**425 MJ/ m^2**
	234.53 MJ/m^2		

Table A.C.82: Green Star. Potential reduction in carbon emissions in a steel framed steel clad wall (Lawson 1996, p. 127)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel frame from recycled content **41.80 MJ/m2** Steel cladding from recycled content **78.93 MJ/m^2**	Reduce in design **22.72 MJ/m2**	425 MJ/ m^2
Green Star, Total Wall	**120.73 MJ/m^2**	**22.72 MJ/m2**	**425 MJ/ m^2**
	143.45 MJ/m^2		

g. Timber Frame, Aluminium Weatherboard Wall

Table A.C.83: Potential reduction in carbon emissions in a timber framed aluminium weatherboard wall (Lawson 1996, p. 126)

Processes where carbon emissions (embodied energy) can be reduced	
	Steel (Aluminium) from average recycled content Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m²** Use Aluminium from recycled contents 1.485 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 240.42 MJ/m²** **Reuse materials and elements** (local salvage/re-use centre) Reuse recycled timber and post-consumer 60% FSC timber + Reuse the recycled timber 40% (7.15+2.75+1.1) x 3.4 Mj/kg = **37.40 MJ/m²** (Lawson 1996, p. 125; JLL 2012) Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m² = **16.43 MJ/m²** (Steel Construction Information 2014)
	Green Star **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber Reuse softwood + softwood plates + softwood weatherboard = 11 MJ/m² **(**Lawson 1996, p. 125**)** x 3.4 Mj/kg x 95% = **35.53 MJ/m²** Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 14.20 MJ/m²** Use Aluminium from recycled contents 1.485 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 216.378 MJ/m²**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled contents **= 15.78 MJ/m²** Aluminium from recycled contents **= 240.42 MJ/m²**	Use recycled softwood **37.40 MJ/m²** Recycled thermal insulation**16.43 MJ/m²**	403 MJ/ m²
Total Walls	**256.20 MJ/m2**	**53.83 MJ/m²**	**403MJ/ m²**
	310.03 MJ/m²		

Table A.C.84: Green Star. Potential reduction in carbon emissions in a timber framed aluminium weatherboard wall (Lawson 1996, p. 126).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Aluminium from recycled contents **= 14.20 MJ/m²** Aluminium from recycled contents **= 216.37 MJ/m²**	Use recycled softwood + weatherboard **35.53 MJ/m²**	403 MJ/ m²
Green Star, Total Wall	**230.57 MJ/m²**	**35.53 MJ/m²**	**403 MJ/ m²**
	266.10 MJ/m²		

h. Timber Frame, Clay Brick Veneer Wall

Table A.C.85: Potential reduction in carbon emissions in a timber framed clay brick veneer wall (Lawson 1996, p. 127).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused the recycled aggregates** Reuse recycled aggregate for brick, 67% (Brick Development Association 2014; Tyrell & Goode 2014), 147 kg/m^2 (Lawson, p.127) x 67% x 0.083 MJ/kg = **8.17 MJ/ m^2** **Reused materials and elements** Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm (Lawson 1996, p.127) 60% x 33 MJ/m^2= **19.8 MJ/m^2** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Reuse materials and elements** Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm = 60% x 33 MJ/m^2= **19.8 MJ/m^2**
Implementation	**Decreased and Replaced energy** **Decrease energy** US-made fly ash brick gains strength and durability from the chemical reaction of fly ash with water. However, 85 per cent less energy is used in production than in fired clay brick, (Structure Magazine 2015); potential 40 per cent energy savings in brick manufacturing using 67% recycled container glass brick grog (Brick Development Association 2014; Tyrell & Goode 2014). Reduced energy 368 MJ/m^2 x 40% = **147.2** MJ/m^2

Life Cycle Stages of building	Construction		Embodied Energy Standard
	Pre-Construction	Construction	
	Potential Reduction in Carbon Emissions		
Measurable energy to reduce in **Building materials and elements**	76% Use recycled aggregate for brick **8.17 KJ/m^2**	60% softwood stud + softwood plates **19.8 MJ/m^2** Use Recycle thermal insulation **16.43 MJ/m^2**	**5**61**MJ/ m^2**
Implementation	40% saving energy in production **147.2** MJ/m^2		
Total Walls	**155.37 KJ/m^2**	**36.23 MJ/m^2**	**561MJ/ m^2**
	191.60 MJ/m^2		

Table A.C.86: Green Star. Potential reduction in carbon emissions in a timber framed clay brick veneer wall (Lawson 1996, p. 127).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		60% softwood stud + softwood plates **19.80 MJ/m^2**	**561 MJ/m^2**
Green Star, Total Wall		**19.80MJ/m^2**	**561 MJ/ m^2**
	19.80 MJ/m^2		

i. Steel Frame, Clay Brick Veneer Wall

Table A.C.87: Potential reduction in carbon emissions in a steel framed clay brick veneer wall (Lawson 1996, p. 128).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled aggregates** - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 3.342 KJ/Kg X 13.9 Kg/ m2 = **46.45 MJ/m2** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m²** - Reuse recycled aggregate for brick, 67% (Brick Development Association 2014; Tyrell & Goode 2014) 147 kg/m² (Lawson 1996, p.127) x 67% x 0.083 MJ/kg = **8.17 MJ/ m²** **Reused materials and elements** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m² = **16.43 MJ/m²** (Steel Construction Information 2014) Reuse 40% recycled steel 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 40% = **45.44 MJ/m2** **Reduced materials in design** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 20% = **22.72 MJ/m2**
	Green Star **Reuse materials and elements** - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 3.342 KJ/Kg X 13.9 Kg/ m2 x 90% = **41.80 MJ/m2** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 15.78 MJ/m²** **Reduced materials in design** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 20% = **22.72 MJ/m2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	Steel from recycled content **46.45 MJ/m²** Aluminium from recycled content **15.78 MJ/m²** 76% Use recycled aggregate for brick **8.17 KJ/m²**	Use Recycle thermal insulation **16.43 MJ/m²** Reuse steel = **45.44 MJ/m2** Reduce in design **22.72 MJ/m2**	**650MJ/ m²**
Total Walls	**70.40 KJ/m²**	**84.59 MJ/m²**	**650MJ/ m²**
	154.99 MJ/m²		

Table A.C.88: Green Star. Potential reduction in carbon emissions in a steel framed clay brick veneer wall (Lawson 1996, p. 128)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel from recycled content **41.80 MJ/m²** Aluminium from recycled content **14.20 MJ/m²**	Reduce in design **22.72 MJ/m2**	**650 MJ/m²**
Green Star, Total Wall	**56 MJ/m²**	**22.72 MJ/m2**	**650 MJ/ m²**
	78.72 MJ/m²		

j. Timber Frame, Concrete Block Veneer Wall

Table A.C.89: Potential reduction in carbon emissions in a timber framed concrete block veneer wall (Lawson 1996, p. 128).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled aggregates** Reuse recycled aggregate for brick, 100% (Brick Development Association 2014; Tyrell & Goode 2014), 137.5 kg/m^2 (Lawson 1996, p.127) x 0.083 MJ/kg = **11.41 MJ/ m^2** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m^2** **Reused materials and elements** Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm, (Lawson 1996, p.127) 60% x 33 MJ/m^2= **19.8 MJ/m^2** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.585kg/m^2 = **16.43 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Reuse materials and elements** Use recycled softwood stud, 60% Reuse softwood stud@100x50mm+ softwood plates@100x50 mm = 60% x 33 MJ/m^2= **19.8 MJ/m^2**

Implementation	**Decreased and Replaced energy in process** **Decrease energy** Geopolymer concrete brick or 100% replacing with recycled results 80% reduction in GHG (Geiger 2010) Reduced Cement = 89Kgs/tonne (Concrete Block Association 2013) / 1000 x 137.5 =12.23 Kg/m^2 Reduced cement 12.23 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 68.53 MJ/ m^2**
	Green Star - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 15.78 MJ/m^2** Reduced Cement = 89Kgs/tonne (Concrete Block Association 2013) / 1000 x 137.5 =12.23 Kg/m^2 Reduced cement 12.23 Kg/ m^2 x 5.6 MJ/kg (Lawson 2996, p.13) x 60% **= 41.11 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	76% Use recycled aggregate for brick **11.41 KJ/m^2** Aluminium from recycled content **15.78 MJ/m^2**	60% softwood stud + softwood plates **19.8 MJ/m^2** Use Recycle thermal insulation **16.43 MJ/m^2**	61**MJ/ m^2**
Implementation	Replacing Geopolymer **68.53 MJ/ m^2**		
Total Walls	**95.72 KJ/m^2**	**36.23 MJ/m^2**	**361MJ/ m^2**
	131.95 MJ/m^2		

Table A.C.90: Green Star. Potential reduction in carbon emissions in a timber framed concrete block veneer wall (Lawson 1996, p. 127).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Replacing Geopolymer **41.11 MJ/ m^2** Aluminium from recycled content **15.78 MJ/m^2**	60% softwood stud + softwood plates **19.80 MJ/m^2**	**361 MJ/m^2**
Green Star, Total Wall	**56.89 MJ/m^2**	**19.80MJ/m^2**	**361 MJ/ m^2**
	76.69 MJ/m^2		

k. Steel Frame, Concrete Block Veneer Wall

Table A.C.91: Potential reduction in carbon emissions in a steel framed concrete block veneer wall (Lawson 1996, p. 128).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled aggregates** Reuse recycled aggregate for brick, 100% (Brick Development Association 2014; Tyrell & Goode 2014) 137.5 kg/m^2 (Lawson 1996, p.127) x 0.083 MJ/kg = **11.41 MJ/ m^2** - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p.13) - 20.10 MJ/Kg = 3.342 KJ/Kg x 13.9 Kg/ m2 = **46.45 MJ/m2** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m^2** **Reused materials and elements** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.65kg/m^2 = **18.25 MJ/m^2** (Steel Construction Information 2014) Reuse 40% recycled steel 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 40% = **45.44 MJ/m2** **Reduced materials in design** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 20% = **22.72 MJ/m2**
	Green Star **Reuse materials and elements** - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 3.342 KJ/Kg X 13.9 Kg/ m2 x 90% = **41.80 MJ/m2** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 15.78 MJ/m^2** **Reused materials in design** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson1996, p. 13) x 20% = **22.72 MJ/m2**
Implementation	**Decreased and Replaced energy in process** **Decrease energy** Geopolymer concrete brick or 100% replacing with recycled results 80% reduction in GHG (Geiger 2010) Reduced Cement = 89Kgs/tonne (Concrete Block Association 2013) / 1000 x 137.5 =12.23 Kg/m^2 Reduced cement 12.23 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 68.53 MJ/ m^2**
	Green Star Reduced Cement =89Kgs/tonne (Concrete Block Association 2013) / 1000 x 137.5 =12.23 Kg/m^2 Reduced cement 12.23 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 60% **= 41.11 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	76% Use recycled aggregate for brick **11.41 KJ/m^2** Steel from recycled content**46.45 MJ/m2** Aluminium from recycled content **15.78 MJ/m^2**	Use Recycle thermal insulation **18.25 MJ/m^2** Reuse recycled steel **45.44 MJ/m2** Reduce steel use in design **22.72 MJ/m2**	**453MJ/ m^2**
Implementation	Replacing Geopolymer **68.53 MJ/ m^2**		
Total Walls	**142.17 KJ/m^2**	**86.41 MJ/m^2**	**453MJ/ m^2**
	228.58 MJ/m^2		

Table A.C.92: Green Star. Potential reduction in carbon emissions in a steel framed concrete block veneer wall (Lawson 1996, p. 127).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Replacing Geopolymer **41.11 MJ/ m^2** Aluminium from recycled content **14.20 MJ/m^2**	Steel from recycled content **41.80 MJ/m2** Reduce steel use in design **22.72 MJ/m2**	**453 MJ/m^2**
Green Star, Total Wall	**56.89 MJ/m^2**	**64.52 MJ/m^2**	**453 MJ/ m^2**
	121.41 MJ/m^2		

l. Steel Frame, timber weatherboard Wall

Table A.C.93: Potential reduction in carbon emissions in a steel framed timber weatherboard wall (Lawson 1996, p. 125)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Steel from average recycled content** - Steel frame from average recycled content = 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 3.342 KJ/Kg X 13.9 Kg/ m2 = **46.45 MJ/m2** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m²**
	Reuse materials and elements (local salvage/re-use centre) Reuse softwood + softwood plates + softwood weatherboard = **74 MJ/m²** (Lawson 1996, p. 125; JLL 2012) - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.65kg/m² = **18.25 MJ/m²** (Steel Construction Information 2014) Reuse 40% recycled steel 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 40% = **45.44 MJ/m2** **Reuse materials in design** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 20% = **22.72 MJ/m2**
	Green Star **Steel from average recycled content** Material-6 Steel, Green Star Technical Manual, steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (Green building Council of Australia 2008) is: - Steel frame roofing from recycled content {34 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x 3.342 kg/ m² x 90% = **41.80 MJ/m²** **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber Reuse softwood + softwood plates + softwood weatherboard = 74 MJ/m² **(**Lawson p. 125) x 95% = **70.3 MJ/m²** Reduce 20% steel in design 3.342 Kg x 34 MJ/Kg (Lawson 1996, p. 13) x 20% = **22.72 MJ/m2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Standard
Measurable energy to reduce in **Building materials and elements**	Steel frame from recycled content **46.45 MJ/m²** Aluminium from recycled content **15.78 MJ/m²**	Use recycled softwood + weatherboard **74 MJ/m²** Use Recycle thermal insulation **18.25 MJ/m²** Reuse recycled steel **45.44 MJ/m2** Reduce steel use in design **22.72 MJ/m2**	**238 MJ/ m²**
Total Walls	**62.23 MJ/m²**	**160.41 MJ/m²**	**238 MJ/ m²**
	222.64 MJ/m²		

Table A.C.94: Green Star. Potential reduction in carbon emissions in a steel framed timber weatherboard wall (Lawson 1996, p. 125).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel frame from 90% Recycled contents = **41.80 MJ/m²**	Use recycled softwood + weatherboard **70.30 MJ/m²** Reduce steel use in design **22.72 MJ/m2**	151MJ/ m²
Green Star, Total Wall	**41.80 MJ/m²**	**93.02 MJ/m²**	**151MJ/ m²**
	134.82 MJ/m²		

m. Cavity Clay Brick Wall

Table A.C.95: Potential reduction in carbon emissions in a cavity clay brick wall (Lawson 1996, p. 129)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled aggregates** Reuse recycled aggregate for brick, 67% (Brick Development Association 2014; Tyrell & Goode 2014), 291 kg/m^2 (Lawson 1996, p.127) x 67% x 0.083 MJ/kg = **8.17 MJ/ m^2** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 15.78 MJ/m^2**
	Green Star **Reuse materials and elements** - Use Aluminium from recycled contents 0.0975 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 14.20 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Decrease energy** US-made fly ash brick gains strength and durability from the chemical reaction of fly ash with water. However, 85 per cent less energy is used in production than in fired clay brick, (Volz & Stovner 2010; Structure Magazine 2015). Potential 40 per cent energy savings in brick manufacturing using 67% recycled container glass brick grog (Brick Development Association 2014; Tyrell & Goode 2014). Reduced energy 728 MJ/m^2 x 40% = **291.2** MJ/m^2 - Geopolymer mortar or replacing Portland with geopolymer cement results 80% reduction in GHG (Geiger 2010), Reduced Cement = 89Kgs/tonne (Concrete Block Association 2013) / 1000 x 50.224 = 4.45 Kg/m^2 Reduced cement 4.45 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 24.92 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008), 4.45 kg Cement/m2 x 60% x 5.6 MJ/kg (Lawson 1996, p. 13) **= 14.95 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	76% Use recycled aggregate for brick **8.17 KJ/m^2** Aluminium from recycled content **15.78 MJ/m^2**		**854MJ/ m^2**
Implementation	40% saving energy in production **291.2** MJ/m^2 Replacing geopolymer **= 24.92 MJ/ m^2**		
Total Walls	**340.07 KJ/m^2**		**854MJ/ m^2**
	340.07 MJ/m^2		

Table A.C.96: Green Star. Potential reduction in carbon emissions in a cavity clay brick wall (Lawson 1996, p. 129).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Aluminium from recycled content **14.20 MJ/m^2**	Replacing geopolymer **= 14.95MJ/ m^2**	**854 MJ/m^2**
Green Star, Total Wall	**14.20 MJ/m^2**	**14.95 MJ/m^2**	**854 MJ/ m^2**
	29.15 MJ/m^2		

n. Cavity Concrete Block Wall

Table A.C.97: Potential reduction in carbon emissions in a cavity concrete block wall (Lawson 1996, p, 129).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled materials as aggregate for concrete block** - Concrete from 100% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (299.57 Kg concrete – 41.93 kg cement) (Lawson 1996, p. 129) = **21.38 MJ/m²**
	Green Star **Reuse recycled materials for concrete block** Material-5 Green Star Technical Manual, is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (299.57 Kg concrete – 24.47 kg cement) (Lawson 1996, p. 129) x 20% = **4.27 MJ/m²**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete block or 100% replacing recycled cement results 80% reduction in GHG (Geiger 2010) Reduced Cement = 89Kgs/tonne (Concrete Block Association 2013) / 1000 x 275 = 24.47 Kg/ m² Reduced cement 41.93 Kg/ m² x 5.6 MJ/kg (Lawson1996, p. 13) **= 234.80 MJ/ m²**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 24.47 kg Cement/m2 x 60% x 5.6 MJ/kg (Lawson 1996, p. 13) **= 140.88 MJ/ m²**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) to reduce		
Measurable energy to reduce in **Building materials and elements**	Use recycled materials as aggregate **21.38 MJ/ m²**		**5**11**MJ/ m²**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement **234.80 MJ/m²**	
Total Walls	**21.38 MJ/ m²**	**234.80 MJ/ m²**	**511MJ/ m²**
	256.18 MJ/m²		

Table A.C.98: Green Star. Potential reduction in carbon emissions in a cavity concrete block wall (Lawson 1996, p. 129).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete block = **4.27 MJ/m²**		**511 MJ/m²**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacement **140.88 MJ/m²**	
Green Star, Total Wall	**4.27 MJ/m²**	**140.88 MJ/m²**	**511 MJ/ m²**
	145.15 MJ/m²		

o. Single Skin Stabilized Rammed Earth Wall

Table A.C.99: Potential reduction in carbon emissions in a single skin stabilized rammed earth wall (Lawson 1996, p. 130).

Processes where carbon emissions (embodied energy) can be reduced	
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer Concrete or 100% replacing with recycled cement (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 570 kg/m^2 (Lawson 1996, p. 124) x 5% Cement (Lawson 1996, p. 41) = 28.5 kg replaced cement/ m^2 28.5 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 273.72 MJ/ m^2**
	Green Star Replacing 60% of cement (Green building Council of Australia 2008) 570 kg/m^2 (Lawson 1996, p. 124) x 5% Cement (Lawson 1996, p. 41) x 60% = 17.10 kg replaced cement/ m^2 17.10 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 95.76 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions (embodied energy)		
Measurable energy to reduce in **Building materials and elements**		Replacing geopolymer **= 273.72MJ/ m^2**	**405MJ/ m^2**
Total Walls		**273.72 MJ/ m^2**	**405MJ/ m^2**
	273.72 MJ/m^2		

Table A.C.100: Green Star. Potential reduction in carbon emissions in a single skin stabilized rammed earth wall (Lawson 1996, p. 129).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**		Replacing geopolymer **= 95.76MJ/ m2**	**405 MJ/m^2**
Green Star, Total Wall		**95.76 MJ/m^2**	**405 MJ/ m^2**
	95.76 MJ/m^2		

p. Single Skin autoclaved Aerated Concrete Block (AAC) wall

Table A.C.101: Potential reduction in carbon emissions in a single skin autoclaved aerated concrete block (AAC) wall (Lawson 1996, p. 129).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled materials as aggregate for concrete block** - Concrete from 800% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (102 + 8.11+ 18.98) Kg concrete – 11.49 kg cement) (Lawson 1996, 9. 129) x 80% = **9.76 MJ/m^2**
	Green Star **Reuse recycled materials for concrete block** Material-5 Green Star Technical Manual, is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (129.09 Kg concrete – 11.49 kg cement) (Lawson 1996, p. 129) x 20% = **1.95 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete block or 100% replacing with recycled cement results 80% reduction in GHG (Geiger 2010) Reduced Cement = 89Kgs/tonne Concrete Block Association 2013) / 1000 x 129.09 = 11.49 Kg/ m^2 Reduced cement 11.49 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 64.34 MJ/ m^2**
	Green Star Replacing max. 60% of cement (Green building Council of Australia 2008) 11.49 kg Cement/m2 x 60% x 5.6 MJ/kg (Lawson1996, p. 13) **= 38.60 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) reduction		
Measurable energy to reduce in **Building materials and elements**	Use recycled materials as aggregate **9.76 MJ/ m^2**		**440MJ/ m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement **64.34 MJ/m^2**	
Total Walls	**9.76 MJ/ m^2**	**64.34 MJ/ m^2**	**440MJ/ m^2**
	74.10 MJ/m^2		

Table A.C.102: Green Star. Potential reduction in carbon emissions in a single skin autoclaved aerated concrete block (AAC) wall (Lawson 1996, p. 129).

Life Cycle Stages of building j	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete block = **1.95 MJ/m^2**		**440 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **38.60 MJ/m^2**	
Green Star, Total Wall	**1.95 MJ/m^2**	**38.60 MJ/m^2**	**440 MJ/ m^2**
	40.55 MJ/m^2		

q. Single Skin Cored Concrete Block Wall

Table A.C.103: Potential reduction in carbon emissions in a single skin cored concrete block wall (Lawson 1996, p. 129).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled materials as aggregate for concrete block** - Concrete from 100% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (175 + 1.6+ 1.8) Kg concrete – 15.88 kg cement) (Lawson 1996, p. 129) = **14.80 MJ/m^2**
	Green Star **Reused recycled materials for concrete block** Material-5 Green Star Technical Manual, is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (1178.40 Kg concrete – 15.88 kg cement) (Lawson 1996, p. 129) x 20% = **2.96 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer concrete block or 100% replacing with recycled cement results 80% reduction in GHG (Geiger 2010) Reduced Cement = 89 Kgs/tonne (Concrete Block Association 2013) / 1000 x 178.40 = 15.88 Kg/ m^2 Reduced cement 15.88 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 88.91 MJ/ m^2**
	Green Star Replacing max. 60% of cement (Green building Council of Australia 2008) 15.88 kg Cement/m2 x 60% x 5.6 MJ/kg (Lawson 1996, p. 13) **= 53.34 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential carbon emission (embodied energy) reductions		
Measurable energy to reduce in **Building materials and elements**	Use recycled materials as aggregate **14.80 MJ/ m^2**		**317MJ/ m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement **88.91 MJ/m^2**	
Total Walls	**14.80 MJ/ m^2**	**88.91 MJ/ m^2**	**317MJ/ m^2**
	103.71 MJ/m^2		

Table A.C.104: Green Star. Potential reduction in carbon emissions in a single skin cored concrete block wall (Lawson 1996, p. 129)

Life Cycle Stages of building j	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% Recycled aggregate for concrete block = **2.96 MJ/m^2**		**317 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer 60% Cement Replacement **53.34 MJ/m^2**	
Green Star, Total Wall	**2.96 MJ/m^2**	**53.34 MJ/m^2**	**317 MJ/ m^2**
	56.30 MJ/m^2		

r. Steel Frame, Compressed Fibre Cement Clad Wall

Table A.C.105: Potential reduction in carbon emissions in a steel framed compressed fibre cement clad wall (Lawson 1996, p. 129)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused the recycled aggregates** - Steel frame from average recycled content = (3.552 + 3.06) Kg x 38MJ/Kg (Lawson 1996, p, 13) - 20.10 MJ/Kg = 6.612 KJ/Kg x 17.9 Kg/ m2 = **118.35 MJ/m2** **Reused materials and elements** Reuse 40% recycled steel, 6.612 Kg x 38 MJ/Kg (Lawson 1996, p.13) x 40% = **100.50 MJ/m2** **recused materials in design** Reduce 20% steel in design 6.612 Kg x 38 MJ/Kg (Lawson 1996, p. 13) x 20% = **50.25 MJ/m2**
	Green Star **Reuse materials and elements** - Steel frame from average recycled content = 6.612 Kg x 38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 6.612 KJ/Kg X 17.9 Kg/ m2 x 90% = **106.51 MJ/m2** **Reused materials in design** Reduce 20% steel in design 6.612 Kg x 38 MJ/Kg (Lawson 1996, p. 13) x 20% = **50.25 MJ/m2**

Implementation	**Decreased and Replaced energy in process** **Decrease energy** Geopolymer or 100% replacing cement results 80% reduction in GHG (Geiger 2010) Reduced Cement = 14%x 16.9 =2.366 Kg/m^2 Reduced cement 2.366 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p.13) **= 13.24 MJ/ m^2**
	Green Star Replacing with geopolymer, Reduced Cement = 14%x 16.9 =2.366 Kg/m2 Reduced cement 2.366 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 60% **= 7.94 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Reduction in Carbon Emissions		Standard
Measurable energy to reduce in **Building materials and elements**	Steel from recycled content **118.35 MJ/m2**	Reuse recycled steel **100.50 MJ/m2** Reduce steel use in design **50.25 MJ/m2**	**385MJ/ m^2**
Implementation	Replacing Geopolymer **13.24 MJ/ m^2**		
Total Walls	**131. 59 KJ/m^2**	**150.75 MJ/m^2**	**385MJ/ m^2**
	282.34 MJ/m^2		

Table A.C.106: Potential reduction in carbon emissions in a steel framed compressed fibre cement clad wall (Lawson 1996, p. 129).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Replacing Geopolymer 7.94 **MJ/m^2**	Steel from recycled content **106.51 MJ/m2** Reduce steel use in design **50.25 MJ/m2**	**385 MJ/m^2**
Green Star, Total Wall	**7.94 MJ/m^2**	**150.76 MJ/m^2**	**385 MJ/ m^2**
	158.70 MJ/m^2		

s. 200 mm Hollow-Core Precast Concrete Wall

Table A.C.107: Potential reduction in carbon emissions in a 200-mm hollow core precast concrete slab wall (Lawson 1996, p. 125-126).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused the recycled aggregates for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083MJ/Kg x (298.5 kg/m^{2}concrete – 41.79kg/m^2 cement) (Lawson 1996, p. 125) x 80% = **17.04 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 3.432 Kg x {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **47.70 MJ/m^2**
	Green Star **Reuse recycled aggregate for concrete** Material-5 Green Star Technical Manual, is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014) embodied energy of aggregate is 0.083 MJ/Kg saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (298.50 kg/m^{2}concrete – 41.79kg/m^2 cement) (Lawson 1996, p. 125) x 20% = **4.26 MJ/m^2** **Steel from average recycled content** Material-6 Green Star Technical Manual, is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: 3.432 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **42.93MJ/m^2**
Implementation	**Decreased and Replaced energy** **Replaced cement** Geopolymer Concrete or 100% replacing with recycled cement (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 298.50 kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 41.79 kg replaced cement/ m^2 in concrete 41.79 kg Cement/m2 x 5.6 MJ/kg (Lawson 1996. p. 13) **= 234.02 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 298.50kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = kg replaced cement/ m^2 in concrete 32 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 60% **=140.41 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	80 % Concrete from recycled aggregate = **17.04 MJ/m^2**	100%Steel, beams from average recycled content = **47.70 MJ/m^2**	**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **234.02 MJ/ m^2**	
Total Floor	**17.04 MJ/m^2**	**281.72 MJ/m^2**	**908MJ/** m^2
	298.76 MJ/m^2		

Table A.C.108: Green Star. Potential reduction in carbon emissions in a 200-mm hollow core precast concrete slab wall (Lawson 1996, p. 125)

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20%Recycled aggregate for concrete = **4.26 MJ/m^2**	90%Steel mesh from average recycled content **42.93 MJ/m^2**	**908 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **140.41 MJ/m^2**	
Green Star, Total Floor	**4.26 MJ/m^2**	**183.34 MJ/m^2**	**908 MJ/ m^2**
	187.60 MJ/m^2		

t. 150 mm Tilt-up Precast Concrete Wall

Table A.C.109: Potential reduction in carbon emissions in a tilt-up precast concrete wall (Lawson 1996, p. 131).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled aggregates for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083MJ/Kg x (360 kg/m^{2}concrete – 50.14 kg/m^2 cement) (Lawson 1996, p. 125) x 80% = **20.57 MJ/m^2** **Steel from average recycled content** - Steel from average recycled content = 4 Kg x {34 MJ/Kg (Lawson1996, p. 13) - 20.10 MJ/Kg} = **55.60 MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 Green Star Technical Manual, is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (360 kg/m^{2}concrete – 50.14kg/m^2 cement) (Lawson 1996, p. 125) x 20% = **5.14 MJ/m^2** **Steel from average recycled content** Material-6 Green Star, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: 4 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **50.40MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer Concrete or 100% replacing cement (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 360 kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 50.14 kg replaced cement/ m^2 in concrete 50.14 kg Cement/m2 x 5.6 MJ/kg (Lawson 1196, p. 13) **= 280.78 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 298.50kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) 60% = kg replaced cement/ m^2 in concrete 32 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 60% **=168.48 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	Concrete from 80% recycled aggregate = **20.57 MJ/m^2**	Steel from 100% average recycled content = **55.60 MJ/m^2**	**818 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, replacing 100% of cement = **280.78 MJ/ m^2**	
Total Floor	**20.57 MJ/m^2**	**336.38 MJ/m^2**	**818MJ/** m^2
	356.95 MJ/m^2		

Table A.C.110: Green Star. Potential reduction in carbon emissions in a tilt-up precast concrete wall (Lawson 1996, p. 125).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Concrete from 20% recycled aggregate = **5.14 MJ/m^2**	Steel mesh from 100% average recycled content **50.40 MJ/m^2**	**818 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer, 60% Cement Replacements **168.48 MJ/m^2**	
Green Star, Total Floor	**5.14 MJ/m^2**	**218.88 MJ/m^2**	**818 MJ/ m^2**
	224.02 MJ/m^2		

u. Porcelain-Enamelled Steel Curtain Wall

Table A.C.111: Potential reduction in carbon emissions in a porcelain-enamelled steel curtain wall (Lawson 1996, p. 131).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused the recycled aggregates** - Steel frame from average recycled content = (2.43 + 4.31) Kg x 38MJ/Kg (Lawson 1996. p. 13) - 20.10 MJ/Kg = 6.74 KJ/Kg x 17.9 Kg/ m2 = **120.64 MJ/m2** - Enamelled Steel facing from average recycled content = 4.86Kg x 38MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 4.86 KJ/Kg x 17.9 Kg/ m2 = **86.99 MJ/m2** Use Aluminium from recycled contents 1.62 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **= 262.27 MJ/m^2** **reduced materials in design** Reduce 20% steel in design 6.74 Kg x 38 MJ/Kg (Lawson 1996, p. 13) x 20% = **51.22 MJ/m2**
	Green Star **Reused materials and elements** - Steel frame from average recycled content = 6.74 Kg x 38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 6.74 KJ/Kg X 17.9 Kg/ m2 x 90% = **108.58 MJ/m2** - Enamelled Steel facing from average recycled content = 4.86Kg x (38MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 4.86 KJ/Kg x 17.9 Kg/ m2 x 90% = **78.29 MJ/m2** Use Aluminium from recycled contents 1.485 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 236.05 MJ/m^2** **Reused materials in design** Reduce 20% steel in design 6.74 Kg x 38 MJ/Kg (Lawson 1996, p. 13) x 20% = **51.22 MJ/m2**
Implementation	**Decreased and Replaced energy in process** **Decrease energy** Geopolymer or 100% replacing with recycled cement results 80% reduction in GHG (Geiger 2010) Reduced Cement = 14% x 14 kg/m2 = 1.96 Kg/m^2 Reduced cement 1.96 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 10.97 MJ/ m^2**
	Green Star Replacing geopolymer or recycled cement = 14%x 16.9 =2.366 Kg/m2 Reduced cement 1.96 Kg/ m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 60% **= 6.58 MJ/ m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in Carbon Emissions		Standard
Measurable energy to reduce in **Building materials and elements**	Steel from recycled content **120.64 MJ/m^2** Enamelled steel from recycled content **86.99 MJ/m^2** Aluminium from recycled content **262.27 MJ/m^2**	Reduce steel use in design **51.22 MJ/m2** Geopolymer replaced **10.97 MJ/m^2**	**865MJ/ m^2**
Implementation	Replacing with Geopolymer **13.24 MJ/ m^2**		
Total Walls	**469.90 KJ/m^2**	**62.19 MJ/m^2**	**865MJ/ m^2**
	523.09 MJ/m^2		

Table A.C.112: Green Star. Potential reduction in carbon emissions in a porcelain-enamelled steel curtain wall (Lawson 1996, p. 131).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel from recycled content **108.58 MJ/m2** Enamelled steel from recycled content **78.29 MJ/m^2** Aluminium from recycled content **236.05 MJ/m^2**	Reduce steel use in design **51.28 MJ/m2** Replacing with Geopolymer 6.58 **MJ/m^2**	**865 MJ/m^2**
Green Star, Total Wall	**422.92 MJ/m^2**	**57.86 MJ/m^2**	**865 MJ/ m^2**
	480.78 MJ/m^2		

v. Glass Curtain Wall

Table A.C.113: Potential reduction in carbon emissions in a glass curtain wall (Lawson 1996, p. 131).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled aggregates** Use Aluminium from recycled content (1.454 + 0.77 + 0.288) kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) **=** 2.512 kg/m2 x 161.9 = **406.69 MJ/m^2** **Reduced materials in design** Reduce 20% Aluminium in design 2.512 Kg x 170 MJ/Kg (Lawson 1996, p. 13) x 20% = **85.40 MJ/m2**
	Green Star **Reuse materials and elements** Use Aluminium from recycled contents 2.512 kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) x 90% **= 366.02 MJ/m^2** **Reused materials in design** Reduce 20% Aluminium in design 2.512 Kg x 170 MJ/Kg (Lawson 1996, p. 13) x 20% = **85.40 MJ/m2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in Carbon Emissions		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled content **406.69 MJ/m^2**	Reduce Aluminium use in design **85.40 MJ/m2**	**770MJ/ m^2**
Total Walls	**406.69 KJ/m^2**	**85.40 MJ/m^2**	**770MJ/ m^2**
	492.09 MJ/m^2		

Table A.C.114: Green Star. Potential reduction in carbon emissions in a glass curtain wall (Lawson 1996, p. 131).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Aluminium from recycled content **366.02 MJ/m^2**	Reduce Aluminium use in design **85.40 MJ/m2**	**770 MJ/m^2**
Green Star, Total Wall	**366.02 MJ/m^2**	**85.40 MJ/m^2**	**770 MJ/ m^2**
	451.42 MJ/m^2		

w. Steel Faced Sandwich Panel Wall

Table A.C.115: Potential reduction in carbon emissions in a steel faced sandwich panel wall (Lawson 1996, p. 132).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reuse recycled aggregates** - Steel frame from average recycled content = (0.774 + 0.185) Kg x 38MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 0.959 KJ/Kg x 17.9 Kg/ m2 = **17.16 MJ/m2** - Enamelled Steel facing from average recycled content = 9.734 Kg x 40 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 9.734 KJ/Kg x 19.9 Kg/ m2 = **193.70 MJ/m2** **Reduced materials in design** Reduce 20% steel in design 0.959 Kg x 38 MJ/Kg (Lawson 1996, p. 13) x 20% = **7.288 MJ/m2**
	Green Star **Reused materials and elements** - Steel frame from average recycled content = 0.959 Kg x 38 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 0.959 KJ/Kg X 17.9 Kg/ m2 x 90% = **15.44 MJ/m2** - Enamelled Steel facing from average recycled content = 9.734 Kg x 40MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg = 9.734 KJ/Kg x 19.9 Kg/ m2 x 90% = **174.33 MJ/m2** **Reduced materials in design** Reduce 20% steel in design 0.959 Kg x 38 MJ/Kg (Lawson 1996, p. 13) x 20% = **7.288 MJ/m2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	Steel from recycled content **17.16 MJ/m^2** Enamelled steel from recycled content **193.70 MJ/m^2**	Reduce steel use in design **7.28 MJ/m2**	**1087MJ/ m^2**
Total Walls	**210.86 KJ/m^2**	**7.28 MJ/m^2**	**1087MJ/ m^2**
	218.24 MJ/m^2		

Table A.C.116: Green Star. Potential reduction in carbon emissions in a steel faced sandwich panel wall (Lawson 1996, p. 132).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel from recycled content **15.44 MJ/m2** Enamelled steel from recycled content **174.33 MJ/m^2**	Reduce steel use in design **7.28 MJ/m2**	**1087 MJ/m^2**
Green Star, Total Wall	**189.77 MJ/m^2**	**7.28 MJ/m^2**	**1087 MJ/ m^2**
	197.05 MJ/m^2		

x. Aluminium Curtain Wall

Table A.C.117: Potential reduction in carbon emissions in an aluminium curtain wall (Lawson 1996, p. 132).

Processes where carbon emissions (embodied energy) can be reduced			
Building materials and elements	**Reuse recycled aggregates** Use Aluminium from recycled content (1.4544 + 0.7704 + 0.288 + 2.4435) kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) = 4.95 64 kg/m2 x 161.9 = **802.44 MJ/m^2** **Green Star** **Reuse materials and elements** Use Aluminium from recycled content (1.4544 + 0.7704 + 0.288 + 2.4435) kg/m2 (170 Mj/kg new – 8.1 Mj/kg from recycled) = 4.95 64 kg/m2 x 161.9 x 90%= **722.19 MJ/m^2**		
Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		Standard
Measurable energy to reduce in **Building materials and elements**	Aluminium from recycled content **802.44 MJ/m^2**		**935MJ/ m^2**
Total Walls	**802.44 KJ/m^2**		**935MJ/ m^2**
	802.44 MJ/m^2		

Table A.C.118: Green Star. Potential reduction in carbon emissions in an aluminium curtain wall (Lawson 1996, p. 132).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Aluminium from recycled content **722.19 MJ/m2**		**935 MJ/m^2**
Green Star, Total Wall	**722.19 MJ/m^2**		**935 MJ/ m^2**
	722.19 MJ/m^2		

A.C.2.3 Potential carbon emission reduction in general Australian roof construction systems

a. Timber Frame, Timber Shingle Roof

Table A.C.119: Potential reduction in carbon emissions in a timber framed timber shingle roof (Lawson 1996, p. 134).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 51 (Design Coalition 2013) = **20.40 MJ/m^2** - Using recycled trusses = 60% x 51 MJ/m^2 = **30.60 MJ/m^2** - Use insulation from recycled materials, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.6255kg/m^2 = **17.57 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 51 (Design Coalition 2013) = **20.40 MJ/m^2** - Using recycled trusses, 55% x 51 MJ/m^2 = **28.05 MJ/m^2**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Reduction in Carbon Emissions		Basic
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled trusses **20.4 MJ/m^2**	Using recycled trusses **30.60 MJ/m^2** Use recycled thermal insulation **17.57MJ/m^2**	**151MJ**/m^2
Total Roof	**20.4 MJ/m^2**	**48.17 MJ/m^2**	**151MJ/ m^2**
	68.57 MJ/m^2		

Table A.C.120: Green Star. Potential reduction in carbon emissions in a timber framed timber shingle roof (Lawson 1996, p. 134).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	Softwood Trusses from recycled trusses **20.40 MJ/m^2**	Using recycled trusses **28.05 MJ/m^2**	**151 MJ/m^2**
Green Star, Total Roof	**20.40 MJ/ m^2**	**28.05 MJ/m^2**	**151 MJ/ m^2**
	48.45 MJ/m^2		

b. Timber Frame, Fiber Cement Shingle Roof

Table A.C.121: Potential reduction in carbon emissions in a timber framed fibre cement shingle roof (Lawson 1996, p. 134).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses = 60% x 43 MJ/m² = **25.8 MJ/m²** - Use insulation from recycled materials, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.6255kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014) Being small and modular in nature, concrete roof tile is less prone to waste. Roof tiles can be crushed and recycled (LEED 2014) Use tiles from recycled roof tiles, 144 MJ/m² x 13% (LEED 2014) **= 18.72 MJ/m²** Use tiles from recycled roof tiles (Herbudiman & Saptaji 2013) from 45% recycled content Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (19 concrete – 2.66 cement) Kg/m² (Lawson 1996, p. 134) x 50% = 0.083 x 16.34 kg/m2 x 50% (Herbudiman & Saptaji 2013) = **6.78 MJ/m²**
	Green Star **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses, 55% x 43 MJ/m² = **23.65 MJ/m²**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Reduction in Carbon Emissions		Basic
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **25.8 MJ/m²** Use recycled thermal insulation **17.57MJ/m²** Recycled fibre cement 13%- **18.72 MJ/m²** Use fibre cement with recycled contents **6.78 MJ/m²**	**291MJ/**m²
Total Roof	**17.2 MJ/m²**	**55.33 MJ/m²**	**291MJ/ m²**
	74.1 MJ/m²		

Table A.C.122: Green Star. Potential reduction in carbon emissions in a timber framed fibre cement shingle roof (Lawson 1996, p. 134).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	Softwood Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **23.65 MJ/m²**	**291 MJ/m²**
Green Star, Total Roof	**17.2 MJ/ m²**	**23.65 MJ/m²**	**291 MJ/ m²**
	40.85 MJ/m²		

c. Timber Frame, Steel Sheet Roof

Table A.C.123: Potential reduction in carbon emissions in a timber framed steel sheet roof (Lawson 1996, p. 133).

	Processes where carbon emissions (embodied energy) can be reduced
Building materials and elements	**Steel from average recycled content** - **Steel sheet** from recycled contents {38 MJ/Kg (Lawson 1996) – 20.50 MJ/Kg} = 17.5 MJ/Kg x 4.9 kg/ **m^2** = **85.75 MJ/m^2** **Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 34 MJ/m^2 (Design Coalition 2013) = **13.6 MJ/m^2** - Using recycled trusses = 60% x 34 MJ/m^2 (Lawson 1996, p. 133) = **20.4 MJ/m^2** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.825kg/m^2 = **17.57 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Steel from average recycled content** Material-6 Steel, Green Star Technical Manual, is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (Green building Council of Australia 2008) is: - **Steel sheet** from recycled content {38 MJ/Kg (Lawson 1996. p. 144) – 20.50 MJ/Kg} = 17.5 MJ/Kg x 4.9 kg/ **m^2** x 90% = **77.17 MJ/m^2** **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 34 (Design Coalition 2013) = **13.6 MJ/m^2** - Using recycled trusses = 55% x 34 MJ/m^2 (Lawson 1996, p. 133) = **18.7 MJ/m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled timber 40% **13.6 MJ/m^2** Steel sheet from recycled content **85.75 MJ/m^2**	Use recycled trusses 60% **20.4 MJ/m^2** Use recycled thermal insulation **17.57 MJ/m^2**	**330MJ/** m^2
Total Roof, Research	**99.35 MJ/m^2**	**37.97 MJ/m^2**	**330MJ/ m^2**
	137.32 MJ/m^2		

Table A.C.124: Green Star. Potential reduction in carbon emissions in a timber framed steel sheet roof (Lawson 1996, p. 133).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel sheet from 90% recycled content = **77.17 MJ/m^2** Trusses from recycled timber 40% **13.6 MJ/m^2**	Use recycled trusses 55% **18.7 MJ/m^2**	**330 MJ/m^2**
Green Star, Total Roof	**90.77 MJ/m^2**	**18.7 MJ/m^2**	**330 MJ/ m^2**
	109.47 MJ/m^2		

d. Steel Frame, Steel Sheet Roof

Table A.C.125: Potential reduction in carbon emissions in a steel framed steel sheet roof (Lawson 1996, p. 135).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Steel from average recycled content** - Steel sheet from average recycled content = 4.9 Kg x {38 MJ/Kg (Lawson 1996, p.135) - 20.10 MJ/Kg} = **87.71 MJ/m²** - Steel frame roofing from recycled content {34 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.33 + 0.754) kg/ **m²** = **71.47 MJ/m²** **Reuse materials and elements** - Use 40% recycled trusses (UK Indemand 2014) 40% x 4.084 kg/m2 x 34 MJ/Kg = **55.54 MJ/m²** - Reduce 20% steel use in design, 4.9 Kg x 34 MJ/Kg (Lawson 1996, p.135) x 20%= **33.32 MJ/m²** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.55kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014)
	Green Star **Steel from average recycled content** Material-6 Steel, Green Star Technical Manual, is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled content) (Green building Council of Australia 2008) is: - Steel sheet from average recycled content = 4.9 Kg x {38 MJ/Kg (Lawson 1996, p. 135) - 20.10 MJ/Kg} x 90% = **78.93 MJ/m²** - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.33 + 0.754) kg/ m² x 90% = **64.32 MJ/m²** Reduce 20% steel use in design, 4.9 Kg x 34 MJ/Kg (Lawson 1996, p. 135) x 20%= **33.32 MJ/m²**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emission (embodied energy)		
Measurable energy to reduce in **Building materials and elements**	Steel frame from average recycled content **71.47 MJ/m²** Steel Sheet from recycled content **87.71 MJ/m²**	Use recycled trusses **= 55.54 MJ/m²** Use recycled insulation = **17.57 MJ/m²** Reduce steel in design **33.32 MJ/m²**	**483 MJ/** m²
Total Roof	**159.18 MJ/m²**	**73.11 MJ/m²**	**483 MJ/** m²
	232.29 MJ/m²		

Table A.C.126: Green Star. Potential reduction in carbon emissions in a steel framed steel sheet roof (Lawson 1996, p. 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel sheet from 90% Recycled content = **78.93 MJ/m²** Steel frame from 90% Recycled content = **64.32 MJ/m²**	Reduce steel in design **33.32 MJ/m²**	483 MJ/ **m²**
Green Star, Total Roof	**143.25 MJ/m²**	**33.32 MJ/m²**	**483 MJ/** m²
	178.57 MJ/m²		

e. Timber Frame, Concrete Tile Roof

Table A.C.127: Potential carbon emission reductions in a timber framed concrete tile roof (Lawson 1996, p. 134).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses = 60% x 43 MJ/m² = **25.8 MJ/m²** - Use insulation from recycled materials, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.6255kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014) Being small and modular in nature, concrete roof tile is less prone to waste. Roof tiles can be crushed and recycled (LEED 2014) Use tiles from recycled roof tiles, 92 MJ/m² x 13% (LEED 2014) **= 11.96 MJ/m²** Use tiles from recycled roof tiles (Herbudiman & Saptaji 2013) from 45% recycled content Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (44 concrete – 6.16 cement) Kg/m² (Lawson 1996, p. 134) x 45% = 0.083 x 37.84 kg/m2 x 50% (Herbudiman & Saptaji 2013) = **1.57 MJ/m²**
	Green Star **Reuse materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses 55% x 43 MJ/m² = **23.65 MJ/m²**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Reduction in Carbon Emissions		
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled trusses **17.2 MJ/m²** **Use tiles with recycled contents 1.57 MJ/m²**	Using recycled trusses **25.8 MJ/m²** Use recycled thermal insulation **17.57MJ/m** Use recycled roof tiles 13%, **11.96 MJ/m²**	**240MJ**/m²
Total Roof	**18.77 MJ/m²**	**55.33 MJ/m²**	**240MJ/ m²**
	74.1 MJ/m²		

Table A.C.128: Green Star. Potential reduction in carbon emissions in a timber framed concrete tile roof (Lawson 1996, p. 134).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	Softwood Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **23.65 MJ/m²**	**240 MJ/m²**
Green Star, Total Roof	**21.51 MJ/ m²**	**23.65 MJ/m²**	**240 MJ/ m²**
	45.16 MJ/m²		

f. Steel Frame, Concrete Tile Roof

Table A.C.129: Potential reduction in carbon emissions in a steel framed concrete tile roof (Lawson 1996, p. 134).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Steel from average recycled content** - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.33 + 0.754) kg/ **m^2** = **71.47 MJ/m^2** **Reuse materials and elements** - Use 40% recycled trusses (UK Indemand 2014) 40% x 4.084 kg/m2 x 34 MJ/Kg = **55.54 MJ/m^2** Reduce 20% steel use in design, 4.9 Kg x 34 MJ/Kg (Lawson 1996, p. 135) x 20%= **33.32 MJ/m^2** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.55kg/m^2 = **17.57 MJ/m^2** (Steel Construction Information 2014) Use tiles from recycled roof tiles, 92 MJ/m^2 x 13% (LEED 2014) **= 11.96 MJ/m^2** Use tiles from recycled roof tiles (Herbudiman & Saptaji 2013) from 45% recycled content Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (44 concrete – 6.16 cement) Kg/m^2 (Lawson 1996, p. 134) x 45% = 0.083 x 37.84 kg/m2 x 50% (Herbudiman & Saptaji 2013) =**1.57 MJ/m^2**
	Green Star **Steel from average recycled content** Material-6 Steel, Green Star Technical Manual, is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (Green building Council of Australia 2008) is: - Steel sheet from average recycled content = 4.9 Kg x {38 MJ/Kg (Lawson 1996, p. 135) - 20.10 MJ/Kg} x 90% = **78.93 MJ/m^2** - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.33 + 0.754) kg/ m^2 x 90% = **64.32 MJ/m^2** Reduce 20% steel use in design, 4.9 Kg x 34 MJ/Kg (Lawson 1996, p.135) x 20% = **33.32 MJ/m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		
Measurable energy to reduce in **Building materials and elements**	Steel frame from average recycled content **71.47 MJ/m^2** Recycled tiles used **11.96 MJ/m^2** Tiles from recycled content **1.57 MJ/m^2**	Use recycled trusses **= 55.54 MJ/m^2** Use Recycled insulation = **17.57 MJ/m^2** Reduce steel use in design **33.32 MJ/m^2**	**450 MJ/** m^2
Total Roof	**85 MJ/m^2**	**106.43 MJ/m^2**	**450 MJ/** m^2
	191.43 MJ/m^2		

Table A.C.130: Green Star. Potential reduction in carbon emissions in a steel framed concrete tile roof (Lawson 1996, p. 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel frame from 90% recycled content = **64.32 MJ/m^2**	**Reduce steel use in design 33.32 MJ/m^2**	450 MJ/ **m^2**
Green Star, Total Roof	**64.32 MJ/m^2**	**33.32 MJ/m^2**	**450 MJ/** m^2
	97.64 MJ/m^2		

g. Timber Frame, Terracotta Tile Roof

Table A.C.131: Potential reduction in carbon emissions in a timber framed terracotta tile roof (Lawson 1996, p. 134).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses = 60% x 43 MJ/m² = **25.8 MJ/m²** - Use insulation from recycled materials, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.6255kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014) Being small and modular in nature, concrete roof tile is less prone to waste. Roof tiles can be crushed and recycled, (LEED 2014) Use tiles from recycled roof tiles, 123 MJ/m² x 13% (LEED 2014) **= 15.99 MJ/m²** Use tile from recycled tiles (Herbudiman & Saptaji 2013) from 45% recycled content Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (49 concrete) Kg/m² (Lawson 1996, p. 134) x 50% = 0.083 x 49 kg/m2 x 50% (Herbudiman & Saptaji 2013) = **2.033 MJ/m²**
	Green Star **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses, 55% x 43 MJ/m² = **23.65 MJ/m²**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Reduction in Carbon Emissions		Basic
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **25.8 MJ/m²** Use recycled thermal insulation **17.57MJ/m** Use recycled tiles 13%, **15.99 MJ/m²** Tile from recycled content **2.033 MJ/m²**	**271MJ/**m²
Total Roof	**17.20 MJ/m²**	**61.39 MJ/m²**	**271MJ/ m²**
	78.59 MJ/m²		

Table A.C.132: Green Star. Potential reduction in carbon emissions in a timber framed terracotta tile roof (Lawson 1996, p. 134).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	Softwood Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **23.65 MJ/m²**	**271 MJ/m²**
Green Star, Total Roof	**21.51 MJ/ m²**	**23.65 MJ/m²**	**271 MJ/ m²**
	45.16 MJ/m²		

h. Timber Frame, Synthetic Rubber Membrane Roof

Table A.C.133: Potential reduction in carbon emissions in a timber framed synthetic rubber membrane roof (Lawson 1996, p. 134).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused materials and elements** - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses = 60% x 43 MJ/m² = **25.8 MJ/m²** - Use insulation from recycled materials, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.6255kg/m² = **17.57 MJ/m²** (Steel Construction Information 2014)
	Green Star **Reused materials and elements** (local salvage/re-use centre) Material-8 Timber, Green Star Technical Manual, 95% of all timber products re-used, post-consumer recycled timber or FSC certified timber - Softwood Trusses from recycled trusses 40% x 43 (Design Coalition 2013) = **17.2 MJ/m²** - Using recycled trusses 55% x 43 MJ/m² = **23.65 MJ/m²**

Life Cycle Stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Reduction in Carbon Emissions		Basic
Measurable energy to reduce in **Building materials and elements**	Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **25.8 MJ/m²** Use recycled thermal insulation **17.57MJ/m²**	**386MJ/**m²
Total Roof	**17.20 MJ/m²**	**43.37 MJ/m²**	**386MJ/ m²**
	60.57 MJ/m²		

Table A.C.134: Green Star. Potential reduction in carbon emissions in a timber framed synthetic rubber membrane roof (Lawson 1996, p. 134).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Building materials and elements**	Softwood Trusses from recycled trusses **17.2 MJ/m²**	Using recycled trusses **23.65 MJ/m²**	**386 MJ/m²**
Green Star, Total Roof	**21.51 MJ/ m²**	**23.65 MJ/m²**	**386 MJ/ m²**
	45.16 MJ/m²		

i. Concrete Slab, Synthetic Rubber Membrane Roof

Table A.C.135: Potential reduction in carbon emissions in a concrete slab synthetic rubber membrane roof (Lawson 1996, p. 135)

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Reused recycled aggregate for concrete** - Concrete from 80% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (360 concrete – 48.88cement) Kg (Lawson 1996, p. 125) x 80% = **19.97 MJ/m^2** **Steel from average recycled content** - Steel mesh +Edge beams from average recycled content = 7.153 Kg x {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **99.42MJ/m^2**
	Green Star **Reused recycled aggregate for concrete** Material-5 Green Star Technical Manual, is considered maximum 20%, therefore reduced embodied energy by this credit (Concrete from 20% Recycled aggregate) (Green building Council of Australia 2008) is: - Concrete from 20% Recycled aggregate (Uche 2008; PCA 2014), embodied energy of aggregate is 0.083 MJ/Kg Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (360 concrete –59.14 cement) Kg (Lawson 1996, p.125) x 20% = **4.99 MJ/m^2** **Steel from average recycled content** Material-6 Green Star Technical Manual, Steel is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from Recycled content) (Green building Council of Australia 2008) is: 7.153 Kg x 90% {34 MJ/Kg (Lawson 1996, p. 13) - 20.10 MJ/Kg} = **89.48 MJ/m^2**
Implementation	**Decreased and Replaced energy in process** **Replaced cement** Geopolymer Concrete or 100% replacing with recycled cement (Nath & Sarker 2014) results 97% reduction in GHG (McLellan et al. 2011) 360 kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson1996, p. 41) = 48.88 kg replaced cement/ m^2 in concrete 48.88 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) **= 273.72 MJ/ m^2**
	Green Star Replacing maximum 60% of cement (Green building Council of Australia 2008) 360 kg/m^2 (Lawson 1996, p. 124) x 14% Cement (Lawson 1996, p. 41) = 29.33 kg replaced cement/ m^2 in concrete 29.33 kg Cement/m^2 x 5.6 MJ/kg (Lawson 1996, p. 13) x 60% **= 164.24 MJ/ m^2**

Life cycle stages of building	Construction		Embodied Energy
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		Basic
Measurable energy to reduce in **Building materials and elements**	Concrete from 80% recycled aggregate = **19.97 MJ/m^2**	Steel mesh, beams from average recycled content = **99.42 MJ/m**	**645MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer replacing 100% of cement = **273.72 MJ/ m^2**	
Total Floor	**19.97 MJ/m^2**	**373.14 MJ/m^2**	**645MJ/** m^2
	393.11 MJ/m^2		

Table A.C.136: Green star. Potential reduction in carbon emissions in a concrete slab synthetic rubber membrane roof (Lawson 1996, p. 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	20% recycled aggregate for concrete = **4.99 MJ/m^2**	90% Steel mesh from average recycled content **89.48MJ/m^2**	**645 MJ/m^2**
Measurable energy to reduce in **Implementation**		Geopolymer 60% Cement Replacement **164.24 MJ/m^2**	
Green Star, Total Floor	**4.99 MJ/m^2**	**253.72 MJ/m^2**	**645MJ/ m^2**
	258.71 MJ/m^2		

j. Steel Frame, Fibre Cement Sheet Roof

Table A.C.137: Potential reduction in carbon emissions in a steel framed fibre cement sheet roof (Lawson 1996, p. 135).

Processes where carbon emissions (embodied energy) can be reduced	
Building materials and elements	**Steel from average recycled content** - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ **m^2** = **61.61 MJ/m^2** **Reuse materials and elements** - Use 40% recycled trusses (UK Indemand 2014) 40% x 3.734 kg/m2 x 34 MJ/Kg = **50.78 MJ/m^2** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.55kg/m^2 = **17.57 MJ/m^2** (Steel Construction Information 2014) Use fibre cement from recycled contents, 106 MJ/m^2 x 13% (LEED 2014) **= 13.78MJ/m^2** Use fibre cement from recycled contents (Herbudiman & Saptaji 2013) from 45% recycled content Saved embodied energy = embodied energy of aggregate 0.083 MJ/Kg x (44 concrete – 6.16 cement) Kg/m^2 (Lawson 1996, p. 134) x 45% = 0.083 x 14 kg/m^2 x 50% (Herbudiman & Saptaji 2013) = **5.81 MJ/m^2**
	Green Star **Steel from average recycled content** Material-6 Steel, Green Star Technical Manual, is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled contents) (Green building Council of Australia 2008) is: - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ m^2 x 90% = **55.44 MJ/m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		
Measurable energy to reduce in **Building materials and elements**	Steel frame from average recycled content **61.61 MJ/m^2** Reuse Fibre cement sheet **13.78MJ/m^2**	Use recycled trusses **= 50.78 MJ/m^2** Use recycled insulation = **17.57 MJ/m^2** Fiber cement sheet from recycled contents **5.81 MJ/m^2**	**337 MJ/** m^2
Total Roof	**75.39 MJ/m^2**	**74.16 MJ/m^2**	**337MJ/ m^2**
	149.55 MJ/m^2		

Table A.C.138: Green Star. Potential reduction in carbon emissions in a steel framed fibre cement sheet roof (Lawson 1996, p, 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel frame from 90% recycled content = **55.44 MJ/m^2**		**337 MJ/m^2**
Green Star, Total Roof	**55.44 MJ/m^2**		**337 MJ/ m^2**
	55.44 MJ/m^2		

k. Steel Frame, Steel Sheet Roof (commercial)

Table A.C.139: Potential reduction in carbon emissions in a steel framed steel sheet roof (commercial) (Lawson 1996, p. 135).

	Processes where carbon emissions (embodied energy) can be reduced
Building materials and elements	**Steel from average recycled content** - Steel sheet from average recycled content = 5.6 Kg x {38 MJ/Kg (Lawson 1996, p.135) - 20.10 MJ/Kg} = **100.24 MJ/m^2** - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ **m^2** = **61.61 MJ/m^2** **Reuse materials and elements** - Use 40% recycled trusses (UK Indemand 2014) 40% x 3.734 kg/m2 x 34 MJ/Kg = **50.78 MJ/m^2** - Use recycled thermal insulation, 49MJ/kg (Lawson 1996) - 20.90 MJ/kg x 0.55kg/m^2 = **17.57 MJ/m^2** (Steel Construction Information 2014)
	Green Star **Steel from average recycled content** Material-6 Steel, Green Star Technical Manual, is considered maximum 90%, therefore reduced embodied energy by this credit (Steel from 90% Recycled content) (Green building Council of Australia 2008) is: - Steel sheet from average recycled content = 5.6 Kg x {38 MJ/Kg (Lawson 1996, p.135) - 20.10 MJ/Kg} x 90% = **90.21 MJ/m^2** - Steel frame roofing from recycled content {38 MJ/Kg (Lawson 1996, p. 135) – 21.5 MJ/Kg} = 17.5 MJ/Kg x (3.384 + 0.35) kg/ m^2 x 90% = **55.44 MJ/m^2**

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential reduction in carbon emissions		
Measurable energy to reduce in **Building materials and elements**	Steel frame from average recycled content **61.61 MJ/m^2** Steel Sheet from recycled content **100.24 MJ/m^2**	Use recycled trusses **= 50.78 MJ/m^2** Use recycled insulation = **17.57 MJ/m^2**	**401 MJ/** m^2
Total Roof	**161.85 MJ/m^2**	**68.35 MJ/m^2**	**401MJ/ m^2**
	230.20 MJ/m^2		

Table A.C.140: Green Star. Potential reduction in carbon emissions in a steel framed steel sheet roof (commercial) (Lawson 1996, p. 135).

Life Cycle Stages of building	Construction		Embodied Energy Basic
	Pre-Construction	Construction	
	Potential Carbon Emission (Embodied Energy) Reduction		
Measurable energy to reduce in **Implementation**	Steel sheet from 90% Recycled content = **90.21 MJ/m^2** Steel frame from 90% Recycled content = **55.44 MJ/m^2**		**401 MJ/m^2**
Green Star, Total Roof	**145.65 MJ/m^2**		**401 MJ/ m^2**
	145.65 MJ/m^2		

APPENDIX D

DATA RELATING TO CHAPTER FIVE

References, specifications and detailed information in these tables relates to data in Chapter Five.

Table A.D.1: Bioclimatic conditions – current; from best practice with green tools (Green Star, LEED and BREEAM); from this research model; and from research and lab

Bioclimatic Design Principles Criteria	**Current conditions, Implemented**	**Conditions with Green tools G.S., LEED, BREEAM**	**Conditions in this research**	**Conditions in research and lab**
Concrete from recycled aggregates	In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities [1]	G.S. and LEED 1-3 points 20-30% RA for structural purpose; BRE 25-50% in 20-40 MPa - no restriction, 100% non-structural [2, 18, 36]	Fully RA for non-structural purpose; 100% RA for non-structural; 80 % RA for structural purpose [6]	ADAA, ASA, UNSW, Standards Australia; [4], fully RA for non-structural; 30-75-80 % RA for structural [13,11]
Concrete block from recycled aggregate	24% recycled content of an aggregate concrete block [8]	G.S., BRE, 40%; US 25% RA structural; 100%, or no natural aggregates in non-structural [18,23,36]	Aggregate for concrete block fully from recycled aggregate [13]	UK, USA, AUS; [11], fully RA for concrete block[13]
Brick from recycled aggregates	Current level of recycled material content in brick is 11% [14,41]	G.S., 30%;[16, 23]; LEED 20%; BRE 11% ISO, up to 10 points for 10% Recycled aggregate [14,16,36]	Reuse the recycled aggregate for brick, 67% [19]	US; UK, Reuse fully recycled aggregate for brick, 6 points [11, 17]
Steel from average recycled content	Primary typically 10-15% of scrap steel, Secondary 100% scrap based production [25, 34]	G.S. Mat-6, 60%; LEED 65-97.5%; BRE, Mat-6, 60%; -97.5% beams, plates; 65% bars; 66% steel deck post-consumer recycled content [23,16,38]	Steel from fully post-consumer recycled contents	Steel from 65-97.5% post-consumer recycled contents [22, 39]
Reuse recycled and post-consumer structural and non-structural steel	Scaffolding, formwork, sheet piles, etc., London Olympic Stadium [32, 34]	G.S., 95% Joinery, 50% structural framing, roofing; LEED 75-100% existing wall, floor, roof; BRE, Mat-6, 60% recycled content [3,5,23,24]	Use 40% recycled and post-consumer steel elements	Steel products are re-usable, steel piles, hollow sections; gauge, purlins, rails [32,.31]
Reduce material use in steel structural design 10-20%	Some current green projects have reduced materials use in design 10-20% [23]	G.S., Mat-6, 10-20% one point; LEED, eliminating need for materials in the design stage; BRE reduced, avoiding over-design [23,21,10,7,32]	Reduced materials use in structural design 10-20%	Integrative Design Process (IDP) Linear design; the London Olympics structure 1/10 [32, 42]
Reuse recycled timber and post-consumer FSC timber	FSC works in 80 countries, 24000 FSC chain of custody certificates are active in 107 countries[23,]	G.S. 95% re-used, post-consumer; FSC certified timber; up to 3 points; LEED, 50% FSC; BRE, 3 points, post-consumer waste stream [22, 23, 32,24,29]	60% of all timber products re-used, post-consumer recycled timber; FSC certified timber	AUS; fully timber products re-used, post-consumer, recycled or are FSC certified timber [43]
Roof tile from recycled tiles	In some countries materials such as concrete roof tiles, removed separated and recycled[44, 45]	G.S. Mat-5, 1 point, no natural aggregates are used; LEED, from the waste, up to3.5 points, BRE, M03, from the waste stream [20,21,23,36]	50% Roof tile from recycled aggregate [21]	US; UK; AUS,50% Roof tile from recycled aggregate RA; roof tiles are 100% recoverable [21, 45]
Thermal insulation from recycled content	Thermal insulation is fully recyclable, i.e. wool content,[31]	G.S. 80% advised; LEED MR4 20%, ½ point, BRE 80%, 1 point, responsibly sourced [12.7,27,37]	Thermal insulation from fully recycled waste [25]	US; UK; Thermal insulation 100% from recycled waste [25]
Portland cement replaced with geopolymer based cement	Geopolymer has been used in structural, non-structural, e.g. GCI in Qld, Wellcamp Airport [46,47,48]	G.S. 60% In situ concrete; 40% precast 30% stressed concrete; LEED, 30% structural; no limit others, BRE, responsibly sourced cement [23,26,7]	Geopolymer based cement fully replaces Portland cement arranged for non-structural, structural	Geopolymer based cement fully replaces Portland cement, arranged for non-structural and structural [13, 28]
Reduce transportation by reusing and recycled materials	National Waste Policy Australia advice to reduce waste, re-use to reduce environmental impact [35]	Green tools credit reusing and recycling up to 40% of materials, not directly credited; obtained from30km radius of the site [2,15,35,37]	Reuse has been considered in material production and building elements	Transportation reduction by increasing reuse and recycling is considered in current study in UK [32]
Transportation by water or rail not truck, Reduce transportation by localizing	15% of bricks are transported to distributor's yard or jobsite by rail and 85% by truck [19, 30]	LEED, Regional Materials, up to 2 points [14] tools advise localizing, using water and rail instead of road[2,15]	Localizing has been considered	Transport of construction materials in UK has been examined in London Olympics [30]

Sources: **1**-(Cement Concrete & Aggregates Australia 2015; Gonzalez-Fonteboa 2005) **2**-(Green building Council of Australia GBCA 2008) **3**-(Subasic 2016) **4**-(Ash Development Association of Australia 2013; Low carbon living CRC 2015) **5**-(Green Building Council of Australia 2012) **6**-Chapter Seven **7**-(US Green Building Council 2010) **8**.(Concrete Block Association 2013) **9**-(GBCA 2016) **10**- (LEED 2016); **11**-(Poon, Kou & Lam 2002; Concrete Block Association 2013) **13**-(Uche 2008; PCA 2014) 14-(Brick Development Association 2009); **15**-(LEED 2014) **16**-(Kang and Kren 2007) **17**-(Volz and Stovner 2010) **18**-(Obla, Kim & Lobo. 2010) **19**-(Brick Development Association 2014; Tyrell & Goode 2014) **20**-(Boral 2014) **21**-(LEED 2014); **22**-(Steel Construction Information 2014) **23**-(GBCA 2008; US Green Building Council 2011) **24**-(LEED US Green Building Council 2005) **25**-(Steel Construction Information 2014; Greenspec 2015) **26**-(Ash Development Association of Australia 2013) **27**-(US Green Building Council 2011) **28**-(Geopolymer House 2011; Nath & Sarker 2014) **29**- (Forest Stewardship Council 2010) **30**-(Learning Legacy 2012; Benn, Dunphy & Griffiths 2014) **31**-(Ecospecifier Global 2016) **32**-(Allwood et al. 2012; UK Indemand 2014, 2015) **34**-(Learning Legacy 2012; Inhabitat 2014; Steel Construction Information 2014) **35**-(DEE 2012) **36**-(Chisholm 2011) **37**- (BREEAM 2014b); **38**-(Dowling 2010) **39**-(Kang & Kren 2007) **41**-(Brick Industry Association 2016) **42**- (CNN 2012) **43**- (FSC 2015) **44**-(Tam, Gao & Tam 2005) **45**-(NSW Government 2010) **46**-(Zeobond Group 2014) **47**-(Geopolymer Institute 2014) **48**-(Wellcamp 2014) | **Table prepared by Author**

Table A.D.2: Bioclimatic conditions of the research considered in current practice; green tools (Green Star, LEED and BREEAM); and from research and lab

Bioclimatic Design Principles Criteria	**Current conditions**	**Australian Tool Green Star (GBCA)**	**US Green Tool LEED**	**UK Green Tool BREEAM**	**Research and Lab**
Concrete from recycled aggregates	In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities [1]	Green Star, one point, 20% of aggregate for structural purpose; no natural aggregate used in non-structural purposes [2]	LEED, recycled content, 10-20% of aggregate up to 3 points; [2, 24]; 20-30% of aggregate for structural 100% non-structural purposes, US [18,36]	BREEAM, 25-50% RA; no restriction in 16 MPa and 40 MPa; 20% Designated concrete 20-40 MPa [2, 36]	ADAA, ASA, UNSW, Standards Australia; [4], fully RA for non-structural; 30-75-80 % RA for structural [13,11]
Concrete block from recycled aggregate	24% recycled content of an aggregate concrete block [8]	Green Star, 40% RA; no natural aggregates in non-structural [23,33]	ASTM, structural 20-25% coarse aggregate; 100% up to 20 MPa [18, 36]	BREEAM, no restriction in 16 MPa and 40 for Concrete block[36]	UK, USA, AUS; [11], fully RA for concrete block [13]
Brick from recycled aggregates	Current level of recycled material content in brick is 11% [14,41]	Green Star, not directly credit, Mat-3, 80% reused material [2,9, 16]	LEED, recycled content in brick 10-20%, MR 4, 2 points, 2 ½ point [14]	BREEAM; all waste reused; recycled content is 11% [14]	US, UK reuse fully recycled aggregate for brick, 6 points [11,14]
Steel from average recycled content	Primary typically 10-15% of scrap steel, Secondary 100% scrap based production [25, 34]	Green Star, Mat-6; maximum 60% post-consumer recycled content [23]	LEED, 65-97.5% post-consumer recycled content [23, 16]	BREEAM, Mat-6;60% recycled content;[38] 97.5% beams, plates; 65% bars; 66% steel deck, [16]	Steel from 65-97.5% post-consumer recycled content [22, 16]
Reuse recycled and post-consumer steel in structural & non-structural	Scaffolding, formwork, sheet piles, etc., London Olympic Stadium [32, 34]	95% of joinery; 50% of structural framing, roofing, designed to be disassembled [5]	LEED, 1-2 points to 75-100% reuse of existing walls, floors and roof.[24, 3]	BREEAM, Mat-6; maximum 60% recycled content [23]	Steel products are re-usable, steel piles, hollow sections; gauge, purlins, rails [32,.31]
Reduce material use in steel structural design	Some current green projects have reduced materials use in design 10-20% [23]	Green Star, Mat-6, grade reduced materials in design,10-20%, [23] Mat-10, one point for 20% reduce	LEED, eliminating the need for materials in the planning and design phases, [10, 7]	BREEAM, grade reduced materials in design [21] avoiding over-design, material reuse [39]	Integrative Design Process (IDP) Linear design; the London Olympics structure 1/10 [32, 42]
Reuse recycled timber and post-consumer FSC timber	FSC works in 80 countries, 24000 FSC chain of custody certificates are active in 107 countries[23,]	Green Star 95% of all timber products re-used, post-consumer; FSC certified timber [22, 23]	LEED, timber products re-used, post-consumer; 50% FSC certified timber, up to 1 point [32, 29, 24]	BREEAM; up to three points where timber is part of a pre-or post-consumer waste stream [36]	AUS; fully timber products re-used, post-consumer, recycled or are FSC certified timber [43]
Roof tiles from recycled tiles	In some countries materials such as concrete roof tiles, removed separated and recycled[44, 45]	Green Star, Mat-5 one point, where no natural aggregates are used in non-structural uses [23]	LEED credits; produced from postconsumer recycled content, from the waste, up to3.5 points [20,21]	BREEAM; M03, roof tiles can be extracted from the waste stream [36]	US; UK; AUS,50% Roof tile from recycled aggregate RA; roof tiles are 100% recoverable [21, 45]
Thermal insulation from recycled content	Thermal insulation is fully recyclable, i.e. wool content,[31]	Green Star, not directly credit but 80% recycled content advised [27,]	LEED, MR4, 20% or more recycled thermal insulation, one point [12, 7]	80% thermal insulation must be responsibly sourced 1 point [37]	US; UK; Thermal insulation 100% from recycled content; [25,]
Portland cement replaced with Geopolymer based cement	Geopolymer has been used in structural, non-structural, e.g. GCI in Qld, Wellcamp Airport [46,47,48]	Green Star; Maximum 60% In situ concrete 40% precast and 30% for stressed concrete; 30% for 1 point and 40% for 2 points [23, 26]	LEED Concrete consists of at least 30% fly ash; 50% recycled content or reclaimed aggregate; 90% recycled content or reclaimed aggregate [23, 12,7]	One point awarded where cement used to make cement as the supply chain process and must be responsibly sourced [40]	Geopolymer cement fully replaces Portland cement, arranged for non-structural and structural purposes [13, 28]
Reduce transportation by reusing and recycling materials	National Waste Policy Australia advice to reduce waste, re-use to reduce environmental impact [35]	Green tools credit the reusing and recycling up to 40% of materials, not directly credited [2, 15, 35]	Green tools credit the reusing and recycling up to 40% of materials, not directly credited [2, 15]	One credit where obtained from waste processing site(s) within a 30km radius of the site, [37]	Transportation reduction by increasing reusing, recycling is considered in current study, UK[39]
Transportation by water or rail not truck, Reduce transportation by localizing	15% of bricks are transported to distributor's yard or jobsite by rail and 85% by truck [19, 30]	Green Star, advise localizing, using water and rail instead of road [2,15]	LEED, Regional Materials, up to 4 points;[14] tools advise localizing, using water and rail instead of road [2,15]	Regional Materials, localizing, using water and rail instead of road [2,15]	Transport construction materials in UK has already examined in London Olympics [30]

Sources: **1**-(Cement Concrete & Aggregates Australia 2015; Gonzalez-Fonteboa 2005) **2**-(Green building Council of Australia GBCA 2008) **3**-(Subasic 2016) **4**-(Ash Development Association of Australia 2013; Low carbon living CRC 2015) **5**-(Green Building Council of Australia 2012) **6**-Chapter Seven **7**-(US Green Building Council 2010) **8**.(Concrete Block Association 2013) **9**-(GBCA 2016) **10**- (LEED 2016); **11**-(Poon, Kou & Lam 2002; Concrete Block Association 2013) **12**- (LEED 2016)**13**-(Uche 2008; PCA 2014) 14-(Brick Development Association 2009); **15**-(LEED 2014) **16**-(Kang and Kren 2007) **17**-(Volz and Stovner 2010) **18**-(Obla, Kim & Lobo. 2010) **19**-(Brick Development Association 2014; Tyrell & Goode 2014) **20**-(Boral 2014) **21**-(LEED 2014); **22**-(Steel Construction Information 2014) **23**-(GBCA 2008; US Green Building Council 2011) **24**-(LEED US Green Building Council 2005) **25**-(Steel Construction Information 2014; Greenspec 2015) **26**-(Ash Development Association of Australia 2013) **27**-(US Green Building Council 2011) **28**-(Geopolymer House 2011; Nath & Sarker 2014) **29**- (Forest Stewardship Council 2010) **30**-(Learning Legacy 2012; Benn, Dunphy & Griffiths 2014) **31**-(Inhabitat 2014; Learning Legacy 2014; Steel Construction Information 2014) **32**- (Ecospecifier Global 2016) **33** (CBA Concrete Block Association 2013) **34**- (Onesteel 2016) **35**- (DEE 2012); **36**- (Chisholm 2011) **37**- (BREEAM 2014b); **38**-(Dowling 2010) **39**-(UK Indemand 2014, 2015); **40**-(BREEAM BRE 2014) **41**-(Brick Industry Association 2016) **42**- (CNN 2012) **43**- (FSC 2015) **44**-(Tam, Gao & Tam 2005) **45**-(NSW Government 2010) **46**- (Zeobond Group 2014) **47**-(Geopolymer Institute 2014) **48**-(Wellcamp 2014) | **Table prepared by Author**

Table A.D.3: Bioclimatic conditions – current; from best practice with green tools (Green Star, LEED and BREEAM); from this research model; and from research and lab + Percentage carbon reductions.

Bioclimatic Design Principles (BDP) Criteria	**Current conditions, Implemented**	**Conditions with Green tools G.S., LEED, BREEAM**	**Conditions in this research**	**Conditions in research and lab.**
Concrete from recycled aggregates	In Australia, there are a number of manufactured and recycled aggregates readily available in certain localities [1]	G.S. and LEED 1-3 points 20-30% RA for structural purpose; BRE 25-50% in 20-40 MPa - no restriction, 100% non-structural [2, 18, 36]	Fully RA for non-structural purpose; 100% RA for non-structural; 80 % RA for structural purpose [6]	ADAA, ASA, UNSW, Standards Australia; [4], fully RA for non-structural; 30-75-80 % RA for structural;[13,11]
Concrete block from recycled aggregate	24% recycled content of an aggregate concrete block [8]	G.S., BRE, 40%; US 25% RA structural; 100%, or no natural aggregates in non-structural [18,23,36]	Aggregate for concrete block fully from recycled aggregate [13]	UK, USA, AUS; [11], fully RA for concrete block;[13]
Brick from recycled aggregates	Current level of recycled material content in brick is 11% [14,41]	G.S., 30%;[16, 23]; LEED 20%; BRE 11% ISO, up to 10 points for 10% Recycled aggregate [14,16,36]	Reuse the recycled aggregate for brick, 67% [19]	US; UK, Reuse fully the recycled aggregate for brick, 6 points; [11, 17]
Steel from average recycled content	Primary typically 10-15% of scrap steel, Secondary 100% scrap based production [25, 34]	G.S. Mat-6, 60%; LEED 65-97.5%; BRE, Mat-6, 60%; -97.5% beams, plates; 65% bars; 66% steel deck post-consumer recycled content [23,16,38]	Steel from fully post-consumer recycled contents	Steel from 65-97.5% post-consumer recycled contents;[22, 39]
Reuse recycled and post-consumer structural and non-structural steel	Scaffolding, formwork, sheet piles, etc., London Olympic Stadium [32, 34]	G.S., 95% Joinery, 50% structural framing, roofing; LEED 75-100% existing wall, floor, roof; BRE, Mat-6, 60% recycled content [3,5,23,24]	Use 40% recycled and post-consumer steel elements	Steel products are re-usable, steel piles, hollow sections; gauge, purlins, rails[32,.31]
Reduce material use in steel structural design 10-20%	Some current green projects have reduced materials use in design 10-20% [23]	G.S., Mat-6, 10-20% one point; LEED, eliminating need for materials in the design stage; BRE reduced, avoiding over-design [23,21,10,7,32]	Reduced materials use in structural design 10-20%	Integrative Design Process (IDP) Linear design; the London Olympics' structure 1/10, [32, 42]
Reuse the recycled timber and post-consumer FSC timber	FSC works in 80 countries, 24000 FSC chain of custody certificates are active in 107 countries[23,]	G.S. 95% re-used, post-consumer; FSC certified timber; up to 3 points; LEED, 50% FSC; BRE, 3 points, post-consumer waste stream [22, 23, 32,24,29]	60% of all timber products re-used, post-consumer recycled timber; FSC certified timber	AUS; fully timber products re-used, post-consumer, recycled or are FSC certified timber[43]
Roof tile from recycled tile	In some countries materials such as concrete roof tiles, removed separated and recycled[44, 45]	G.S. Mat-5, 1 point, no natural aggregates are used; LEED, from the waste, up to3.5 points, BRE, M03, from the waste stream [20,21,23,36]	50% Roof tile from recycled aggregate [21]	US; UK; AUS,50% Roof tile from recycled aggregate RA; roof tiles are 100% recoverable [21, 45]
Thermal insulation from recycled content	Thermal insulation is fully recyclable, i.e. wool content,[31]	G.S. 80% advised; LEED MR4 20%, ½ point, BRE 80%, 1 point, responsibly sourced [12.7,27,37]	Thermal insulation from fully recycled waste [25]	US; UK; Thermal insulation 100% from recycled waste; [25]
Portland cement replaced with Geopolymer based cement	Geopolymer has been used in structural, non-structural, e.g. GCI in Qld, Wellcamp Airport [46,47,48]	G.S. 60% In situ concrete; 40% precast 30% stressed concrete; LEED, 30% structural; no limit others, BRE, responsibly sourced cement [23,26,7]	Geopolymer based cement fully replaces Portland cement arranged for non-structural, structural	Geopolymer based cement fully replace with Portland cement, arranged for non-structural and structural;[13, 28]
Reduce transportation by reusing and recycled materials	National Waste Policy Australia advice to reduce waste, re-use to reduce environmental impact [35]	Green tools credit reusing and recycling up to 40% of materials, not directly credited; obtained from30km radius of the site [2,15,35,37]	Reuse has been considered in material production and building elements	Transportation reduction by increasing reusing and recycling is considered in current study in UK;[32]
Transportation by water or rail not truck, Reduce transportation by localizing	15% of bricks are transported to distributor's yard or jobsite by rail and 85% by truck [19, 30]	LEED, Regional Materials, up to 2 points [14] tools advise localizing, using water and rail instead of road[2,15]	Localizing has been considered	Transport the construction materials in UK has already examined in London Olympics; [30]
Carbon Emissions Reduction	**Six case studies Current Implementation** **Between -23 % to 57 %**	**Examine the six case studies with Green Tool** **Between 17 to 32 %**	**The six case studies with Research Model** **Between 50 to 65 %**	**UK Government has funded UK-Indemand Center[32]** **Proposes 80 %**

Sources: 1-(Cement Concrete & Aggregates Australia 2015; Gonzalez-Fonteboa 2005) **2**-(Green building Council of Australia GBCA 2008) **3**-(Subasic 2016) **4**-(Ash Development Association of Australia 2013; Low carbon living CRC 2015) **5**-(Green Building Council of Australia 2012) **6**-Chapter Seven **7**-(US Green Building Council 2010) **8**.(Concrete Block Association 2013) **9**-(GBCA 2016) **10**- (LEED 2016); **11**-(Poon, Kou & Lam 2002; Concrete Block Association 2013) **13**-(Uche 2008; PCA 2014) 14-(Brick Development Association 2009); **15**-(LEED 2014) **16**-(Kang and Kren 2007) **17**-(Volz and Stovner 2010) **18**-(Obla, Kim & Lobo. 2010) **19**-(Brick Development Association 2014; Tyrell & Goode 2014) **20**-(Boral 2014) **21**-(LEED 2014); **22**-(Steel Construction Information 2014) **23**-(GBCA 2008; US Green Building Council 2011) **24**-(LEED US Green Building Council 2005) **25**-(Steel Construction Information 2014; Greenspec 2015) **26**-(Ash Development Association of Australia 2013) **27**-(US Green Building Council 2011) **28**-(Geopolymer House 2011; Nath & Sarker 2014) **29**- (Forest Stewardship Council 2010) **30**-(Learning Legacy 2012; Benn, Dunphy & Griffiths 2014) **31**-(Ecospecifier Global 2016) **32**-(Allwood et al. 2012; UK Indemand 2014, 2015) **34**-(Learning Legacy 2012; Inhabitat 2014; Steel Construction Information 2014) **35**-(DEE 2012) **36**-(Chisholm 2011) **37**- (BREEAM 2014b); **38**-(Dowling 2010) **39**-(Kang & Kren 2007) **41**-(Brick Industry Association 2016) **42**- (CNN 2012) **43**- (FSC 2015) **44**-(Tam, Gao & Tam 2005) **45**-(NSW Government 2010) **46**-(Zeobond Group 2014) **47**-(Geopolymer Institute 2014) **48**-(Wellcamp 2014) | **Table prepared by Author**

Table A.D.4: Bioclimatic criteria examined in general Australian floor, wall and roof construction systems using the research model and the Green Star rating tool

Bioclimatic criteria		A.1 Floor construction systems	A.2. Wall construction systems	A.3. Roof construction systems
Concrete from recycled aggregates	Study	80% RA for fixing posts in the ground [1]	80 % RA for concrete slab on ground [1]	80 % RA for concrete slab on ground [1]
	Green Star	20% RA for fixing posts in the ground [2]	20 % RA for fixing posts in the ground [2]	20 % RA for fixing posts in the ground [2]
Concrete block and brick from recycled aggregate	Study	-	Concrete block wall from (67-100%) RA [3]	-
	Green Star	-	Concrete block wall from 20% RA [3]	-
Brick from recycled aggregate	Study	Brick from 67% RA for posts Use recycled bricks 60% [4]	Brick wall from 67% RA [4]	-
	Green Star	-	-	-
Steel from average recycled content	Study	Use steel produced with 100% recycled content [8,13]	Use steel produced with 100% recycled content [8,13]	Use steel produced with 100% recycled content [8,13]
	Green Star	Use steel produced with 90% recycled content [6,7]	Use steel produced with 90% recycled content [6,7]	Use steel produced with 90% recycled content [6,7]
Reuse recycled and post-consumer structural and non-structural steel	Study	Reuse 40% recycled steel in structural and non-structural elements [31,32]	Reuse 40% recycled steel in structural and non-structural elements [31,32]	Reuse 40% recycled steel in the structural and non-structural elements [31,32]
	Green Star	-	-	-
Reduce material (steel) use in design 10-20%	Study	Reduced 20% steel use in design [12, 14]	Reduced 20% steel use in design [12, 14]	Reduced 20% steel use in design [12, 14]
	Green Star	Reduced 20% steel use in design, [15,16, 5, 6, 12]	Reduced 20% steel use in design, [15,16, 5, 6, 12]	Reduced 20% steel use in design, [15,16, 5, 6, 12]
Reuse recycled timber and post-consumer FSC certified timber	Study	Use 100%, recycled timber or FSC certified timber, reuse [6, 17]	Use 100%, recycled timber or FSC certified timber, reuse [6, 17]	Use 100%, recycled timber or FSC certified timber, reuse [6, 17]
	Green Star	Use 100%, recycled timber or FSC certified timber, reuse [6, 7, 12, 18, 19]	Use 100%, recycled timber or FSC certified timber, reuse [6, 7, 12, 18, 19]	Use 100%, recycled timber or FSC certified timber, reuse [6, 7, 12, 18, 19]
Roof tile from recycled tiles	Study	-	-	Use 13% recycled tile, tiles with 45% recycled content [5, 20]
	Green Star	-	-	-
Thermal insulation from recycled content	Study	-	Thermal insulation 100% from recycled content [8]	Thermal insulation 100% from recycled content [8]
	Green Star	-	-	-
Replaced Portland cement with geopolymer cement	Study	Replace 100% of Portland cement with geopolymer [12, 21]	Replace 100% of Portland cement with geopolymer [12, 21]	Replace 100% of Portland cement with geopolymer [12, 21]
	Green Star	Replace 60% of Portland cement with geopolymer [6 ,9, 22]	Replace 60% of Portland cement with geopolymer [6 ,9, 22]	Replace 60% of Portland cement with geopolymer [6 ,9, 22]

Sources: 1-(CCAA) 2015; Gonzalez-Fonteboa 2005) **2**-(Green building Council of Australia 2008) **6**-Chapter Seven **3**-(Uche 2008; PCA 2014) **4**-(Brick Development Association 2014; Tyrell & Goode 2014) **5**-(LEED 2014) **6**-(GBCA 2008; US Green Building Council 2011) **7**-(LEED US Green Building Council 2005) **8**-(Steel Construction.Information 2014; Greenspec 2015) **9**-(Ash Development Association of Australia 2013) **10**-(Ecospecifier Global 2016) **12**-(Allwood et al. 2012; UK Indemand 2014), 2015) **13**-(Inhabitat 2014; Steel Construction.Information 2014) **14**-(CNN 2012) **15**-(US Green Building Council 2010) **16**-(LEED 2016) **17**-(FSC 2015) **18**-(Steel Construction Information 2014) **19**-(FSC 2010) **20**-(NSW Government 2010) **21**-(DEE 2012) **22**-(US Green Building Council 2010) | (RA = Recycled Aggregate, PC = Portland cement, GC = Geopolymer Cement.| **Table Prepared by Author,**

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