Earthship Architecture:

Post occupancy evaluation, thermal performance & life cycle assessment

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Abstract

Minimising environmental impact from buildings and building construction processes while providing thermal comfort to the occupants are some of the main goals of green building design. Many different approaches exist to achieve these goals, one of which is the "Earthship", invented by American architect Michael Reynolds. The Earthship is an earth-sheltered autonomous house with walls made substantially from waste products, most notably, discarded car tyres. This thesis presents original research to investigate claims about Earthship performance: that it provides passive thermal comfort in any climate and is the most sustainable green building design in the world. This investigation has been conducted by using Life Cycle Assessment (LCA) to evaluate the overall environmental impact of the Earthship and to compare it to a variety of similar building types characterised by their wall construction materials and other design features. To support assumptions in the LCA, a Post Occupancy Evaluation and a Thermal Performance study were conducted to estimate heating and cooling energy use in a variety of climates. The environmental credentials of the Earthship are then compared to that of other housing types, using both the LCA and thermal modelling approaches.

A post occupancy evaluation (POE) of Earthship homes in Taos, New Mexico, USA, was conducted. This included interviews and surveys of the occupants, and monitoring of the indoor thermal environment. Some aspects of the POE were also extended to an international cohort of Earthship occupants to help justify the assumptions that Earthships provide a level of amenity comparable to conventional housing. The indoor monitored data were also used to calibrate a thermal simulation model of an Earthship home in Taos to ensure the accuracy of the model. The tested approach and parameters to model this Earthship were then used in a model to predict the indoor temperature and theoretical heating and cooling energy requirement of an Earthship design in cold climates and in a warm Mediterranean climate of Adelaide, Australia – the particular context of the LCA study. Thermal modelling of other building types, characterised by their wall materials, was conducted for the Adelaide climate, to predict the heating and cooling energy requirement which was needed for the comparative LCA study.

The research produced the following results. Firstly, in the extreme climate of Taos, the Earthship is able to provide thermal comfort without active heating and cooling systems, and that people are generally very satisfied with the level of comfort and amenity provided. Secondly, in the Adelaide climate, Earthship performance would be similar to Taos; approaching zero energy use for heating and cooling, while in cold and overcast climates minimal space heating may be required. Finally, in the Adelaide climate and context, of all the house types considered, the Earthship had the least environmental impacts and these were considerably less than conventional grid connected homes. The Earthship's comparatively low environmental impact arises from the holistic design, in particular the greenhouse and earth-sheltering, which enable occupants to be extremely energy and water efficient, and therefore live within the limits of modestly sized "off-grid" systems (autonomously) while still enjoying a high level of comfort and amenity. The use of tyres to construct the Earthship's external walls proved to be a low impact method for constructing a retaining wall capable of being earth-sheltered.

The study has provided scientific evidence about the thermal performance and environmental credentials of the Earthship and other housing types, supporting claims that Earthships can provide passive thermal comfort in many climates and that it may be the most sustainable green building design compared to the other building types investigated by this study.

Publications

Publications arising from this research are listed below.

Freney, M., Soebarto, V., & Williamson, T. J. (2013). Earthship monitoring and thermal simulation. *Architectural Science Review, 56*(3), 208-219.

Freney, M., Soebarto, V., & Williamson, T. J. (2013). Thermal comfort of global model earthship in various European climates. Paper presented at the 13th International conference of the International Building Performance Simulation Association, Chambery, France.

Freney, M., Soebarto, V., & Williamson, T. J. (2012). Learning from 'Earthship' based on monitoring and thermal simulation. Paper presented at the 46th Annual Conference of the Architectural Science Association, Griffith University, Queensland Australia.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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1 Introduction

This thesis evaluates the environmental impacts of an autonomous housing type called “Earthship”, an earth-sheltered, off-grid home, constructed substantially from waste products, most notably, discarded car tyres. Earthship inventor, American architect Michael Reynolds claims that his designs provide passive thermal comfort in almost any climate and that the Earthship is “the most versatile and economical sustainable green building design in the world.” (Earthship Biotecture, 2012c)

It compares the environmental credentials of the Earthship to other housing types, using Life Cycle Assessment (LCA) as the basis for this comparison, coupled with other methods such as thermal modelling and post occupancy evaluation to support key assumptions of the LCA study.

This introductory Chapter outlines the forces driving the need for more “sustainable” housing, explains why this research is necessary, and concludes with an outline of the research approach.

1.1 Overview

1.1.1 Sustainability

Humanity’s growing population is currently faced with the dilemma of how to live sustainably on a finite planet. In 2010 it was estimated that there were approximately 6.8 billion people on Earth. In the 1980s the global population was approximately 4.5 billion and this is predicted to double to 9 billion by sometime between 2040 and 2050 (United Nations Department of Economic and Social Affairs, 2010). On the other hand various authors argue that the population is likely to contract significantly, and that a totally different lifestyle will be necessary as we adapt from a high energy society powered by fossil fuels, to a society powered by renewable energy (Heinberg, 2003, p. 178; Holmgren, 2002, p. xxix).

Irrespective of whether humanity finds a way to sustain the current rate of population growth or whether “energy descent” (Holmgren, 2002) causes a decline, our current methods of living are under question as concerns about climate change, pollution, species extinction, resource depletion, global trade systems, the economic system, and food and water security all have the potential to seriously disrupt our global civilisation.

The concept that everyone has an “ecological footprint” (Wackernagel & Rees, 1996) has gained currency in mainstream society, and this has raised awareness of how our lifestyles affect the environment. A lifestyle paradigm sometimes called “downshifting” and “voluntary simplicity” (Gregg, 1936) in which people earn less money so that they can enjoy more time to do the things that matter to them, is gaining popularity. While many are motivated by a desire for more time with family and a less materialistic lifestyle, a minority are motivated by concerns for the environment and social inequity (Hamilton, 2003, p. 8).

Furthermore, the prevalent current economic paradigm of economic growth, measured by an increase in gross domestic product (GDP) as a measure of welfare is coming under criticism while other (more realistic?) economic paradigms that recognise non renewable resources as capital rather than expendable income, offer greater probability for delivering a meaningful and dignified life for all of humanity (Cobb & Cobb, 1994; Schumacher, 1973). Similarly, Lovins (1977, pp. 54-60) argued for “soft energy paths” on the basis that, from a socio-political perspective, decentralised renewable (“soft”) energy was far more desirable than centralised fossil or nuclear (“hard”) energy.

While it may be politically impossible to equalise ecological footprints at a global level, policy aimed at environmentally sustainable development is becoming more common in many countries as governments respond to changes in peoples' attitudes, ethics and values. For example the installation of technology such as domestic solar hot water systems, roof mounted photovoltaic energy and rainwater tanks is increasingly the norm in Australia and has been subsidised by various government rebate schemes. Although many people are enticed into purchasing these systems to reap a financial benefit, such systems are also marketed as being of benefit to the environment reflecting the desire of many to "do their bit" for the environment (Brandao, 2007, p. 9).

At an international level, governments have failed, post Kyoto, to develop a legally binding global agreement to limit greenhouse gas emissions as witnessed by the United Nations Climate Change Conference in Copenhagen in 2009 (International Institute for Sustainable Development, 2009). Some see, perhaps more seriously, that governments seem to be totally ignoring the warnings from various sources that peaking crude oil supplies could wreak havoc upon our oil dependent civilisation which relies heavily upon an ever increasing supply of cheap oil, for which we are yet to find an alternative (Heinberg, 2003; Leggett, 2005). While new oil and gas discoveries tend to dilute the warnings they only delay the inevitable exhaustion of these finite resources.

Within this context the challenge for designers of the built environment seems to be: how to provide for a lifestyle that would be acceptable and equitable (globally), without exacerbating climate change, resource scarcity or pollution, for a population that is projected to grow, and then, possibly dwindle?

There are many opinions about how to tackle this problem, each characterised by beliefs about our current situation. Williamson, Radford & Bennetts (2003, p. 54) have presented a range of ethical positions that describe the environmental movement. Shallow Environmentalism considers long term resource management over many human generations, but stops short of imposing constraints that would interfere with short term human interests. Intermediate Environmentalism is typified by much of the environmental conservation movement on the basis that saving the wilderness and wildlife serves both humans and the environment. It sees human and non human issues as both deserving consideration. Deep Environmentalism positions the status of human needs back even further on the basis that the "unique ability of humans to recognize that they are dominating means that they have an ethical responsibility to allow other species space to live" (p. 57). Other ethical conundrums are explored such as the "non-identity problem" which argues that in terms of planning for the well being of future generations – who would not exist if not for decisions taken today – it is impossible to predict their needs, it is not reasonable to be held accountable (given our limited knowledge about them and the future), and efforts at conservation may actually make things worse for more people than would depletion of resources (pp. 51-53).

Holmgren (2009) has considered the problem from more of an "energetic" viewpoint, arguing that our energy supply, which will be constrained by availability (peak oil) and the effects of its use (climate change), will be the defining factors of our future society. He argues that energy decline is most probably inevitable and advocates a "society-wide redesign and reorganization" (p. 28) around the principles of re-localisation (Hopkins, 2008) and Permaculture (Mollison & Holmgren, 1978). For example, suburban backyards could be redesigned to become highly productive food producing gardens, reclaiming food security, stimulating neighbourly cooperation with garden chores, babysitting, bartering, and reducing the need for transport. An advantage of this system is that it can be driven from the bottom up, starting immediately, without any policy changes (Holmgren, 2005; Mobbs, 2012).

In Australia, government policies propose the upgrading and expansion of public transport, increased rebates for photovoltaic systems, education on the benefits of recycled water and water efficient appliances, expanding the Home Star energy efficiency rating system, et cetera (The Parliament of the Commonwealth of Australia, pp. xvii-xxi). While these are admirable objectives, with reference to the issues outlined previously, it is doubtful that they are (a) affordable (b) possible with ever reducing reserves of energy, and (c) effective at addressing environmental and societal issues. For example, recent controversy regarding home energy efficiency rating schemes has cast serious doubt upon their ability to deliver more energy efficient homes (Williamson, Soebarto & Radford, 2010). On the contrary, there is evidence that such schemes are *preventing innovation* and construction of truly energy efficient homes. These views should be taken seriously, yet there are others who argue that such rating schemes contribute to improved energy performance (Ambrose, James, Law, Osman & White, 2013).

1.1.2 Sustainable Housing

Designers of the built environment are increasingly aware of the need for environmentally sustainable design, although exactly what this entails is difficult to agree upon. At the urban planning scale there is a drive to develop sustainable cities based on "green urbanism" principles such as increased urban density, zero emissions and zero waste (Lehmann, 2010). At the scale of buildings and homes, there is some consensus among architects that energy efficiency is paramount (Vakili-Ardebili & Boussabaine, 2007).

The energy crisis of the 1970s catalysed the energy efficiency movement and there was much innovation and experimentation with novel and ancient housing methods. There was renewed interest in "earth-sheltered" and "under-ground" houses, which have their origins in ancient times (Baggs, Baggs & Baggs, 1985, p. 2), due to their natural ability to regulate indoor air temperatures which reduces or obviates the need for space heating and cooling (Sterling, 1979).

Subsequently passive solar design was developed and disseminated with a view to reducing the energy required for heating and cooling (Greenland, Szokolay & Royal Australian Institute of Architects, 1985; Mazria, 1979) although widespread uptake of the concept did not occur due to the return of cheap energy in the early 1980s, and it is yet to be adopted as a mainstream design strategy.

Another approach to energy efficiency (and water efficiency) is the concept of the Autonomous House (Vale & Vale, 1975) which operates independently of electricity, water and sewer infrastructure thereby eliminating the occupants' consumption of grid electricity and mains water by instead using the limited capacity of the battery bank and renewable energy system, water storage tanks, and the seasonal variations of sun, wind and rain.

Reliance on seasonal flows of energy is in agreement with McHarg's (1969) suggestion that humans become the stewards of the biosphere and to do so they must "design with nature" (p. 5). Indeed many ancient cultures left behind examples of how buildings could be constructed with natural materials and function effectively without the need for active heating and cooling and reticulated water (Anderson, 2009).

Unfortunately, reality shows that the abundance of cheap energy in the 20th century has resulted in the use of technology that requires large amounts of electricity (e.g. air conditioners) and generates large amounts of pollution, as opposed to ancient technology that cleverly harnessed the natural flows of energy provided by the wind, sun and earth without excessive impacts to the environment (Reynolds, 1990). Cheap fossil energy has enabled higher levels of comfort in the home, but at the expense of the environment. And for how much longer will energy remain cheap?

Embodied energy and operational energy have become common measures by which buildings are environmentally assessed as they reflect the quantity of resources, and the associated pollution, involved during a building's life cycle. When discussing the energy efficiency of a building there are three main areas of consideration: the pre-use, construction or manufacturing phase, the use or occupancy phase, and to a lesser extent the post-use, end-of-life (EOL) or demolition phase.

A concern during the construction phase is the environmental impact of materials. The methods of producing the materials and their application in the design of a building relate directly to their environmental impact. The "embodied energy" of the material is the term given to the energy (and therefore carbon emissions) required to manufacture a material or product. This needs to be considered and balanced against the energy efficiency gains that the materials will provide (Horne, Grant & Verghese, 2009, p. 78) and as buildings become more energy efficient during their use phase, the embodied energy becomes relatively more significant. Similarly the energy used during the demolition and recycling of the building starts to become more significant as improvements to the energy efficiency of the other life cycle phases occur. Factors such as longevity (durability/maintainability), recyclability and toxicity of the material are also integral to the overall, life cycle impact of a building material/product (Lewis & Gertsakis, 2001, pp. 61-63).

The behaviour of the house's occupants is also integral to the energy use and thus the environmental impacts of the dwelling; after all, the house would create very few emissions, once constructed, if it were unoccupied. Typically the environmental impacts arising from the operation of a house represent the vast majority of impacts throughout its life cycle, dwarfing those of the construction and end-of-life stages (Adalberth, 1997; Blanchard & Reppe, 1998). In contrast, a low energy house can be quite the opposite with greater embodied energy, arising from extra insulation and double glazed windows for example, and less operational energy, due to the reduced need for heating and cooling (Blengini & Di Carlo, 2010); however, even a well designed "sustainable house" will have high electricity bills if the occupants are not conscious of energy consumption and proper operation of their house.

Home automation (Cawson, Haddon & Miles, 1995) provides scope for building designers to over-ride uninformed behaviour of the occupants by pre programming various systems, appliances and lighting to operate intelligently in response to sensors. Feedback systems use touch screens to display "real time" information to occupants so that they can monitor the performance of their house and learn how to operate their homes in a more efficient and environmentally friendly manner much like the fuel economy gauge in modern cars teach people how to drive more economically and environmentally. For example, usage of electricity, water and gas can be displayed and equated with greenhouse gas emissions and a dollar value. The goal of this is to bring about positive behaviour change, towards a more resource efficient lifestyle (CSIRO, n.d.).

1.1.3 Earthships

This is the backdrop to the rationale for the Earthship, an autonomous housing concept created by architect Michael Reynolds (Reynolds, 1990).

According to Reynolds (1990) the Earthship uses waste materials such as old car tyres and beverage containers for wall construction and is highly energy and water efficient such that occupants can live comfortably and economically "off-grid" thereby avoiding the major utilities bills (electricity, water, sewer). He claims it is also possible to grow food, indoors, throughout the year, using the greywater produced by the building. Its name stems from its autonomy, its ability to "sail" (operate) on the Earth using natural phenomena such as sun, wind, rain and snow, and furthermore it is built largely of earth (Reynolds, 1990, p. 25).

The Earthship is marketed as an exemplar of sustainable housing, combining many strategies and systems for reducing its impact on the environment and providing various services to the occupants in a self-sufficient, environmentally friendly manner. Reynolds' Earthship Biotecture website claims that "the Earthship is the epitome of sustainable design and construction. No part of sustainable living has been ignored in this ingenious building" and "Earthships can be built in any part of the world and still provide electricity, potable water, contained sewage treatment and sustainable food production." (Earthship Biotecture, 2012c).

Thus, there is an assumption in the marketing of Earthships that its design automatically leads to a sustainable building outcome. For example, it is implied that the reuse of waste products for construction, food production, efficient off-grid systems, and excellent thermal performance of the building result in reduced environmental impacts; however, little empirical evidence exists regarding the environmental impacts of the Earthship. These included studies by Grindley and Hutchinson (1996), Ip and Miller (2009) and Kruis and Heun (2007) which evaluated the thermal behaviour of the Earthship in variety of climates, and Life Cycle Assessment (LCA) studies by Clauzade et al. (2010) Corti and Lombardi (2004) which evaluated various end-of-life scenarios for waste tyres. There has been, however, no literature regarding LCA of tyre walls, or self sufficient homes built with tyres. Similarly, in the marketing of other wall construction systems such as strawbale, rammed earth and mudbrick, there is a paucity of data regarding their life cycle impacts. Similarly, there are few studies that compare the impacts of off-grid versus conventional utilities systems.

In summary, there are many ideas and examples of how humans can live in comfortable houses, with modern conveniences, in a way that reduces the impact on the environment, however what is not clear is which of these ideas offer the most environmental benefits, and what level of comfort and convenience is attainable for a global population. When this is clear it is possible for us all to start moving in that direction, some people taking a step up to a more comfortable lifestyle and others taking a step down from an exorbitant lifestyle.

One way to answer such questions, as recommended by Ian Lowe AO, president of the Australian Conservation Foundation, is Life Cycle Assessment (LCA);

> *"We have to make responsible choices about the essentials of a civilised life: food, shelter, water and waste management. Intuition is not a reliable guide, neither is superficial analysis. We need sophisticated Life Cycle Assessment. LCA is systematic analysis considering all steps of the process of using natural resources to provide our needs. It also assesses the impacts of by-products of that process."* (Horne, Grant & Verghese, 2009, p. vii)

This thesis uses LCA, Post Occupancy Evaluation and Thermal Modelling to evaluate the Earthship and compare it to other homes. A better understanding of the environmental impacts arising from the use of Earthship design principles will help in the evaluation of how future homes could be designed and constructed (or existing homes retrofitted) to address "sustainability" issues.

1.2 Research Aims

The research seeks to understand: a) the environmental impacts of the Earthship lifecycle, b) the amenity it provides to its occupants in terms of thermal comfort, electricity, water, and sewage treatment and c) the occupants' motivations for seeking this lifestyle. As LCA is best conducted as a comparative exercise, the environmental impacts of other housing types are also investigated. It was expected that the research would prove, or otherwise, the claims about the Earthship, and investigate claims about Earthship performance, namely that it provides passive thermal comfort in any climate and is the most environmentally sustainable building design in the world.

In order to achieve these aims this research:

1. compares the environmental impacts of the Earthship lifecycle, including construction, operation and end-of-life (recycling and demolition), to that of other construction methods and utilities systems:
    a) the off-grid systems of the Earthship which enable it to function autonomously will be compared to conventional grid connected infrastructure and,
    b) the unusual Earthship wall constructions will be compared to conventional (e.g. brick veneer, timber frame) and alternative (e.g. strawbale, rammed earth) wall construction methods.
    c) The unusual Earthship design features (the greenhouse and earth berm) will be evaluated in the context of the Earthship and in the context of the other wall construction methods.

Supporting this overall aim are studies which, while of interest in their own right, provide information which is essential in addressing the overall aim:

2. a study to gain a better understanding of the thermal performance of the Earthship in various climates including its climate of origin, Taos, New Mexico, USA. Provision of thermal comfort is critical to the amenity provided by a house and this aspect is also critical to the LCA: many

studies have documented the substantial environmental impacts arising from the energy used to heat and cool homes. Thermal performance of other housing types is also investigated to enable a direct comparison to the Earthship.

3. a study of the level of amenity provided by the Earthship's off-grid systems and what is involved with maintaining these systems throughout the use phase of the home is conducted in order to establish whether or not the Earthship provides a commensurable level of amenity compared with conventional grid connected houses.
4. finally, the research seeks an insight into the lifestyle the Earthship provides its occupants, trying to understand why they have chosen to live "off-grid" in a house made from "waste".

The overall hypothesis is that the Earthship provides a highly acceptable level of amenity ("modern conveniences" and thermal comfort) with much lower environmental impact than other conventional (and alternative) houses.

1.3 Method

LCA was the methodology selected as the main basis for this study because it is a method for quantifying potential environmental impacts; however, various other methods have also been employed to give support to key assumptions made in the LCA. The following sections of this Chapter give an overview of the methods used in each study and the relationships between the studies are illustrated in Figure 1.1. More detailed accounts of the various methods are described in the Chapters dedicated to each study.

1.3.1 Post Occupancy Evaluation (POE)

The aim of a POE is to gain an understanding of how the building is actually performing as opposed to how the designers anticipated it would perform (Roaf, Horsley, Gupta & Leaman, 2004, p. 491). The scope of a POE may include issues such as noise, lighting, thermal comfort, energy use and occupant satisfaction, however there is no defined method for conducting a POE (Roaf, Horsley, Gupta & Leaman, 2004, p. 495).

This POE study sought information regarding the level of amenity provided by the Earthship in terms of the thermal comfort and modern conveniences it provides. Three sub-studies formed the POE; the methods used were, a) monitoring of the thermal performance of Earthships in Taos, New Mexico, USA, where Earthships originated, b) surveys and interviews of Earthship occupants in these Earthships, and c) surveys of Earthship occupants around the world.

The POE is described in detail in Chapter 3 whereas the following sections provide a brief outline of each sub-study.

1.3.1.1 Earthship Thermal Performance Monitoring

Due to the significant impact that heating/cooling energy can have on environmental impacts of a home, this study explored this issue in great detail, especially in the context of Earthship construction. Whereas many LCA studies include energy modelling, this study included an extensive *Earthship Thermal Performance Monitoring* study in which air temperature, radiant temperature, and relative humidity inside six Earthships in Taos, New Mexico, USA were recorded and analysed over a seven month period and one building was recorded for the full 2012 calendar year. This study confirmed anecdotal evidence that Earthships built in Taos, New Mexico USA require little or zero heating/cooling energy to remain at acceptable temperatures despite the extreme climate (Freney, Soebarto & Williamson, 2013a).

1.3.1.2 Earthship Daily Comfort

Participants in the *Earthship Thermal Performance Monitoring* study were asked to complete a questionnaire titled *Earthship Daily Comfort* which aimed to gather data on their perceptions of thermal comfort and of how they had used natural ventilation (or not) to alter the indoor temperature. The data regarding natural ventilation provided information that would be useful in developing a simulation model of the Earthship, in particular the natural ventilation regime. Also, the data relating to perceptions of comfort was cross referenced to the monitored data from the *Earthship Thermal Performance Monitoring* study, enabling a measured temperature reading to be correlated to the occupants' comfort level evaluations.

The results of this study were used to refine the predictions about Earthship energy use in the Adelaide climate (this study is outlined below in section 1.3.2.2), providing greater credibility about heating/cooling energy use of an Earthship in the LCA study.

1.3.1.3 Earthship Occupant's Questionnaire & Interview

A survey titled *Earthship Occupant's Questionnaire* was developed to gather information that would enable conclusions to be drawn about the extent to which the Earthship occupants' lifestyle was comparable to a conventional lifestyle: essentially, did the off-grid Earthship systems provide similar functionality to grid connected homes in terms of thermal comfort, and provision of utilities such as power, water and sewage treatment. It also aimed to find out the level of maintenance required for an Earthship home as these data were needed for the LCA study, and other issues such as ability to insure the home, to establish the degree to which the Earthship is commensurable with a "normal" home.

This survey was circulated online via email and social media, however occupants who participated in the monitoring study were instead interviewed using the survey as the basis of the interview.

1.3.2 Thermal Performance Simulations

Three thermal simulation studies were conducted, one which investigated the thermal performance of the Global Model Earthship that was monitored as part of the POE study, another which simulated heating/cooling energy requirements in the Adelaide climate, based on a number of design variables such as external wall type, and one focusing on the performance of the Global Model Earthship in various European climates, conducted in response to concerns about Earthship performance in Europe (Hewitt & Telfer, 2012). These studies are outlined below.

1.3.2.1 Earthship Thermal Performance Simulation in Taos

The aim of this study was to develop a simulation model that could accurately predict indoor air temperature of an Earthship in Taos. If this was achievable, the model would offer a reasonable estimate for heating and cooling energy required for other climates such as the Adelaide climate - the context of the LCA study.

DesignBuilder/EnergyPlus software was used to model the thermal performance of the Earthship that was monitored for the full year. Information gleaned from the *Earthship Daily Comfort* questionnaire was used to make assumptions regarding parameters for natural ventilation. Results from the simulation were compared to the measured results from the *Earthship Thermal Performance Monitoring* study and statistical analysis was used to establish the accuracy of the simulation results.

1.3.2.2 Earthship Thermal Performance Simulation in Adelaide & Other Climates

As the climate in Adelaide is very different to Taos, another study was required to understand how an Earthship would perform in this different climate. Furthermore, as the aim of the LCA study was to compare Earthship to other housing types, this study was designed to test the thermal performance of various thermal envelopes (i.e. walls, roof, floor, and glazing materials) in the Adelaide climate and hence the theoretical heating/cooling energy required to achieve comfort conditions – a key input to the LCA study.

The focus of this study was upon the external wall materials so that, for example, the thermal performance of a tyre wall could be compared to a Strawbale wall, rammed earth wall, brick veneer wall, et cetera. The effect of the Earthship's greenhouse was also tested by including this as a variable in all the thermal envelope configurations and, where the external wall type was capable of acting as a retaining wall, the berm was also included as a variable to understand how it effects the heating/cooling energy requirement.

Similar to the previous simulation study in Taos, a DesignBuilder/EnergyPlus model was developed using many key variables from the Taos study, in particular assumptions regarding the method for modelling the tyre wall which had proved successful in the Taos study were retained in this study.

Due to concerns about the performance of Earthships recently constructed in Europe (Hewitt & Telfer, 2012) the performance of the Global Model Earthship was investigated in five different climates in Europe which ranged from cold and cloudy to hot and sunny. This study used the same DesignBuilder/EnergyPlus model as the Taos study.

1.3.3 LCA Study

The life cycle assessment (LCA) study uses the methods described by the ISO14040 series of standards which is outlined in more detail in Chapter 5; however a brief overview of how the LCA process was used in this study is given below.

Firstly, the goal and scope of the study were defined via a review of the literature which established some common themes and approaches to this kind of study. Importantly, a "functional unit" was defined as the basis for the comparative study between the Earthship and other house types: in brief, the thermal envelope of a "whole house" (external walls, internal walls, glazing, roof, floor), of a fixed floor area was defined. Assumptions regarding energy, water and wastewater were also defined as part of the functional unit.

Secondly, research was conducted to establish the Life Cycle Inventory (LCI): i.e. the flows of materials, energy and emissions into and out of the system being analysed. A significant task involved the compilation of a Building Elements Inventory which quantifies volumes of materials (and processes) used to build the various thermal envelopes and systems under analysis. To create the inventory, Computer Aided Modelling (CAD) software (industrial design/mechanical engineering software called SolidWorks) was used to model the geometry of the major elements of the thermal envelope: roof, external walls, internal walls, floor and glazing and thereby calculate volumes and masses of materials. Processes involved in the manufacture of building materials, for example, mixing of adobe render, were quantified in terms of their energy use and, where data were available, consumables such as lubricants were also included. The materials and processes involved with the lifecycle of the Earthship systems (energy, water, wastewater) were quantified via data supplied by manufacturers, such as product data sheets, and where this was not adequate, discussion with the company's technical staff.

The Building Elements Inventory addressed the "manufacturing" stage of the lifecycle. To address the "use" or "occupancy" stage, results from the thermal modelling study in the Adelaide climate informed assumptions regarding heating/cooling energy. Other energy use (e.g. appliances) and water use for grid connected housing were estimated from publications by government agencies, and for the Earthship, information published by Earthship architect, Michael Reynolds.

To address the "end-of-life" or "demolition/recycling" lifecycle stage research was conducted into the construction and demolition industry practices, especially in the local context of Adelaide.

Using SimaPro life cycle assessment software the data collected in Building Elements Inventory (described above) were analysed to produce the Life Cycle Inventory for each variant of the functional unit. The LCI is a list of "flows" of inputs such as waste, energy and raw materials and emissions to air, land and water which is subsequently analysed to understand the environmental impact of these "flows" of substances.

The third stage of the LCA is Impact Assessment (LCIA), in which the flows of substances are analysed, producing quantitative results. SimaPro was used to characterise the LCI results in terms of impact categories such as global warming potential, ozone depletion, smog, land transformation & use, water depletion, eutrophication, and toxicity. Subsequently these results were normalised against Australian per capita averages to better understand the scale of the impacts, and finally the normalised results were weighted according to scales developed by the Building Products Innovation Council (BPIC). BPIC is Australia's peak body, representing the building material industry, which have in conjunction with the Federal Government, developed life cycle inventory data and various guidelines and protocols to assist life cycle assessment practitioners (BPIC, 2014). It should be noted that the practice of weighting results is controversial because it involves value judgements about the relative importance of various impact categories, for example, global warming potential versus water depletion – which is the more serious issue?

The final stage of LCA is Interpretation in which the LCIA results are systematically evaluated and tested for sensitivity.

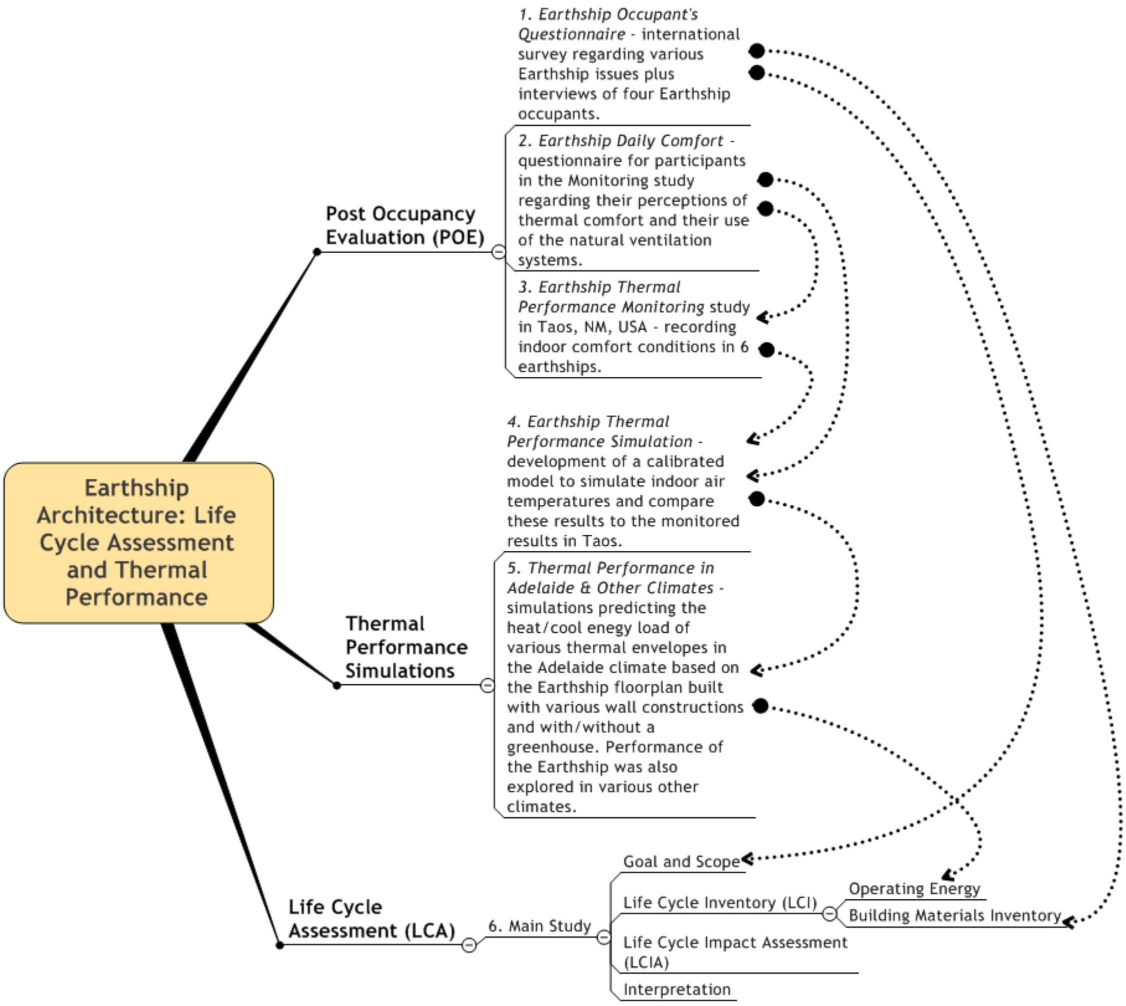

Figure 1.1 - Overview of Studies and their Relationships

1.4 Structure of Thesis

To achieve these aims this thesis has been structured as follows;

Chapter 1 gives an overview of the study, describing the research aims and methods.

Chapter 2 reviews the literature relevant to this research, encompassing the following topics: issues relating to Earthships, contemporary sustainability issues, eco houses, life cycle assessment, post occupancy evaluation, thermal performance of buildings and thermal modelling. This Chapter gives an overview of how and why ecological housing has developed over the past century and explores the methods used to evaluate and measure performance.

Chapter 3 describes a post occupancy evaluation (POE) of Earthships in the USA in which indoor temperature and humidity was monitored and occupants were asked about their perceptions of thermal comfort, their involvement with the operation of the natural ventilation systems, and their feelings about the level of amenity provided by their home's off-grid systems. It also describes a post occupancy evaluation of Earthships throughout the world in which a wide variety of issues pertaining to Earthship were investigated with a view to establishing the level of comfort and amenity provided by the off-grid systems and thermal envelope. Other aspects such as maintenance and running costs were included, as were questions pertaining to the occupants' motivations for adopting this type of lifestyle.

Chapter 4 describes thermal modelling studies which investigate the thermal performance of the Earthship and various other house designs. It includes a thermal simulation exercise in which predicted (simulated) indoor air temperature of one of the Taos Earthships was compared to the measured indoor air temperature collected during the POE study, and another study investigates the thermal performance of various thermal envelope configurations, characterised by their external wall materials, in the Adelaide climate. The results of these studies provide the basis for comparing the (thermal) energy efficiency of a variety of wall constructions in the subsequent LCA study.

Chapter 5 details the method used for the Life Cycle Assessment study. It includes stage 1 of the LCA, definition of the goal and scope, and the rationale for decisions regarding Life Cycle Inventory databases and Life Cycle Impact Assessment models.

Chapter 6 details the second stage of the LCA: Life Cycle Inventory (LCI) in which calculations of material quantities for each thermal envelope (walls, roof, floors, glazing, and systems) are presented.

Chapter 7 details the third stage of the LCA: Life Cycle Impact Assessment (LCIA) whereby the LCI data are used to estimate the potential environmental impacts in terms of various impact categories. It details the final stage of the LCA; Interpretation, in which the LCI and LCIA results are evaluated in terms of data quality and completeness. A profile of each construction type is presented with significant issues highlighted and discussed. The sensitivity of various assumptions is also presented.

Chapter 8 concludes the study. It details the significance of the research and gives recommendations for how Earthship design should be adapted for Australian (temperate) climates, suburban contexts, and for further research required to address questions arising from this study.

2 Background & Literature Review

This Chapter presents a summary and discussion of the literature relevant to this study. It encompasses the following topics:

Sustainability Issues:

Climate Change
Resource Depletion
Population Growth
Sustainable Architecture

Sustainable Housing Approaches:

Autonomous Houses
Sustainable Houses
Earthships

Methods of evaluating sustainable architecture:

Post Occupancy Evaluation
Thermal Modelling of buildings
Life Cycle Assessment of buildings

The Chapter concludes with recommendations for the methodological approach to this study.

2.1 Sustainability Issues

In The Limits to Growth, Meadows and The Club of Rome (1972) present theories on why the economic growth paradigm is not sustainable. Yet since this time there has been no abatement in human population, pollution or resource use. Heinberg (2007) argues that it is now evident that resources are becoming scarce, particularly crude oil, but also fertile soil, precious metals and fresh water. Pollution of the air, land and water has also increased dramatically and the Intergovernmental Panel on Climate Change (IPCC) warns that the evidence for a warming climate system is now unequivocal (IPCC, 2007, p. 30) and that there is "very high confidence that the global average net effect of human activities since 1750 has been one of warming" (p.37) due mainly to greenhouse gas emissions and to a lesser extent by land-use change.

Lynas (2008) conducted an extensive survey of all the scientific literature on the possible effects of climate change and categorised them according to the amount of temperature change; from 1 to 6 degrees of warming. The conclusions he draws from the literature are alarming, as even low levels of warming can escalate to very dangerous levels of warming due to positive feedback mechanisms such as melting of the polar ice caps and thawing of the permafrost which cause increasing amounts of greenhouse gases to be released. The review by Lynas and the position of the IPCC demonstrate the consensus amongst the majority of scientists: a wide range of very serious impacts to the biological systems that sustain us are unavoidable and already happening. Similarly Wackernagel and Rees, contend that our "ecological footprint" has increased to the point where our planet can no longer support it and therefore we need extra planets to supply our resources and assimilate our wastes (Wackernagel & Rees, 1996).

There is, however, controversy arising from a number of scientists regarding whether climate change is anthropogenic, or if it is, how threatening it might be, and what are the best solutions to tackle any problems. Hulme (2009) explains this in his book, *Why We Disagree About Climate Change*: the discourse around climate change represents differing beliefs about how we should live on the planet which relate to issues such as faith, politics, risk, history, psychology, sociology and media. Although it is a physical phenomenon, it is also a cultural and ethical one, representing a problem that may be impossible to solve. Despite the controversy and difficulty in agreeing upon the causes of climate change there are many approaches to adapting to, and mitigating, the effects of changing climates, especially in relation to buildings.

Greenhouse gas (GHG) emissions caused by buildings in Australia have been estimated at 26% of all Australian emissions with nearly half of this caused by energy use in residential buildings (CSIRO, n.d.). So how might architecture and design contribute to emissions reductions?

In terms of building design which will reduce GHG emissions, the IPCC has suggested;

"Efficient lighting and daylighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycling of fluorinated gases; integrated design of commercial buildings including technologies, such as intelligent meters that provide feedback and control; solar photovoltaics integrated in buildings." (IPCC, 2007, p. 60)

However, when trying to design "greener" buildings it is important to look beyond the narrow focus of GHG emissions. As outlined in the introductory Chapter, Williamson, Radford and Bennetts (2003) have described a wide range of interpretations of sustainability, highlighting the fact that it is difficult to define sustainable architecture. They propose a checklist of criteria to guide the designer towards a more "sustainable" outcome. It includes discourse issues such as: climate change, pollution, resource depletion, biodiversity, indigenous flora and fauna, society and culture, health, comfort, cost effectiveness, and longevity, and for each of these, suggestions are made about practical means for achieving sustainable outcomes (see Appendix B for an assessment of the Earthship using these criteria).

Although it is difficult to define sustainable architecture some issues have been agreed upon, for example the aim to reduce energy use (Vakili-Ardebili & Boussabaine, 2007) as this has a clear link to GHG emissions. The question then arises; how to measure performance. Home energy rating schemes (HERS) in Australia and abroad are increasingly used by governments as a means for reducing the energy used for heating and cooling the home (Soebarto & Williamson, 2001), and a national mandatory energy efficiency rating scheme for certain electrical appliances was recently introduced in Australia, replacing numerous state government policies (Commonwealth of Australia, 2013b). While these schemes help to measure and regulate the "use" or "occupancy" life cycle stage of the home, the manufacturing/construction stage and end-of-life/disposal stage are not addressed by any mandatory rating schemes, or regulations in Australia.

Recently, however, a new wave of "zero carbon" architecture has entered the mainstream which aims to reduce carbon emissions throughout the lifecycle of the home. For example the now defunct Integrated Design Commission, an advisory body to the South Australian government, recently ran the Zero Carbon Challenge (Integrated Design Commission, n.d.). Entrants in the competition were required to use Life Cycle Assessment software to evaluate their "zero carbon" home designs to minimise embodied energy and future emissions. This new focus on the whole lifecycle, from "cradle to grave", is becoming the new paradigm for evaluating products, systems and architecture, and is increasingly used during the design phase and for post design activities such as eco labelling (Lewis & Gertsakis, 2001).

Measuring the sustainability of homes is a complex, multidimensional task, yet scientific approaches such as Life Cycle Assessment, Post Occupancy Evaluation and Thermal Modelling are increasingly being used to evaluate existing designs or optimise future designs before they are constructed.

The following section of this Chapter reviews key theories and approaches to sustainable architecture and design, concluding with a description and analysis of the Earthship concept. The final section examines methods for evaluating sustainable architecture, concluding with recommendations for this study.

2.2 Sustainable Housing Approaches

This section examines a range of approaches to sustainable architecture, concluding with an in depth analysis and discussion of the Earthship and issues pertaining to it.

2.2.1 Sustainable Houses

Roaf, Crichton and Nicol (2005, p. 344) list the goals of sustainable houses as; use as little energy as possible; provide that energy from clean renewable resources; reduce waste throughout the whole life cycle of the building; use ecological materials and products; not destroy biodiversity and ecosystems; promote health of all; ensure comfort and enable survival in extreme weather.

A common design approach is to build an energy efficient home with “natural building” methods such as adobe, cob, rammed earth, rammed earth tyres, earthbags, cast earth, strawbale, straw-clay, stone, papercrete, cordwood masonry, and log homes (Chiras, 2004).

Another approach, to which Chiras (2004) dedicates a Chapter, is earth-sheltered homes. Earth-sheltered architecture was investigated extensively by a team at the University of Minnesota (Sterling, 1979) (Sterling, Farnan & Carmody, 1982) (Carmody & Sterling, 1983). They cite numerous benefits including energy conservation, protection from fire and storms, improved aesthetics and lower life cycle costs (pp. 13-19) in agreement with Baggs, Baggs and Baggs (1985) who documented technical details of earth-sheltered and earth-covered buildings in Australia. This is highly relevant to Earthships which feature extensive earth-sheltering.

2.2.2 Autonomous Houses

Before the industrial revolution buildings were autonomous, at least in the sense that they were not connected to energy, water and sewer infrastructure; however, the occupants generally spent a lot of time and effort gathering fuel, collecting water, and disposing of human waste, to ensure adequate operation of the building. Post industrial revolution, the first attempt at designing and constructing an autonomous house may have been Buckminster Fuller’s Dymaxion Dwelling Machine in the 1930s. It was heated and cooled by natural means, made its own power and used minimal quantities of construction materials (Buckminster Fuller Institute, 2013) although it should be noted that many of the materials employed had very high embodied energy and hence it may not have been rated favourably by a LCA . Vale & Vale (1975) identified autonomous houses as being part of the solution to declining energy reserves many decades ago. This is one approach towards achieving the goals of eco houses, described by Vale & Vale as having qualities of a space station in terms of its ability to operate without reliance on typical utilities such as electricity, water and sewage treatment. It is sometimes known as “off-grid” living (Rosen, 2007). Instead it uses the “life-giving properties of the Earth” to provide these amenities without damage to the environment (p. 7); however, later (Vale & Vale, 2000) the definition is somewhat relaxed to include the possibility of connection to the electricity grid on the proviso that it is in “energy balance” whereby the renewable energy system of the house generates more electricity than it draws down from the grid. This compromise to the autonomy of the house was desirable to avoid the need for a battery bank and the associated environmental impacts (Vale & Vale, 2000, pp. 122-128).

Earlier, Vale & Vale (1975) position the autonomous house concept as being a logical starting point for an individual (or family) to take immediate action towards addressing resource scarcity and pollution. A transition to a more autonomous, self sufficient society is described, in which the city is supported by suburban and semi rural food producing autonomous houses (and properties) thereby giving people choice about where and how they might live, albeit within the constraints of equally shared resources.

There are many examples of autonomous houses and two examples are briefly described here. The Hockerton Housing Project (circa 1996), designed by Vale & Vale, is a group of five terrace houses in Hockerton, UK designed with environmentally sustainable principles (Smith, 2005, p. 93). These houses use only one tenth of the energy a typical house would consume by removing the need for space heating or cooling through the use of earth sheltering and passive solar design. The design integrates commercial and residential spaces and is substantially self sufficient in terms of water and energy use. A "self sufficient house" in Freiburg (Stahl, Voss & Goetzberger, 1994) was constructed to demonstrate that "a solar house could operate completely independently of other energy... despite a strong variation of insolation between summer and winter" (p. 111). The project was successful in being self sufficient in solar energy with only a small requirement for energy storage; however, it did not attempt to manage waste water or be self sufficient in water.

2.2.3 Earthship

The Earthship is another type of autonomous house. It was developed by architect Michael Reynolds of Earthship Biotecture, Taos, New Mexico, United States of America, whose interest in radically changing housing emerged during his undergraduate studies in architecture. Reynolds built his first tyre home in the mid 1970s (Chiras, 2000, p. 112) and has been experimenting constantly with unconventional forms of architecture ever since. Reynolds has written extensively on the topic of autonomous, ecological housing (Reynolds, 1990, 1991, 1993, 2000, 2005). His books outline the philosophy that underpins his Earthship concept and they explain in detail his novel construction methods that utilise waste car tyres and waste beverage containers for the construction of load bearing thermal mass walls. Other topics include autonomous energy, water and sewer systems - which are integral to his goal of a house that "takes care of" the inhabitants – and guidelines for the development of communities are also documented. Of note is his conjecture that ecological, autonomous housing and well designed communities could lead to a new paradigm in the way humans live on the planet, one in which waste is redefined and efficiency is foremost. He asserts that a house with zero utilities bills enables the occupants to transcend the prevailing western lifestyle and embark on a new concept of living, one that "…could change the nature of the human mind itself. It could provide the basis and a direction for conscious evolution on the Earth." (Reynolds, 1990, p. 19).

The Earthship Biotecture principles which define the characteristics of Earthship design include; thermal/solar heating & cooling; solar & wind electricity; contained sewage treatment; building with natural & recycled materials; water harvesting; and a means of producing food that uses wastewater for irrigation (Earthship Biotecture, 2012e).

While many of these principles may be common with other architectural philosophies, Earthship is unique in its aim to bring all these principles together holistically.

The root of these principles is Reynolds' ethical standpoint. He argues that the electricity, water and sewer grids are a "poisonous web" (Reynolds, 1990, p. 4) that is continuously expanding, spreading pollution, and enslaving humans to the economic system via ever rising energy and water utilities bills. He argues that housing that overcomes these problems "could provide a basis and a direction for conscious evolution on the Earth" (p. 19), because, once freed from the need to pay monthly utility bills, and the fear of the consequences of defaulting, and with a house that provides much of our food, we would be less stressed and have time for more meaningful endeavours.

Reynolds (1990, p. 21) describes the Earthship as "interfacing" with and harnessing, rather than resisting, the natural phenomena of the Earth such that its requirements for energy, water and sewer infrastructure are nullified. Reynolds claims that the Earthship can “reduce and even *eliminate* your utilities bill” (Earthship Biotecture, 2012e) due to the use of off-grid renewable energy systems (wind and or solar which charge batteries), water collection (in underground tanks), wastewater treatment using biological filters (no chemicals) and the highly effective thermal performance arising from the earth-sheltered, passive solar design.

The following table contrasts the self reliant off-grid Earthship, to the conventional infra-structure dependant house.

Earthship	*Conventional*
Occupant’s Mindset	
Conscious resource constrained lifestyle (choosing this). Ethics and values drive behaviour.	Convenience and comfort driven, with minimal thought about consequences to ecological impacts. Financial constraints drive behaviour.
Independent	Reliant
Design & Construction Strategies	
Passive solar heating and cooling (solar orientation)	Mechanical/active heating, ventilation and cooling systems (orientated towards the street or views)
Solar and wind generated electricity (self sufficient – limited supply)	Mains electricity typically generated via non-renewable energy (totally dependent on grid – practically unlimited supply)
On-site sewage treatment	Sewer infrastructure, sewage treatment and disposal
Building with natural and recycled materials	Building with new materials, often with adverse environmental impacts
Water harvesting (self sufficient – limited supply)	Reticulated water infrastructure (although use of rain water tanks is increasing) (totally dependent on grid – practically unlimited supply)
Food Production	Ornamental garden and or lawn
DIY construction	Construction by professional builder

2.2.3.1 Earthship Issues

This section discusses how Earthships may enable humans to adapt to the challenges of the 21st century; climate change, resource depletion, pollution, population growth etc.

Limiting Consumption

A consequence of the Earthship’s autonomous systems is that there are *real limits* to the water and electricity resources available to the occupants. Electricity use needs to be monitored daily, especially during cloudy periods, and water use also needs to be monitored, although not as frequently. Simple feedback mechanisms that enable the occupant to monitor water and energy use are incorporated into the design to facilitate regular checking of energy/water levels. This drives positive behaviour change as the occupants must plan their activities in accordance with the sun, wind and rain, or face the immediate consequences of depleting their battery bank or water tanks.

Growing Food

Inherent in the Earthship is a system for growing food in a way that makes it manageable, convenient and successful. By locating a planter within the greenhouse space - the main purpose of which is to provide thermal comfort in the living space - occupants have direct access to an area that is ideal for growing food and other plants year round, thereby reducing environmental impacts of food production in a variety of ways: a) it contributes to a reduction in “food miles”, b) it reduces the amount of fertiliser required to be imported as the greywater contains nutrients, and c) it reduces the amount of fresh water required to grow food. Furthermore, as the planter is irrigated and automatically fertilised by warm wastewater on a frequent basis due to the water use of the occupants (e.g. a daily shower) the plants tend to thrive in response to the frequent watering. Even lazy gardeners are likely to have a thriving garden.

Materials

The Earthship concept also responds to the issue of materials. Perhaps the most unusual aspect about the Earthship is the use of scrap car tyres which are used for the construction of load bearing earth retaining walls which are typically used to form the external walls of the house. Reynolds says that a normal house sits upon the earth, whereas the Earthship is of the earth (Reynolds, 1990, p. 66). It is essentially earth reconfigured to make walls. The structure of the wall is such that it “floats” (p. 69) on the earth without concentrating loads and stresses, and forms its own footing (p. 66) thereby avoiding the need for reinforced concrete footings (although a reinforced concrete bond beam is typically constructed on top of the tyre wall). The tyre walls also make excellent retaining walls so berms (earth piled against the wall) are used extensively for many reasons (Freney, 2009); they reduce the visual impact of the building by disguising it as nature, they reduce the need for maintaining external walls (for example painting is not required), they hide and protect underground water tanks, they shed water away from the building, and they help to maintain indoor air temperatures at comfort levels throughout the year (Baggs, Baggs & Baggs, 1985, pp. 41-42).

Non load bearing walls, such as internal walls, can be made from discarded beverage containers (glass, aluminium, plastic) in a mortar of cement in keeping with Reynolds’ philosophy of using waste materials. He argues that tyres and beverage containers are “indigenous” building materials that can be found all over the planet, and that their properties render them ideal building blocks for sustainable housing (Reynolds, 1990, pp. 74-79).

Earthships may also feature roofs with sheet metal tiles made from the housings of appliances such as fridges and washing machines (Figure 2.1) although this seems to be aimed at making an ideological statement more so than providing easily installed roofing. However, this recycling/reuse approach may be highly relevant if working to a tight budget or in a resource constrained future.

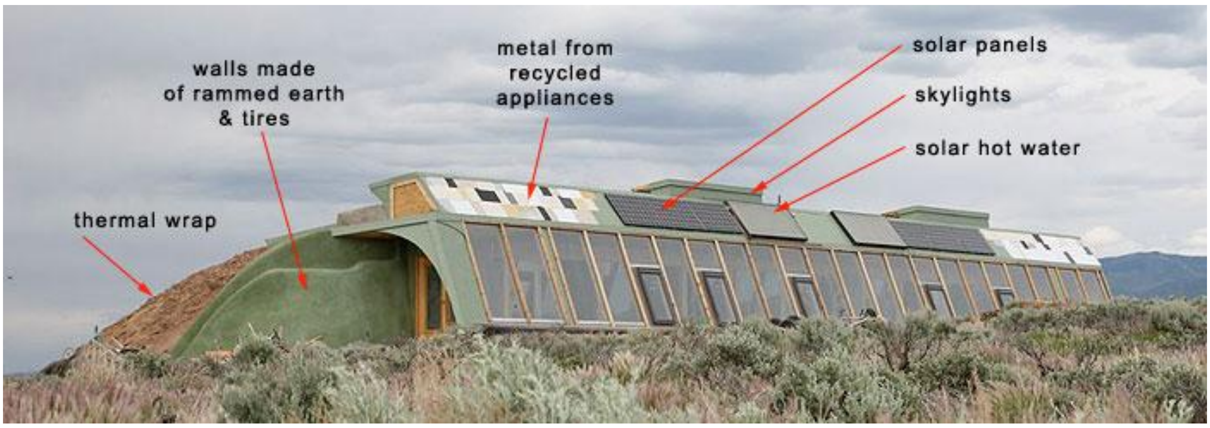

Figure 2.1 - Global Model Earthship in Taos, New Mexico, USA (Earthship Biotecture, 2012a)

Wastewater
A major issue for all housing is disposal of wastewater. Without effective systems for treating and managing wastewater (sewage) the environment becomes polluted and human health degenerates due to water borne diseases; this is the reality in many "developing" parts of the world (World Health Organisation, 2013). The Earthship has a wastewater management system that requires no chemicals and only a small amount of electricity to intermittently power a low wattage pump. It is a biological system which uses the system's biota to treat the water to a standard suitable for toilet flushing and irrigation of food crops. Only a minimal amount of maintenance and care is required by the occupant; it requires plants to be tended, filters to be cleaned and harsh cleaning chemicals to be avoided. The system comprises an indoor garden bed (a planter) located in the greenhouse. This is where greywater is treated and used for irrigation of food crops; the effluent of the system is suitable for toilet flushing. Blackwater from the toilet is treated by a conventional septic tank and a second planter which is located immediately outdoors, adjacent the greenhouse. Any effluent from the blackwater system is dispersed sub-surface via a conventional drainage field. The greywater system can be isolated easily by the occupant via a three way valve so that greywater can be diverted directly to the septic system thereby making the system compliant with most wastewater regulations. Water is used four times in an Earthship. Firstly, for the primary purpose such as taking a bath. Secondly, for irrigating indoor plants which provide food, oxygen, regulate humidity and remove contaminants from the water. Thirdly, for toilet flushing, and fourthly, treated blackwater is used for irrigating the landscape after passing through the septic tank and outdoor biological filter (Reynolds, 2005, p. 15). In contrast, most water in conventional homes is used just once, or not at all (such as running off cold water before showering).

Reynolds abandoned his experiments with composting toilets even though he understood their potential as a water saving device. He developed a solar toilet in which "extreme temperatures and direct sun simply fry the solids and evaporate the liquids" (Reynolds, 1993, p. 96). He found that the majority of people were disgusted by innovations such as this (p. 98) and instead he focused on improving the conventional flush toilet system by using treated greywater.

Accessible Construction
Earthship building techniques have been intentionally developed so that they are easily learned and executed, thereby empowering people to build their own shelter predominantly with waste materials. Reynolds says that "general application of common human capabilities must guide in the evolution of materials and methods for housing of the future" (Reynolds, 1990, p. 76). Typically, family, friends or people interested in attending "workshops" will assist with the labour intensive process of compacting earth into the tyres to form the main walls of the house. Reflecting on a successful career of building walls with "waste" (strawbale building), Steen et al. (1994) say that:

> *"One of the most satisfying aspects of the journey has been watching people who appear to have done very little physical work in their lives participate in a strawbale wall-raising, and leave with the belief that they too could build a house of their own."*

The Earthship construction method has recently been taught successfully to people caught in natural disaster areas; the Andaman Islands, following the 2004 Boxing Day Tsunami (Hodge, 2007) and in Haiti in response to the earthquake in 2010 (Earthship Biotecture, 2012b).

2.2.3.2 Earthship Problems
The Earthship concept is however not without challenges. Among them are: issues relating to compliance with building regulations, life-cycle issues, applicability in an urban or suburban context and its suitability in climates other than its origin, New Mexico.

Compliance with Building Regulations
Earthship construction raises many questions especially from regulators who are generally aghast at Reynolds' designs, in particular the concept of "running sewage through the living room" (Hodge, 2007) which is in reference to the indoor greywater planter. The use of waste materials, especially tyres,

which, for example, are illegal “contraband” in the State of California USA, also tends to worry building code officials whose codes may not include this type of construction material. Lack of data regarding physical and structural properties of tyre walls may also stymie the official building approval processes.

Reynolds contends that “the dangers of doing sustainable housing slightly imperfectly are not nearly as severe as not doing it at all” (Quinn, 2009); however, this viewpoint is generally not shared by building regulators who are responsible for ensuring the safety of thousands, if not millions of people. To them Earthships are a risky proposition and inevitably they dictate expensive and unnecessary compromises, or outright refusal to permit the building of an Earthship. Similar resistance to sustainable building initiatives was experienced by Michael Mobbs in the retrofit of his inner Sydney apartment (Mobbs, 1998).

Life Cycle Issues

Earthship buildings rely on technology such as batteries and solar panels which will eventually need to be replaced. The water system relies on tanks, pumps, filters, and a pressure tank and the wastewater system requires a significant amount of space, materials and regular maintenance to work effectively. These are amenities that houses connected to typical infrastructure do not need. The materials used to construct the Earthship are unusual and little is known about the expected lifespan of the building and what happens to the building materials when the house is eventually demolished.

Applicability in Suburbs

Spatially and aesthetically, Earthships challenge the normal parameters for a suburban development. They require wide blocks (long East West dimension) to ensure good solar access, with enough room for the earth-berms. Their glass facade, bermed walls and utilitarian roof (including solar panels, solar hot water, battery box, skylights/vents) may not be considered “normal” and contrast sharply with adjacent houses. This poses the question: is it possible and desirable to build Earthships into existing suburban developments where infrastructure already exists, or are they more suited to new and/or isolated development sites?

Aesthetics

The aesthetic of the Earthship is a controversial aspect that Reynolds has not conceded. Presumably this arises from his artistic bent which is evident in his diverse works of art which can be found throughout his books and his buildings in the form of sketches, diagrams, paintings and artefacts. Indeed Reynolds’ Earthships could be considered to be art as many of them are unique and handmade, with many decorative elements. They are often coloured, inside and out, in bold colours and their forms are often highly organic and unusual, yet it seems like a logical, even inevitable, aesthetic solution given the goals of reusing materials and of adhering to the passive solar, earth sheltered design formula. For example the angled glazing of the greenhouse is a characteristic of the Earthship that is very unconventional but it persists in Reynolds’ designs due to the passive solar benefits it provides. People sometimes describe Reynolds’ Earthship aesthetic as “Hobbit homes” or “Star Wars” (referring to Luke Skywalker’s home on the desert planet of Tatooine); however, Reynolds calls it “Dr Suess”; he seems to understand that people find it a little wacky. He insists, however, that the aesthetics can be more conventional – but he’s not interested in that.

There are now many examples of a more conventional Earthship aesthetic, perhaps the most well known is the “Groundhouse” in Brittany, France (Howarth & Nortje, 2010) which has featured on Kevin McCloud’s Grand Designs television show, and a suburban development in the Netherlands (Vereniging Aardehuis Oost Nederland, 2011). Both have opted for a totally different aesthetic which, arguably, may appeal to a wider market – but will they work as efficiently?

Figure 2.2 - Proposed Aardehuis Earthship Development in the Netherlands (Vereniging Aardehuis Oost Nederland, 2012)

Applicability in other Climates
Reynolds has acknowledged the need for adaptation to different climates in his book Comfort in Any Climate (Reynolds, 2000) where he describes the basic design changes required for a variety of different climates and geological conditions (e.g. high water table). The other issue is the thermal performance of the Earthship in Taos and other climates which is only just starting to be investigated. The extreme climate of Taos would seem to guarantee that its performance in milder climates was assured; however, recent reports have indicated that in cold, cloudy winter climates thermal comfort levels have not been adequate and backup heating has been required (Hewitt & Telfer, 2012).

2.2.3.3 Gaps in Knowledge About Earthship
Research into the performance of Earthships is only just beginning. The few studies that have been conducted are reviewed later in this Chapter but in summary they have found that Earthships provide thermal comfort and an acceptable level of amenity in a variety of climates albeit with the need for some adaptations to local climates. However, much of the research relies heavily on anecdotal evidence and there are few empirical studies which have rigorously measured Earthship performance. These studies have focused on thermal performance, especially in European climates, and regulatory issues associated with the unusual construction methods of the Earthship. Some of the studies have been conducted on buildings that are demonstration projects, not people's homes, adding uncertainty about the results. While there is much commentary on the lifecycle impacts of Earthships, there has been no lifecycle assessment study with a comparison to other homes.

Hence, this research seeks to thoroughly investigate the performance of existing Earthships, including an assessment of their lifecycle impacts, thermal performance and their capacity to provide basic amenities to their occupants.

Therefore, the following section reviews methods for evaluating building performance.

2.2.3.4 Potential Problems with Tyres used as a Construction Material
Off-gassing, leachate and flammability are the main concerns raised about using tyres as a building material (Hewitt & Telfer, 2012, pp. 46-48). While these issues may be problematic in other contexts in

which tyres exist, in the context of a tyre wall, they are either not applicable, or they can be managed by engineering and construction measures.

Off-gassing of tyres is evident when walking into a tyre retailer's showroom; the smell of tyres is obvious, yet this smell does not exist in Earthships (findings from this study support this claim - refer Section 3.2.1.3). The most likely reason for this is that in an Earthship wall the tyres are covered with a layer of render (earth, lime or cement) which prevents exposure to sunlight and dramatically reduces exposure to air (the render may "breathe" somewhat or may have cracks so some air exposure is inevitable), and this prevents the main off-gassing catalysts - light and air - from coming into contact with the tyres (Earthship Biotecture, 2012d). Another factor in the rate of off-gassing is the age of the product or material, for example the interiors of new cars have a strong odour due to off-gassing of the plastics used in the dashboard, and other fittings, but over time the quantity of volatile compounds being released into the air decreases and therefore the strength of the odour decreases. Because the tyres used in an Earthship are not new, and have spent thousands of hours in a harsh outdoor environment, the majority of volatile compounds that cause off-gassing have already been released into the environment long before they reach the Earthship construction site. Furthermore, Earthships are well ventilated buildings, and the harmful effects of any off-gassing from tyres, or other building materials, would be mitigated by cross ventilation.

It is true that toxic substances leach out of tyres in the presence of water (Amoozegar & Robarge, n.d.) and the extent of this is dependent upon factors such as the pH (acidity/alkalinity) of the water, the duration and level of exposure e.g. tyre is saturated/covered/totally immersed, or is only partially in contact with water (Claus, 2005); however, studies indicate that the quantity of toxic leachate is so small that they pose negligible effect on water quality (Claus, 2005; Humphrey & Katz, 2001). Furthermore, in a properly constructed Earthship, water is unlikely to come into contact with tyres and, if it does, this is likely to be limited to brief, partial contact rather than prolonged, saturated conditions, due to the use of water barriers, landscaping and engineered drainage systems in Earthship construction.

Flammability of tyres is certainly an issue when they are stored outdoors in large, haphazard piles, whereas when they are filled with compacted earth, arranged in a wall structure and rendered, the fire risk is negligible. This is because, in a tyre pile, oxygen is readily available in and around the tyres, facilitating combustion, whereas in a tyre wall oxygen is excluded as they are filled and covered with a non-flammable material. Even an un-rendered tyre wall has been demonstrated to withstand a fire as this was put to the test in an arson attack on an Earthship in Glasgow, Scotland (Hewitt & Telfer, 2012, p. 48).

2.2.3.5 Earthship Biotecture Designs

Reynolds has constantly evolved the Earthship design since its inception in the early 1970s with a view to improving thermal performance, water and energy efficiency, ease of construction and reducing construction costs. This has resulted in various designs to suit different climates and budgets. This section briefly outlines three typical designs that represent some of Reynolds' most successful experiments and which are the focus of this thesis.

U Module Earthship

The original U Module Earthship, described extensively in Reynolds' early books (Reynolds, 1990, 1991, 1993), is characterised by tyre walls arranged in a "U" shape with an integral greenhouse which allows for unimpeded movement of air and occupants between the main living spaces and the greenhouse space. Figure 2.3 shows a typical floorplan of a "3U" Earthship in which the middle and right U are open to the greenhouse but the left U is isolated by a wall with double doors. Note also that the bathroom is located at the end of the greenhouse.

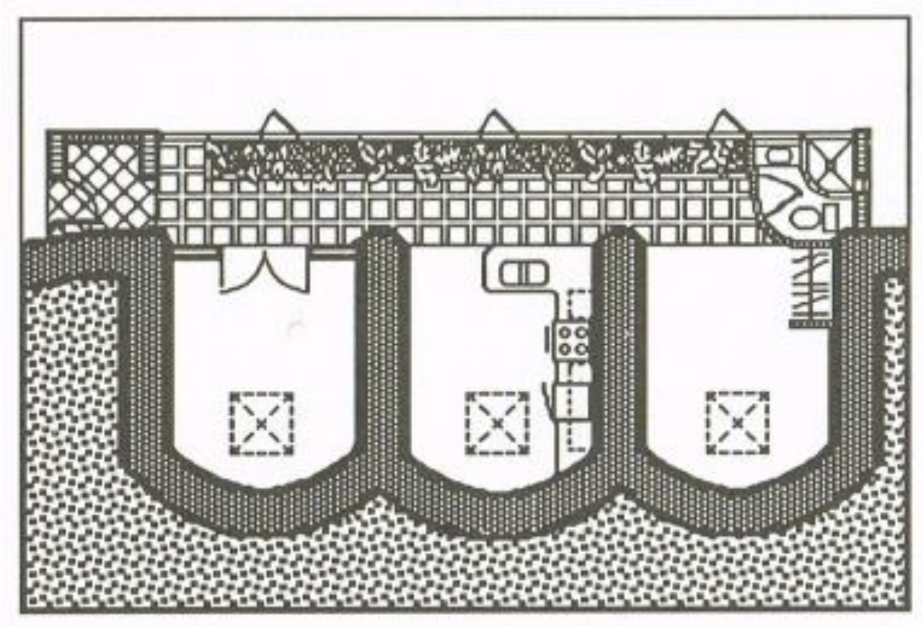

Figure 2.3 - Floor plan of U Module Earthship (skylight shown in dotted line) (Reynolds, 1990, p. 54)

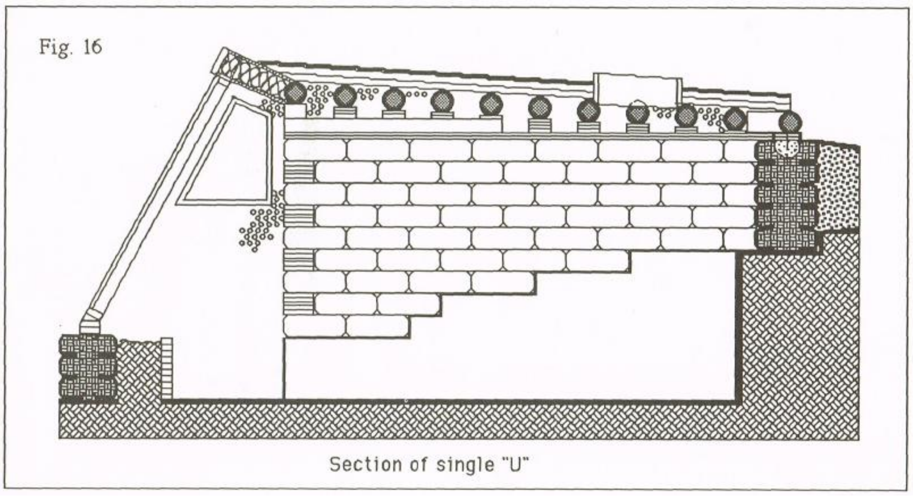

Figure 2.4 - Section view of U Module Earthship (Reynolds, 1990, p. 88)

Packaged Earthship

The Packaged Earthship was a significant departure from the U Module design aimed at simplifying construction and reducing construction costs (Earthship Biotecture, 2014b). Instead of the U Module tyre wall layout, the tyre walls are straight with internal walls made using aluminium or glass beverage containers in a cement mortar. It has a simple roof that slopes toward the greenhouse side of the house and consequently the rain water tanks ("cisterns") are located near the tyre wing walls at each end of the patio. The greenhouse is integral like the U Module design but the glazing is vertical rather than sloped, presumably to facilitate construction.

Figure 2.5 - Floorplan of Packaged Earthship (Earthship Biotecture, 2014b)

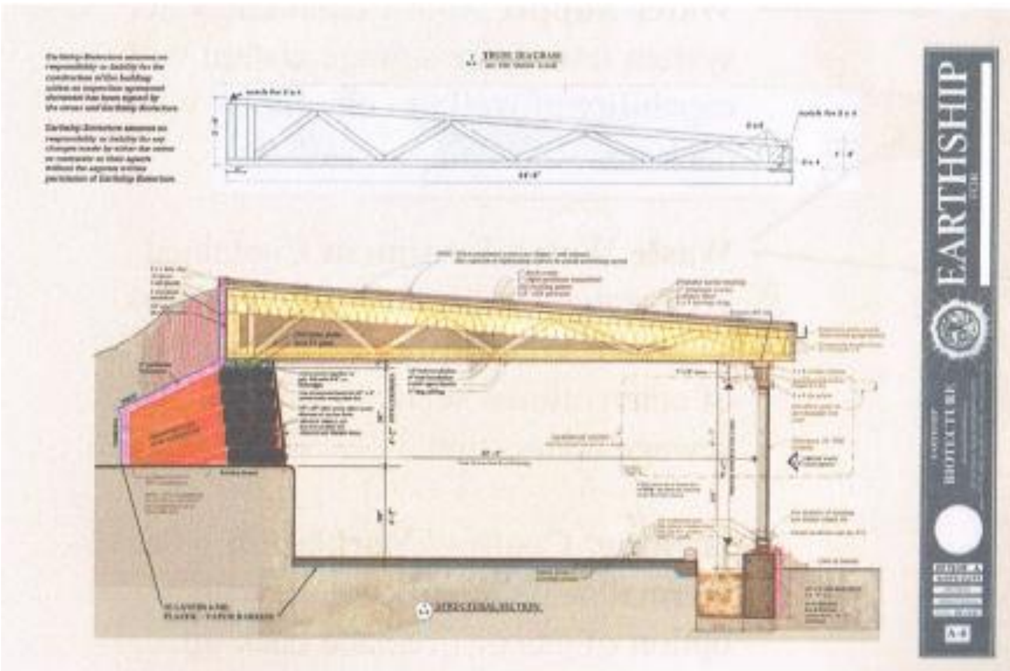

Figure 2.6 - Section view of Packaged Earthship (Earthship Biotecture, n.d.)

Global Model Earthship

The Global Model Earthship is one of the most recent designs developed in the late 2000s. It has angled exterior glazing like the U Module design but it also features a new element: a glazed partition wall that delineates and isolates the greenhouse space from the main living spaces. This enables the occupants to control air flow between the greenhouse space and living spaces. The roof slopes to the rear of the Earthship and has a solar powered, hot pipe system on the roof to melt snow and catch water. Rain water tanks are located to the rear of the building, in the berm, close to the roof gutter. Other innovations include the introduction of earth tubes to each main room for passive cooling and cross ventilation (indicated by blue arrows in floorplan and section views). These replace the traditional operable skylight (roof window) toward the rear of the rooms; a typical feature of the U Module and Packaged designs.

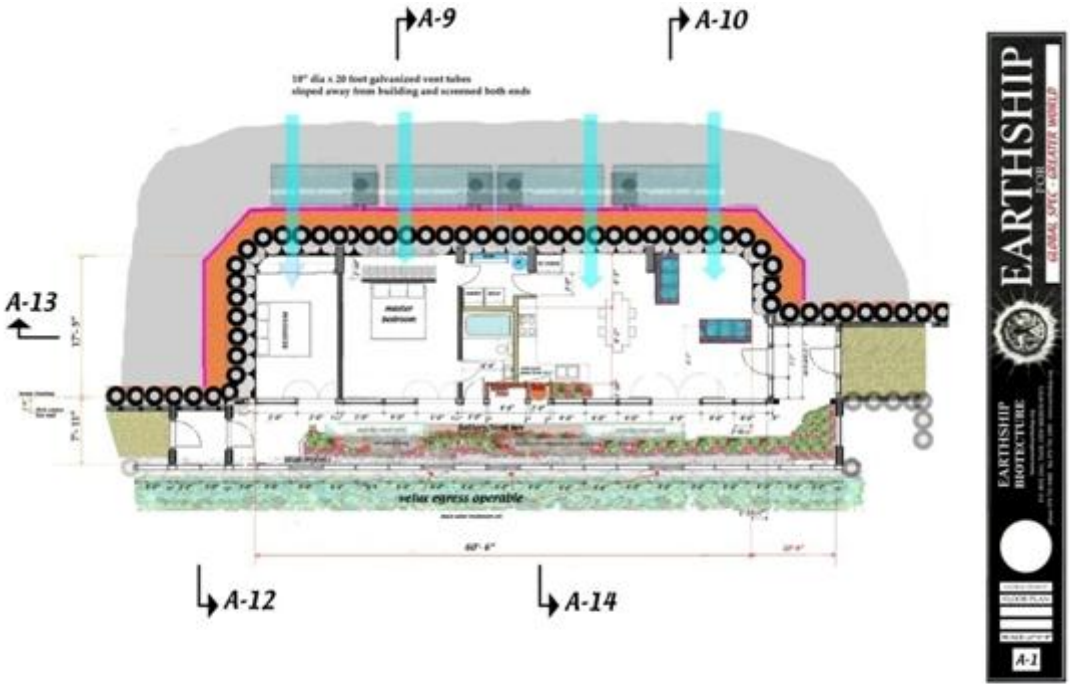

Figure 2.7 - Floorplan of Global Model Earthship (supplied by Earthship Biotecture)

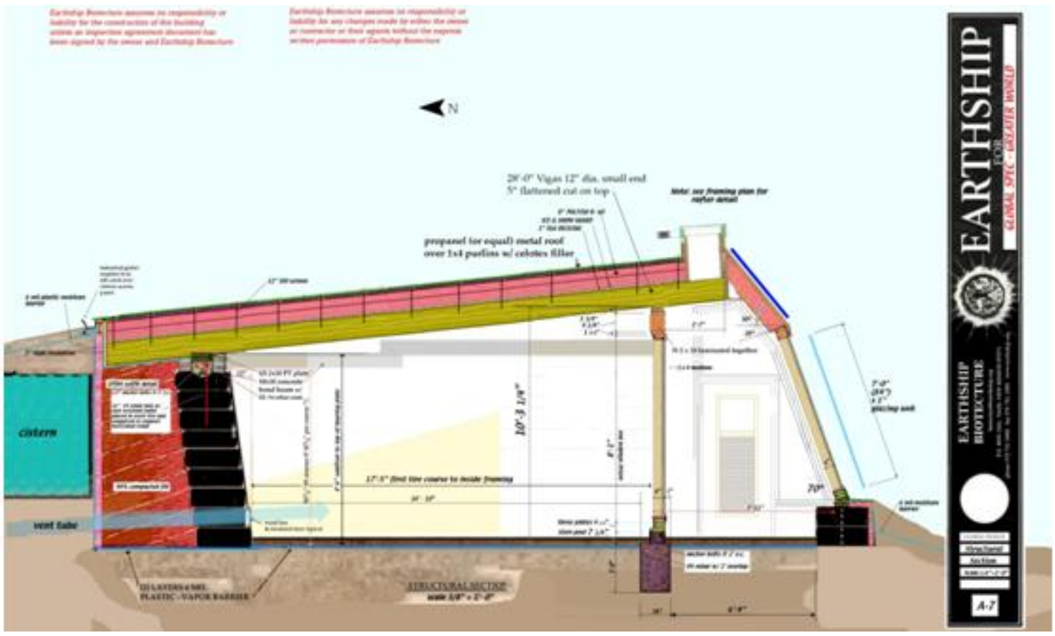

Figure 2.8 - Section view of Global Model Earthship (supplied by Earthship Biotecture)

2.3 Methods of evaluating building performance

This section focuses on methods used to evaluate building performance. There are a number of ways in which the performance of a building can be evaluated and/or predicted. These include: Post Occupancy Evaluation, Thermal Modelling and Life Cycle Assessment. Each method is described and significant studies that employ these methods, especially those related to Earthship and earth-sheltered housing, are reviewed apropos of developing a valid method for this study.

2.3.1 Post Occupancy Evaluation

Post Occupancy Evaluation (POE) is a methodology that is used to understand how a building has actually been performing while in use by its occupants. This information is often compared to predictions or claims made by the designers to establish whether their goals have been realised.

> *"Post occupancy evaluation (POE) of buildings tries to answer two broad questions: "How is a building working?" and "Is this what was intended?" POE is about real-world outcomes and their consequences ("ends") rather than design prescriptions ("means"). It aids learning from experience to improve the next generation of buildings – a kind of quality control writ large."* (Roaf, Horsley, Gupta & Leaman, 2004, p. 491).

The scope of POE ranges enormously as there are many aspects of a building which can be evaluated and consequently there are many techniques that may be employed in a POE (Roaf, Horsley, Gupta & Leaman, 2004, p. 495). POE is not routinely carried out – due to myriad issues (Roaf, Horsley, Gupta & Leaman, 2004, p. 493) – and consequently there is a paucity of research in this field. This may however soon change as the recently developed Living Building Challenge (International Living Future Institute, 2012) environmental rating scheme for buildings uses POE as one of the measures for assigning a rating. This is quite a departure from most rating systems which are typically based on predictions about future building performance rather than actual building performance.

Monitoring of indoor comfort conditions, such as air temperature and humidity, is a method frequently used in a POE. It is sometimes used as a means for validating the results of a thermal modelling simulation: by comparing the results of the simulation with the results of the monitoring study the accuracy of the thermal model can be established (Soebarto, 2009) (Bou-Saada & Haberl, 1995).

Another method is to use questionnaires and interviews to gain an understanding of how the occupants of buildings feel about various issues (Roaf, Horsley, Gupta & Leaman, 2004). This has been one of the approaches used by Hewitt and Telfer (2012) in their investigations of six Earthships built in Europe, and they also cite thermal monitoring and thermal modelling (simulation) results of an Earthship in Brighton, UK conducted by Ip and Miller (2009). This is the most extensive review of Earthship performance to date. They found that the indoor temperature was often in the comfort range during summer, but in the winter it was often below comfort temperature; however this may have been due to the building being unoccupied and still in its initial charging stage (when the soil temperature around the building is stabilising). This study incorporated a large number of temperature sensors located within the tyre wall, under floor, and within the living spaces, to improve the understanding of the thermodynamics of the Earthship structure in the UK climate.

The key findings of the research by Hewitt and Telfer (2012) were:

- With the exception of Earthship Brighton, only anecdotal evidence was available for thermal performance of European Earthships (p. 149).
- The thermal performance in cool temperate climate Earthships (France, Brighton UK, and Netherlands) were below expectations: heat loss through the uninsulated floor the suspected culprit (p. 147), whereas in a hot climate, Earthship Valencia (Spain) has "suffered occasionally" from overheating during summer although this problem is reported to have been solved by installing external blinds (p. 148).
- The study in Earthship Brighton (UK) points to "significant shortcomings with thermal performance, although with the caveat that there has not been anyone living in the property, and therefore there has been none of the background heat that would be associated with activities such as cooking" (Hewitt & Telfer, 2012, p. 147)
- Air leakage of Earthship Brighton was 8.43 ACH at 50Pa which is compliant with regulatory limits but is "actually a very poor result for a low-energy building...requirement for Passivhaus buildings is a maximum of 0.6 ACH." (Hewitt & Telfer, 2012, p. 150)

- The Groundhouse Earthship (Brittany, France) is reported to have “maintained a consistently comfortable temperature” (Hewitt & Telfer, 2012, p. 147) based on ad hoc air temperature measurements by the occupant.
- With regards to European Earthship utilities systems, “most are off-grid” (p. 151) with the exception of the Groundhouse which had dual systems for electricity and water: a grid connected photovoltaic system and mains water for backup.

Key recommendations focused on addressing the reports of sub standard thermal performance of Earthship in temperate climates include:

- Upgrading the external fabric to avoid thermal bridging and air infiltration (p. 152).
- Adding an efficient auxiliary heating system and including a mechanical ventilation heat recovery system (p. 152).
- Insulating external envelope to achieve a U-value of 0.15 W/m^2K although the design should be “specifically tailored to suit the climate it’s being built in” (Hewitt & Telfer, 2012, p. 151).
- Double glazing south facing windows (in the northern hemisphere), and for other orientations, and triple glazing for other orientations (p. 151).
- Designing a greenhouse, to create a buffer zone from the main internal spaces to outside spaces (p. 152).
- Including shading devices such as louvres or a *brise soleil* (deciduous vines) to reduce summer solar heat gain (p. 156).

They conclude that although the desire to live an environmentally friendly lifestyle and/or one free of “the most egregious aspects of the financial system” (p. 157), Earthships are not likely to become mainstream because they are suited to low density housing and their differing materials and construction methods are not compatible with existing material supply chains and skill sets.

A post occupancy evaluation of Reynolds’ first demonstration project in the UK, Fife, Scotland, has been analysed by Gaia Research (2003) in terms of concerns raised by local authorities relating to thermal performance, day lighting, flat roof construction, (lack of) heating system, tyre and can walls, and ventilation. They concluded that tyre walls are a viable construction method deserving of Type Approval based on the following issues relating to tyres;

- fire resistance: in an Earthship tyres are covered in thick layers of non-combustible earth and/or cement based render thus overcoming concerns about combustion of tyres which are otherwise highly flammable;
- toxic leachate: a waterproof membrane isolates tyres from water thus preventing the possibility of toxic substances migrating from tyres to water, and further, studies by Edil and Bosscher (1992) indicate that even in the presence of water, tyres do not cause adverse effects on water quality;
- durability: tyres are highly durable and only degrade in the presence of UV light, excessively high temperatures, abrasion, and certain oxidising agents – all of which are not present in Earthship construction. They also cited evidence from studies of tyre reefs which indicate that even in a harsh marine environment, tyres are remarkably durable and non-toxic.

Finally, in France, Howarth and Nortje built and monitored the air temperature of their Earthship inspired home called the Groundhouse (Howarth & Nortje, 2010) which appeared on TV show Grand Designs with the result that it “proved conclusively that a modified Earthship design works well in northern Europe” (Howarth, 2012). The home has two wood heaters to “provide extra warmth and ambience when necessary” (2012). This use of heaters is of some concern which arises perhaps due to some departures from Reynolds' standard design, in particular the use of an operable glazed facade and absence of a glazed partition wall that isolates the greenhouse from the living spaces.

2.3.2 Thermal Modelling

Thermal modelling or thermal simulation is a scientific method used to predict the thermal performance including energy use of buildings (Soebarto & Williamson, 2001), although more often in Australia it is used as a tool at the end of the design process to rate a building's theoretical energy use against minimum energy performance standards set by legislation (Soebarto & Williamson, 2001).

Thermal modelling software is able to model various indoor comfort conditions such as air temperature, humidity and lighting levels, arising from a wide range of variables including climate and weather conditions of the site, the building fabric, orientation and design, and occupant behaviour, especially in relation to use of heating, cooling and natural ventilation systems. The software uses weather data, sophisticated heat flow algorithms and the physical properties of materials to calculate the building's theoretical thermal performance, thereby enabling an assessment regarding the potential energy efficiency and thermal comfort. By monitoring indoor conditions (see POE section above) researchers are able to "calibrate" a thermal model and use statistical analysis to evaluate the accuracy of the predicted results compared to the measured results (Bou-Saada & Haberl, 1995; International Performance Measurement & Verification Protocol Committee, 2002).

The first study to investigate the thermal performance of the Earthship was conducted by Grindley and Hutchinson (1996). The indoor air temperature in an Earthship in Taos, New Mexico, USA was monitored for three days and analysed and a subsequent thermal modelling exercise was used to calibrate a simulation model in the Taos climate and predict the thermal performance in the Taos and UK climates. They predicted that the Taos Earthship would overheat in the summer and would require some backup heating during winter nights, and the UK Earthship would also overheat in the summer and would need only 325kWh pa of heating in the winter months.

Kruis and Heun (2007) measured indoor and outdoor temperatures of an Earthship in New Mexico USA and compared this with results of an EnergyPlus thermal model of the Earthship. Their model predicted the indoor temperature of the Earthship "quite closely" (p. 5) – generally to within 1°C of the actual temperature. They outline a strategy for modelling the tyre wall using EnergyPlus which overcomes some of the peculiarities of the structure of the tyre wall although they concede that there is some uncertainty regarding the accuracy of model (p. 2-3). This relates to not being able to model the moisture content of the soil in the berm and the validity of using EnergyPlus' ground contact model for high thermal mass (i.e. earth sheltered) structures. The study also simulated the Earthship performance in various climates in the USA: humid continental (Grand Rapids), continental sub-arctic (Anchorage), tropical savannah (Honolulu) and semi arid (Albuquerque). They found that heating and cooling energy use would be reduced in all climates although backup heating/cooling would be required at times.

One important factor for modelling an earth-sheltered building is the temperature of the earth that surrounds it, however estimating this temperature is not straightforward. There is a circular cause and consequence dilemma in which the temperature of the building affects the temperature of the earth and vice versa. However methods for calculating the temperature "under slab" or at various depths below the slab (or adjacent an earth-sheltered wall) have been developed. One such method is by Williamson (1994) and this was developed further and used in this study (Freney, Soebarto & Williamson, 2013a) (Freney, Soebarto & Williamson, 2013b).

Related to this is the issue of simulation software's capacity to accurately model heat transfer in earth-sheltered designs such as the Earthship. Staniec and Nowak (Staniec & Nowak, 2009, p. 1908) note that "most building energy simulation models do not allow to incorporate soil cover accurately" (sic). They used a finite element package, FlexPDE, to calculate soil heat transfer, the results of which were exported to EnergyPlus to model the thermal properties of earth-sheltered homes in Poland.

The documentation supporting EnergyPlus concedes that its use of conduction transfer functions (CTF) initially had some difficulties with modelling "thermally massive constructions with long characteristic times" (US Department of Energy, 2012) (p. 38); however, it indicates that the CTF method implemented in the software overcame these problems (p. 27), but it is not explicit about how accurate modelling of a thermally massive structure would be. Mithraratne and Vale (2006) however, concluded that EnergyPlus was capable of accurately predicting the indoor air temperature of the Hockerton Housing Project in the UK which is a high thermal mass, earth-sheltered, design.

2.3.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is also known as Life Cycle Analysis, or Cradle to Grave Analysis. It is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle" (ISO, 2006, p. 2). LCA developed in the late 1960s and rapidly evolved in response to various factors, notably the oil crisis of the 1970s (Horne, Grant & Verghese, 2009, p. 2). By the late 1990s the International Organisation for Standardisation (ISO) had established a series of standards to guide practitioners in their use of LCA methodology: the ISO 14040 series of standards (ISO, 1997), which are referenced by the Australian/New Zealand counterparts, define core procedures and terminology.

During the first decade of the 21st century, LCA has proliferated and become a common tool that underpins other assessment methods such as the well known "eco-footprint" (Wackernagel & Rees, 1996). LCA has become one of the most credible methods for evaluating the environmental impacts of products and services. Horne, Grant and Verghese (2009, p. 89) argue that "LCA has a major role in highlighting the impacts of different built environments across their various life cycles."

Life cycle thinking is a new way to critically examine design with a view to developing sustainable solutions that benefit the triple bottom line: improving economic, environmental, and social outcomes. One of the greatest contemporary exponents of this is McDonough (2009) who uses the term Cradle to Cradle to emphasise the importance of recycling materials without degradation of material properties ("up-cycling") at the end of a product's useful life.

The main difficulties with LCA include the need for accurate data and the complexities of correctly articulating the scope of the study. Although this slowed the uptake of LCA initially, these issues are now better understood and LCA has rapidly developed (Horne, Grant & Verghese, 2009, p. 4-5).

Acquisition of accurate Lifecycle Inventory (LCI) data (i.e. inputs and outputs of industrial processes) is another significant challenge as manufacturers are often reluctant to share this information, perhaps for fear of incriminating themselves as environmentally irresponsible. Furthermore, LCI data needs to be location specific, as environmental impacts for a given process can vary greatly depending on the country/region in which the material/process originates, and, LCI data must be frequently updated due to changes in our technological, social and environmental spheres. It is difficult to obtain up to date, location specific data, nevertheless there is a global effort to gather and maintain this information and consequently LCA is becoming more reliable. In Australia, the National Life Cycle Inventory Database (AusLCI) Project was initiated in cooperation with academia and industry to develop national inventory data and to link with similar international schemes (Horne, Grant & Verghese, 2009, p. 17).

Articulating the scope of the study involves correctly defining a key "question" and a critical aspect of this is to define an appropriate "functional unit". Horne, Grant and Verghese (2009, p. 4) give an example of a study of a coffee machine: if the functional unit is defined as the coffee machine (product level) this will give a very different result to an assessment with a functional unit defined as "impact per production of 10,000 cups of coffee" (functional level). In terms of the functional unit of a home, Horne raises an interesting question regarding definition of the functional unit, "for example, is 'energy use per house', 'energy use per bed space', or 'energy use per square metre' an appropriate unit, and what is the sensitivity of results to assumed maintenance regimes and design life?" (p. 89).

There are various approaches to LCA ranging from “quick and dirty,” “Streamlined LCA” that can quickly provide designers with quantitative data (Lewis & Gertsakis, 2001, p. 53), for example the impacts of various materials could be compared, to more thorough and rigorous “full LCA” that take months or years to conduct.

To establish a method for this LCA study it was useful to review the literature regarding Life Cycle Assessment (LCA) and Embodied Energy (EE) of walls and buildings. Of particular interest was definition of the functional unit, approaches to modelling recycled materials and common building materials in the Australian context, and findings regarding relative impacts of operational energy, construction materials, process energy, maintenance, and end-of-life processes.

A summary of the most relevant literature is summarised and discussed below.

2.3.3.1 Ximenes and Grant (2012)

This study compared the environmental impacts of two building options for two house designs for Sydney, Australia in terms of GHG emissions, particulate and chemical emissions to the air caused by incineration of timber, and toxicity arising from landfill leachate.

A standard house design (brick veneer on concrete slab floor) was evaluated as built, and compared to a “timber maximised” design in which the standard design was reconfigured to use the maximum amount of timber by, for example, replacing the concrete slab floor with a suspended timber floor. The study investigated the effect of various end-of-life scenarios for the houses with a focus on options for disposing of the timber components and these included construction and demolition landfill with methane capture, incineration, incineration with energy capture, mulching, and recycling. A range of values for the degradation of timber in landfill were also investigated as this is a highly contentious issue.

To compare the impacts of construction and end-of-life to the operation of the homes, AccuRate energy modelling software was used to establish the heating and cooling energy of 3-4 Star rated house designs. All design options achieved the same rating and these data were adjusted based on the floor area of the homes used in this study. The functional unit of the study was the major building elements of homes in the context/climate of Sydney, and their operation over a 50 year life span.

The study’s findings were consistent with similar studies (Carre, 2011) which found that timber maximised designs lead to fewer greenhouse gas emissions over the life of the home, however assumptions regarding the decomposition rate of timber in landfill and other end-of-life parameters, significantly affected the GHG emissions.

Although only basic energy modelling was conducted it was tentatively concluded that heating and cooling energy was still the most significant GHG driver, however the cradle to grave life cycle GHG emissions of the construction materials was also still a very significant factor: it was a third to a half of the heating and cooling energy GHG emissions.

2.3.3.2 Carre (2011)

The focus of this LCA study was the wall and floor materials of a typical Australian house. The study included modelling of the heating and cooling energy of the homes’ thermal envelopes (using AccuRate) for the Melbourne, Sydney and Brisbane climates for both 5 and 6 star energy ratings. The energy efficiency was achieved through construction methods that minimised the addition of embodied energy.

The functional unit was defined as “1 square metre of internal floor area (including double garage), 76% of which is climate controlled, for 1 year” with units of m^2.a.

Material quantities for the Life Cycle Inventory (LCI) were based upon a typical house design supplied by the Housing Industry Association (HIA). Areas and distances for major elements of the house were calculated from the HIA architectural drawings and, from this, material quantities were calculated using standard quantity factors developed by Lawson (1996) although these were adjusted in some cases to reflect current building practices.

The building life span was assumed to be 50 years. This was acknowledged as being arbitrary and therefore a sensitivity study was conducted including 60 and 75 year life spans.

The study found that over the life cycle of the home the impacts caused by heating and cooling energy were greater than construction and end-of-life phases; however, in Sydney and Brisbane construction and end-of-life (EOL) contributed to 45% and 43% respectively whereas in Melbourne the same construction type (type C) accounted for 24%.

In terms of construction and materials the study found that timber based wall and floor constructions had lower global warming impacts than equivalent steel framed walls and concrete slab floors. Concrete slab floors generate 13% higher global warming impacts compared to elevated timber floors and steel frame walls generate 21-43% higher global warming impacts than timber frame.

Findings regarding land and water use impacts were clouded by uncertainty arising from "provisional" data which reflect simple aggregations of water and land use which do not reflect issues such as resource depletion in a local geographical context. For example, in reality water use in South Australia may have higher impacts than water use in Queensland (where water is abundant). It was found that timber constructions require far more land and water resources than steel or concrete based constructions.

Photochemical oxidation tended to be higher for timber structures however there was uncertainty regarding how relevant this was in the context of timber where such emissions are usually generated in low population areas where smog is unlikely to occur.

A life span sensitivity study found that increased lifespan decreased the relative impact of the construction and end-of-life stages (EOL) compared with the heating and cooling energy.

Materials for maintenance were included in the study however it was acknowledged that very little data is available on this subject.

2.3.3.3 Peuportier (2001)

In a whole building LCA of three French houses, Peuportier (2001) used a functional unit of $1m^2$ of living area to compare the different floorplans and technology embodied by each design: "standard", "solar" and "wooden frame". The study also reported results based on the whole house as the functional unit.

It was found that there was a doubling of CO_2 emissions for a large house when compared to a small house, whereas when CO_2 emissions for these differing sized houses were normalised based on floor area the results were similar (Peuportier, 2001, pp. 448-449). No mention of the expected life span of the house was mentioned or factored, presumably due to similar life expectancy of the construction methods.

The avoided impacts arising from the use of construction materials made from recycled materials were modelled such that half their impacts were attributed to the construction phase, and half were attributed to the end-of-life phase, and that this positive affect was (and should only be) counted once (corresponding to one round of recycling). Equations for calculating inventories were developed to reflect this.

2.3.3.4 Blengini and Di Carlo (2010)

This study used a functional unit of $1m^2$/year as the functional unit in a whole building LCA of a low energy house compared with a standard house which mimicked the low energy house in terms of size features, geographical/climatic conditions and lifespan. The differentiating features were the amount of glazing (and therefore the amount of external wall area), insulation and equipment. The assumed life of the building was 70 years.

This study found that the role of recycled materials and recycling materials (at end-of-life) was important and that there was no single dominating factor contributing to the environmental impacts of low energy houses unlike conventional designs which tend to be dominated by heating related impacts (p. 663).

Correspondingly, the LCA approach is highly applicable to low energy design houses, "the lower the operational energy, the more important is the adoption of a life cycle approach." (p. 663).

2.3.3.5 Treloar, Owen and Fay (2001)

This study investigated the embodied energy of a rammed earth wall from "cradle to gate" - it did not consider the operational energy or end-of-life disposal. Rammed earth wall construction was compared to a brick veneer and cavity brick construction. The house design was standardised on an actual residential design (3 bedroom, single story, 150.7m^2) and the external walls and substructure (footings) were changed for each study. Results were reported on the basis of gigajoules of embodied energy per house; thus the functional unit was the entire structure (including walls, sub structure and roof) of the house.

They concluded that rammed earth has substantially less embodied energy than cavity brick, however when compared to brick veneer there is uncertainty due to the quality of the data and methodology. Reductions in the cement content of rammed earth are recommended to further improve the embodied energy result.

2.3.3.6 Pierquet, Bowyer and Huelman (1998)

This study compared embodied and operational energy of eleven wall types in the context of cold regions in the USA. The end-of-life phase was not considered. The wall systems studied included various insulated stud frame designs in both timber (of various dimensions and insulative values) and steel, plastered strawbale, cordwood, expanded polystyrene structural insulated panels, autoclaved cellular concrete, and expanded polystyrene insulating concrete forms.

Although the study focuses on the wall materials, details of standardised foundations and standardised roof system are also described (so that embodied energy could be calculated). The fact that they were standardised indicates some methodological problems warned of by Kotaji, Schuurmans and Edwards (2003, p. 15) relating to the importance of considering all affected elements of the building i.e. it is highly probable that footing design would have to be altered in accordance with the physical characteristics (e.g. weight and width) of the wall system.

Quantities of materials for each wall were listed in terms of mass or area, and where only slight variations existed between wall types, the material list was duplicated with additions and subtractions of materials to reflect the design of the similar wall.

This study emphasised how the period used to calculate the total energy savings dramatically affected the results and it suggested a long period e.g. 30 years to get an accurate indication of the overall energy use. It found that the walls with the least "environmental burden" were strawbale and 2" x 6" stud wall with more than usual insulation.

2.3.3.7 Blengini (2009)

This study investigated the recycling and demolition potential of a block of flats. The demolition of the building was closely monitored which enabled assessment of the end-of-life phase of the building, an aspect which is often overlooked due to lack of data and the more significant impacts arising from the use and construction phases.

The functional unit was 1m^2 of net floor area per year.

Alternative end-of-life scenarios were modelled, which revealed a significant potential for reducing impacts of the building shell (use phase excluded) through recycling. Further research of the recycling potential of building materials was recommended.

The study found that recycling was economically viable and energetically and environmentally beneficial. Importantly, it avoided dumping in landfill which avoids unnecessary use of scarce land (especially in urban areas). It found that the type of material and the availability of the relevant recycling processes was a decisive factor in determining the avoided impacts arising from the recycling process and that materials that require a lot of energy to recycle could contribute negatively to lifecycle impacts.

2.3.3.8 Kellenberger and Althaus (2009)

This study's aim (Kellenberger & Althaus, 2009) was to identify which elements of the building's lifecycle were insignificant in LCA terms and could therefore be ignored, simplifying the LCA process to make it more manageable. It found that the building process and off-cut waste can be ignored whereas ancillary materials (e.g. nails and screws in timber frame wall systems) and transport were significant impact drivers.

2.3.3.9 Fay, Treloar and Iyer-Raniga (2000)

A Life Cycle Energy Assessment (LCEA) of an existing house in Melbourne, Australia investigated the effects of various design strategies such as improved insulation and double glazed windows. It took into account the energy required for heating and cooling and hot water heating, cooking, lighting, and major appliances and assumed a lifespan of 50 years. The study indicated that improved insulation, although effective in reducing operational energy requirements, may not be an effective way to reduce the net life cycle energy. It recommends methods such as improving window glazing (e.g. double glazing), correct orientation of windows, use of high thermal mass/low embodied energy materials, reduction of air infiltration, use of renewable energy, and wider thermostat settings. A sensitivity study investigating the effects of different lifespans (25, 75 & 100 years) found that longer lifespans resulted in only marginal reductions in life cycle energy due to the energy saved by installing extra insulation (Fay, Treloar & Iyer-Raniga, 2000, p. 39).

2.3.3.10 Blanchard and Reppe (1998)

An existing residential home was evaluated using cradle to grave LCA and Life Cycle Economic Cost (LCC) and compared to a theoretical "energy efficient house" that featured materials and components with less embodied energy or a lower rate of replacement, and was based on the same floorplan and design as the base case house (Blanchard & Reppe, 1998, p. 6). The study found that the total life cycle energy of the home could be improved by a factor of 2.8 by improving the thermal envelope with products such as cellulose insulation (as opposed to fibre glass batt insulation which has a higher embodied energy), more energy efficient appliances, and improved heating, ventilation and air conditioning (HVAC) system. Most of the energy was saved during the use phase of the "standard" and "energy efficient house".

2.3.3.11 Sartori and Hestnes (2007)

This study reviewed 60 Life Cycle Energy Assessments of buildings in nine countries (two of which were full LCAs). Most studies were limited to embodied energy and operational energy although the definition of embodied energy varied: energy for construction and transportation of materials was counted in some studies but not others.

It reported that the sum of energy for construction, transportation of materials and demolition was negligible or approximately 1% of the total life cycle energy. Very few studies included waste management as part of the building life cycle.

A linear relation was found between operational energy and total life cycle energy despite the wide range of variables such as climate, building design/size and materials. This was due to the dominance of operational energy in all cases which overshadows the effects of other life cycle energy phases. Another relationship found was that of embodied energy versus operational energy. Higher embodied energy results in lower operational energy and lower total energy use. For example the embodied energy of a "solar house" was double that of an equivalent "conventional" house but the total energy was half that required by the conventional house (calculated over a 50 year time frame).

2.3.3.12 Thormark (2002)

Recycling of building materials is of interest due to the modern tendency for an increased proportion of total energy use attributable to building materials, increasing benefits of recycling (e.g. avoiding landfill), and decreasing life-span of buildings. In this study the recycling potential of a low-energy dwelling was estimated and compared to the energy used during construction and operation of the building.

In this study it was found that reusing materials (as opposed to recycling) reduced the embodied energy of a family home by 45% (p. 429). Over a 50 year lifetime the low-energy building had the potential for 37-42% of embodied energy to be reclaimed through recycling, and the recycling potential was about 15% of total energy use indicating that the end-of-life phase of a building has great potential to reduce overall energy use (p. 434).

2.3.3.13 Kotaji, Schuurmans and Edwards (2003)

Kotaji et al (2003) have described an approach for LCA of buildings and building components which highlights the importance of developing an appropriate functional unit and specifying a realistic service life. They also highlight problems in comparing LCA studies arising from a lack of standardised approaches to LCA of buildings/building products.

2.3.4 LCA Software

Software and digital databases of LCI data have been developed to facilitate LCA studies. Curran and Notten (Curran & Notten, 2006, p. 13) list eighteen LCA software tools. Of these, two are specifically aimed at building materials and products (BEES and Environmental Impact Estimator), whereas others are able to evaluate a wider range of products/systems.

The type of products/systems able to be analysed is limited by the datasets of Life Cycle Inventory (LCI) data which are used by the LCA software to calculate flows of substances throughout the system and the environment. There are three software packages listed by Curran and Notten which have over 1000 LCI datasets (EMIS, GaBI and SimaPro).

Over the last few years web-based LCA applications have become available, enabling access by anyone via the internet. These tend to be simpler versions of the more sophisticated packages such as GaBI and SimaPro, and usually have limited functionality that is specifically aimed towards certain professions such as industrial design or architecture. The advantage of these packages is that their simplified workflow enables LCA novices to quickly learn how to use the software and start experimenting with various design options. An example of this is eTool (eTool, 2013), developed in Australia for LCA of buildings and homes.

SimaPro (the software selected for this study) is packaged with the Ecoinvent database which contains several thousand industrial processes including building materials, energy, transport and waste treatment (Ecoinvent, 2013) and it includes the Australasian LCI database which includes similar categories of LCI data specific to Australia – it is maintained by Tim Grant of Life Cycle Strategies Pty. Ltd. (Life Cycle Strategies, 2013). SimaPro is one of the leading, most advanced software packages for conducting LCA, used by academics and LCA practitioners.

2.4 Summary

The design response to the perceived threats of climate change, resource depletion and pollution varies greatly with radical earth-sheltered autonomous homes such as the Earthship at one end of the scale and more conventional, yet energy efficient homes, which use passive solar design at the other. The latter represent the vast majority.

While the Earthship concept offers many potential solutions, it also has challenges to overcome if it is to become more widely accepted, in particular the issue of alleged sub standard thermal performance, prompting a recommendation that "monitoring and evaluation of Earthships needs to take place more widely, to help increase understanding of how they are performing." (Hewitt & Telfer, 2012, p. 149).

A variety of studies aimed at evaluating building performance, and Earthship performance, were reviewed with a view to establishing a suitable methodology for this study. Although the methods employed by the studies tended to vary, common approaches and assumptions emerged:

- Thermal performance is a key element of POE and is often measured via monitoring indoor comfort conditions such as air temperature, globe temperature and relative humidity. Interviews of occupants are also an established means for eliciting information regarding perceptions of thermal comfort.
- Thermal modelling is a powerful tool to predict energy use for heating and cooling.
- Thermal modelling results can be calibrated to achieve greater accuracy, by using statistical analysis of monitored versus simulated results.
- EnergyPlus software is able to produce reasonably accurate results in the context of earth-sheltered homes.
- Defining the functional unit as the "whole house" of a fixed floor area and changing variables such as wall material is a common approach.
- Lifecycle impacts should not only focus on energy use but also on water use and wastewater treatment.
- Functional equivalence must be maintained when evaluating the effects of key variables, for example footing designs should be varied in accordance with variations to wall materials.
- The typical assumption for life span of the house was 50 years although this varied among studies and was often flagged as being contentious and arbitrary and driven by market forces rather than materials and construction.
- The effects of recycling materials at end-of-life can be significant.
- Some issues do not affect LCA results significantly and could be ignored, for example construction material off-cut waste and energy used in on-site construction processes.
- SimaPro LCA software and the associated databases are commonly used for this type of study.

3 Post Occupancy Evaluation

3.1 Introduction

Post Occupancy Evaluation (POE) of built Earthship homes in Taos, New Mexico, USA, has been conducted to achieve a number of aims. Firstly, it aims to investigate the claim that Earthship occupants generally experience a thermally comfortable indoor environment thus requiring little or no active heating or cooling (Earthship Biotecture, 2014a), and that indoor living spaces are not dark and gloomy, despite being earth sheltered with windows arranged on only one wall (on the sun facing side) (Anonymous, 2012; Sturges, 2011). Secondly, it aims to collect data to be used to calibrate and validate thermal simulation models of Earthship designs and analyse indoor temperature and hypothetical energy use. Thirdly, it aims to investigate the level of amenity provided by the Earthship's off-grid systems (energy, water and wastewater) compared with grid connected homes to investigate whether people living in Earthships "rough it" (go without amenities) or enjoy a similar level of amenity as people who live in conventional homes. Overall, the findings of the POE will be used to substantiate many of the assumptions in the Life Cycle Assessment (LCA).

Three sub-studies have been designed to achieve the research aims of the Post Occupancy Evaluation:

1. *Earthship Occupants' Questionnaire*
2. *Earthship Comfort Levels*
3. *Earthship Daily Comfort*

This Chapter documents these studies, each with a section explaining a detailed account of the method, results, discussion and summary. The Chapter concludes with a discussion of the overall findings from the POE.

3.2 Earthship Occupants' Questionnaire Study

This study was designed to gather information regarding a wide range of topics. An online questionnaire titled Earthship Occupants' Questionnaire was developed to gather information regarding the following topics (refer to Appendix C, for a copy of the questionnaire).

- The general location of the Earthship to establish climate type;
- Design aspects including: construction materials for walls, roof and floor, greenhouse design (integral or separable), renewable energy system, water supply, wastewater system, and toilet;
- Comfort related aspects including: how heating and cooling is achieved, how comfortable the occupants feel during the main seasons, natural lighting, air quality, and sound quality;
- Maintenance, running costs and insurance;
- Performance and basic specifications of off-grid systems;
- Lifestyle and behaviour which relates to energy use, water use, dealing with household waste, and self-sufficiency initiatives;
- Motivation for living in an Earthship; and

- Basic details regarding occupants such as number of adults and children.

Where possible an interview was conducted using the questionnaire as the basis. This ensured that key questions were answered while allowing the interviewee to elaborate on issues important to them and to discuss issues outside the scope of the questionnaire. The interview was conducted during the field trip to Taos in December 2011.

3.2.1 Earthship Occupants' Questionnaire Results

A list of Earthship occupants from around the world was created by a) searching the internet for anyone claiming to live in an Earthship, b) via an email distributed by Earthship Biotecture, and c) via an advertisement on the Earthship Biotecture website. Anyone claiming to live in an Earthship was invited to participate in the online survey. There were 43 responses, however only 16 responses were analysed due to many respondents failing to substantially complete the questionnaire.

Of the responses analysed some indicated that their homes did not have all the Earthship features, but they still identified themselves as "Earthship" occupants, perhaps due to the self-sufficient nature of their home or the construction method – these responses have been identified in the results to distinguish from the genuine Earthships.

Where the number of responses does not add up to 16 it is because respondents were able to select multiple responses to a question. A summary of key data is included in Appendix C.

3.2.1.1 Location & Occupancy

Out of the 16 responses, twelve responses were from the USA including three from Taos, one response was from Australia, one from Spain, one from Canada, and one from New Zealand. The Earthships were inhabited by up to four people (two adults and two children) over a period of up to 18 years. The average duration (age of Earthship) was 6.3 years and the average occupancy rate was 2.5 people.

3.2.1.2 Design aspects

External Wall Materials

Eleven questions were aimed at understanding design aspects of the Earthship homes including wall, roof and floor materials, and floor area of the living space and greenhouse. All but one of the "Earthships" had external walls made from tyres filled with compacted earth – the other one used bales of tyres.

The majority of responses indicated that they used manual techniques to ram the tyres with earth however, three reported using a combination of machines and manual techniques and one reported using a machine only.

Eleven reported building their tyre wall on "natural" uncompacted earth with no footings, one used a gravel filled trench as the only footing and three used reinforced concrete footings.

Four reported not having an earth berm, and six reported use of insulation within the berm.

Internal Wall Materials

Nine Earthships used aluminium cans for internal walls, five used glass bottles, five used tyres, three used rammed earth, two used light earth (clay and straw), and eight Earthships used dry wall timber frame (stud wall).

The Earthship Biotecture designs typically use aluminium cans and or glass bottles in a cement mortar for internal wall construction however these results indicate that people are experimenting with other ways, especially the conventional "dry wall" system (plasterboard on timber frame).

Roofing Materials

All roof frames/trusses of these Earthships were made with timber, with one “vaulted dome” (presumably ferro-cement), and the majority were clad with steel sheet-metal panels.

Floor Materials and Area

Seven were reinforced concrete, 6 unreinforced concrete, 2 flagstone, 1 mud, and 1 brick. The floor area of the main living space ranged from 70 to 275m^2 (average of 154m^2) and the greenhouse floor area ranged from 19 to 121m^2 (average of 47m^2).

3.2.1.3 Comfort

Thermal Performance

A question soliciting the occupants’ comfort evaluations was contained in the survey: “On the whole, how would you describe the conditions in your house during the following times of the year and time of day? (click the button that best corresponds to your perceptions)”. Respondents could select from a seven point scale from “Very Comfortable” (1) to “Neutral” (4) to “Very Uncomfortable” (7) for four times of year: “Winter during nighttime”, “Winter during daytime”, “Summer during nighttime” and “Summer during daytime”.

A similar question regarding the local climate was also included, “On the whole, do you like or dislike the climate where your house is located? Please try to explain why.” Respondents could select from a seven point scale from “Like very much” (1) to “Neutral” (4) to “Dislike very much” (7).

The results indicate comfortable conditions are experienced by the occupants most of the time. During winter nighttime two out of 16 respondents rated their Earthship as a 5 indicating slight discomfort and one as “neutral” (4), while the remaining 13 reporting comfort (scores of 1-3) of various levels (average score was 2.3). During summer daytime there was one “neutral” response and one slight discomfort response (average score was 2.1). For the remaining two times all responses indicated comfort with many “very comfortable” (1) ratings: the average score for winter daytime was 1.3 and summer nighttime was 1.4).

Regarding the respondent’s feeling about the climate they lived in, with the exception of one respondent who was “neutral”, all were reporting “like” responses (average score was 1.8).

Thirteen out of 18 responses indicated that they burnt wood to keep warm in the winter, but usually only when there were overcast conditions, for example:

> *“We burn wood only during cold cloudy weather. When it is sunny, it is almost too hot inside.” Taos NM*

While burning wood in cold cloudy weather may sound obvious and consistent with the operation of non-Earthship homes in cold cloudy climates, it should be noted that Taos is extremely cold during winter (minus 20 is not uncommon) and during sunny winter weather it is “almost too hot” indicating the powerful energy capture potential of the greenhouse and energy storage of the thermal mass construction.

Humidity

The following questions were used to investigate the occupant's responses to humidity levels:

“How would you describe the humidity in your Earthship for each season of the year?” Responses could be made on a 7 point scale: “Too dry” (1), “Comfortable” (4), “Too moist” (7) for: “Summer”, “fall”, “winter” and “spring”. A further question was asked: “Do you have any problems with mould growing in the house (due to excessive humidity)?” Responses could be made on a 7 point scale: “Lots of mould” (1), “some patches of mould” (4) “no mould” (7).

The majority of respondents reported “comfortable” humidity conditions in all seasons: in autumn (fall) the average score was 4.0; winter, 4.4; spring, 4.3; and summer, 4.1. Three of the responses indicated conditions were somewhat humid in summer, one in autumn, four in winter and three in spring. In summer two responses were slightly dry (score of 3) and in autumn there was one slightly dry (3) response.

Eight out of 16 respondents reported "no mould" and 5 reported some patches of mould. No one reported "lots of mould" (and there were no scores lower than 4). The average score was 5.8.

Lighting, Air & Sound Quality

Seven questions were aimed at evaluating lighting, air and sound quality in the Earthship. A seven point scale was used to respond to the questions: Strongly agree (1), agree (2), slightly agree (3), neutral (4), slightly disagree (5), disagree (6), strongly disagree (7).

The questions and average response scores were:

"On clear days I don't need to use artificial lighting" - 1.2 (strongly agree)

"On overcast days I always use artificial lighting" - 5.3 (slightly disagree)

"During the night my lighting system provides adequate illumination" - 1.2 (strongly agree)

"There is no smell of car tires in or around my Earthship" - 1.2 (strongly agree)(Note: American spelling of tyres used intentionally)

"The air inside my Earthship feels and smells fresh" - 1.4 (strongly agree/agree)

"There is no echo inside my Earthship" - 1.2 (strongly agree)

"Our Earthship is well insulated from outside noise" - 1.3 (strongly agree/agree)

The responses indicated that during daytime the Earthships did not require artificial lighting although overcast conditions may necessitate some extra lighting. At nighttime the off-grid systems were able to provide adequate lighting levels.

There was no indication of problems with tyre smells. Only one respondent disagreed about a fresh smell in their Earthship and this was due to the indoor greywater system not functioning properly: *"grey water digester needs a better design to reduce mold and odors. Greywater is smelly and needs some way to aerate and freshen the water. Slight moldy smell when you enter home."* Compounding this problem was the occupant's inability to isolate the smells from the greywater system as there was no glazed partition wall to segregate the greenhouse and greywater planter away from the living space in this particular Earthship. Only one person disagreed with the statement "There is no echo inside my Earthship" with the remainder of respondents strongly agreeing or agreeing with this statement. There was universal agreement with the statement "Our Earthship is well insulated from outside noise".

Earthship Operation

In response to the question, "Please try to estimate how many minutes per day you spend 'sailing' your Earthship to ensure that it doesn't get too hot inside", the average response was 8.8 minutes per day to take actions such as "put down awnings", "make sure all skylights and doors and windows are open", "vent greenhouse while keeping inner rooms closed". In contrast, one respondent in Colorado reported zero minutes for actions to prevent overheating and commented *"Summer settings are pretty much static, i.e. all screened windows open, all the time."*

A similar question regarding actions taken to prevent the indoor temperature getting too cold in the winter indicated that many Earthship dwellers use slow combustion heaters to provide backup heating especially in cloudy weather. The average time was 26 minutes per day for building and tending the fire however this included one estimate that was 4 hours per day which was far in excess of the other estimates which were in the range of 5 to 30 minutes. Discounting the 4 hour estimate the average time spent "sailing" the Earthship in winter was 13 minutes per day.

3.2.1.4 Maintenance, running costs and insurance

Respondents were asked to estimate their annual bills for gas, electricity, water and sewage, to estimate the rate of replacement of major components of their off-grid systems and to rate their experience with obtaining insurance for their Earthship. All responses were converted to US dollars using conversion rates of 0.97, 1.28, 0.98, and 1.21 for Australian, Spanish, Canadian and New Zealand currencies respectively.

The responses for electricity bills included four grid connected systems. Seven responses reported zero electricity bill, US$485 per year for electricity was reported by one Earthship owner, presumably for fuel for the 2.5kW generator which was used when solar power was not available, and a US$1000 electricity bill per year was due to “no solar panels” and grid connection. Four other responses ranged between US$1 and US$150 per year; however, it was not clear what these electricity expenses were as they were for off-grid systems. Based on the data the average annual bills were US$233 for electricity, US$185 for gas, US$31 for water, and US$1.6 for sewer. Despite the fact that some of the Earthships were connected to utility systems and/or a generator, this was atypical, and the low utilities bills reflect the substantial level of autonomy and the inherent efficiency of the Earthship design.

Respondents reported that maintenance to the external envelope was minimal with maintenance tasks such as repairing window caulking and oiling external timbers being the most common.

Estimates regarding rates of replacement of system components were:

- Water filters – responses ranged from 6 months to 20 years. The average was 3.8 years.
- Pumps – responses ranged from 5 to 20 years. The average response was 10.1 years.
- Inverter – responses ranged from 5 to 40 years. The average response was 18.1 years.
- Battery charger – responses ranged from 5 to 40 years. The average response was 20 years.
- Batteries – responses ranged from 5 to 20 years. The average response was 13.8 years.
- Solar Panels – responses ranged from 10 to 40 years. The average response was 30.7 years.

These responses revealed a wide range of estimates regarding predicted replacement rates. Various factors would drive actual replacement rates of the system components such as adherence to the manufacturer’s use and maintenance specifications, climate, and quality of the components; therefore, these estimates were used as a guide only and assumptions made in the LCA regarding system component life expectancy were estimated based on manufacturers’ claims or took a conservative estimate (more frequent than the average response) as documented in Chapter 6, Table 6.40.

Eleven out of 18 respondents indicated that their Earthship was insured and on a seven point scale from “difficult” (1) to “average” (4) to “easy” (7), six reported a “difficult” rating, two gave an “average” rating and two gave an “easy” rating (average score 3.7), indicating that it is often possible to obtain insurance. This result helped legitimise the functional equivalency of the Earthship with “conventional” homes adding credibility to the comparative LCA study.

3.2.1.5 Performance and basic specifications of off-grid systems

A question was asked in relation to the renewable energy system, water collection and storage system, hot water system, and wastewater system: “How does the performance of your Earthship systems compare with the performance of conventional systems? Think about how effective they are at providing you with what you need - enough power, water and sewage treatment. And remember, conventional systems can sometimes let you down too (blackouts, water shortages etc). Please try to explain your answer.”

There was a five point scale for responses: “Much better than a conventional system” (1), to “a little better...” (2), “about the same as...” (3), “a little worse than...” (4), to “much worse than a conventional system” (5). Respondents were also able to leave a comment.

The average scores of the responses were “a little better” for all systems: 1.8 for the renewable energy system, 1.9 for the water collection and storage system, 2.1 for the hot water system, 1.8 for the wastewater system. These responses indicate that, in the eyes of the occupants, the Earthships' systems perform well compared to conventional grid connected utilities systems.

Some anecdotes from the respondents are presented below to give an insight into the realities of off-grid systems. In general, the comments indicate that people enjoy their off-grid lifestyle, although they have to be aware of the limits of their systems, modify their behaviour to suit weather conditions, and attend to maintenance of the system.

Comments regarding electricity system

Occupants of Earthships indicated that having their own off-grid system gave much benefit over relying on the mains electricity.

> *“Electricity- Our first winter here, the gas lines in Taos broke during the coldest recorded time in the history of this place. The residents went out and bought space heaters which put the grid down for them (blackouts). People were going into their cars for heat. They also had no water, as pipes froze. Our grid never goes down, although we do have to manage our use of our big ass television during the cloudy days of winter.”Taos USA*

> *“Requires more maintenance (water in batteries, watching battery voltage level), but when storms blackout rural electric grids, I still have power.” Colorado USA*

> *“WE have to be much more concious (sic) of our energy useage (sic) and the amount of power that individual items use but we have never had a blackout.” Australia*

> *“never out of power. self-reliant.” Taos USA*

However, they also indicated that they had to maintain the system and adjust their behaviour for the system to work sufficiently,

> *“Electrical system has been nearly perfect, no failures, replaced low-end golf cart batteries at 7 years” New Mexico, USA*

> *“Owning the maintenance of the system means that I have to do occasional “controlled black-outs” with no back-up grid to cover.” Colorado USA*

> *“I time when I do things relative to the sun coming in. laundry, dishwasher, power tools, etc.” Taos USA*

Comments regarding water system

Most occupants of Earthship indicated the health benefits associated with collecting and using rain water; however, they also emphasised that regular maintenance would always be required.

> *“We get our water from the sky, although during drought we have used the community well. We don't like or want the chemicals that are put into the common water supply- so if we have less water than those who are on the grid, it is ok with us; we feel we have safe, healthy drinking water. Sewage- we have a septic tank and overflow catchment which can feed fruit/nut trees and bushes.” Taos USA*

> *“Dry years require water trucks to top off cisterns once or twice per year. Filters and maintenance is more costly and not as reliable as city water. BUT our water doesn't come from aquafirs (sic) or resevíors (sic)!” Colorado USA*

> *“Requires maintenance of changing water filter, replacing booster pumps.....but my water is excellent and without chlorine! yeah!!” Colorado USA*

> *“it's free. it's clean. it rains torrentially here a couple of times a year and we have 36 thousand litres storage which is more than enough for us.” Spain*

> *"The biggest gripe we have about water is the drought. But beyond this, maintaining the filters (cleaning them) is a repetitive task. This is a dry, dusty, windy place and we have not figured out how to collect water with less dirt in it." Taos USA*
>
> *"Only ran out of water twice. Fairly inexpensive to refill ($150 for 2,500 gallons)." Taos USA*
>
> *"old scupper water collection system is problematic and requires cleaning several times per year. Covered gutters would help. Filters must be cleaned. Sureflo DC pumps must be rebuilt about ever (sic) 3 years of use." New Mexico USA*

Comments regarding the solar hot water system

Occupants of Earthships indicated that a backup system to boost the solar hot water was important for times when there wasn't much sunshine, and that they derived pleasure from knowing that their hot water was being generated by renewable energy.

> *"we haven't installed a backup system so if there is no sun we have no hot water - we are planning to get a back up gas heater this year." Spain*
>
> *"We have a solar water heater (no propane back up) so, if we have 3 cloudy days in a row, on the 3rd day the hot water is gone and we have to use the stove to heat up water. This happens less than 5x a year, so we don't need to change that." Taos USA*
>
> *"I would say it is a little better than a conventional system because when I am enjoying my tub filled with water heated by the sun I can completely relax knowing that the way I am getting this pleasure has no part in the destruction/poisoning of our world. The hot water is very, very hot." Taos USA*

Comments regarding wastewater system

Earthship Occupants indicated that although there were minor inconveniences and annoyances with the wastewater system (such as having a stained toilet bowl from flushing with treated greywater) it was overall a beneficial system that provided an opportunity to grow food, and it provided useful shading for the living spaces due to the plants that grow in the indoor planter.

> *"the plus side is the garden the downside is the toilet gets dirtier using grey water than it would with clean drinking water but this is niggling." Spain*
>
> *"We love our grey water and black water! The system works very well. Flushing the toilet with grey water results in a toilet that either needs cleaned (sic) every day or residents who understand that toilet bowls for systems which use grey water to flush should not be white. It does not smell bad, but it stains. All in all, our 'waste' water is an extremely valuable resource." Taos USA*
>
> *"We have to be careful what goes into the Wastewater system but otherwise really can see no difference." Australia*
>
> *"always works. contained, clean. self-reliant." Taos USA*
>
> *"Also our system provides us with grey water and black water (overflow catchment off the septic) which is as useful to us as our drinking water- we have the healthiest plants... the best tomatoes." Taos USA*
>
> *"We actually grow food in our greenhouse. And the angle of the sun in the summer means it doesn't come so far into the house so we don't use much shading for our front face." Taos USA*

Toilet

The questionnaire did not ask respondents to rate their toilet however they were asked what type of toilet they had and to mention any issues.

Four out of 16 respondents had toilets that flush with greywater, eight used fresh water, and four used composting toilets.

Laundry

Two questions were asked about laundry facilities:

"Do you have laundry facilities in your Earthship or do you use a Laundromat?" and "How do you dry clothes?" Fifteen out of 16 had laundry facilities, while one used the Laundromat. Two used an electric dryer, 4 used a gas dryer, 9 used an indoor clothes line and 11 used an outdoor clothes line.

3.2.1.6 Lifestyle and Behaviour

Behaviour

Participants were asked to indicate the extent to which they agreed or disagreed with various statements regarding lifestyle and behaviour on a seven point scale: Strongly Agree (1), Agree (2), Slightly Agree (3), Neutral (4), Slightly Disagree (5), Disagree (6), Strongly Disagree (7).

The key findings for each statement are tabled below.

Table 3.1 - Questionnaire Results: Behaviour change

Statement in Questionnaire	Response/Result
"For high energy activities such as clothes washing I wait for days when my renewable energy system will be working well."	Average result was 2.8 (slightly agree) of 16 responses. Two people disagreed.
"I don't mind having to wait for suitable weather conditions to do high energy activities such as clothes washing."	Average results was 1.7 (agree) of 14 responses. No one disagreed.
"I am diligent about turning off appliances when they are not in use."	Average result was 1.6 (agree) of 16 responses. One person disagreed.
"I am diligent about turning off lights when they are not in use."	Average result was 1.9 (agree) of 16 responses. Two people disagreed.
"I bathe everyday whether I need to or not."	Average result was 4.3 (neutral/slightly disagree) of 16 responses. 9 were in the disagree range (5-7) although 4 strongly agreed.
"I have water efficient spouts and shower roses."	Average result was 2.5 (agree/slightly agree) of 16 responses. 3 people disagreed.
"I have designed my garden to be water efficient."	Average result was 2.5 (agree/slightly agree) of 16 responses. 2 people disagreed.
"I bathe more frequently than I would in a "normal" home because I know the water is recycled for toilet flushing and irrigation."	Average result 5.9 (disagree) of 16 responses. Only one person agreed.
"Approximately what percentage of your food do you produce using your recycled wastewater i.e. in your greenhouse or the blackwater planter?"	Average result 12%. Responses were 0% (6 responses), 3% (1), 5% (3), 10% (2), 15% (1), 30% (2) and 80% (1).

The results indicate that the majority of people have willingly adapted their behaviour to suit the limits imposed by their Earthship, for example, by planning electricity intensive activities around weather conditions. They also make efforts to reduce resource use by switching off lights and appliances and using water efficient water fixtures.

Lifestyle
To compare perceptions of the Earthship lifestyle to a conventional lifestyle the following question was asked:

"Compared to conventional housing, your Earthship may have enabled you to lead a very different lifestyle. Thinking about your accommodation and lifestyle prior to living in your Earthship, compared to your Earthship lifestyle right now, to what extent do you agree with the following statements";

Statements and key findings are tabled below.

Table 3.2 - Questionnaire Results: Lifestyle

Statement in Questionnaire	Result
The temperatures in my Earthship are MORE COMFORTABLE than my previous home	Average result 2.2 (agree) of 16 responses. No one disagreed, however 4 were neutral.
My Earthship lifestyle is MORE EXPENSIVE than my previous lifestyle	Average result 6.4 (disagree/strongly disagree) of 16 responses. No one agreed, however one was neutral.
My Earthship lifestyle is MORE DAMAGING to the environment than my previous lifestyle	Average result 6.9 (strongly disagree) of 16 responses. No one agreed or was neutral or slightly disagreed: everyone strongly disagreed or disagreed.
My Earthship lifestyle is MORE RELAXED than my previous lifestyle	Average result 1.9 (agree) of 16 responses. No one disagreed. Two were neutral.
My Earthship lifestyle is MORE ENJOYABLE than my previous lifestyle	Average result 1.4 (strongly agree/agree) of 16 responses. No one disagreed. One was neutral.
My Earthship lifestyle is MORE HEALTHY than my previous lifestyle	Average result 1.9 (agree) of 16 responses. No one disagreed. Two were neutral.

The second and third statements were framed in the negative, eliciting "disagree" response whereas the other questions were framed in the positive eliciting "agree" responses, indicating general agreement that the Earthship lifestyle has many advantages compared to a conventional lifestyle.

3.2.1.7 Motivation for living in an Earthship

The question regarding Earthship occupants' motivation for living in an Earthship had multiple choice options and an open-ended response field. 11 out of 16 (69%) respondents cited "reduce my eco-footprint" as the motivation to live in an Earthship.

9 out of 16 (56%) respondents cited "Reduce my utility bills"

13 out of 16 (81%) cited "Become more self-sufficient"

Comments from Earthships occupants regarding their motivation for living in an Earthship revealed that they were seeking a home that provided a healthy environment that was enjoyable to live in, yet was not a burden on the environment.

> *"I continue to be struck by how little impact my earthship has on Mother Nature. That is very important to me!" Colorado USA*

> *"to be off-grid, recognize that the centralized grid is flawed, and fortunately not everyone is forced into it. The gird (sic) is much more expensive in macro and micro sense. Huge investment into nuclear hydro coal and other huge power systems, highly destructive to any local ecosystem. Micro - will be more expensive to all every day. Biggest savings is on heating and cooling. No*

Need to Heat or Cool an earthship. Its design does this effortlessly, continuously. seriously. Pragmatically, the proof is in how it actually works in use. functional." Central USA

"WE were looking for greater self sufficency (sic) in all things, food energy etc as well as a more peaceful lifestyle." Australia

"We didn't want a mortgage or to have to pay fat executives for the privilege of electricity and water. we liked the look of the earthships. We also wanted to build our home ourselves." Spain

"Health concerns- Seasonal Affective Disorder- get more sun in the winter than conventional housing... also better air quality and exposure to the sun/sky seems to make people happier and healthier." Taos USA

"I like the idea of using what the Lord gives us each day to live from." Taos USA

"For my son and to be the best example I can be for the world. to be self-reliant." Taos USA

"The overall practicality of living with the greenhouse and all that light and sun, in a home that I could build myself." Colorado USA.

3.2.1.8 Final Comments

A final open ended question concluded the questionnaire: "If there is anything else you would like to share about your Earthship experience please use the comments box below."

Responses were very positive yet often acknowledged the fundamental difference of living off-grid, for example:

"It is quite simply the best and most comfortable place I have ever lived. It requires awareness and thought - but life should."

"This life style is not for everyone but we enjoy it very much."

"I know that most people think living off grid is 'roughing it'. We feel that could not be farther from the truth. Having lived in an earthship for 2 years, we can't imagine living in any other type of home... why would we? We absolutely love it here... and after 2 years, we often still just stop and look at each other as if we won the lottery and make repeated remarks about how much we love the house, our home. It does what we think all homes should do- provide the basics- heating, cooling, food, water, energy- a connection to the earth- not separate from it- a haven, a place to rest, relax, recharge and feel protected and cared for. When you come home, do you feel the love? We do. It makes all the difference in the world."

3.2.2 Interview Results

While conducting indoor thermal monitoring of several Earthship dwellings in Taos, New Mexico, interviews were conducted with some of the residents, one adult occupant of each of the following Earthship homes (House #2, House #4, House #5, and House #6 – refer to Section 3.3 for a description of these homes). Audio was recorded, reviewed and summarised. The full summaries are contained in Appendix C and the most pertinent findings are noted below.

All houses were located in the Greater World Community and hence were totally off-grid.

3.2.2.1 House #2

The occupant of house #2 has lived all over the world in a variety of climates, prior to settling in the Greater World Community in a newly built, one bedroom Global Model Earthship.

She found the thermal comfort provided by her Earthship to be very comfortable despite having no heater or cooler. Installation of screen doors at each end of the greenhouse has helped decrease the greenhouse temperature during summer.

Running out of electricity occasionally causes her some anxiety and so she has developed some strategies such as purchasing appliances that run off propane or are hand-powered (e.g. a coffee grinder) so that she can go about her daily routine even when electricity generation is low. Her only utility bill (other than internet) is US$100 for propane and she is not concerned about regular expenses for battery maintenance, reassured by the experience of other Earthship owners that the lifespan of the batteries is approximately 20 years.

She has come close to running out of water a few times but manages this by adapting her behaviour to conserve water during times of drought, for example while washing her hands she turns off the faucet while she lathers the soap. During the wet season she can relax some of these activities and may switch to flushing the toilet with rain water rather than greywater to avoid the slightly unpleasant smell of greywater in the toilet bowl. She enjoys gardening with greywater and has learned to deal with pests by organic means.

The thermal comfort provided by the home and the beautiful scene created by the greenhouse garden and the nearby mountains bring her great joy and contentment. The self sufficient nature of the home is reassuring to her as she knows that she is not subject to the vagaries of utilities prices that are beyond her control. She has been successful with growing a variety of food producing plants as well as beautiful herbs whose fragrance wafts into the living space whenever the doors to the greenhouse are open. She is even trying to grow her own coffee and has ambitions to grow her own tobacco (or was she joking?).

The “spaceship” look of the Earthship does not worry this occupant who appreciates function over form, however she appreciates the beauty of traditional materials such as timber and adobe which are prominent inside the home which she has decorated extensively with antiquities from her travels and her own woven tapestries.

Her Earthship is unique in that she went to the trouble and expense to have it LEED certified. LEED (Leadership in Energy and Environmental Design) is an environmental performance rating scheme in the U.S. developed by the U.S. Green Building Council. This certification has enabled her to recoup various expenses relating to the house construction/fit out due to tax concessions/rebates offered to LEED certified homes.

She has also adjusted her travel behaviour. Transport is kept to a minimum by limiting trips into town to one per week.

In summary this occupant loves living in her Earthship in The Greater World community and is able to enjoy all the modern conveniences such as a washing machine, computer, refrigerator, hot water, shower, and bath yet without the utility bills and the associated environmental impacts that she perceives are associated with utilities infrastructure. She has to be a little careful with water and electricity use at times but she seems to enjoy this challenge perhaps because it is relatively easy for her to meet this challenge and because she has been a conscientious energy saver throughout her life.

3.2.2.2 House #4

The occupant of House #4 really appreciated the uplifting feeling that Earthships instilled in him, especially when compared to the “sick” building which he had previously inhabited. Although the previous building was a luxury “dream home”, after experiencing Earthships he realised that qualities such as natural light and naturally stable indoor temperatures were extremely important to his feeling of wellbeing. He quickly purchased land in the Greater World Community and built one of the first prototype Global Model Earthships.

After five years of living in an Earthship he has come to appreciate the minimal utilities bills, which is limited to a small propane bill (due to cooking appliances and solar hot water back up).

The 1000W photovoltaic system has the battery bank fully charged by 10:30am on most days so this is when he starts to undertake energy intensive activities such as clothes washing and he has asked his partner and guests to avoid the use of appliances such as hair dryers.

He does not worry about running out of water as his storage capacity (2800 gallon or 10500 L) and roof catchment area (1200 sq ft or 111 m2) is adequate to deal with six months of drought. Furthermore he has an “observation tube”, a transparent section of pipe in the house, which enables him to very conveniently monitor his water reserves.

His enthusiasm for the Earthship and the Greater World Earthship community is fuelled by a desire to secure a comfortable home for his loved ones in what he perceives to be a very uncertain future, especially in terms of energy security. He also acknowledges the isolation of the community and has set about addressing this via advanced food production systems such as aquaponics, and also intends to purchase an electric vehicle.

3.2.2.3 House #5

Compared to the draughty rental home in Albuquerque, New Mexico, USA the occupant of house #5 very much enjoys her U Module Earthship (built in the 1990s) which affords a very pleasant, low cost life style which has enabled her to “escape the rat race”.

She has become very proficient at regulating the indoor comfort conditions via “cracking” (opening slightly) the various natural ventilation features such as windows, roof vents, skylights, and door at the appropriate times of day. The slow combustion heater is only used rarely during prolonged overcast conditions. In general she finds the indoor temperature very comfortable.

The home has 3000 gallons (11,350 L) of water storage, and is very water efficient, using a waterless composting toilet located in an outhouse, dug into the side of the berm, and it has the usual Earthship greywater planter which deals with kitchen and shower wastewater.

Her electricity use is very frugal and consequently she has never run out of electricity. The photovoltaic system is only 220watts although this is augmented by a small wind turbine. She manually adjusts the angle and direction of the PV panels, which are mounted on a tracking frame, to optimise their energy output.

Transport is limited to about three trips to town per week in her car; however, she would prefer an efficient public transport system rather than having to own a car.

She finds her Earthship lifestyle very relaxing and appreciates living in a community nearby people who can help her out with maintenance of her home.

3.2.2.4 House #6

Prior to living in an Earthship in the Greater World Earthship Community, the occupant in House #6 grew up in an old three story home built in approximately 1910. It had no insulation, a steam radiator and was either too hot or too cold. She also spent time in a conventional home in Seattle before starting her Earthship adventure in 2001 with her husband. They built an Earthship based on the “Packaged” Earthship design by Reynolds which features vertical glazing and an integrated greenhouse.

While the family generally enjoys a good level of thermal comfort, she mentioned that there are various micro climates in her home, such as the corridor which is a bit cold, probably due to it connecting with the unusual northern entry through the berm. A gas heater has been installed for space heating although this is very rarely used.

Their solar hot water service has no boost capability e.g. by propane; however they rarely run out of hot water due to the abundant sunshine, despite being a family of two adults and two children.

The greywater system works well with the exception that the treated greywater used for toilet flushing often has a sulphurous smell, and therefore they sometimes use rainwater for toilet flushing, and they have also experimented with using hydrogen peroxide to neutralise the chemicals which causes the offensive smell.

They have 3500 gallons (13,250 L) of water storage which, due to the size of the family, occasionally runs out by the end of the dry season necessitating a water delivery.

Their electricity system provides for all their needs although they have to avoid energy use as much as possible during the infrequent overcast conditions. The system is relatively small compared to typical Australian systems at only 405W. Recently they had to purchase a new battery bank at a cost of approximately US$1,000 which they expect to be necessary roughly every five years.

The issue of transport is managed by car pooling with other community members, although there is little else that can be done to avoid many car trips due to the need to transport children to and from school: a school within the community would be great.

Reflecting on her experience as an architect, she laments that "people aren't ready for it", referring to the Earthship's radical methods such as building with tyres and indoor greywater systems, but in conclusion she says "I wish it was more mainstream".

3.2.3 Summary of Earthship Occupants' Questionnaire Study

The Earthship Occupants' Questionnaire study gathered information regarding a range of Earthship design and lifestyle issues from sixteen Earthship occupants from five different countries.

The study found that the majority of Earthships were off-grid, and that these off-grid systems perform to a high standard although there may be maintenance issues that must be attended to for the systems to work reliably, or limitations about how the system can be used. For example the wastewater system may be susceptible to poisonous cleaning chemicals, and the use of appliances may need to be delayed until there is sufficient sunshine. These issues seem to be tolerated, as the trade off is better quality, such as water with no chemicals (such as chlorine and fluoride), better reliability, for example, no electricity outages, and better efficiency such as the use of wastewater for irrigation. Furthermore, economic advantages were indicated by the utilities bills estimates (although this did not factor in replacement of system components) and by the response to the question regarding the expense of the Earthship lifestyle which overwhelmingly indicated a less expensive lifestyle. It was found that Earthship occupants living in a variety of climates report a high degree of thermal comfort. They reported being more happy and relaxed and that they enjoyed their lifestyles more, and they thought that their lifestyles were less damaging to the environment. The most common motivation for living in an Earthship was to be more self sufficient, followed by a desire to reduce their "eco-footprint" and lastly, to reduce utility bills.

Interviews of four Earthship occupants in Taos corroborated the quantitative and qualitative research studies regarding indoor comfort conditions and the amenities provided by the off-grid systems, and they also shed light on the Earthship lifestyle which was characterised by thermally comfortable conditions and adequate water and electricity supply, although this waxed and waned according to season, especially so for water. Furthermore there were minimal expenses, and an overall appreciation of the Earthship and the lifestyle it affords, despite some behaviour adaptations that were necessary.

3.3 Earthship Comfort Levels Study

This study was designed to investigate the thermal performance and illumination levels in a variety of Earthship designs in Taos, New Mexico, USA. Data were recorded in six Earthship homes and the results are presented and discussed in terms of international standards.

3.3.1 Study Design

3.3.1.1 House Selection

Earthship Biotecture identified six homes that could be used in the study based on design and the willingness of the owners to participate in the study. The homes represent a variety of designs although the more recent "Global Model" Earthship represented four out of the six. The homes are briefly described as follows;

- House #1 is a Global with two bedrooms. It was the second Global Model built at the Greater World community in Taos. At the time of installing the monitoring hardware it was a nightly rental, however it was purchased and occupied from April 2012.
- House #2 is a newly built Global Model with one bedroom, occupied by one person.
- House #3 is a newly built Global Model with one bedroom. At the time of installing the monitoring hardware it was a nightly rental, however it was purchased and occupied from approximately April 2012.
- House #4 is a Global Model with a few variations such as a higher ceiling with correspondingly higher greenhouse glazing. This home was occupied by a couple and also used as a nightly rental.
- House #5 is one of the original designs (circa 1990) which features two U modules and an integrated greenhouse (i.e. no glazed partition wall) with angled glazing. This home was occupied by one person.
- House #6 is a "Packaged" design (i.e. with vertical glazing and integrated greenhouse i.e. no glazed partition wall) and was added to later with a two storey wing made with tyres and insulated externally with polyiso rigid insulation. This home was occupied by a family of four.

These homes represent a variety of Earthship designs, ranging from the early model U module design of the 1990s, the Packaged design which features vertical glazing, through to the most recent (at the time of writing) Global Model design. The four Global Model Earthships are very similar yet each has some point of difference, be it occupancy during the monitoring period, or some slight design variation. The range of designs has enabled a comparison of performance between old and new.

All homes are located in the Greater World Earthship community, located 15 miles outside of Taos, New Mexico, USA, on 633 acres of mesa (tableland).

3.3.1.2 Monitoring Period

The data collection period was from 17 December 2011 to 31 July 2012 capturing the coldest and warmest times of the year in Taos, New Mexico, USA; however, House #1 was monitored for longer, until 5 January 2013 (the reason for this is explained in the next section).

3.3.1.3 Equipment & Data Collection

Two types of "logger" (also known as "sensor") technology were utilised in the study to measure air temperature, globe temperature, relative humidity and light level. Five houses were monitored with small, easily installed, battery operated Hobo brand loggers. One house (#1) was monitored with a system (also Hobo brand) capable of relaying data to a website so that it could be monitored remotely while the study was in progress. This system was used as a weather station recording outdoor air temperature and relative humidity data which were used for analysis of all houses due to their close proximity to each other. Images of the hardware used in the study can be found in Appendix A: "Earthship Comfort Levels Participant Information Sheet".

The indoor data loggers were located in standardised locations throughout all the Earthships to reduce variables, although this was subject to approval of occupants and in some cases alternative locations needed to be found. The following diagram (Figure 3.1) shows a typical cross section and floor plan of the monitored Earthships to illustrate the typical layout of the loggers. Specific locations of the loggers in each house is documented in Appendix C.

A logger that recorded air temperature, globe temperature (using a matt black ping pong ball as recommended by Szokolay (2008, p. 18)) and relative humidity were located at the rear of the building, offset from the tyre wall approximately 150mm, at a height of approximately 1700mm above floor level in the living space (living room or bedroom), although in House #1 this was varied to 2000mm for practical reasons. An air temperature and relative humidity logger was located in the greenhouse inside a solar radiation shield, and positioned above the planter about 600mm offset from the external glazing at 1700mm above floor level. ASHRAE Standard 55 specifies that air temperature should be measured at heights of 100mm, 1100mm and 1700mm for standing occupants ASHRAE (2013, p. 14). As multiple height measurements were beyond the scope of this study 1700mm was selected for practical reasons. This was also the height at which relative humidity and globe temperature were measured.

In three houses, light level loggers were positioned at 700mm above floor level in the living space (bedroom or living room) towards the rear, adjacent the tyre wall. The outdoor data weather station which measured air temperature (inside a solar radiation shield) and relative humidity was positioned approximately 4-5m to the rear of House #1 (on the berm) at a height of approximately 1200mm above the berm's ground level.

Data were collected at hourly intervals (on the hour) for the battery loggers, and at 5 minute intervals for the "internet" system (House #1); however, in general only hourly data, recorded on the hour, has been used for the analysis of House #1.

The battery operated data loggers were returned by post in August 2012 so that the data could be downloaded and analysed, whereas the internet connected system in House #1 remained in Taos until early 2013 so that a full year of data could be collected for at least one house. Although seven and a half months of data collection, which spanned the coldest and hottest times of year in Taos, was deemed adequate for the study (and was desirable in terms of the timeframe of the study) collecting a full year of data in House #1 enabled a more thorough analysis, including all seasons.

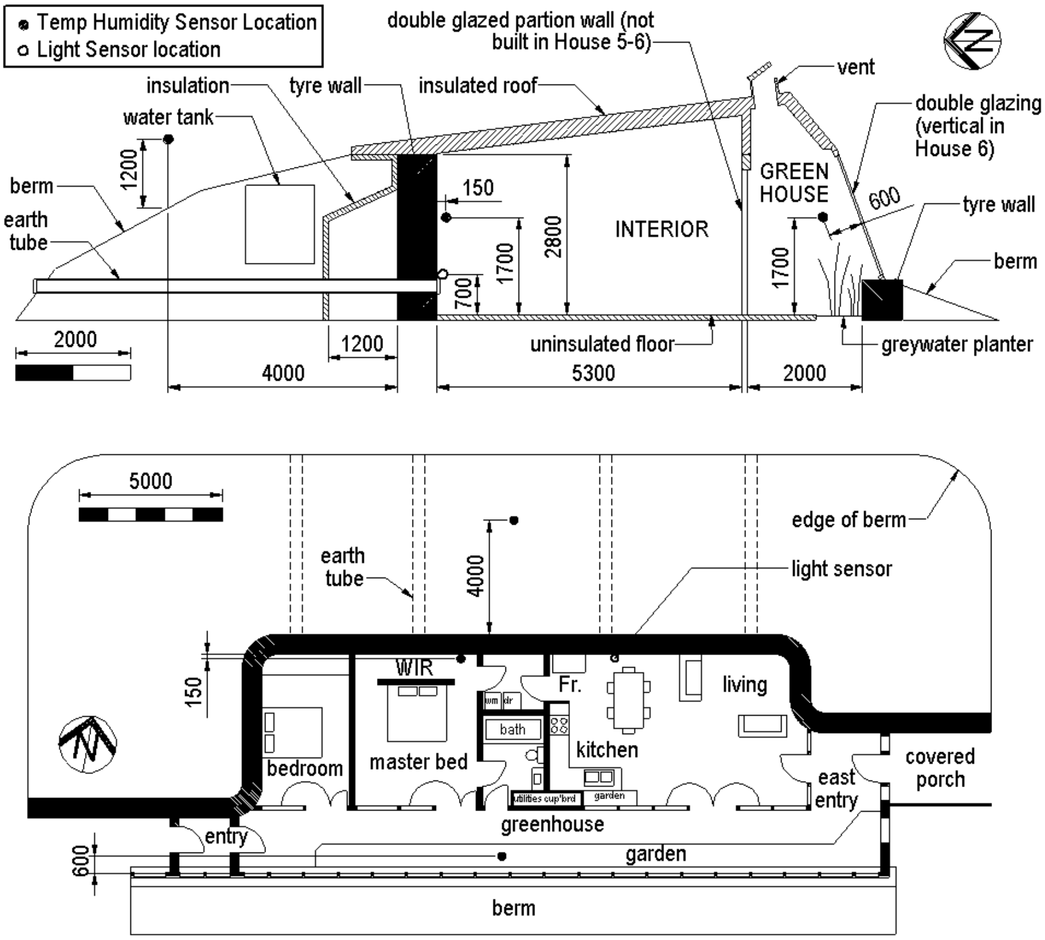

Figure 3.1 - Generic layout of loggers (sensors) in monitored Earthships (these diagrams depict a Global Model Earthship)

3.3.1.4 Limitations

There were three limitations in this monitoring study:

1. Ground temperature was not measured due to difficulty and expense. A sensor would need to be installed sub-floor necessitating building works which was beyond the scope of this study. Instead the ground temperature was predicted using software developed by Williamson (1994).
2. In relation to the previous limitation (ground temperature) soil characteristics were not known. In particular, density, conductivity, specific heat, moisture content, compaction of soil in the berm, et cetera, were all variables that had to be estimated.
3. Solar radiation was measured in the greenhouse of House #1 due to difficulties with reliably mounting the sensor outdoors (snow covering the sensor was a concern). Although these data were not particularly useful for use in the simulation study – necessitating acquisition of solar radiation data from a third party – it was useful for analysing the measured indoor temperature data.

3.3.2 Thermal Performance Results & Discussion

The analysis of the results has been approached in a variety of ways. Firstly, the performance of House #1 (which was monitored for a full year) is compared to the Adaptive Comfort Model of ASHRAE, Standard 55-2010 (ASHRAE, 2010) to establish a theoretical temperature comfort range in the Taos climate. It is acknowledged that this adaptive model of the Standard was developed from studies of office buildings; however, this research is interested in testing its applicability in residential buildings. Secondly, data from extreme weeks in winter and summer are presented and discussed for all six of the monitored Earthships in order to demonstrate their performance in extreme weather conditions. A typical week in spring is also presented to demonstrate performance in milder conditions. Thirdly, the issue of thermal lag is briefly investigated in order to better understand the rate of temperature change and compare Earthship performance with other thermal mass homes. Finally, all six Earthships are analysed in terms of the proportion of time the indoor air temperature was within various temperature bands, indicating which had the greatest thermal performance over the whole monitoring period.

Appendix C contains additional graphs displaying indoor air temperature, greenhouse air temperature, and outdoor air temperature for each house for the same weeks. This gives a clearer view of the data but does not allow for easy comparison between houses. Additional weeks are given for House #1 due to its extended monitoring period: a week in autumn and a winter week in January 2013 which included the coldest outdoor temperature during the extended monitoring period.

3.3.2.1 Adaptive Comfort Comparison – House #1

The Adaptive Comfort Model is based on the idea that humans can adapt to different temperatures as they change throughout the year and that the indoor conditions that most people find comfortable are influenced by these changing outdoor conditions.

Although the Adaptive Comfort Model (ASHRAE, 2010) is not intended to be used in climates as cold as Taos it has been used in Figure 3.2 to evaluate the average indoor and greenhouse temperatures in House #1 compared to the acceptable temperature in a naturally ventilated building as per ASHRAE Standard 55-2010, Addendum D (ASHRAE, 2012). Section 5.3 of this Standard describes a method for determining thermal conditions that would be acceptable to 80% of people in occupant-controlled naturally conditioned spaces. One of the criteria for using this method is that the prevailing mean outdoor temperature is greater than 10°C and less than 33.5°C. Unfortunately the Standard does not specify how to determine the thermal comfort range when the prevailing mean outdoor temperature is outside this range, as it is for the colder half of the year in Taos. Consequently Figure 3.2 shows the thermal comfort acceptability limits that adhere to this criterion in dark grey shaded area ("T80%adapt"); however, a light grey shaded area ("T80%extrap") has been used to indicate an extrapolation of the acceptability limits for the purposes of discussing the results of this study. This has been done by plotting the minimum and maximum limits for a 10°C mean monthly outdoor temperature for all months with mean monthly temperatures less than 10°C.

It is acknowledged that it is preferable to use the operative temperature to measure thermal comfort in buildings (ASHRAE, 2013, p. 14); however, in this study it was found for all houses monitored there was little difference between air temperature and globe temperature measurements: in the range of 0.13 to 0.22°C. In other words the air temperature closely approximated the operative temperature. Hence air temperature has been the basis for analysis in this study.

In Figure 3.2 it can be seen that the average maximum and minimum bedroom air temperature of House #1 ("TaveMaxBR" and "TaveMinBR" respectively) stayed within the acceptability limits for the months where the acceptability limits could be calculated (April to September). In the colder months, the average minimum is within the extrapolated acceptability limits although occasionally the extreme maximum ("T96%ileMaxBR") was even warmer than the comfort range despite subzero mean monthly outdoor temperature (Text). Note that there was no active heating or cooling employed in this building.

The greenhouse of House #1 had average maximums and minimums ("TaveMaxGH" and "TaveMinGH" respectively) either side of the acceptability limits indicating that it is generally not suitable for habitation (as intended by the architect); however, although the greenhouse temperature reached an average maximum that is well above the acceptability limit, the average minimum is often just within the acceptability limit indicating that there were many periods (generally each day) when the greenhouse provided thermally comfortable conditions.

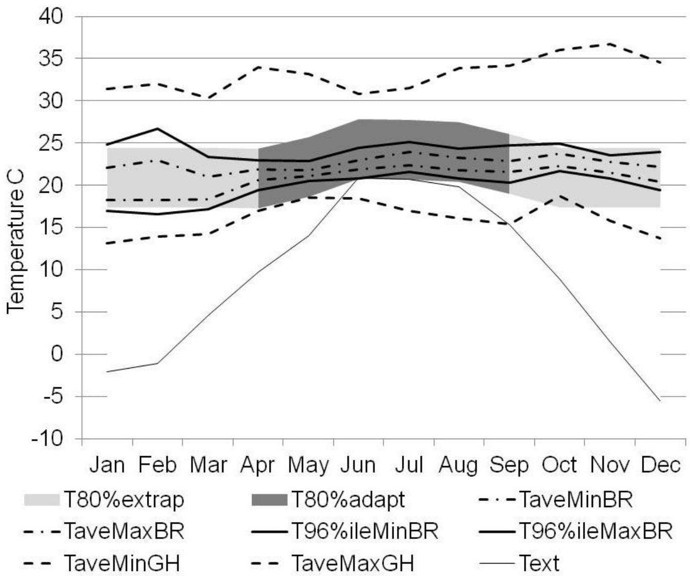

Figure 3.2 - Measured indoor temperatures in House #1 compared to acceptable adaptive temperatures

3.3.2.2 Seasonal Analysis

The measured results for indoor and greenhouse air temperatures are shown for selected weeks in winter, spring and summer for all Earthships enabling a direct comparison in Figure 3.3 to Figure 3.8. Outdoor air temperature (measured behind House #1) and solar radiation (measured inside the greenhouse of House #1) are also displayed so that the prevailing weather conditions can be understood. Peak outdoor temperature is indicated by a red circle. The winter and summer weeks were selected to represent extreme conditions when the minimum or maximum outdoor air temperature was recorded for the monitoring period. Furthermore the winter week includes a cloudy day (22 Dec 2011) to show the effect of limited solar radiation on the passive solar designed Earthship homes.

Winter Performance Discussion

In the winter, the Global Model Earthships (Houses #1-4) had the most stable and comfortable indoor temperature compared to the U module and Packaged design, although the performance of House #4 was more variable and this may have been due to occupant behaviour. House #1 and #3 were remarkably stable, their indoor temperatures ranging from approximately 18-25°C whereas House #2 was approximately 2°C cooler during the nighttime with similar daytime maximums. House #4 had similar performance on 21 December, but was consistently lower in temperature from 22-26 December, finally catching up on 27 December – possible reasons for this are now discussed.

On the first day (21 December 2011) in the winter week (Figure 3.3), all Global Model Earthships (Houses #1-4) had an indoor maximum within approximately 2°C of each other with diurnal swings of approximately 4-6°C; however, over the course of the following two days (22-23 December) the indoor air temperature nighttime minimum and daytime maximum in House #4 dropped to approximately 4°C less than the other Global Model Earthships, yet by 25 December the temperature in House #4 was restored to be within 2°C of the other Global Model Earthships and by 27 December the daytime maximum was similar to other Global Model Earthships. The temperature in the greenhouse (Figure 3.4) of House #4 followed a similar pattern and gives a clue as to what may have been causing the lower indoor air temperature in House #4. The hypothesis is that an external window (in the greenhouse) may have been inadvertently left open for a few days, starting on 23 December causing the greenhouse temperature to be less than normal. By 27 December, a few days later, House #4 had the highest greenhouse temperature indicating that there was nothing fundamentally wrong with the greenhouse of House #4 and that occupant behaviour was the likely cause of the previously recorded lower greenhouse temperatures and the concomitant lower indoor air temperature.

In House #5 (U module) the indoor diurnal air temperature range was approximately 10°C whereas in the Global Model Earthships it was approximately 4-6°C. The indoor air temperature ranged from approximately 13-26°C. In the "greenhouse" (i.e. which in the U module design is the front portion of the living space adjacent the angled greenhouse glazing) the diurnal temperature range was similar to that of the Global Model Earthships' greenhouse space (40°C).

In House #6 ("Packaged" design) the indoor air temperature was generally cooler than the other Earthships. It had a diurnal temperature swing of approximately 8°C with the temperature ranging from a minimum of approximately 10.5°C to 18.5°C. In the "greenhouse"(i.e. which in the Packaged design is the front portion of the living space adjacent the angled greenhouse glazing), the diurnal temperature range was approximately 20°C, although on the cloudy day (23 December 2011), it was approximately 6°C.

The U module (#5) and Packaged design (#6) Earthships showed greater variability in the indoor and "greenhouse" temperatures compared to the Global Model Earthships. This is most likely to be due to the Global Model's segregated greenhouse which is isolated from the main living space by a double glazed wall which is operable with various windows and doors enabling control over when living room air mixes with the greenhouse air.

In winter the "extrapolated" Adaptive Comfort Model temperature range was 17.5 to 24.5°C. As discussed in the previous section the monthly average analysis shows that House #1 remained within the comfort zone, and this is corroborated by the results of the "winter week" which show House #1 was within 18-25°C, slightly exceeding the comfort limit (by less than 1°C) for an hour in the middle of the day on 25 and 26 December 2011, despite an outdoor temperature of approximately 2°C. House #3 showed very similar results and remarkably, both House #1 and #3 were able to maintain comfort conditions despite the cloudy day and freezing (subzero) outdoor temperatures. House #2 dropped just below comfort range to approximately 16°C on two mornings although it quickly returned to comfort conditions (with the exception of the cloudy day). Likewise, House #4 dropped to approximately 13.5°C on the same two mornings but returned to comfort conditions quickly with the exception of the cloudy day. The temperature in House #5 (U module) also dropped briefly below comfort temperature in the early mornings and performed similarly to House #4 on the cloudy day. House #6 was typically well below the extrapolated comfort conditions with early morning temperatures as low as 10.5°C (although note that it was often 15 to 19°C below zero outside) with the exception of the middle of the day when comfort conditions were achieved (with the exception of the cloudy day). Erratic temperature fluctuations in House #6 on the first day of the winter week can be explained by use of a gas heater.

In summary, during this extreme winter week when outside temperatures were generally subzero, one of the Global Model Earthships (House #1) was able to stay within the "extrapolated" ASHRAE adaptive comfort limit for Taos of 17.5-24.5°C without any active heating. Another Global Model (House #3) performed similarly but slightly exceeded the maximum comfort limit for about 3 hours (during the middle of the day) – based on performance during previous days this could have been avoided by increasing the ventilation rate (it was only 5°C outside). The other Global Model Earthships had comfortable daytime temperatures but were slightly below the minimum limit in the early hours of the morning (midnight to sunrise). The U module design was very slightly above (0.5-1.0°C) comfort level during the middle of the day (on two days only) but was otherwise comfortable with the exception of the early hours of the morning from midnight to sunrise; however, the temperature near the external glazing (where the kitchen was located) was often very hot. The Packaged design was generally the coldest, only occasionally reaching comfort conditions during the middle of the day (at the rear of the living room), whereas towards the front of the living room, adjacent the glazing (i.e. the "greenhouse" area) there were slightly excessive temperatures, higher than comfort level, in the middle of the day with comfort conditions before and after, although overnight the comfort conditions are not met due to low temperatures.

The extreme diurnal temperature swing in the Global Model Earthships' greenhouses is approximately 40°C on a sunny day, demonstrating the powerful heating potential of the greenhouse. The dramatic temperature difference between the greenhouse and the living spaces, especially in the Global Model Earthships, demonstrates the efficacy of the entire building fabric at regulating the extreme energy flows to achieve comfort conditions in the living spaces. Various design features and strategies are responsible for this: correctly located thermal mass and insulation, double glazing throughout the building, ventilation of the greenhouse through high level skylights, "cracked" (slightly ajar) earth tubes to provide fresh air, and high level hopper windows to control air mixing between the greenhouse and the living spaces – the ventilation must be operated correctly by the occupants to ensure the best result. Only House #5 and #6 had heaters installed (slow combustion and gas respectively) and it appears that the gas heater was used intermittently during the first and second day of the extreme winter week in House #6.

Spring Performance Discussion

Spring-time performance is only discussed very briefly because, in general, all the Earthships were able to maintain comfort conditions during the spring week despite nighttime temperatures that were often subzero (Figure 3.5 and Figure 3.6).

In April the ASHRAE Adaptive Comfort Model indicates a comfort range of 17.3-24.3°C for the Taos climate (measured mean monthly temperature of 9.7C).

House #5 (U Module) was often slightly above (3.5°C) the upper comfort limit during the middle of the day and House #6 (Packaged design) was often slightly below (1°C) the lower comfort limit between midnight and sunrise. House #1 (Global Model) had a remarkably stable indoor temperature range, remaining between approximately 21-22°C.

Summer Performance Discussion

According to the ASHRAE Adaptive Comfort Model the comfort range in the Taos Climate during June and July (their summer) that would be acceptable to 80% of people is approximately 21-28°C (ASHRAE, 2012) based on the measured mean monthly summer temperature of 21°C.

The indoor air temperature for the summer week Figure 3.7 shows that, as for the winter week, House #1 had remarkably stable temperatures which ranged throughout the week from approximately 23-25°C

– well within the Adaptive Comfort limits, and without using any active cooling. The other Global Model Earthships performed similarly although were not as stable. For example, House #3 reached approximately 28°C on the hottest two days, and overnight dropped to 21.5°C on 23 December 2011, yet towards the end of the week it was more stable, similar to House #1. The U module design (House #5) had the hottest indoor maximum air temperatures which were above the comfort limit, especially around midday, ranging from 22-33.5°C with a typical diurnal swing of 9-12°C. The Packaged design (House #6) ranged from 21-29°C throughout the week only occasionally above the upper limit during the middle of the day.

The greenhouse temperatures (Figure 3.8) during the summer week reveal that, surprisingly, House #1 was usually cooler in the greenhouse than outside during the middle of the day. This was also the case for House #6 (Packaged design) although this is not as surprising due to the vertical glazing of the Packaged Design which admits less insolation than the angled glazing of House #1 (Global Model design). In the other Earthships, temperatures in the greenhouse during summer daytime were approximately 2-6°C warmer than outside conditions.

These findings are interesting because other studies have predicted or measured "overheating" conditions in Earthships (Hewitt & Telfer, 2012; Ip & Miller, 2009), whereas these data indicate that the Global Model Earthship is capable of maintaining a comfortable temperature in the living space and that the temperature in the greenhouse is cooler than outside during the middle of the day when it would be expected to be hottest. This may be due to the cooling effect of the earth tubes and or due to evapotranspiration of the plants in the greenhouse. In the U module Earthship the temperature fluctuated quite significantly and extended well above the adaptive comfort limit (28°C) for this time of year. This is consistent with the results of a previous study in which overheating was predicted for a similar Earthship design (Grindley & Hutchinson, 1996).

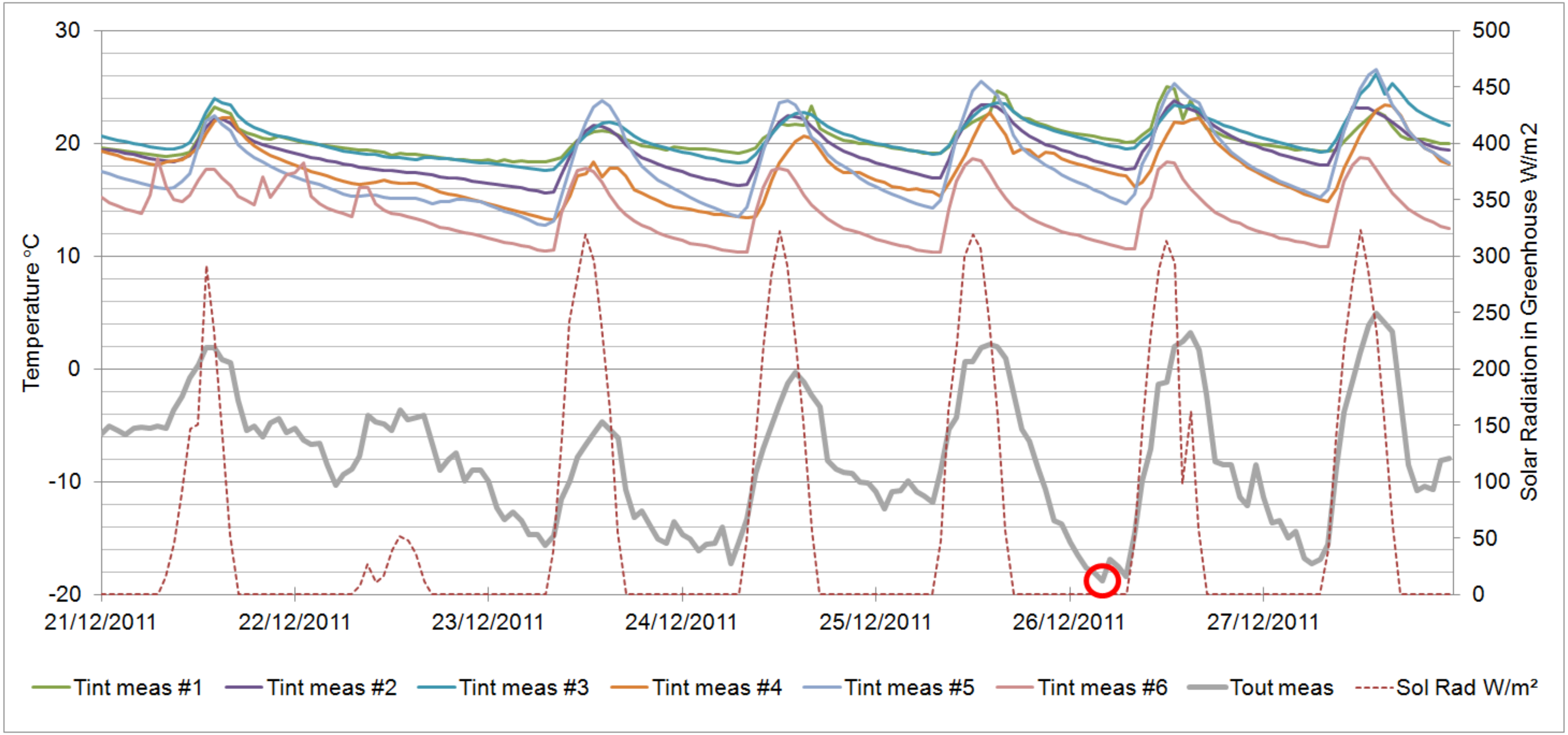

Figure 3.3 - Indoor air temperature, all houses, during winter week with coldest outdoor temperature

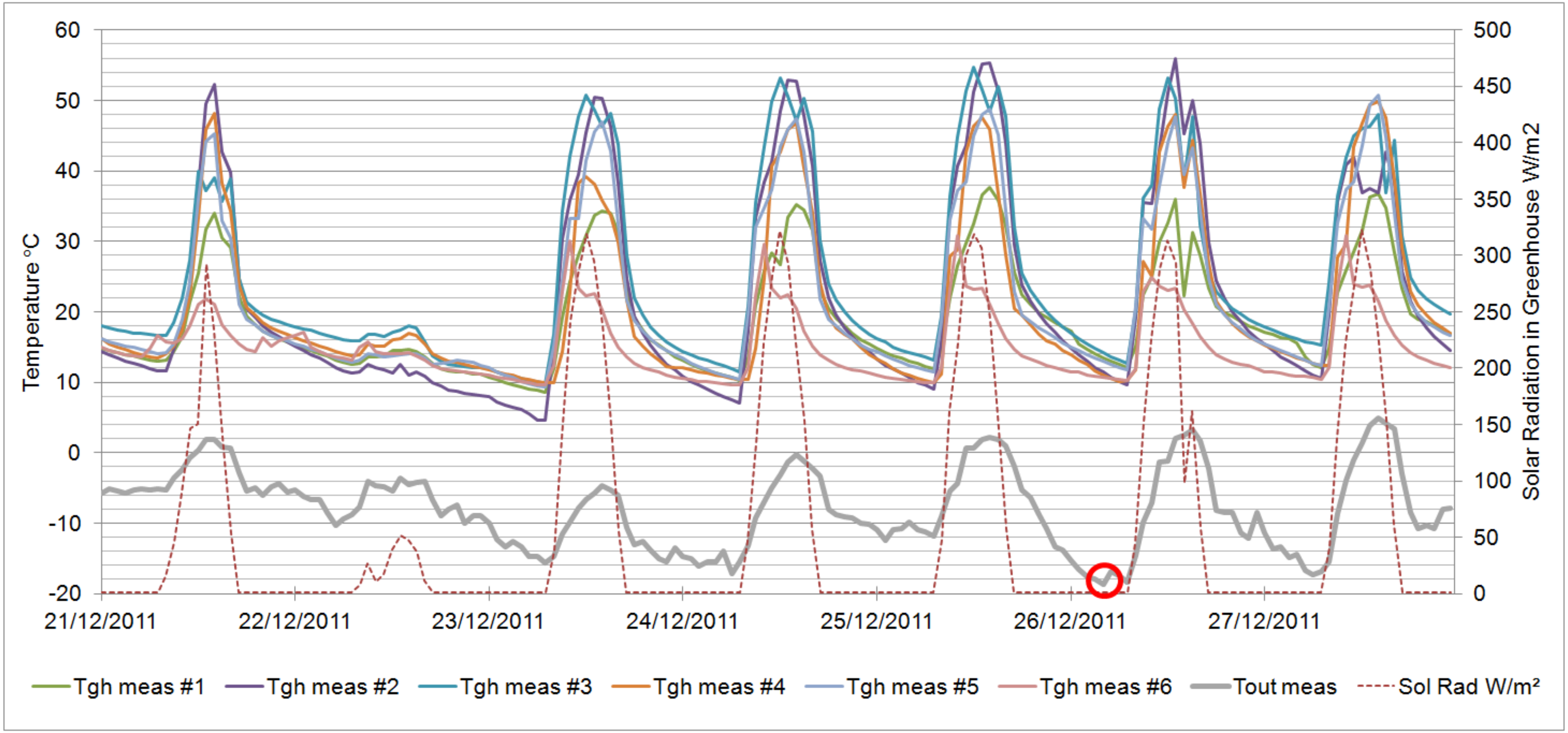

Figure 3.4 - Greenhouse air temperature, all houses, during winter week with coldest outdoor temperature

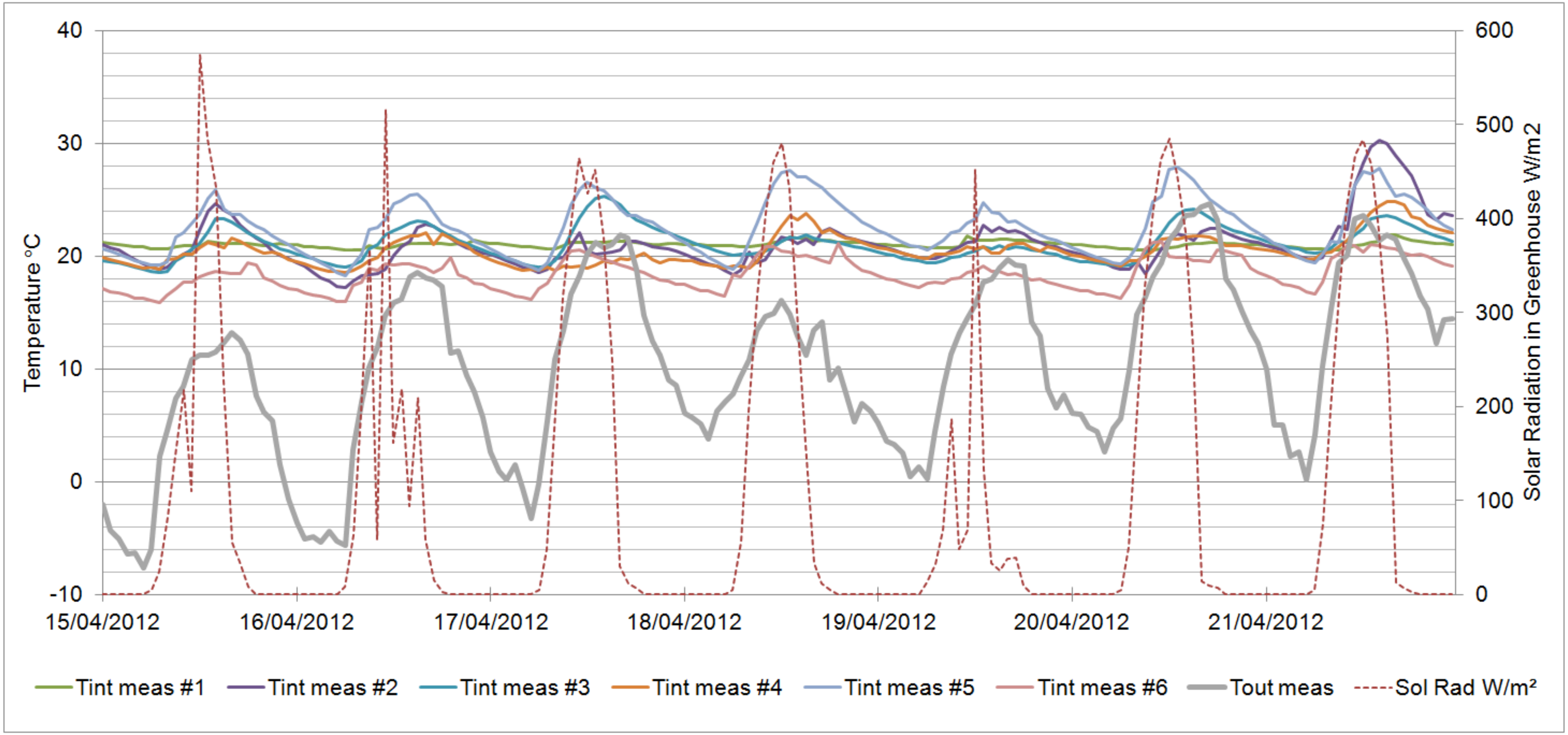

Figure 3.5 - Indoor air temperature, all houses, during typical spring week

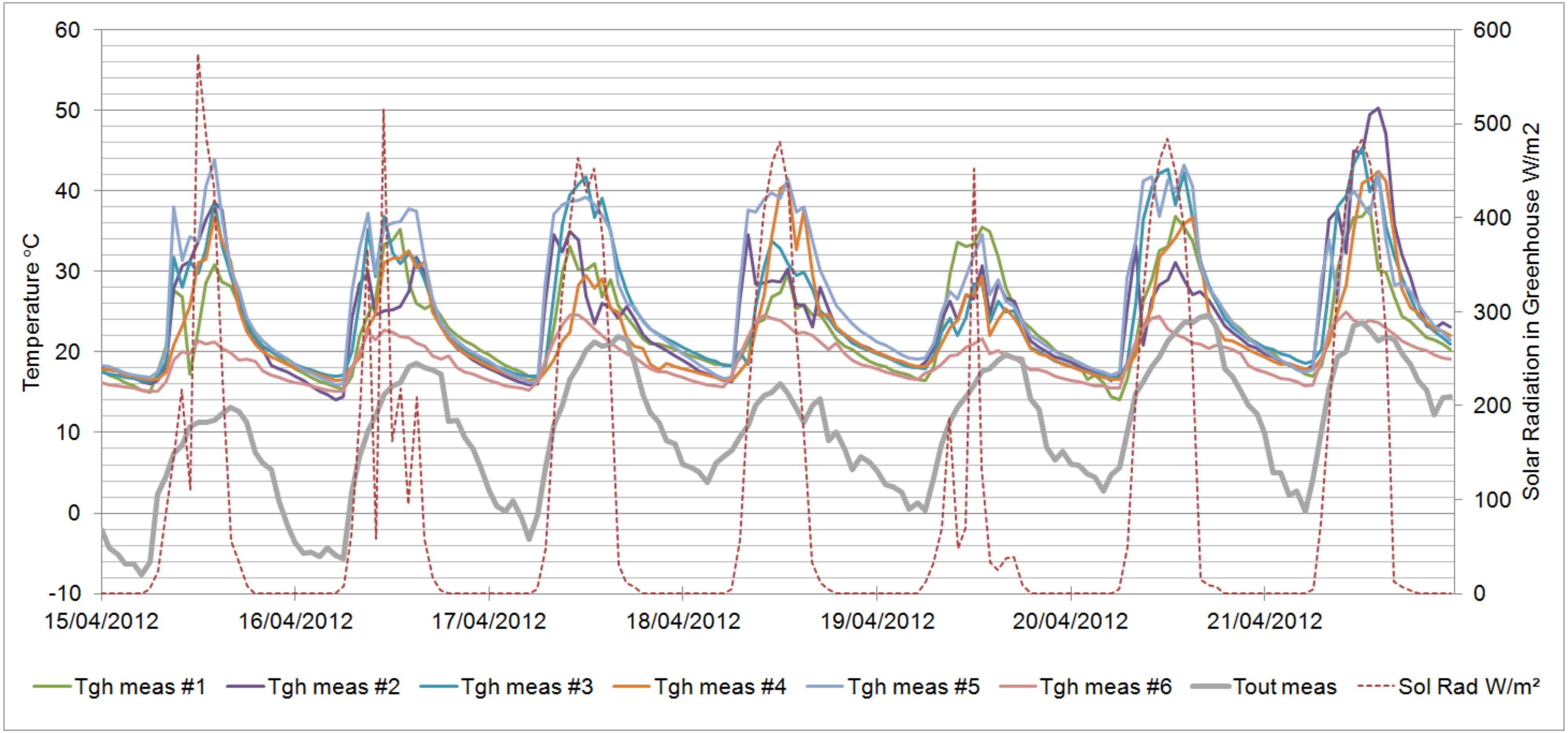

Figure 3.6 - Greenhouse air temperature, all houses, during typical spring week

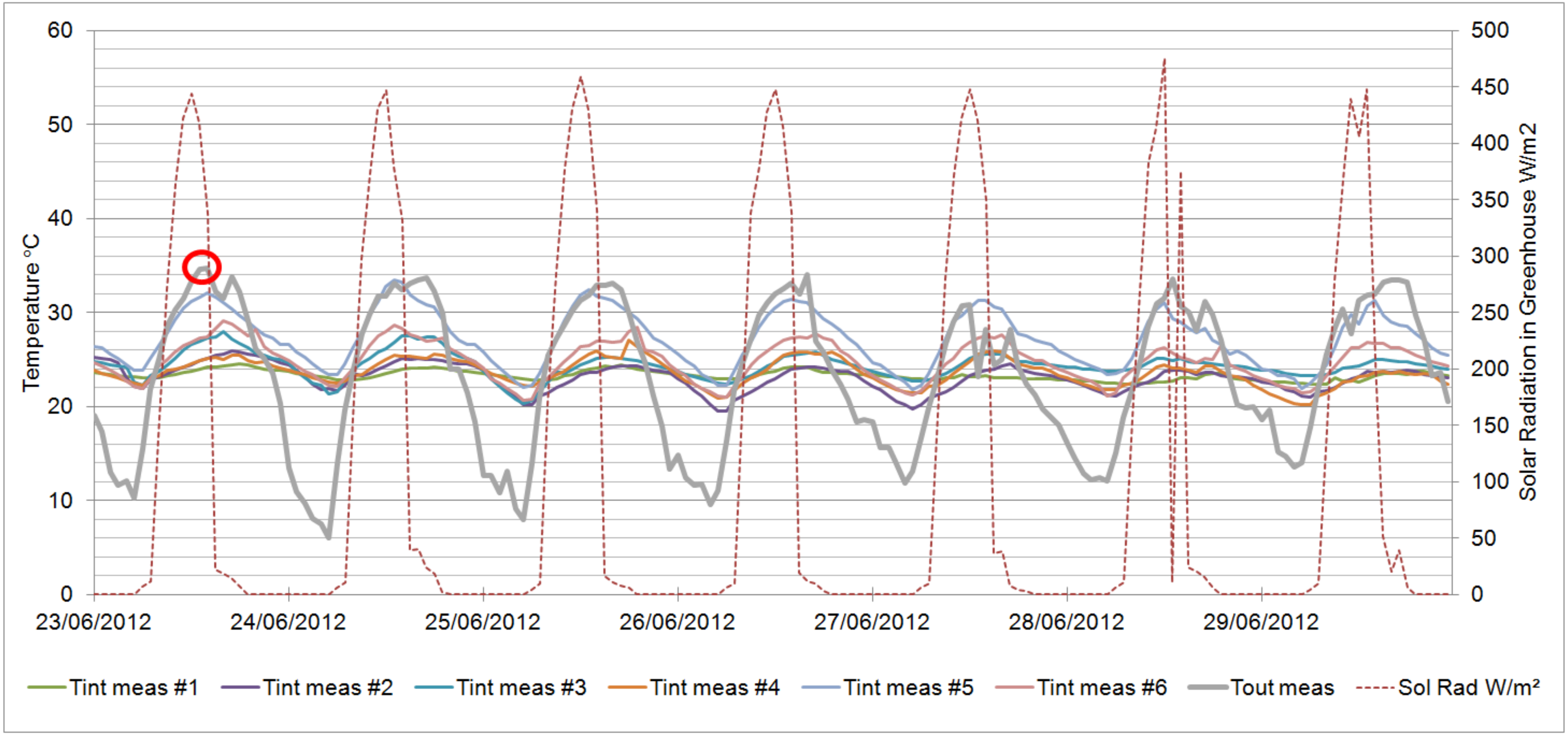

Figure 3.7 - Indoor air temperature, all houses, during summer week with hottest outdoor temperature

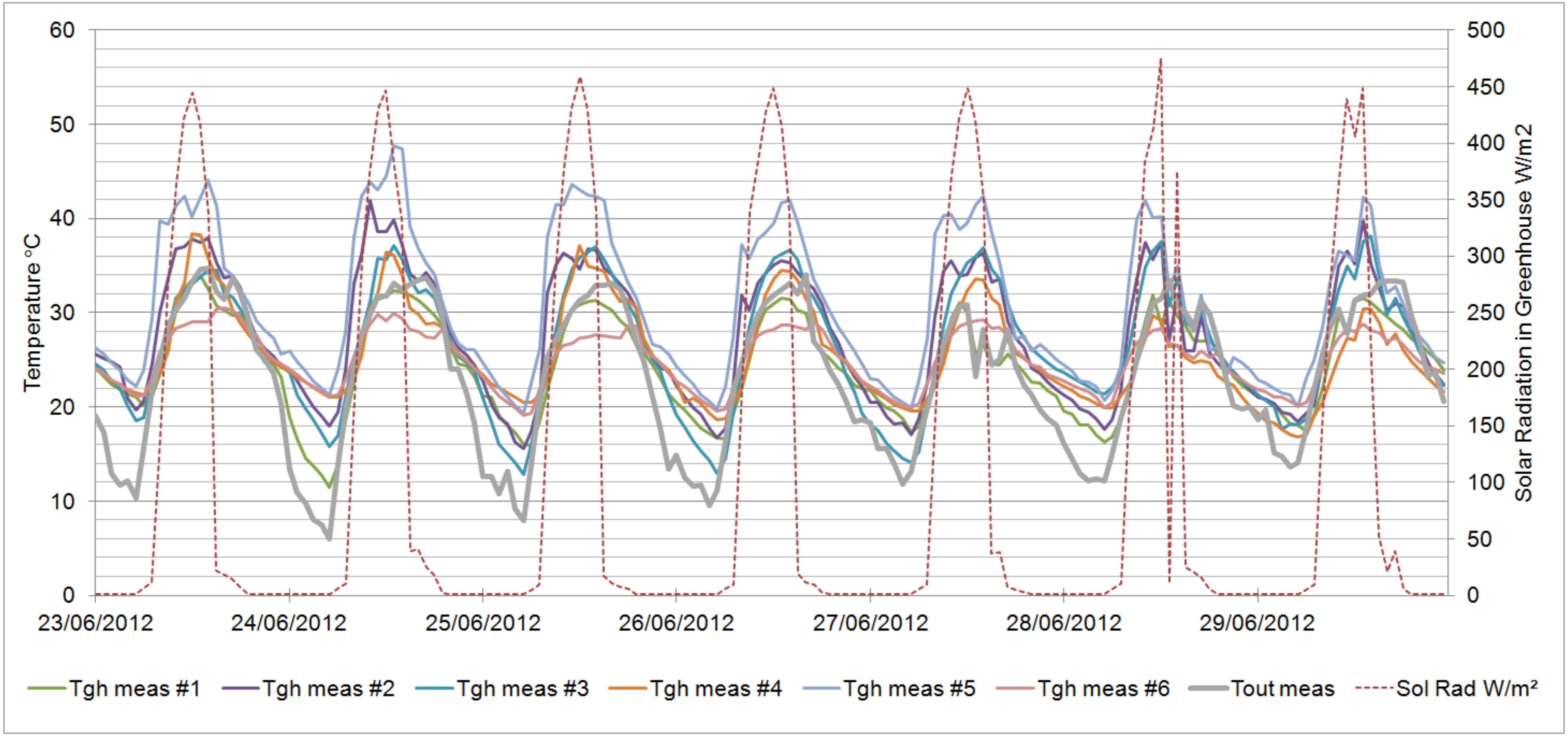

Figure 3.8 - Greenhouse air temperature, all houses, during summer week with hottest outdoor temperature

3.3.2.3 Thermal Lag Analysis

In Figure 3.9 (winter week) and Figure 3.10 (summer week) indoor conditions of House #1 are contrasted with greenhouse conditions, outside air temperature and solar radiation (measured inside the greenhouse). Vertical blue lines are drawn to highlight the time lag between peak (maximum) solar radiation, peak outdoor temperature, and peak indoor temperature. Maximum and minimum outdoor temperatures for the monitoring period are highlighted by a red circle.

On 25 December 2011 (winter), peak solar radiation occurred at midday, followed one hour later by peak air temperatures outdoors and in the greenhouse, followed another hour later by peak indoor air temperature. A similar sequence of peaks occurs on the other days too, although, for example, on 27 December 2011 the outdoor, indoor and greenhouse peaks occur simultaneously one hour after the solar radiation peak.

On 25 June 2012 (summer), peak solar radiation occurs at midday, followed one hour later by a peak in the greenhouse, followed another two hours later by a peak in outdoor air temperature and another one hour later the indoor temperature peaks. On other days of the summer week, although not identical, the timing and sequence of peaks is very similar.

One of the benefits that is claimed by builders and architects of thermally massive buildings in warm to hot climates, is that the maximum indoor temperature is significantly offset from the outdoor maximum due to the “flywheel effect” in which the thermal mass absorbs and stores heat during the hottest part of the day and releases heat into the living spaces during the cool nighttime, thereby acting as an efficient regulator of indoor temperatures (Easton & Wright, 2007, p. 43). This analysis indicates that Earthships in the Taos climate perform slightly differently, delaying peak indoor temperatures by only an hour in the winter and up to four hours during the summer, yet the flywheel effect can still be seen as the indoor temperature remains comfortable for the vast majority of the time.

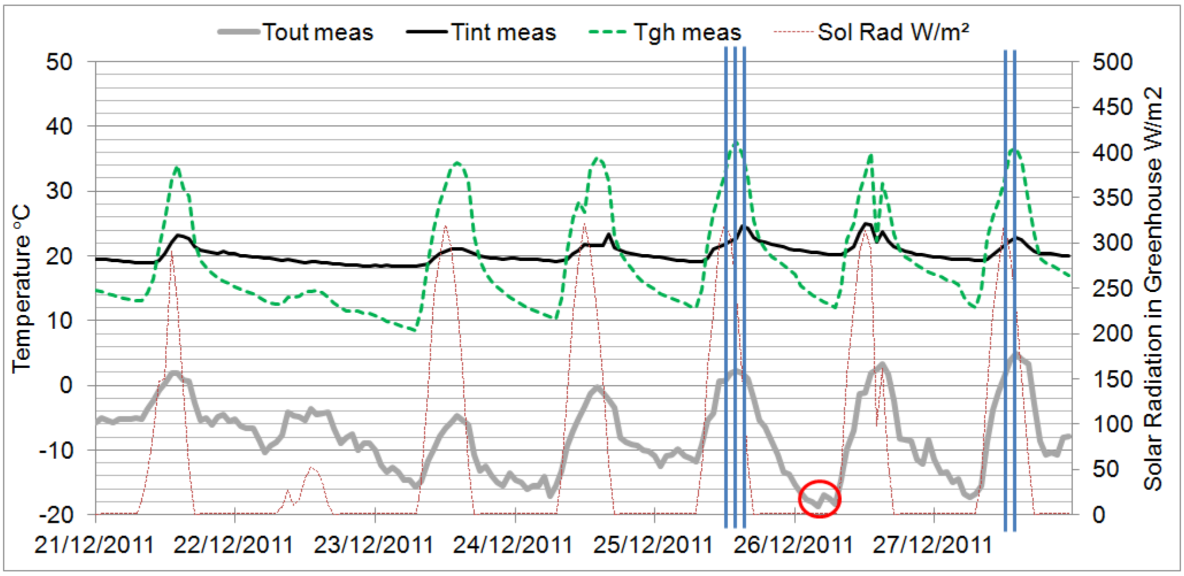

Figure 3.9 - Winter week, House #1, thermal lag

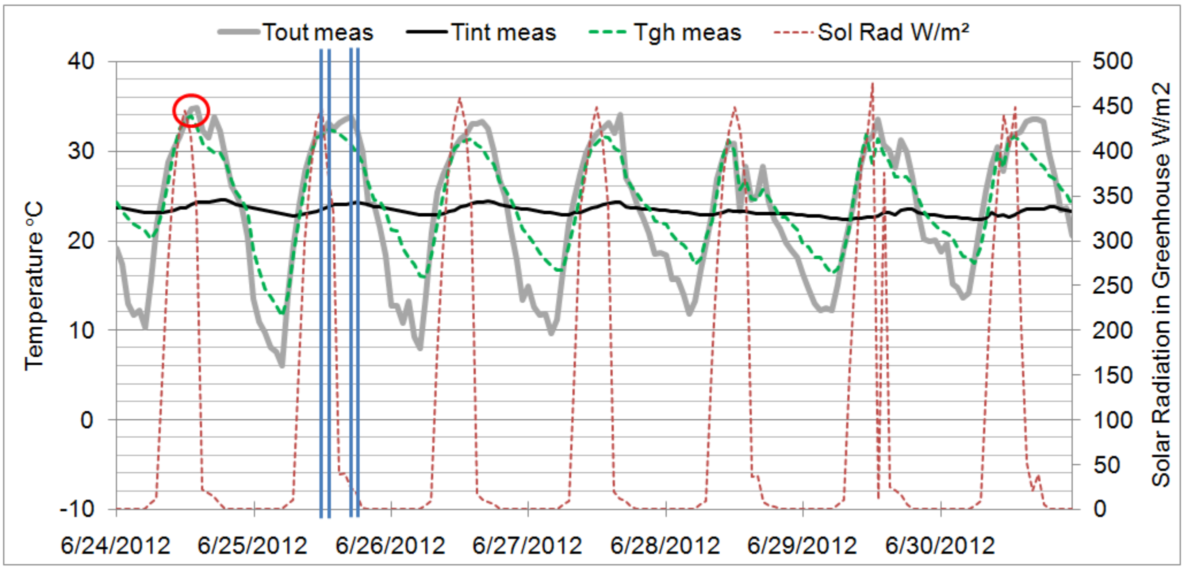

Figure 3.10 - Summer week, House #1, thermal lag

3.3.2.4 Temperature Band Analysis

To give a better understanding of how the Earthships performed throughout the entire monitoring period, indoor air temperatures are tabled and categorised in accordance with how many hours the indoor air temperature was within a certain temperature range ("band"). The results are presented in terms of the percentage of time the indoor air temperature was within a certain temperature band: refer to Figure 3.11. Two sets of results are given for House #1 to reflect the standard (7.5 month) and extended (12 month) monitoring period.

The results show that the indoor air temperature of the Global Model Earthships (House #1-4) are usually between 18 and 25°C whereas the U module Earthship (House #5) has a warmer profile and the Packaged Earthship (House #6) has a cooler profile. In House #1 (Global Model) the temperature is between 21 and 23°C (comfort range for all seasons) for over 50% of the time, and between 18° and 24° for 91% of the time (over twelve months).

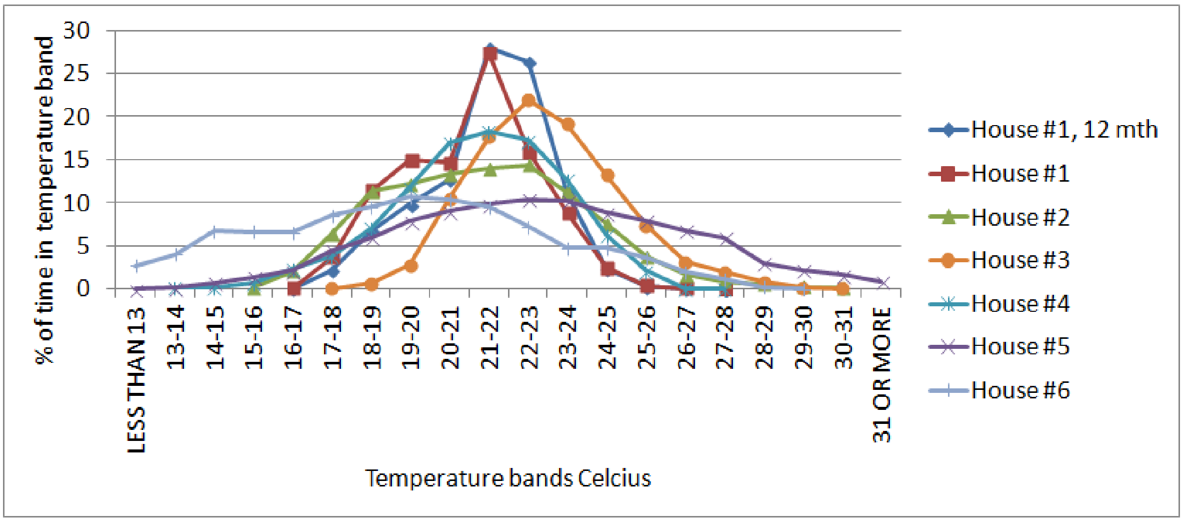

Figure 3.11 - Percentage of time within a certain temperature band

3.3.2.5 Standardised Effective Temperature Analysis

To investigate the effect of humidity on the comfort levels, hourly data recorded for relative humidity and dry bulb temperature were plotted on a psychrometric chart for the hottest and coldest months and average months in autumn and spring for House #1 (Global Model) according to the Standardised Effective Temperature (SET) comfort model (Szokolay, 2008, p. 21-22). The SET model is suitable for naturally conditioned homes such as the Earthship, whereas the comparable ASHRAE model (which considers humidity and operative temperature) is intended for air conditioned buildings (ASHRAE, 2010, p. 4-5). The SET comfort model does not, however, consider the effect of clothing insulation values.

Mean monthly outdoor air temperature ($T_{o.av}$) was calculated based on measured results from Taos for December (coldest winter month), April (average spring month), June (hottest summer month) and October (average autumn month). Then upper (T_U) and lower (T_L) temperature comfort limits, which would be acceptable to 90% of the population, for each selected month were calculated using the equations prescribed by Szokolay (p. 20):

$$T_U = 17.8 + (0.31 \text{ x } T_{o.av}) + 2.5°C$$

$$T_L = 17.8 + (0.31 \text{ x } T_{o.av}) - 2.5°C$$

The SET comfort conditions are indicated in the psychrometric chart by a red boundary. Data falling within this boundary is considered to be in the comfort zone. Refer to Figure 3.12 to Figure 3.15.

The SET analysis indicates that the conditions within House #1 would be uncomfortable for significant periods of time; however this conflicts with the findings of the Earthship Daily Comfort questionnaire which showed that other Earthships, one of almost identical design, provided conditions that the occupants found to be comfortable most of the time. This discrepancy can be explained by occupant behaviour aimed at adapting to the indoor conditions. The SET model indicates indoor conditions that were slightly too warm in the winter and slightly too cool in the summer, yet this could be dealt with easily by the occupants by altering their clothing, wearing lighter clothing than usual in winter and heavier clothing than usual in summer, or they could increase the rate of ventilation to bring about more comfortable indoor conditions. In spring relative humidity in the range of 60-70% indicated discomfort according to the SET model, although the temperature was in the ideal range for the majority of the time.

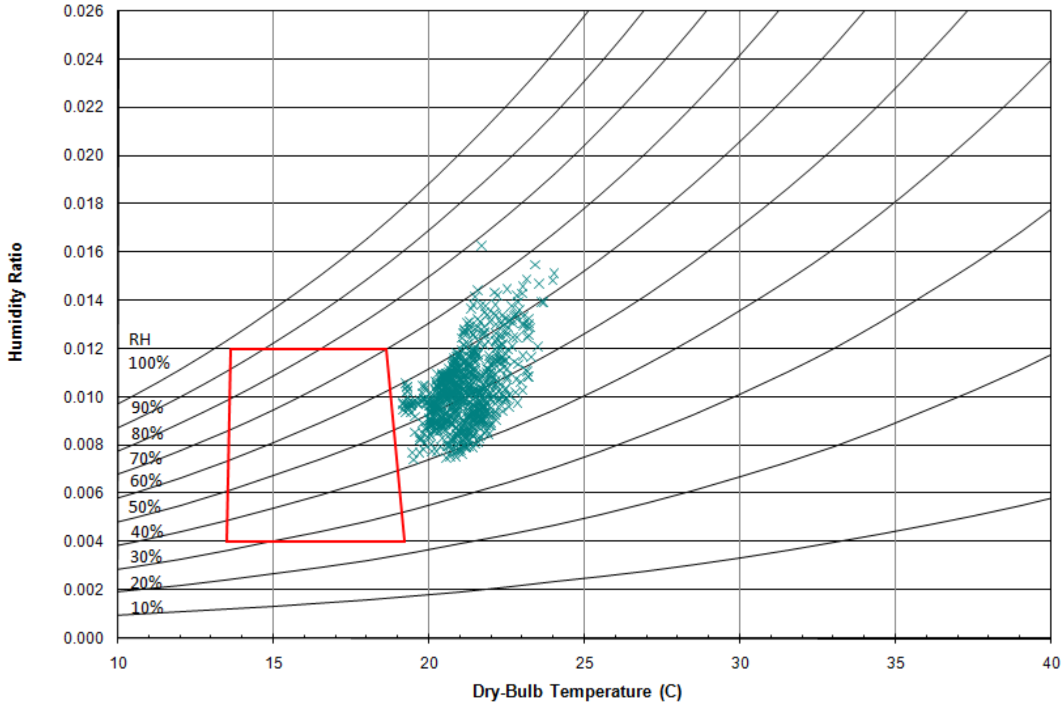

Figure 3.12 - House #1, Dec 2012 (Winter) - Standardised Effective Temperature (SET) Comfort Zone

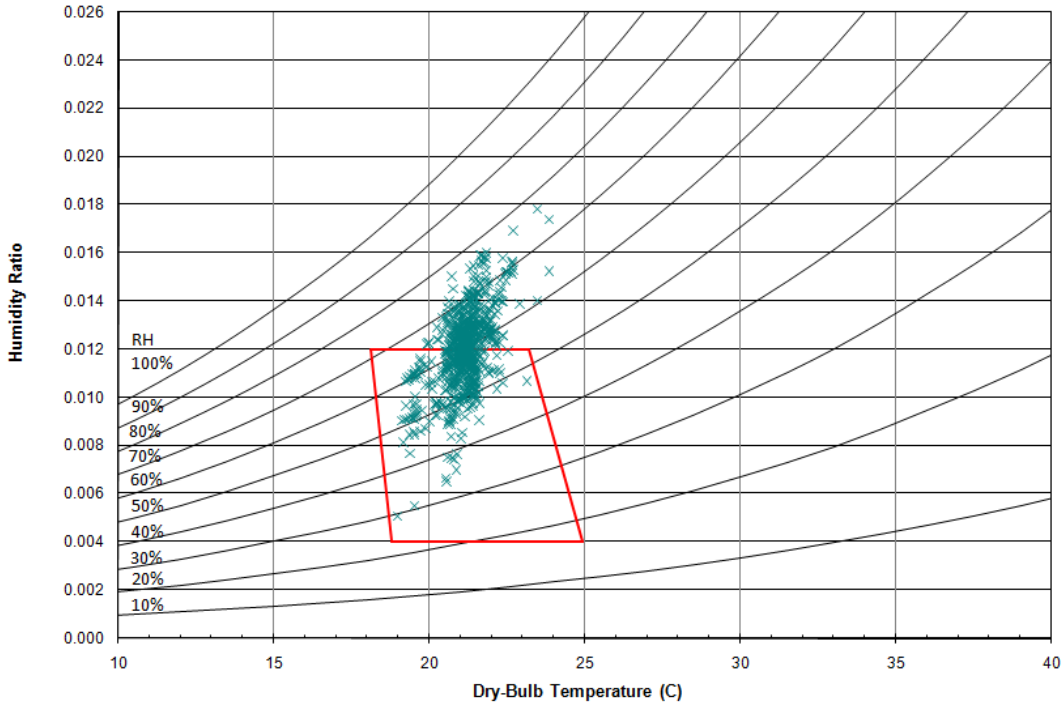

Figure 3.13 - House #1, April 2012 (Spring) - Standardised Effective Temperature (SET) Comfort Zone

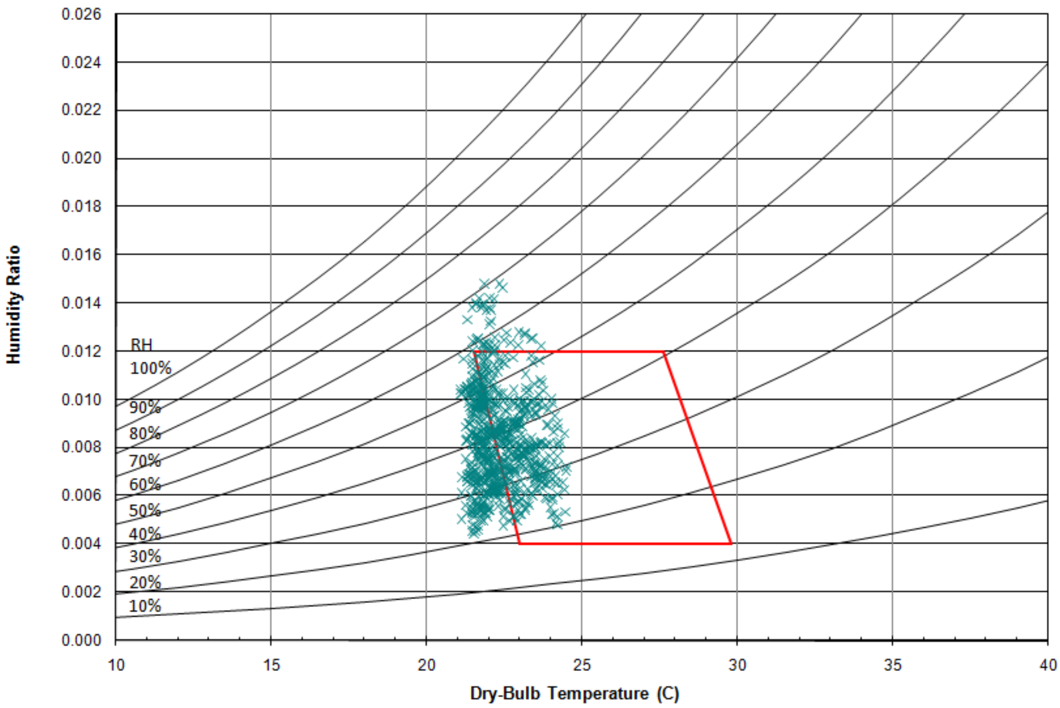

Figure 3.14 - House #1, June 2012 (Summer) - Standardised Effective Temperature (SET) Comfort Zone

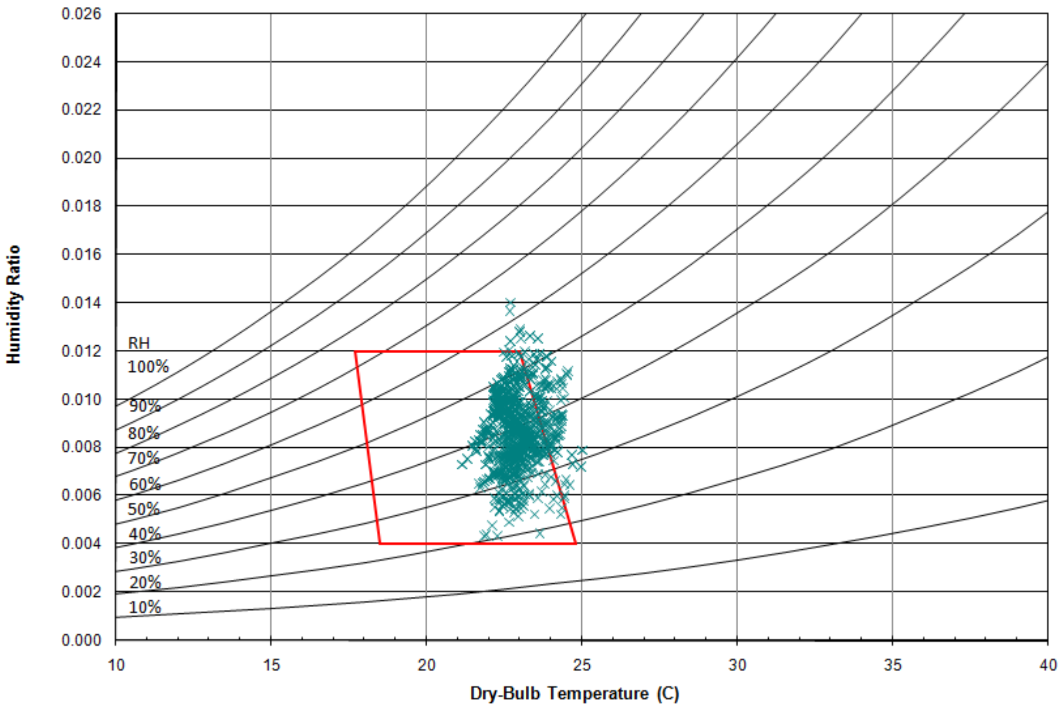

Figure 3.15 - House #1, October 2012 (Autumn) – Standardised Effective Temperature (SET) Comfort Zone

3.3.3 Illumination Levels Results & Discussion

Illumination levels during which electric lighting was not used were studied to investigate concerns that Earthships may tend to be dimly lit due to their earth-sheltered design and to provide data on assumptions regarding lighting energy use in the LCA study. The sensor was placed adjacent the rear (tyre) wall at a height of approximately 700mm above floor level (refer to Figure 3.1). Results at 1pm, in three Earthships, are presented in Figure 3.16 in terms of monthly averages, thereby showing results for what would be expected to be the brightest time of the day, and Figure 3.17 shows results at various times of day for one of the Earthships to help understand lighting levels throughout the day.

Blinds were installed on the interior side of the angled greenhouse glazing in House #4.No other house had shading of the greenhouse, except for the plants growing within.

The monthly analysis reveals that illumination levels are highest in winter (January) when sun penetrates deep into the living spaces. As the sun rises higher in the sky, reaching its peak in summer (June), illumination levels reach their minimum.

In the winter, when solar radiation is able to penetrate deep into the living spaces, the results show a wide range of difference. For example, in January (winter) House #3 is approximately 300lux brighter than House #4 (which may have been using the blinds), whereas in summer, when solar radiation is excluded from the living spaces, the difference is only approximately 50lux.

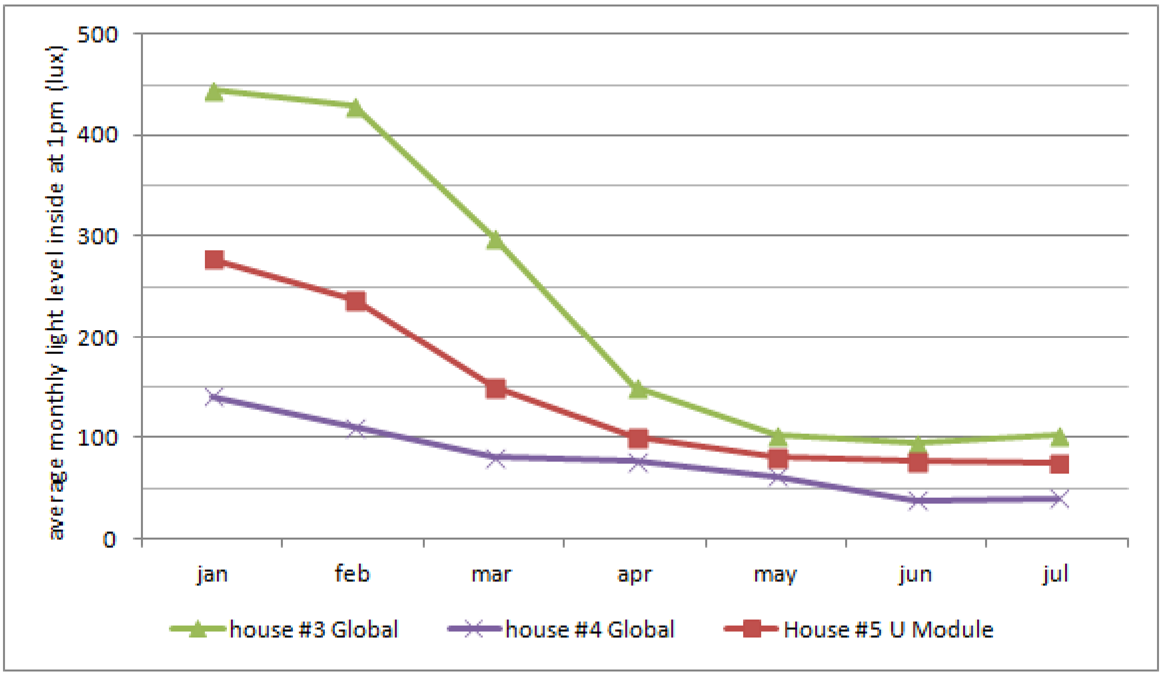

Figure 3.16 - Monthly average illumination level inside at 1pm

Results recorded at 9am, 11am, 1pm, 3pm and 5pm are presented in Figure 3.17 for House #3.

As expected the highest illumination levels are in the middle of the day and the lowest early in the morning and late in the afternoon. The seasons accentuate this daily pattern with much greater differences in illumination levels in winter (January - March), less so in spring and the least difference in summer.

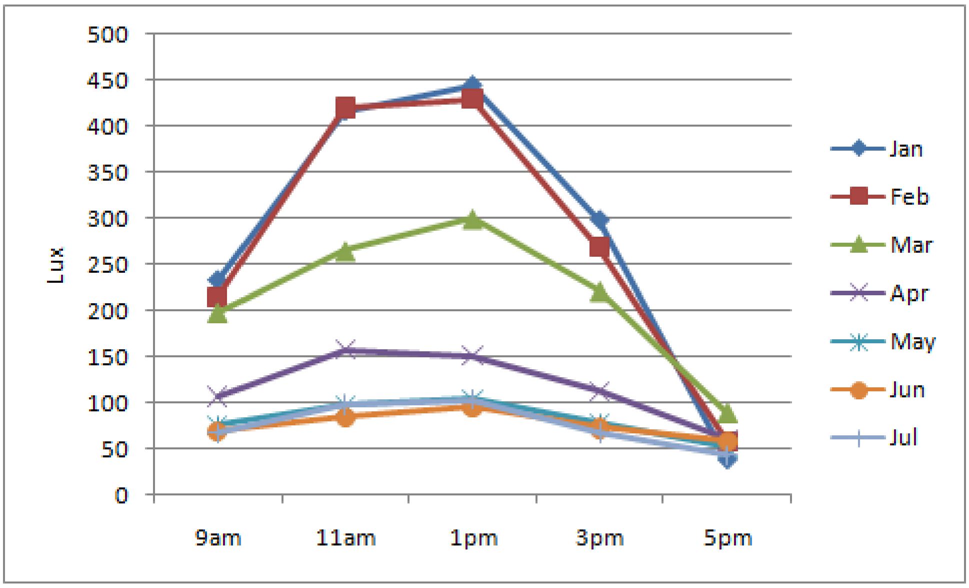

Figure 3.17 - Average monthly illumination level at different times of day, house #3, (global model Earthship)

A level of 50lux is considered to be an average desirable level of light in living rooms in Australia (Pears & Environment Australia, 1998), 80lux is quoted for toilets and 160lux for general tasks in kitchens by the Australian Standard for interior and workplace lighting (Standards Australia, 2008, p. 19-20). Thus the measurements from these Earthship homes indicate that, in the Taos climate, daylighting is generally of a sufficient level to avoid the need for artificial lighting at most times of the day, in most seasons, for typical domestic activities. Summer has the lowest illumination levels indicating that artificial lighting may be needed for some daytime activities; however, the energy use associated with this could be supplied directly from the solar panels and would be unlikely to draw power from the battery bank.

3.3.4 Summary of Earthship Comfort Levels Study

The Earthship Comfort Levels monitoring study found that this small sample of six Earthships in the Greater World Community, Taos, New Mexico, USA, provided thermal comfort to the occupants: for the vast majority of time, indoor temperatures were within the range of the ASHRAE Adaptive Comfort Model, and the associated survey of the occupants of the monitored homes confirmed that the conditions they were experiencing were acceptable. While the older U Module Earthship built in the 1990s and the Packaged design both employed very occasional backup heating during extremely cold outdoor weather conditions, the newer “Global” model Earthships achieved comfortable conditions without any active heating or cooling.

The monitoring also indicated that daytime indoor light levels were of acceptable standard and therefore no electricity was needed for lighting during the day.

The Standardised Effective Temperature (SET) analysis indicated that high humidity in the living spaces, particularly in winter and less so in spring and autumn, coupled with too warm winter temperatures and too cool summer temperatures, may contribute to uncomfortable conditions; however, as the SET results are not consistent with the comfort vote responses, further investigation is warranted. More importantly, however, the fact that overall the occupants expressed no dissatisfactions over the thermal conditions in their dwellings indicate that they would have adjusted their clothing and ventilation to stay comfortable.

3.4 Earthship Daily Comfort Study

This study was designed to investigate the perceptions of Earthship occupants with regard to the indoor comfort conditions they experienced and their involvement with the operation of their home's natural ventilation systems.

3.4.1 Study Design

Of the six Earthships that were monitored, two were nightly rentals and therefore were only occasionally occupied, and the other four were homes that were occupied fairly constantly. An adult from each Earthship home (as opposed to the rental Earthships) was asked to complete a questionnaire titled Earthship Daily Comfort. They used the questionnaire for one week in winter, spring and summer. The aim of this was to understand how Earthship dwellers perceived the conditions in their home – for example did they feel too hot or too cold – and to understand how they responded to the indoor comfort conditions in terms of actions such as altering their amount of clothing, using natural ventilation, et cetera. It was anticipated that they would be actively managing the indoor conditions and would be, in general, experiencing comfortable indoor conditions, although perhaps they might be willing to tolerate occasional discomfort or accept a wider indoor temperature range than that which is considered normal.

The Earthship Daily Comfort questionnaire was designed to enable correlation with the data collected from the Earthship Comfort Levels monitoring programme. This was achieved by asking the respondents to record the time and date of their responses to questions that were time dependent, for example they were asked "please indicate RIGHT NOW how you feel at this moment" with possible responses ranging from "hot" to "cold" (see Appendix C for a copy of the questionnaire). Thus it was possible to compare their response at a given time with the data collected at that time, and observe how they perceived the indoor comfort conditions of their home.

3.4.2 Results of Earthship Daily Comfort Study

This section presents key results of the Daily Comfort Questionnaire. The results are derived from the responses to the questionnaires and are cross referenced to data collected in the Thermal Performance Monitoring study.

There were four respondents to the questionnaire, two from one house (House #6 Packaged design) and one for House #2 (Global Model) and House #5 (U Module). The occupants filled out the questionnaire every day for approximately one week in winter, spring and summer.

Of particular interest are the occupants' responses to two questions relating to thermal comfort:

"*Please indicate how you feel RIGHT NOW at this moment*" with possible responses being: "cold, cool, slightly cool, neutral, slightly warm, warm, hot". This question is subsequently referred to as the "Comfort" response.

"*Please indicate how you would RATHER be feeling RIGHT NOW at this moment*" with possible responses of: "cooler, no change, warmer". This question is subsequently referred to as the "Rather" response.

Table 3.3 presents a cross tabulation of the responses to the two questions described above and Figure 3.18 displays the results in graph format. It shows that of the 59 responses, collected in both the greenhouse and living areas, approximately half of the responses (50.8%) indicate the occupants were very comfortable, and wanted no change in the conditions. Interestingly, 16.9% reported that they wanted "no change" but were also "slightly cool" and similarly 3.4% wanted "no change" but were "slightly warm", thus the proportion wanting "no change" was 71% (42 out of 59 respondents).

In terms of the responses that would rather have "cooler" conditions (11), all of the associated comfort responses (18.6%) were "slightly warm"; a logical result; however, of those that preferred "warmer" conditions (6), the comfort rating responses varied: 1.7% (1 response) had felt “cool”, 6.8% (4) had been “slightly cool” and 1.7% (1) “neutral”; a total of 10.2% (6) who would rather have been “warmer”.

Table 3.3 - Cross correlation of comfort and rather responses (all houses)

n = 59			Rather			Total
			Cooler	No Change	Warmer	
Comfort	Cool	Count	0	0	1	1
		% of Total	0.0%	0.0%	1.7%	1.7%
	Slightly cool	Count	0	10	4	14
		% of Total	0.0%	16.9%	6.8%	23.7%
	Neutral	Count	0	30	1	31
		% of Total	0.0%	50.8%	1.7%	52.5%
	Slightly warm	Count	11	2	0	13
		% of Total	18.6%	3.4%	0.0%	22.0%
Total		Count	11	42	6	59
		% of Total	18.6%	71.2%	10.2%	100.0%

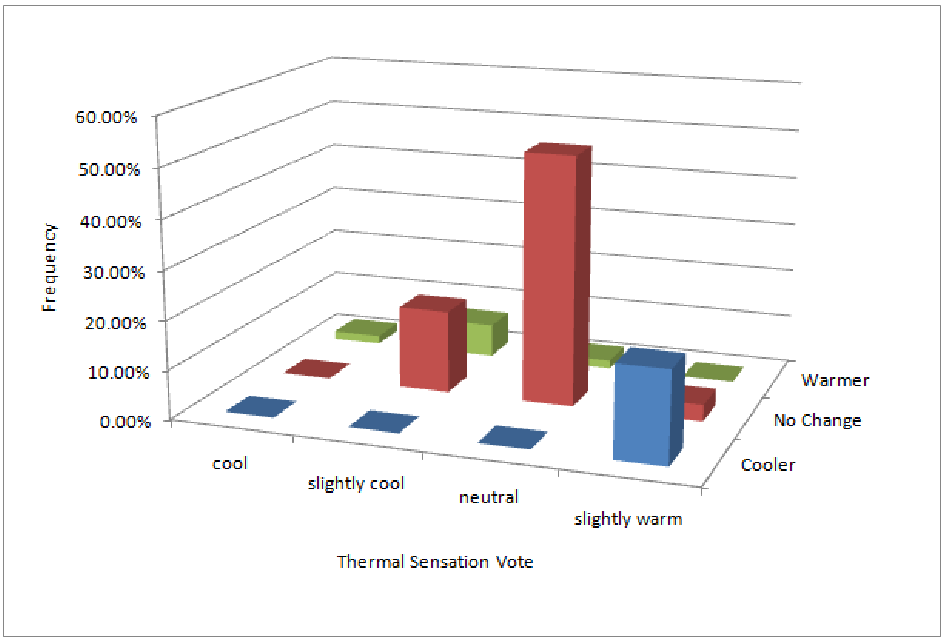

Figure 3.18 - Frequency of Thermal Sensation Votes

3.4.2.1 Adaptive Comfort Model Analysis

Figure 3.19 presents the indoor operative temperature and the external 7 day running (“prevailing”) mean air temperature for the respondents who wanted “no change” in the living areas only. For these responses the indoor operative temperature is plotted against the prevailing mean outdoor temperature calculated as per the ASHRAE Standard. The red and blue lines indicate the upper and lower limits (respectively) of the ASHRAE Adaptive Comfort Model. The limits are based on temperatures that 80% of the population find comfortable based on the prevailing mean outdoor air temperature (ASHRAE, 2012) (equations are given below). The dotted part of the ASHRAE limits represent an extrapolation of the ASHRAE Adaptive Comfort range which is only intended for use in climates with prevailing mean outdoor temperatures above 10°C and below 33.5°C.

$$T_U = 17.8 + (0.31 \text{ x } {}_{pma(out)}) + 3.5°C$$

$$T_L = 17.8 + (0.31 \text{ x } T_{pma(out)}) - 3.5°C$$

These results indicate that the Adaptive Comfort Model may be an accurate way of predicting the range of comfort temperatures in the Taos Earthships, although, as some of the votes lie outside the comfort range, it indicates that Earthship occupants may be more willing to accept slightly higher or lower temperatures (up to 2.5°C) than the general population.

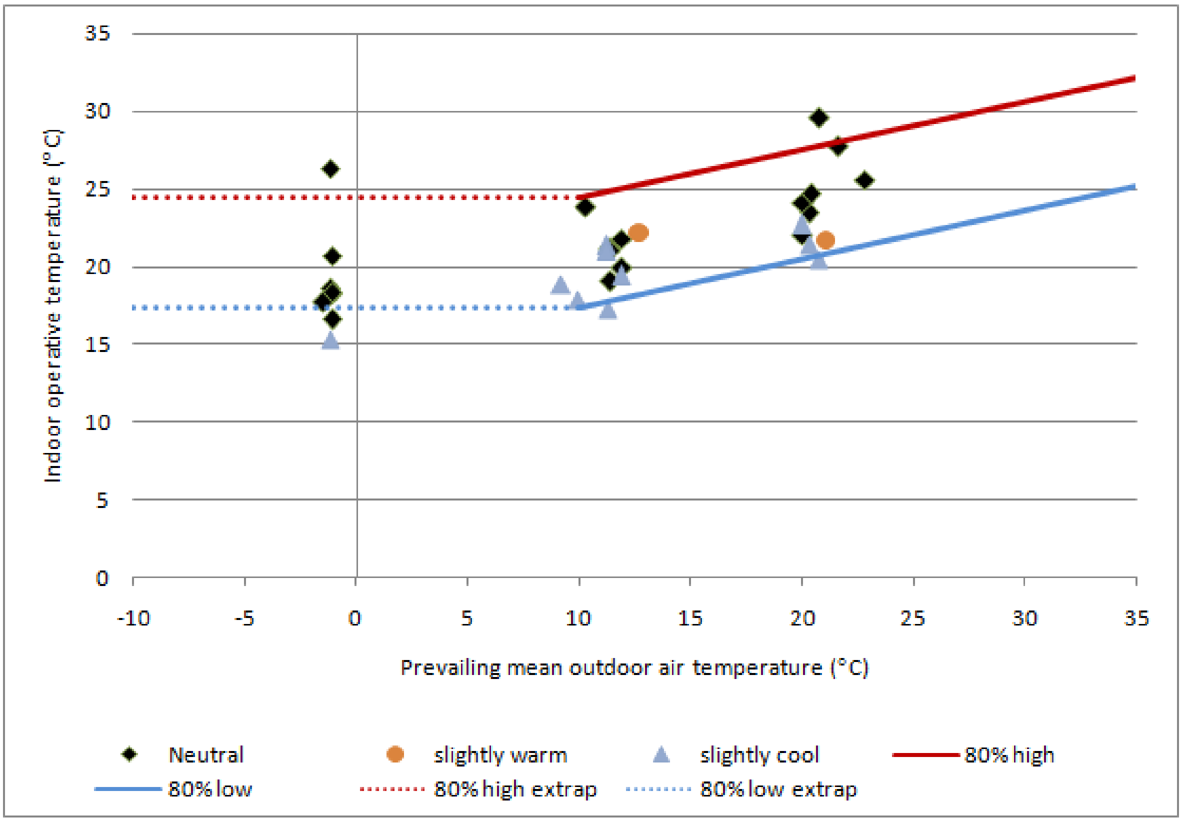

Figure 3.19 - ASHRAE Adaptive Comfort analysis, all houses (N=37)

3.4.3 Summary of Earthship Daily Comfort Study

Questionnaire responses from four Earthship occupants (three homes) indicate that for the majority of the time they were very comfortable and did not mind occasionally being slightly cool or slightly warm.

The measured indoor operative temperature recorded at the time the responses were made, generally falls within the comfort range of the ASHRAE Adaptive Comfort Model indicating that this ASHRAE Standard is accurately predicting the range of temperatures at which Earthships provide thermally comfortable conditions. Furthermore, the Standard, which is not intended for climates as cold as Taos, can be extrapolated to predict a comfortable indoor temperature range in cold climates, although this conclusion is tentative due to the small data set.

3.5 Chapter Summary

The POE studies investigated a wide range of issues relating to the “as built” performance of Earthship homes, improving the understanding of these issues and providing data necessary for justifying the assumptions of the subsequent Thermal Performance study and LCA study.

Overall the POE studies indicate that Earthship inhabitants live a fairly “normal” life in the sense that they have all the usual modern conveniences enjoyed in developed countries yet they are highly aware of the limitations and maintenance requirements of their off-grid systems, and are willing to trade off some conveniences that grid-connection would provide, for what they perceive to be a more relaxing, healthy, ecological, and enjoyable lifestyle. The monitoring of six Earthships in Taos confirms anecdotal evidence, and supports the claim that Earthships in Taos remain comfortable with either zero or minimal heating and cooling despite the extreme climate. Furthermore, the survey of Earthship occupants around the world indicated that they also enjoy comfortable indoor conditions for the majority of the time without significant heating and cooling needs; however, the use of wood fires during overcast winter weather was reported by many.

4 Thermal Performance Studies

4.1 Introduction

This Chapter discusses the thermal modelling studies to investigate the thermal performance of the Earthship and compares it with similar designs and with various other construction types and materials. The first study explores the effect of wall construction materials on the quantity of energy required to maintain comfort conditions inside a home, in the Adelaide climate, thereby providing data required for the LCA study which will be presented in Chapter 5. It is primarily concerned with the effect of the external walls. As Earthship wall construction is unusual and anecdotal reports of Earthship thermal performance are generally very favourable, an investigation of how the Earthship external wall performs and compares with other external wall types is of interest and highly relevant to the comparative LCA study. The study also explores the effect of other design features typical to Earthship design - an attached greenhouse and earth-sheltering berms - as well as the effect of other design and construction issues such as the quantity of glazed area and internal wall construction materials.

The second study aims to fine tune and validate a simulation model of the Global Model Earthship in the Taos (USA) climate, using a calibration process which utilises the measured data from the POE study presented in Chapter 3.

The third study then uses findings from the above calibration process to re-evaluate the thermal performance of the Earthship in the Adelaide climate. The results of the third study are compared to the first study, highlighting the effect of changes in assumptions arising from the calibration process, and presenting a range of values for heating and cooling energy for use in the LCA study.

The fourth and final study investigates the simulated performance of the Earthship in a variety of warm and cold climates in Europe using the calibrated model with a view to addressing the claim that Earthships perform well in a wide variety of climates and investigating the claims of sub-standard performance in some European climates (Hewitt & Telfer, 2007).

4.1.1 Definitions

In this study “thermal envelope” or “envelope” is used to describe the main components of the building that affect its thermal performance; the floor, roof, external walls, internal walls and glazing.

“Heating and cooling load” is used to describe the total energy load required to provide comfort conditions in the home, as opposed to “operational energy” which is used to describe not only heating and cooling energy but also other energy required for appliances, lighting, hot water, and any other equipment. The term “loads” is used to describe the theoretical quantity of heating and/or cooling loads which are the sum of the total heat losses (heating load) or heat gains (cooling load) as opposed to “energy” which factors in other issues such as the efficiency of the heating and cooling plant (e.g. “Star” rating of the appliance), and the fuel type (e.g. gas versus electricity).

“Equator facing” refers to the side of the house that faces the equator, and hence receives the most solar radiation. It is the north side of houses in the southern hemisphere and the south side of houses in the northern hemisphere.

“Glazed area” refers to the amount of glazing as a percentage of the equator facing wall area, not of the floor area (which is a more common way of expressing glazed area). This is due to the design of the user interface of the thermal modelling software. For example “50 percent glazed area” means that half of the equator facing wall is glazed. (No other walls are glazed in an Earthship.)

“Living space” is used to differentiate from the “greenhouse space” (which is not intended as a living area).

4.1.2 Thermal Modelling Software

All studies were conducted using the DesignBuilder/EnergyPlus software to simulate theoretical heating and cooling energy loads and/or indoor temperature and relative humidity when no heating or cooling was used. DesignBuilder (DesignBuilder, 2013a) version 2.4.2.020 and EnergyPlus (US Department of Energy, 2012) version 6.0.0.023 were used in this study.

4.2 Study 1: Adelaide Climate, Thermal Envelope Variables

4.2.1 Introduction

This study was designed to estimate the energy loads in a house design based on the Earthship principles in the Adelaide, South Australia, climate subject to a number of alterations, namely the external wall construction, internal wall construction, greenhouse, berm and window area. The effect of floor plan and glazing layout was also briefly investigated for a “conventional” home for comparison.

Although in reality Earthship buildings use zero or minimal space heating and cooling, in this study heating and cooling is assumed to be employed because this parameter is being used to evaluate the performance of various wall constructions which generally employ heating and cooling systems. In the context of the LCA study, the heating and cooling load is of interest as it is well known that heating and cooling energy is a significant contributor to a building's lifecycle impacts. In Australia it is estimated to represent approximately 38% of energy use in the home, equating to approximately 20% of the home’s greenhouse gas emissions (Milne & Riedy, 2010).

Heating and cooling loads are also a proxy for the innate comfort level provided by the wall type in the absence of heating or cooling: the more energy required for heating/cooling the less comfortable the home would be without a heating/cooling system. One of the claims about Earthship, and to a certain extent strawbale, rammed earth and mudbrick, is that these construction types need little or no heating and or cooling when coupled with passive solar design principles.

The calculation method uses well respected tools and up to date data, however, it must be noted that all the results presented here are only indicative and must not be construed as being perfectly representative of reality. They do however provide a solid basis for comparison. Furthermore, a subsequent study (Study 3) tests the sensitivity of various key parameters and modelling assumptions giving a range of potential figures for heating/cooling energy use.

4.2.2 Assumptions & Study Design

A model house design was developed as a vehicle to investigate a variety of design features and material options that comprise the thermal envelope with a view to understanding their effect on thermal performance and heating/cooling energy use.

The design parameters investigated were:

- external wall construction materials
- internal wall construction materials
- inclusion/exclusion of attached greenhouse (as per the Earthship design)

- inclusion/exclusions of earth sheltering (as per the Earthship design)
- glazed area of equator facing side of house (orientation of glazing was not investigated)

The thermal envelope layout and design of each hypothetical house is based on the Global Model Earthship design: it is long in the east-west axis and shallow in the north-south axis with an attached greenhouse on the equator facing side which is segregated from the living space by a glazed partition wall (in Study 1 this was assumed to be single glazed and in the other studies it was assumed to be double glazed). External walls are earth-bermed. Internal walls run north-south dividing the living space into a single row of rooms which all adjoin the greenhouse; there are no rooms at the rear of the house that do not receive direct sunlight from the greenhouse, which acts as a corridor.

For comparison to the Global Model Earthship's passive solar design, a more conventional (square) floor plan was also modelled. Its external walls were assumed to be insulated timber frame (TF) and the internal walls lightweight (LW). It was modelled as a square floor plan of the same area and ceiling height as the Global model Earthship, with the same roof, floor and glazing type. The glazing area was modelled as being evenly distributed across all external walls rather than exclusively on the equator facing wall.

The following sections describe key assumptions such as site characteristics and climate, dimensions of the building, construction materials types and properties, occupancy rates, natural ventilation schedules/rates, and heating and cooling settings.

4.2.2.1 Adelaide Climate

The context of the study is Adelaide, the capital city of South Australia (Lat. -34.92 SL, Long. 138.62 EL). Its climate is temperate (Bureau of Meteorology, 2013a) and is characterised by hot, dry summers and mild to cool, wet winters. According to the Bureau of Meteorology's 30 year climate data, the highest mean maximum occurs in January (33.7°C); the lowest mean minimum occurs in June (5.5°C); the mean annual highest temperature is 42°C and the lowest is 2°C(Bureau of Meteorology, 2012). Adelaide is the driest capital city in Australia with an average annual rainfall of 549mm (Bureau of Meteorology, 2013b). Daily global average solar radiation in the summer is 7.6kWh/m2 and in the winter, 2.5kWh/m2 (Lee, Frick, ANZSES & Energy Partners, 2006).The Adelaide Climate is classified by the Köppen classification system as "Csb" (Peel, Finlayson & McMahon, 2007), i.e. "temperate" or "warm Mediterranean".

Winter temperatures are cold enough to require homes to be heated whereas in summer frequent hot days necessitate air conditioning. Nighttime temperatures in the summer offer some relief usually dropping sufficiently to cool buildings with natural ventilation by purging hot air and replacing it with cool night air.

Humidity is low to moderate which assists with comfort levels on hot summer days by allowing perspiration to work effectively. Adelaide's average annual rainfall is distributed mainly throughout the winter months with very little rainfall during summer. The following graphs show the mean maximum and minimum air temperature and relative humidity for Adelaide, measured at a weather station in Kent Town, 2 km from Adelaide CBD(Bureau of Meteorology, 2011).

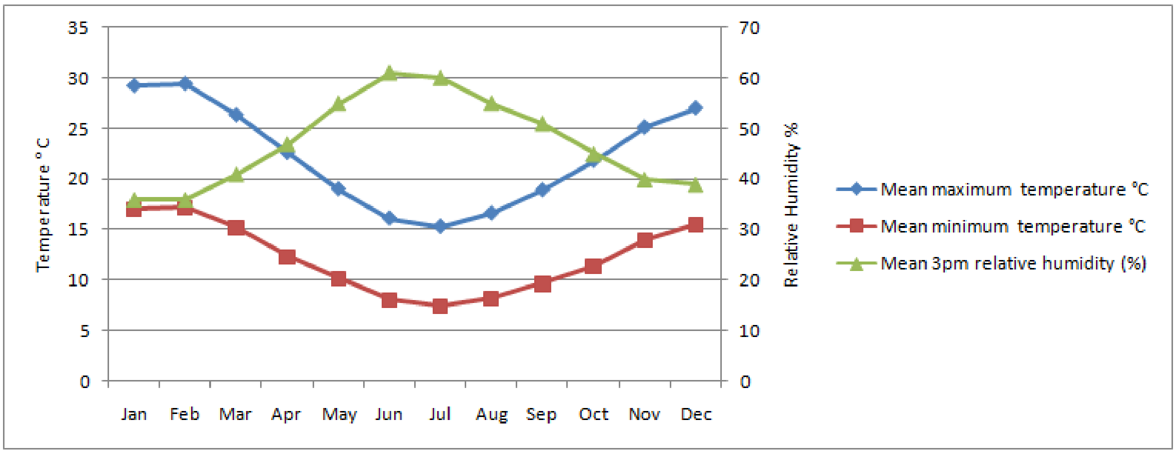

Figure 4.1 - Adelaide's Mean Monthly Maximum and Minimum Air Temperature

Adelaide Climate Data

The EnergyPlus software uses Representative Meteorological Year (RMY) climate data for Kent Town, Adelaide as per the files available from the EnergyPlus Weather Data webpage (U.S. Department of Energy, 2013).

RMY refers to "a composite of 12 typical meteorological months of best fit for a range of weather elements" (Lee & Snow, 2008, p. 1) consisting of hourly data such as temperature, humidity, wind speed, precipitation and solar radiation for a given location.

4.2.2.2 Ground Temperature

To clarify the term "ground temperature", it typically refers to the temperature of the ground under the floor slab, and in the case of earth-sheltered design, the bermed walls also have "ground" adjacent to them. The under floor ground temperature is influenced by the indoor temperature and outdoor temperature whereas the ground temperature often cited in earth-sheltered house literature (Baggs, Baggs & Baggs, 1985) generally refers to the temperature of the earth at various depths without considering the effect of indoor temperature, so these two should not be confused.

Throughout all thermal modelling studies, a validated model developed by Williamson (1994) *TgroundS,* was used to predict the ground temperature. The model estimates the ground temperature at given depths below floor level, based on the mean monthly temperature, assumptions regarding the indoor temperature, and various attributes of the floor and the ground beneath (soil). These attributes are: U-value, transfer modulus, lag time, internal admittance and lead time, all of which can be defined for the "core" (central) and "edge" areas of the floor slab. Refer to Appendix D for further information.

TgroundS was developed further in Study 2 and 3 to account for the effect of the Earthship greenhouse and other modelling assumptions regarding earth sheltering.

4.2.2.3 Site Parameters

The default "template" data provided by DesignBuilder for "Adelaide City" was used as per Table 4.1. This defines various key aspects of the site including latitude, longitude, elevation, precipitation and exposure to wind.

Table 4.1 - DesignBuilder Site Parameters

Parameter	Value
Latitude	-34.92 deg
Longitude	138.62 deg
Elevation above sea level	50.0m
Exposure to wind	"Normal"
Precipitation	750mm (note: this is higher than Bureau data)
Site orientation	0 deg (i.e. North facing)
Surface solar reflection	0.20

4.2.2.4 Occupancy, HVAC and other Assumptions

Occupancy was assumed to be 3.6 people (0.03 people/m^2) approximating two adults with two children, and that they would be at home from 3pm to 10am on the next day, every day (i.e. not at home for 5 hours in the middle of the day).

The temperature at which the heater turned on was 18°C and was scheduled for operation during May to September only (roughly, Adelaide's winter), which are the cooler months in Adelaide. The temperature at which the cooler was turned on was 26°C and was scheduled for operation during November to March (roughly, Adelaide's summer).

Natural ventilation was set to occur at 3 air changes per hour (ACH) in the living space and 3ACH in the greenhouse from November to March when the indoor temperature was above 21°C, and the outside air temperature was below 21°C. Internal windows (i.e. the glazed partition wall between the greenhouse and the living space) were assumed to be left open (30% open)from 11am to 4pm during May to September to promote air mixing between the greenhouse and living space during the cold months but not during the warm summer months. Shading of the greenhouse was achieved using internal blinds with high reflectivity slats, controlled via a solar controller that closed the blinds when solar radiation exceeded 200 W/m^2, otherwise they were always open. Further energy savings might be possible by closing blinds at night to prevent heat loss during winter; however, this scheme was not modelled.

Ground temperatures were calculated using software *"TgroundS"* (Williamson, 1994) based on the berm dimensions shown in Figure 4.2 and Figure 4.3.

Air infiltration was assumed to be 0.7ACH.

Table 4.2 - HVAC and Occupancy Settings

	Occupancy	Heating	Cooling	Natural Ventilation	Internal Window Operation	Greenhouse Blinds Operation
Set Point Living Spaces	NA	18 deg C	26 deg C	21 deg C	NA	NA
Set Point Greenhouse		NA	NA	21 deg C	NA	200W/m^2
Month						
Jan	3.6 people (0.03 people/m2) from 3pm to 10am the next day.		All hours, daily, Nov-Mar	All hours, daily, Nov-Mar, 3ACH in living and greenhouse		Blinds normally open but close when insolation exceeds 200W/m^2
Feb						
Mar						
Apr						
May		All hours, daily, May-Sep			30% of glazed area open, May-Sep	
Jun						
Jul						
Aug						
Sep						
Oct						
Nov						
Dec						

4.2.3 Design & Construction Details

The floor is typical of Australian constructions and is also similar to the thermal mass floors used in Earthships which are concrete, mud or flagstone. The roof is engineered to provide an insulation value of R5.1 for the complete roof system. This is the value prescribed in Table 3.12.1.1a *Roof and Ceiling – Minimum Total R-Value* of the National Construction Code of Australia (Australian Building Codes Board, 2012) for the coldest Adelaide climate (zone 6) and highest absorptance roof, and is comparable to the highly insulated roof of the Earthship.

Common wall construction details including Brick Veneer, Reverse Brick Veneer, Double Brick, Timber Frame, have been sourced using current design details for Australia and New Zealand (Insulation

Council of Australia and New Zealand, 2010).Other types of wall construction details have been sourced from the literature: Steen, Steen, Bainbridge and Eisenberg (1994) for strawbale, Middleton and Young (1979) for mudbrick and rammed earth and also Easton and Wright (2007) for rammed earth.

Table 4.3 presents the construction layers (from outside layer to inside layer) and the U-value calculated by DesignBuilder software based on the material types and thicknesses.

Table 4.3 - Construction Layers (thicknesses in millimetres) and resultant U Values

Type	Description (outside to inside)	U value (W/m2-K)	Type	Description (outside to inside)	U value (W/m2-K)
Floor	100mm thick concrete, uninsulated	3.355	Mudbrick	275mm mudbrick	1.863
Glazing, external	Double glazed, 4mm clear, 6mm air, 4mm clear	3.146	Mudbrick Insulated	25mm lime sand render, 100mm expanded polystyrene, 275mm mudbrick	0.326
Glazing, internal	Single glazed, 6mm clear	5.801	Precast Concrete Insulated Panel, no berm	60mm concrete, 55mm extruded polystyrene,150mm concrete	0.438
Roof	0.4mm steel, 196mm cellulose, 13mm plasterboard	0.196	Rammed Earth (RE)	300mm rammed earth	2.128
Brick Veneer	110mm brick, 40mm air gap with reflective foil, 70mm glass fibre, 10mm plasterboard	0.337	RE Insulated	25mm lime render, 100mm EPS, 300mm rammed earth	0.333
Concrete Block Insulated	100mm EPS, 300mm concrete blocks (hollow, heavyweight)	0.346	Reverse Brick Veneer	8mm Cement fibreboard, 70mm glass fibre, 40mm air gap with reflective foil, 110mm brick, 10mm plasterboard	0.322
Double Brick	110mm brick, 50mm glass fibre, 110mm brick, 10mm plasterboard	0.512	Strawbale	50mm lime render, 450mm strawbale, 50mm lime render	0.108
Earthship, bermed, insulated	100mm EPS, 1000mm earth, 10mm rubber, 630mm earth, 10mm rubber, 25mm lime render	0.235*	Heavyweight internal wall	150mm mudbrick (adobe). Note this wall type also used for Partition Wall.	2.703
Earthship, no berm, insulated	25mm lime render, 100mm EPS, 10mm rubber, 630mm earth, 10mm rubber, 25mm lime render	0.299	Timber Frame	10mm cement fibreboard, air gap with reflective foil, 90mm glass fibre batt, 10mm plasterboard.	0.424
Earthship, no berm uninsulated	10mm rubber, 630mm earth, 10mm rubber, 25mm lime sand render	1.233	Traditional Cob	20mm external render, 500mm clay soil 40% sands, 13mm plaster	1.560
Lightweight internal wall	10mm plasterboard, 90mm air gap, 10mm plasterboard	2.246	Timbercrete Super Insulator Block	90mm Timbercrete, 110mm expanded polystyrene (heavyweight), 90mm Timbercrete	0.245(Timbercrete, 2013)

* does not include effect of berm

4.2.3.1 House Design & Dimensions

Figure 4.2 and Figure 4.3 illustrate the dimensions and layout of the house with and without the greenhouse respectively. As mentioned previously the layout is based on a Global Model Earthship; however, the external wall constructions were varied to understand their effect on heating and cooling loads. The next section describes the various wall constructions.

The design shown is for the southern hemisphere (Adelaide) and hence glazing is arranged to face north.

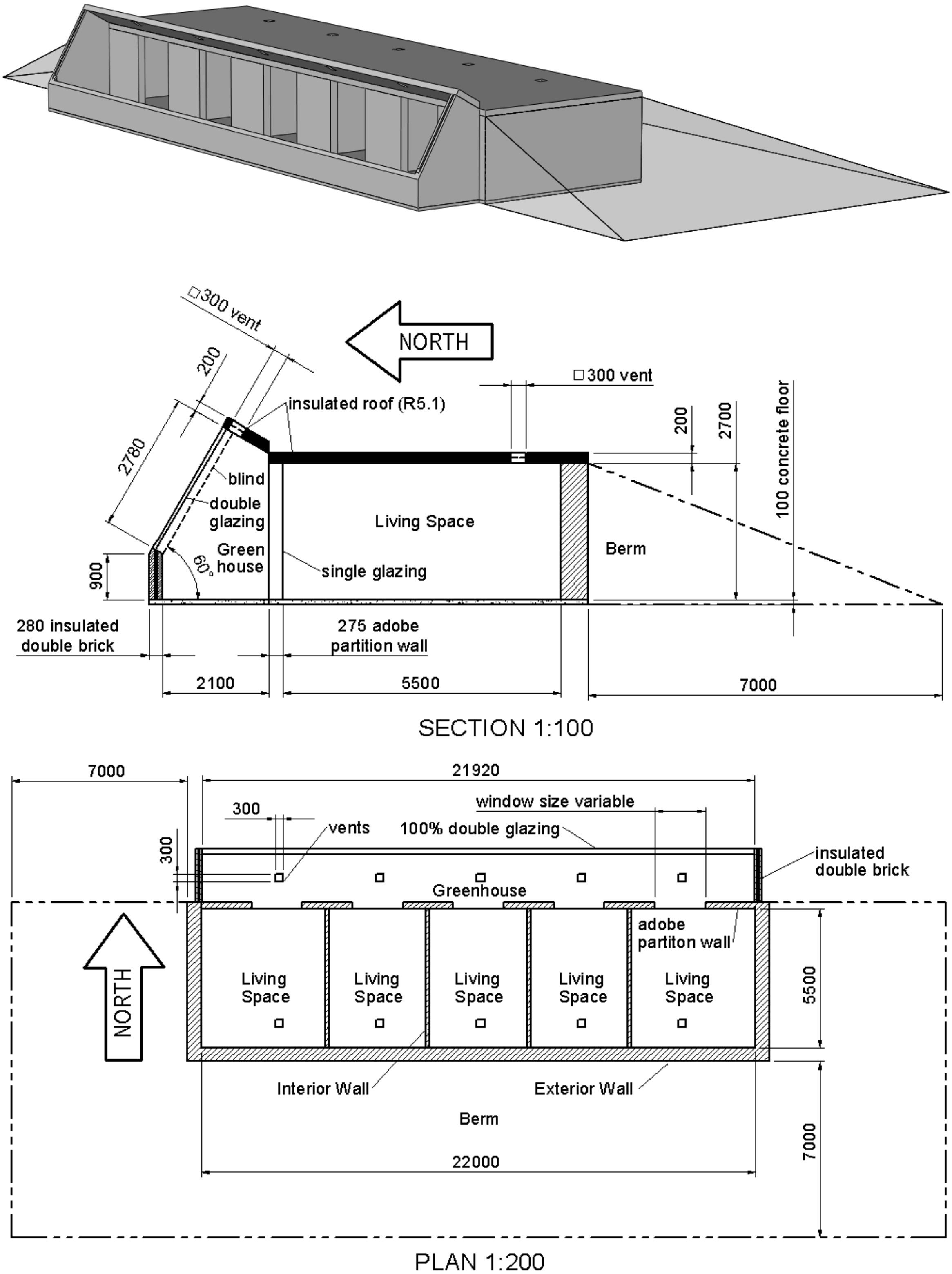

Figure 4.2 - Passive solar thermal model with greenhouse

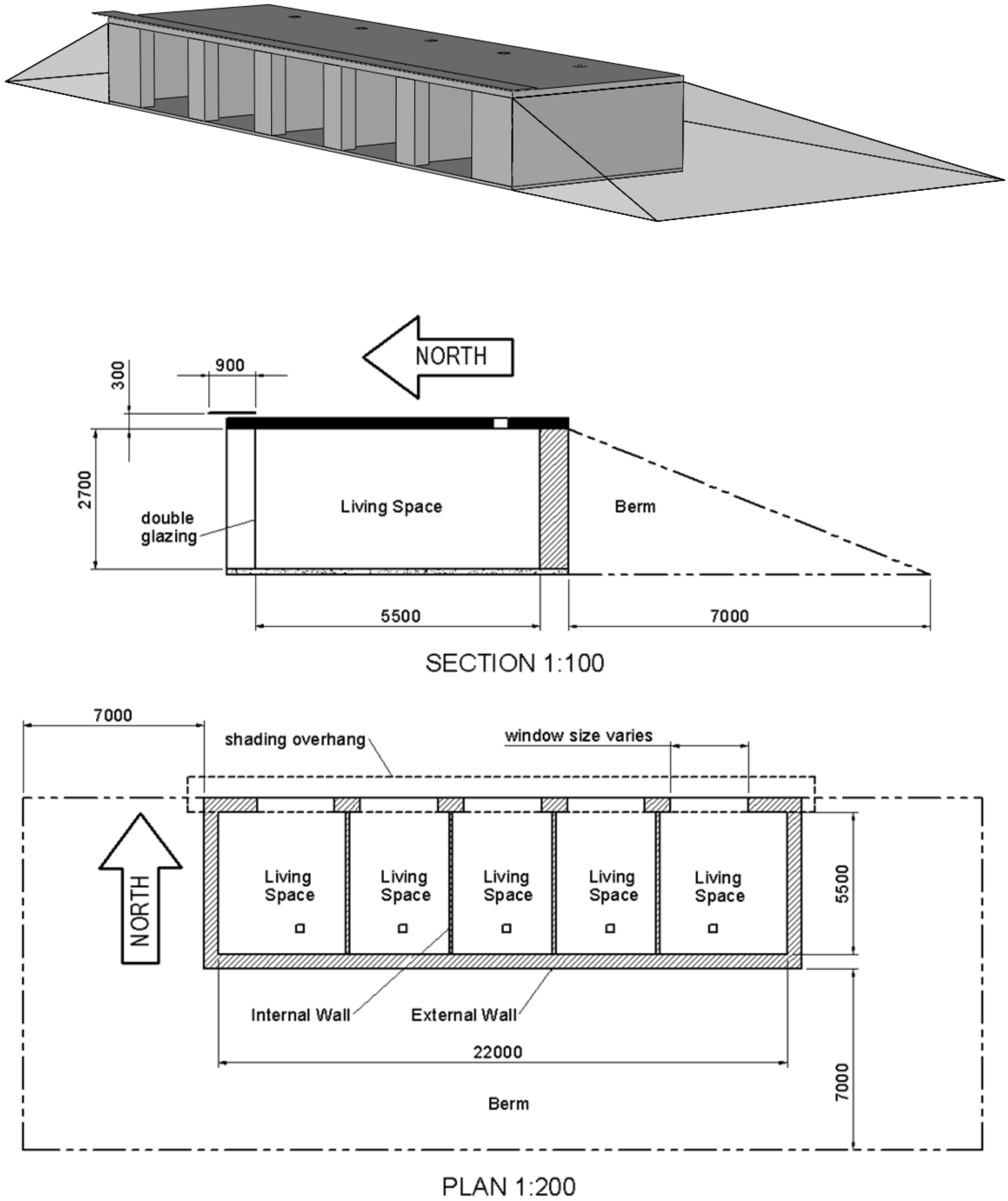

Figure 4.3 - Passive solar thermal model without greenhouse

Figure 4.4 illustrates the floor plan of the conventional home which was modelled with insulated Timber Frame (TF) external walls, lightweight (LW) internal walls and all other constructions as per the passive solar design model above. It has the same area and ceiling height as the Global Model Earthship with the same roof, floor and glazing type.

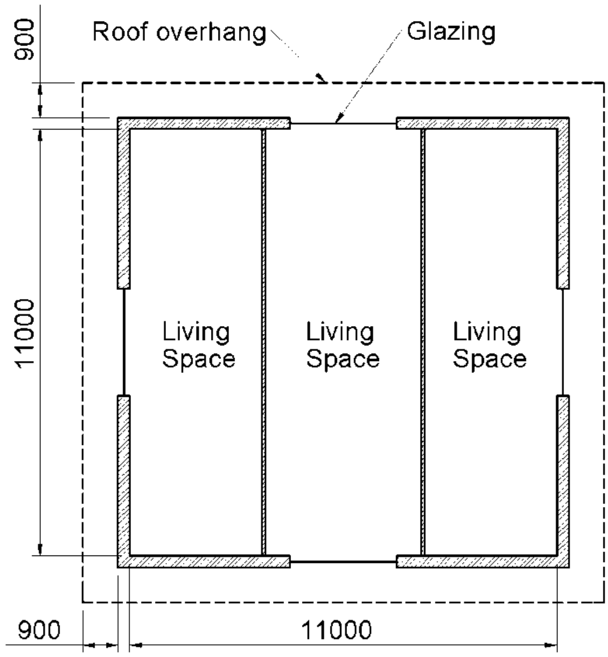

Figure 4.4 - Conventional house thermal model - floor plan

4.2.3.2 Material Properties

In general, default settings for materials from the DesignBuilder database were used i.e. conductivity, specific heat, density, thermal absorptance (emissivity) and solar absorptance. Where default settings were not used, references are given.

Table 4.4 - Wall Material Properties

Material	Density kg/m3	Specific Heat J/kg.K	Conductivity W/m.K	Thermal Absorptance (emissivity)	Solar Absorptance	Thermal Resistance m2.K/W (R value)	Where Used
Air gap >= 25mm (no foil)						0.18	Light Weight Internal
Air gap >= 25mm with foil (Robinson & Powlitch, 1954)						0.6	Brick Veneer Reverse Brick Veneer
Brick, mud	1730	880	0.750	0.9	0.6		Thermal Mass Internal Mudbrick Mudbrick with Insulation
Brickwork, inner leaf	1700	800	0.620	0.9	0.7		Double Brick Reverse Brick Veneer
Brickwork, outer leaf	1700	800	0.840	0.9	0.7		Brick Veneer Double Brick
Cement fibreboard, magnesium oxysulphide binder	350	1300	0.082	0.9	0.6		Reverse Brick Veneer Timber Frame
Concrete	2400	1000	1.400	0.9	0.6		Precast Concrete Insulated Panels
Concrete Blocks/tiles – block, hollow, heavyweight	1220	840	1.350	0.9	0.6		Concrete Block Insulated
Earth, common	1460	880	1.280	0.9	0.7		Earthship
Earth, rammed (CIBSE, 2006)	1960	840	1.210	0.9	0.7		Rammed Earth Rammed Earth with Insulation
Earth, rammed (Goodhew & Griffiths, 2005)	1800	630	0.55	0.9	0.7		Rammed Earth
Earth, rammed (Taylor, 2005)	2050	600	1.000	0.9	0.7		Rammed Earth Rammed Earth with Insulation
Expanded Polystyrene (EPS) (heavyweight)	25	1400	0.035	0.9	0.6		Timbercrete Super Insulator Block
Expanded Polystyrene (EPS) (standard)	15	1400	0.040	0.9	0.6		Concrete Block Insulated Mudbrick with Insulation Rammed Earth with Insulation Earthship
Extruded Polystyrene (XPS)	32	1400	0.028	0.9	0.6		Precast Concrete Insulated Panels
Glass fibre slab	25	1000	0.035	0.9	0.6		Brick Veneer Double Brick Reverse Brick Veneer Timber Frame
Plaster, dense	1300	1000	0.570	0.9	0.6		Cob

Material	Density kg/m3	Specific Heat J/kg.K	Conductivity W/m.K	Thermal Absorptance (emissivity)	Solar Absorptance	Thermal Resistance m2.K/W (R value)	Where Used
Plasterboard (wallboard)	900	1000	0.210	0.9	0.6		Brick Veneer Double Brick Light Weight Internal Reverse Brick Veneer Timber Frame
Render, external	1300	1000	0.570	0.9	0.6		Cob
Render, lime & sand	1600	1000	0.800	0.9	0.6		Mudbrick with Insulation Rammed Earth with Insulation Strawbale Earthship
Rubber	1500	1470	0.170	0.9	0.6		Earthship
Soil, alluvial clay, 40% sands	1960	840	1.210	0.9	0.6		Cob
Strawbale	125	1000	0.050	0.9	0.6		Strawbale
Wood, soft	593	2510	0.130	0.9	0.78		Light Weight Internal (bridging air gap)

Table 4.5 - Roof & Floor Material Properties

Material	Density kg/m3	Specific Heat J/kg.K	Conductivity W/m.K	Thermal Absorptance (emissivity)	Solar Absorptance	Thermal Resistance m2.K/W (R value)	Where Used
Steel	7800	450	50.000	0.3	0.3		Roof
Cellulose	48	1381	0.040	0.9	0.6		Roof
Plasterboard (ceiling)	900	1000	0.210	0.9	0.6		Roof
Cast concrete	2000	1000	1.130	0.9	0.6		Floor

Table 4.6 - Glazing Material Properties

Material	Outside Emissivity	Inside Emissivity	Conductivity W/m.K	Solar Transmittance	Outside Solar Reflectance	Inside Solar Reflectance	Where Used
Glass, generic clear 6mm thk	0.84	0.84	0.900	0.775	0.071	0.071	Internal windows
Glass, generic clear 4mm thk	0.84	0.84	1.00	0.816	0.075	0.075	External windows

Table 4.7 - Glazing Material Performance

Material	Total Solar Transmission (SHGC)	Direct Solar Transmission	Light Transmission	U-value (ISO 10292/EN673) W/m2.K	U-Value W/m2.K	Thermal Resistance m2.K/W (R value)	Where Used
Double glazed unit 4mm clear glass, 6mm air, 4mm clear glass	0.74	0.67	0.801	3.272	3.146	0.317*	External windows
Glass, generic clear 6mm thk	0.828	0.79	0.881	5.739	5.801	0.172*	Internal windows

* DesignBuilder calculation

4.2.3.3 External Wall type

Eighteen external wall types were included in the study. They were selected to represent a wide range of construction methods, from conventional to alternative, all of which were compared to the Earthship rammed-earth-tyre wall.

Timber frame, brick veneer and double brick were included as they are fairly common throughout Australia, whereas reverse brick veneer, although uncommon, was chosen as it is acknowledged as being a good method of positioning large amounts of thermal mass within the building envelope - a passive design principle(Hollo, 1995, pp. 30-33) - using fairly conventional construction methods that are achievable by the typical builder. Less common alternative constructions such as Strawbale, rammed earth, and mudbrick are included as these are perceived as environmentally friendly, energy efficient building methods. Refer to Table 4.8 for a full list of wall construction types and their abbreviations.

The selection of wall types also represent different approaches to providing thermal comfort: some walls rely on insulation, others use thermal mass, or a combination of insulation and thermal mass.

Wall types that are often used for “earth-sheltered” designs – in which walls have mounds of earth piled against them to form an earth berm – have been modelled with and without a berm and with and without external insulation, so that the effects of the berm and insulation can be ascertained. This is particularly relevant to the Earthship concept which would be more readily applicable to suburban environments if the berm was unnecessary. If insulation could replace the berm, issues such as the physical space required for a berm, and the unusual aesthetic of the berm could be overcome.

Another configuration of the Earthship wall that was investigated relates to Michael Reynolds’ innovation called the “Thermal Wrap” (Reynolds, 2000, p. 61), a vertical 100mm layer of expanded polystyrene foam (EPS) within the berm, offset 1200mm from the tyre wall. Simulations with and without the thermal wrap were conducted to ascertain whether this innovation is appropriate in the Adelaide climate.

The effect of adding insulation to mudbrick and rammed earth has also been modelled due to recent media reports that these constructions are not energy efficient despite anecdotal evidence to the contrary (Thomas, 2011).

4.2.3.4 Internal wall type

Two types of internal wall were investigated, “thermal mass” and “light weight”. The conventional light weight method of building internal walls in Australia is a timber (or steel) frame with plaster board lining whereas a thermal mass wall such as mudbrick, rammed earth, or fired brick is less common but is known to improve the thermal performance of the building (Hollo, 1995, pp. 30-33).

Internal walls are aligned north south as per the typical Earthship design at a spacing of 4 metres.

Including this variable enabled a direct comparison of the effects of the internal wall material on the heating and cooling load.

4.2.3.5 Nomenclature

An abbreviated name for each thermal envelope is defined by the components comprising it using the abbreviations in Table 4.8.

The naming structure for all variations is;

[External Wall] [Berm] [Internal wall] [Greenhouse] [%Window Area]

The External Wall classification refers to the layers of construction materials that comprise the wall. It does not include the berm. The inclusion of a berm is designated by the letter B. If a berm is not included in the wall construction a dash or a space is displayed where the “B” would otherwise appear. For the majority of wall types the Berm classification is not applicable.

The Internal wall type is designated next as either Thermal Mass (TM) or Light Weight (LW).

The inclusion of a greenhouse in the thermal envelope is designated by GH. If a greenhouse is not included in the thermal envelope a dash or a space is displayed where the “GH” would usually appear.

The window size is expressed as the percentage of glazed area in relation to the area of the equator facing wall.

Two examples:

SB - TM - 60 = Strawbale external wall (with no berm) with Thermal Mass internal walls, greenhouse not included, equator facing wall is 60% glazed.

ES B LW GH 80 = Earthship external wall, with berm, with Light Weight internal walls, greenhouse is included, equator facing (partition) wall is 80% glazed.

Table 4.8 - Thermal Envelope Components and their Abbreviations

Description	Abbreviation
External Walls	
Brick Veneer (with insulation)	BV
Concrete Block Insulated	CBI
Concrete Block Insulated, bermed	CBI B
Double Brick (with insulation)	DB
Earthship, bermed	ESB
Earthship, bermed with thermal wrap	ESTWB
Earthship, no berm	ES
Earthship, no berm, insulated	ESI
Mudbrick	MB
Mudbrick Insulated	MBI
Precast Concrete Insulated Panel	PCCIP
Precast Concrete Insulated Panel, bermed	PCCIPB
Rammed Earth	RE
Rammed Earth Insulated	REI
Reverse Brick Veneer (with insulation)	RBV
Strawbale	SB
Timbercrete Super Insulator Block	TCSIB
Timber Frame (with insulation)	TF
Internal walls	
Light Weight	LW
Thermal Mass	TM
Other	
Greenhouse	GH

4.2.3.6 Attached Greenhouse

The effect of attaching a greenhouse to the glazed, equator facing side of the house was investigated as this is a well-known passive solar design strategy (Hollo, 1995, p. 28; Mazria, 1979, p. 52-53) and is almost always employed in Earthship designs. Each thermal envelope was modelled both with and without the greenhouse to understand its effect.

The greenhouse is assumed to have 100% glazed area, with double glazed windows. The partition wall separating the greenhouse from the living space was modelled as a mudbrick wall 275mm thick with single glazing. This positions thermal mass effectively; for regulating the temperature in the greenhouse and transferring it to the living space (Hollo, 1995, pp. 28-29; Mazria, 1979, p. 181). The volume of this mass is affected inversely by the size assumed for the windows in this partition wall.

The greenhouse was modelled with double glazed windows and double brick walls with an insulated cavity (identical to the external wall type “Double Brick” described later - refer Table 4.3). This construction was used to model the greenhouse walls as it is similar in terms of the location of insulation and thermal mass to Reynolds’ “can walls” which use aluminium beverage cans in a thick mortar of cement, in a double leaf, insulated format (Reynolds, 1990, p. 157). This modelling approach (approximation) was favoured as it would be difficult to accurately simulate the “can wall” due to its unusual design.

The greenhouse equator facing glazing is angled at 60° (from horizontal),as per Reynolds’ specifications for maximising winter heat gain (Reynolds, 1990, p. 31), which is approximately perpendicular to the mid-winter sun in Adelaide, thereby maximising winter solar gain, but also creating a potential problem of overheating in the summer. Overheating has been addressed by internal blinds in these simulations; however, other shading strategies will be discussed later.

Figure 4.2 shows the thermal model design with greenhouse and Figure 4.3 shows it without the greenhouse.

4.2.3.7 Area of Glazing

This variable was included as it is well known that the amount of glazing has an effect on the heating and cooling load of the house. To minimise heating and cooling requirements the area of glazing must be carefully designed to balance solar gains with the house's capacity to react appropriately to this energy source, which is primarily a function of the thermal envelope's insulation and thermal mass characteristics. Mazria (1979) recommends a ratio of 11% to 25% of equator facing glass to floor area (p. 119-122) and for a design such as that modelled in this study, Baverstock (1986, p. 4-4) recommends a ratio of glass to wall (for the equator facing wall) of 63%.

The area of equator facing glazing was varied to establish the optimal area of glazing for each combination of external and internal walls, in terms of minimising the heating and cooling load. The optimal area of glazing was also contingent upon the presence (or not) of the attached greenhouse so the optimal glazing area was calculated for configurations with and without the greenhouse. NOTE: the area of external glazing of the greenhouse was constant at 100%. The varying glazed area in the case of the attached greenhouse configuration refers to the partition wall separating the greenhouse from the living area of the house – refer Figure 4.2.

4.2.4 Results & Discussion

Simulations were conducted for each external wall type (ref Table 4.8) combined with the light weight or thermal mass internal walls and each of these combinations was modelled with or without the greenhouse (refer Figure 4.2 and Figure 4.3). Each combination, characterised by external wall, internal wall and inclusion or exclusion of a greenhouse, was then modelled with a range of window areas of the equator facing wall to determine the optimal glazing area: the area at which the total heating and cooling load was minimised. The heating and cooling loads for each variation were recorded in a spreadsheet and totalled in kilowatt hours (kWh) per annum (unless stated otherwise).

The results of these simulations are presented and discussed below in terms of the effect of the various elements of the thermal envelope.

4.2.4.1 Optimal Glazed Area

The optimal glazed area was found to be quite small for the "with greenhouse" thermal envelopes whereas for the "without greenhouse" envelopes there was a wide range of optimal values based on their external wall type. In the case of the attached greenhouse envelopes, the optimal glazed area for the partition wall between the greenhouse and the living area was quite low, in the range of only 5 to 20 percent (refer Figure 4.5). This is at odds with current Earthship designs which have a partition wall that is approximately 90 percent glazed. The small glazed area for the "with greenhouse" design is optimal due to the need to limit heat gain from the greenhouse to the main living area (by conduction and radiation through the windows) during the summer; limiting heat loss in the winter may also be a factor. The optimal glazed area was determined by the quantity of thermal mass in the external walls: large quantities of thermal mass tended to have a higher optimal glazed area whereas the light weight designs required less glazed area for optimal performance.

For the "without greenhouse" thermal envelopes the optimal glazed area ranged from 30 to 70 percent (refer Figure 4.6) with a tendency for the envelopes with thermal mass internal walls to be optimal at a higher glazed area compared to the same envelope with light weight internal walls which required less glazed area for optimal heating/cooling performance. This was expected as it is well known that in a temperate climate, thermal mass constructions are better able to store energy from solar heat gain (and release it later when it is needed), compared to lightweight structures which rely on insulation as part of the approach to maintaining comfortable temperatures(Reardon, 2010). The results indicate that very large glazed areas - which are not good insulators - should be avoided (or augmented with close fitting curtains) for light weight structures.

For a given external wall type, the effect of internal wall type had varying effects on optimal glazed area. The "with greenhouse" envelopes' optimal glazed area was generally 5 to 10 percent higher for the thermal mass internal walls compared to the light weight internal walls. The exception to this was the insulated, bermed concrete blocks (CBI B) which had an optimal glazed area of 10 percent for both the thermal mass and light weight internal wall types.

The “without greenhouse” thermal envelopes were more sensitive to the internal wall type and again there was the universal result that thermal mass internal wall designs were optimal with more glazed area than the light weight internal wall designs. The optimal glazed area was 10 to 30 percent higher for the thermal mass internal walls compared to the light weight walls.

Establishing the optimal glazed area seems sensible in terms of improving energy efficiency; however, for many envelope types it was not critical; glazed areas higher than optimal generally did not result in large increases in the heating and cooling load in absolute terms; however, for highly energy efficient designs (i.e. SB – TM GH and ESTW B GH) the load may actually double e.g. for the Earthship from approximately 500kWh p.a. to 1000kWh p.a. Also, for the lightweight envelope (TF – LW) the glazed area did have a substantial impact, especially when there is an attached greenhouse. The glazed area is therefore quite influential on heating and cooling energy for some construction types and not so for others, although this depends on whether the comparison is absolute or relative.

To ensure adequate natural lighting and views to the greenhouse and outdoors, the glazed area may need to be slightly above optimal. A value of 50 percent glazing was calculated to provide adequate natural light (refer to Table 4.9). The daylight factor and interior illumination level (Ei) for the various areas of glazing were calculated by equations given by Assisted Interior Design () assuming that the outdoor illumination level was 5000lux.

For the LCA study which will be discussed in Chapter 5-7, it was decided to adopt the results for thermal envelopes with a figure of 50 percent of glazed area rather than the optimum glazed area, which varied for each thermal envelope, as this would cause complexity in terms of calculating material quantities for the various thermal envelopes and, what is more, it might be argued that homes with differing areas of glazing were not “functionally equivalent”, for example, due to differing quantities of natural light (and hence different energy use for lighting) and different feelings of wellbeing. Furthermore, a 50 percent glazed area of equator facing wall represents an approximate average in terms of the optimum (minimum) heating and cooling load for the various thermal envelopes: for “with greenhouse” envelopes the optimum was often lower than 50 percent, whereas “without greenhouse” envelopes the optimum was generally higher than 50 percent, and the effect of increased areas of glazing for the “without greenhouse” envelopes was minimal. Thus this approximation seemed reasonable and greatly facilitates the presentation and discussion of the results.

Hence many of the following analyses in this section of the thesis use the results for 50 percent glazed area as the basis for analysis and discussion.

Table 4.9 - Illumination Level Calculations

Glazed Area %	total window area (m^2)	total floor area (m^2)	% glazed to floor area	Daylight factor	Ei (lux)
5	2.725	121	2.25	0.23	11
10	5.455	121	4.51	0.45	23
20	10.905	121	9.01	0.90	45
30	16.36	121	13.52	1.35	68
40	21.815	121	18.03	1.80	90
50	27.265	121	22.53	2.25	113
60	32.72	121	27.04	2.70	135
70	38.17	121	31.55	3.15	158
80	43.625	121	36.05	3.61	180
90	49.08	121	40.56	4.06	203
100	54.53	121	45.07	4.51	225

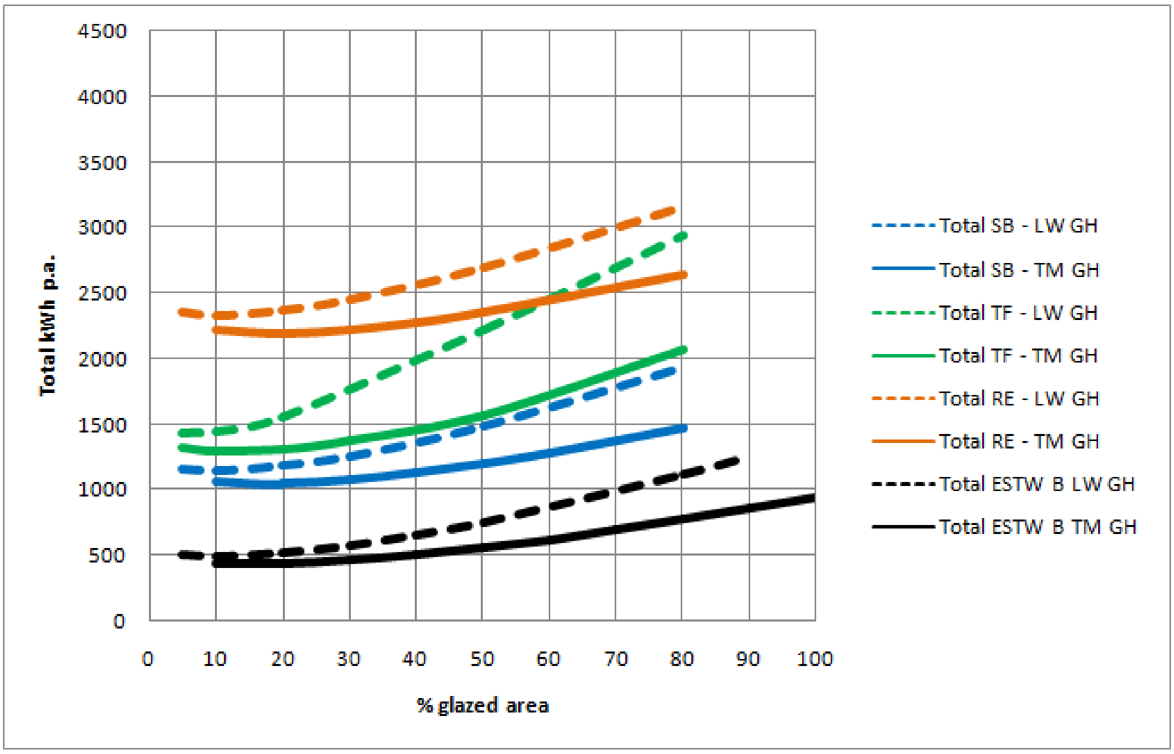

Figure 4.5 - Total Heating and Cooling Loads With Greenhouse for various glazed areas

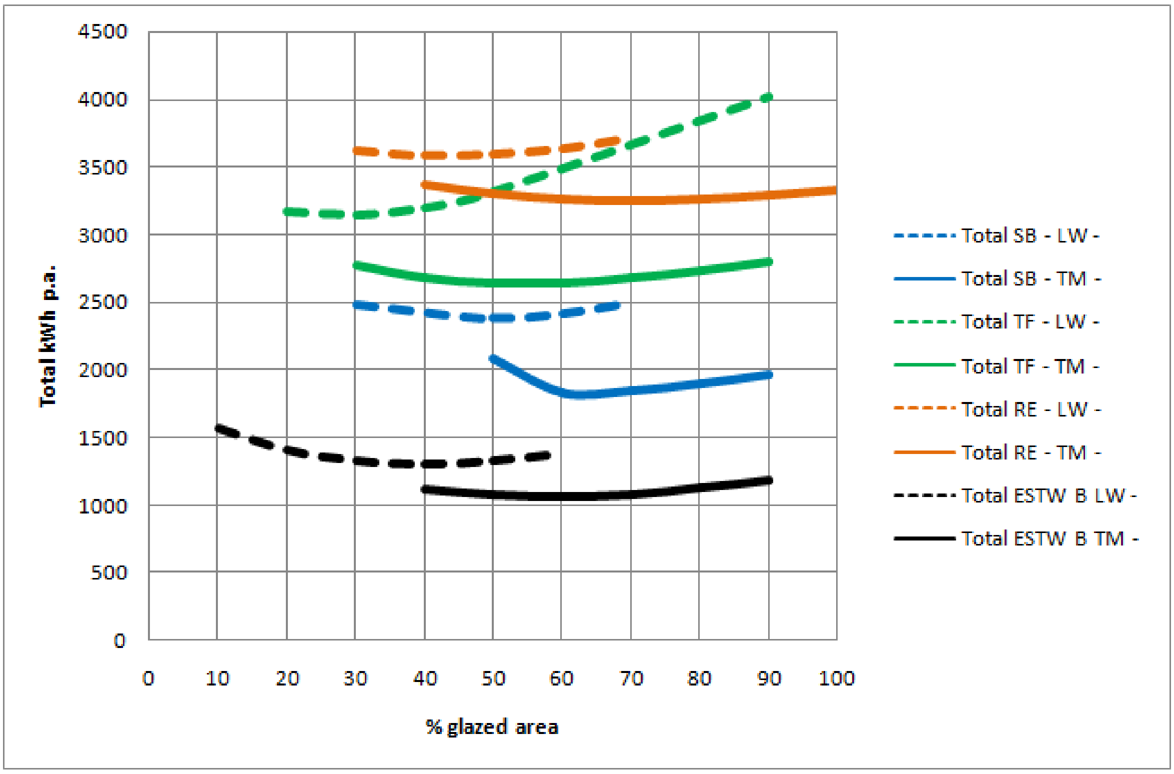

Figure 4.6- Total Heating and Cooling Loads Without Greenhouse for various glazed areas

4.2.4.2 Effect of the Greenhouse on Optimal Glazed Area

Figure 4.5 and Figure 4.6 also reveal the effect of the greenhouse. For the “without greenhouse” thermal envelope designs, as the glazed area increases above optimal, the increased energy usage is fairly minimal – the curves are generally quite flat. Thus there is scope to increase the glazed area (of the equator facing wall) to improve views or natural lighting without significantly increasing the heating/cooling load. In contrast, the energy use of the “with greenhouse” envelopes increase at a greater rate than the “without greenhouse” envelopes, because of the high temperatures in the greenhouse which tend to be conducted through large single glazed parts of the partition wall with the living area.

The Timber Frame external wall with light weight internal wall (TF LW) follows this general pattern but has a higher rate of increased energy use as the glazing increases in area, indicating that very large glazed areas for a construction such as this, combined with a greenhouse, should be avoided (as they will need substantial HVAC requirements).

4.2.4.3 Effect of the Greenhouse on Heating and Cooling load

Figure 4.7 displays the heating and cooling loads for the “with greenhouse” and “without greenhouse” configuration of each thermal envelope combination of external and internal wall type. The potential energy saved for each configuration (with 50 percent glazed area) due to the presence of the greenhouse is shown by the black bar. The results are ranked by the amount of energy saved due to the greenhouse, on an annual basis in kWh.

Timber Frame (TF) and Brick Veneer (BV) benefit the most indicating that retrofits of equator facing greenhouses may be particularly useful for these wall types, provided substantial quantities of thermal mass can also be retrofitted into the design. (For the “with greenhouse” envelope models the partition wall was adobe and 50% glass rather than the external wall construction material). The insulated, non-bermed Earthship (ESI -) benefits similarly. In contrast, the designs that are inherently more energy efficient do not benefit as much from the greenhouse. (The benefit for them is approximately 500-700kWh p.a. which is still a substantial energy saving.)

In summary, when coupled with a small to moderate amount of glazing in the partition wall, which is assumed to be made from thermal mass materials such as adobe, the greenhouse contributes to significant energy savings by reducing heating loads, albeit with a slight increase in cooling loads (heating/cooling breakdown is discussed in the following section). Shading of the greenhouse in summer (e.g. via reflective automatically controlled blinds) may be necessary to achieve these results although the effect of using blinds was not tested in this study. Natural ventilation techniques and the use of earth tubes (which are typical of the Global Model Earthship design, but were not modelled) may also help to address high indoor temperature.

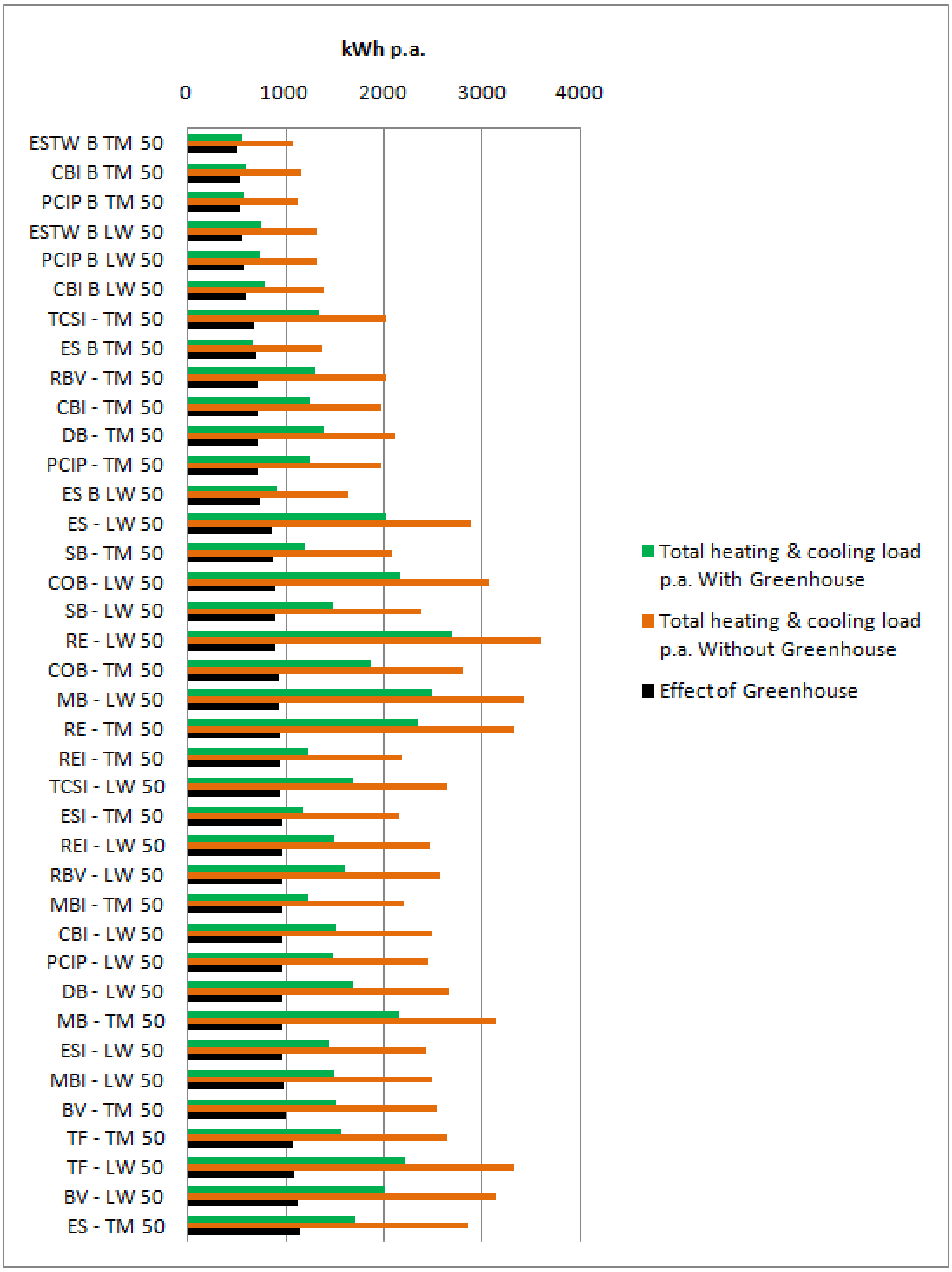

Figure 4.7 - Total Heating and Cooling Load With and Without Greenhouse and Energy Savings due to Greenhouse

4.2.4.4 Influential drivers of Heating and Cooling Loads

To better understand how the design of the thermal envelope affected energy use, the heating and cooling loads were plotted separately for a selection of external wall types with various quantities of thermal mass and insulation: Strawbale, Timber Frame, Rammed Earth, and Earthship with Thermal Wrap and Berm (refer Figure 4.8 - Figure 4.11).This analysis reveals that in Adelaide the heating load is always dominant with only one exception, the ESTWB TM GH (Figure 4.11) which has a dominant cooling load when the glazed area is approximately 80 percent or above probably due to excessive conduction of hot greenhouse air with the living spaces (during summer) caused by the large glazed area.

There is an almost linear relationship between glazed area and the cooling load regardless of the configuration of the thermal envelope. The cooling load is usually decreased by thermal mass internal walls when compared to light weight internal walls, and this is more pronounced for the thermal envelopes with a greenhouse combined with large glazed areas; however, in general the effect of internal wall type on the cooling load is minimal or negligible. The heating load is also decreased by a thermal mass internal wall when compared to a light weight internal wall; however, this effect is far greater than the cooling effect and is more pronounced for designs without a greenhouse.

There was a high degree of consistency in terms of the effect of the internal wall material in both the "with greenhouse" and "without-greenhouse" thermal envelopes. The envelopes with thermal mass internal walls (TM) increased the opportunity for the building to enjoy a larger glazed area, and with decreased heating and cooling loads, whereas light weight internal walls (LW) require a smaller less glazed area to achieve the minimum heating and cooling load and had a higher energy requirement than the equivalent thermal mass design. This can be explained by the capacity of the thermal mass to absorb the solar heat gains and regulate the indoor temperature appropriately, whereas light weight designs are not able to absorb as much heat and consequently they require less solar heat gain to function optimally for their design type, but ultimately cannot achieve the same level of energy efficiency.

These findings are consistent with passive solar design principles which recommend the inclusion of thermal mass inside the building envelope (Hollo, 1995, pp. 30-33).

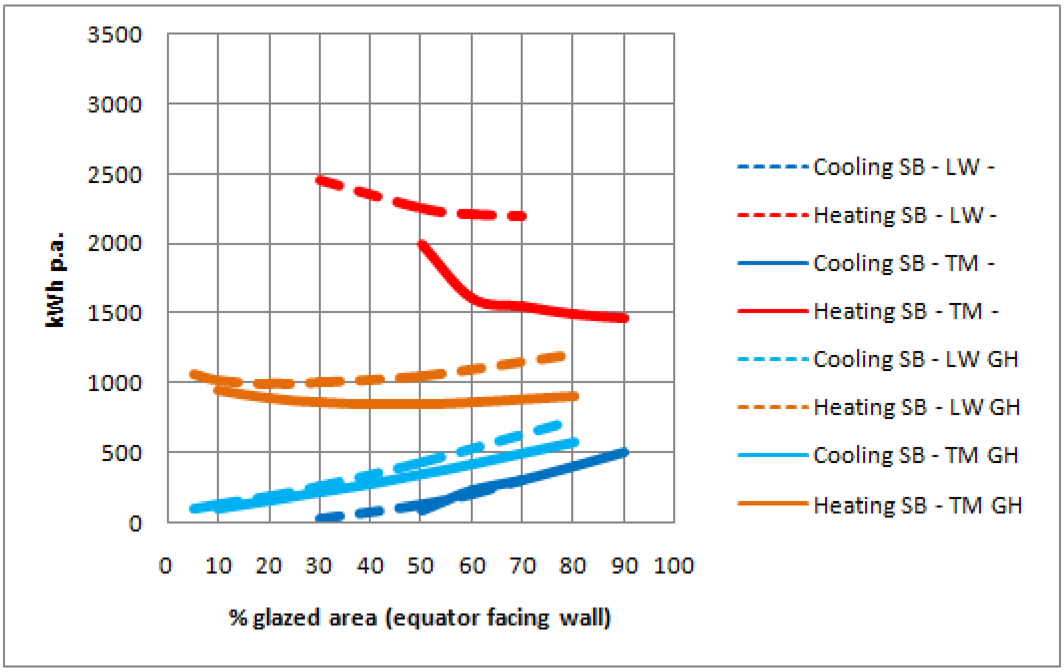

Figure 4.8 - Effect of internal wall type and greenhouse on heating &cooling load on Strawbale external wall envelope

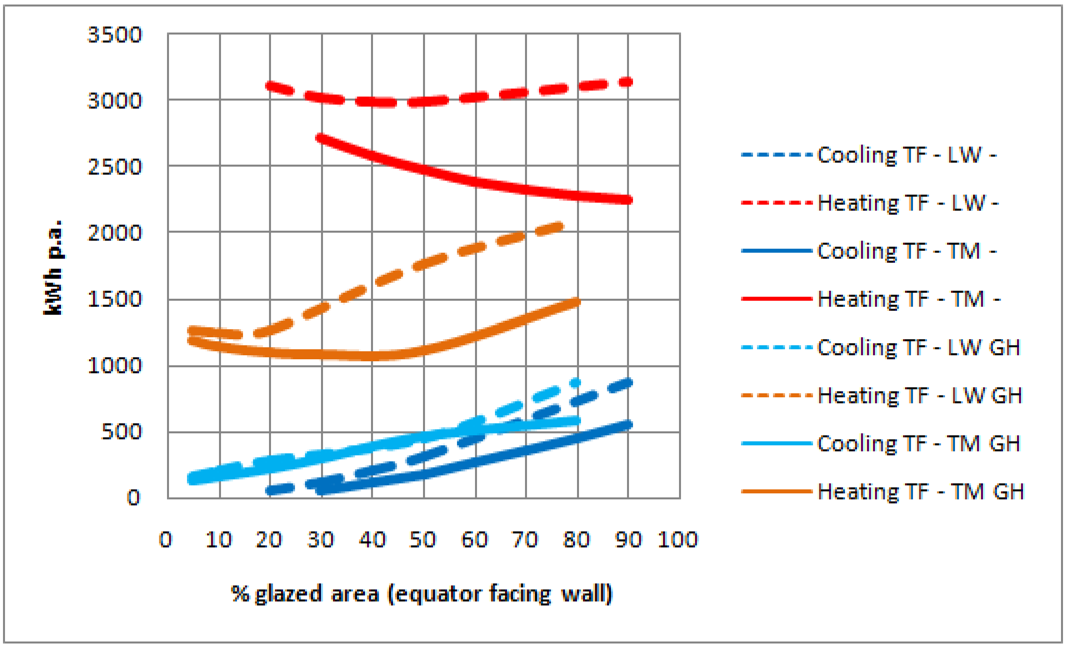

Figure 4.9 - Effect of internal wall type and greenhouse on heating &cooling load on Timber Frame external wall envelope

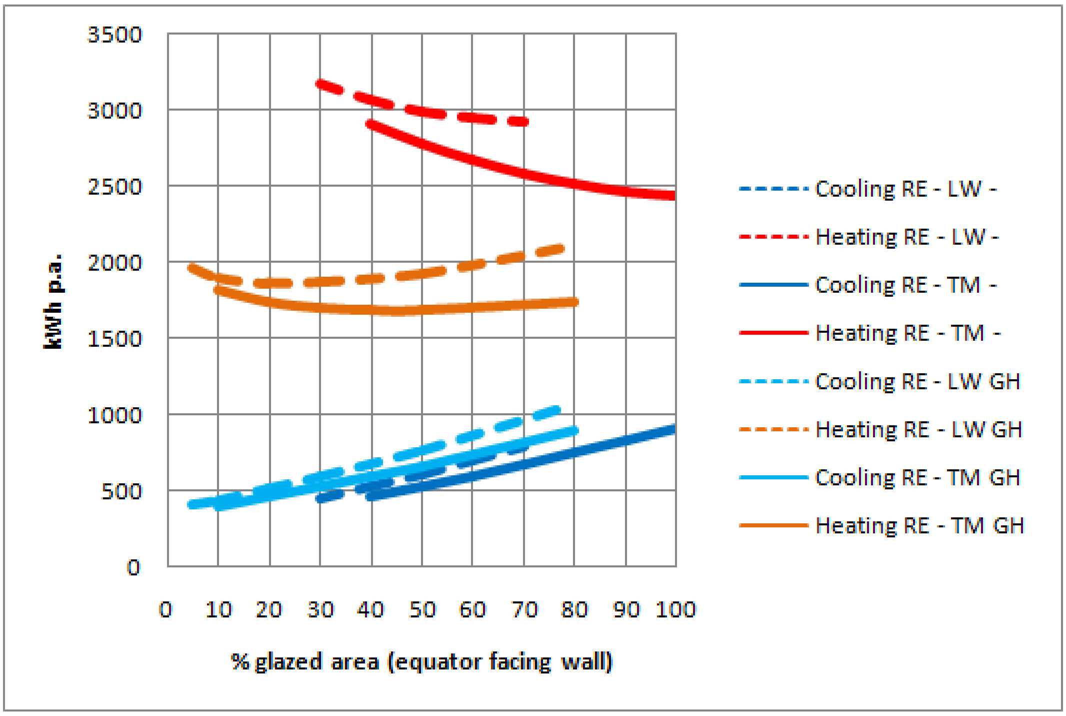

Figure 4.10 - Effect of internal wall type and greenhouse on heating &cooling load on Rammed Earth external wall envelope

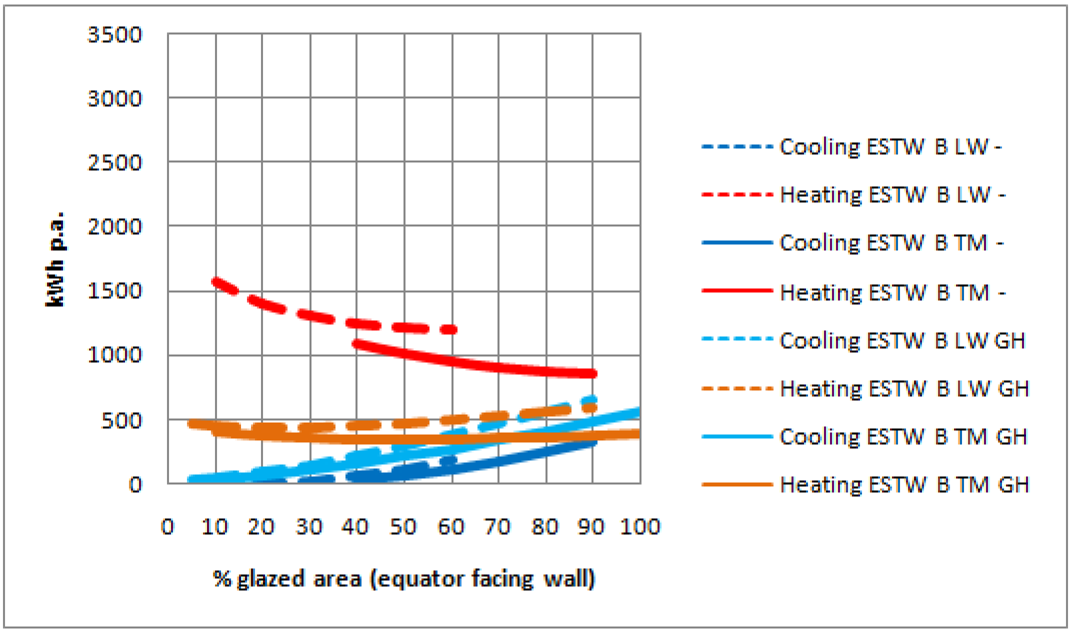

Figure 4.11 - Effect of internal wall type and greenhouse on heating &cooling load on Earthship with Thermal Wrap and Berm external wall envelope

4.2.4.5 Effect of the Berm

Figure 4.12 presents the energy saving due to the berm for thermal envelopes with a glazed area of 50 percent. Only external wall types which were deemed to be structurally capable of withstanding the significant forces exerted by the berm were modelled. Thermal envelopes are compared on the basis that one has a berm whereas the other does not, yet the external wall construction is basically identical. (Note that ESTW indicates insulation positioned within an Earthship berm, whereas ESI indicates an Earthship wall (rammed earth tyres) with a layer of insulation on the exterior side of the tyre wall in the absence of a berm.)

The total heating and cooling load for the bermed configuration is listed followed by the non-bermed configuration, then the net energy saving which is labelled the “berm effect”. The results are listed in order of the net energy saving arising from the berm.

It can be seen that the berm reduces energy use in the order of 40-60 percent compared to the non-bermed counterpart indicating that it is a significant energy saving measure.

Less energy efficient thermal envelopes, such as the uninsulated Earthship without greenhouse, benefits the most from a berm. Not surprisingly, thermal envelopes that are inherently energy efficient do not benefit greatly from the berm in terms of net energy saved but may save a similar amount of energy relative to their non-bermed counterpart.

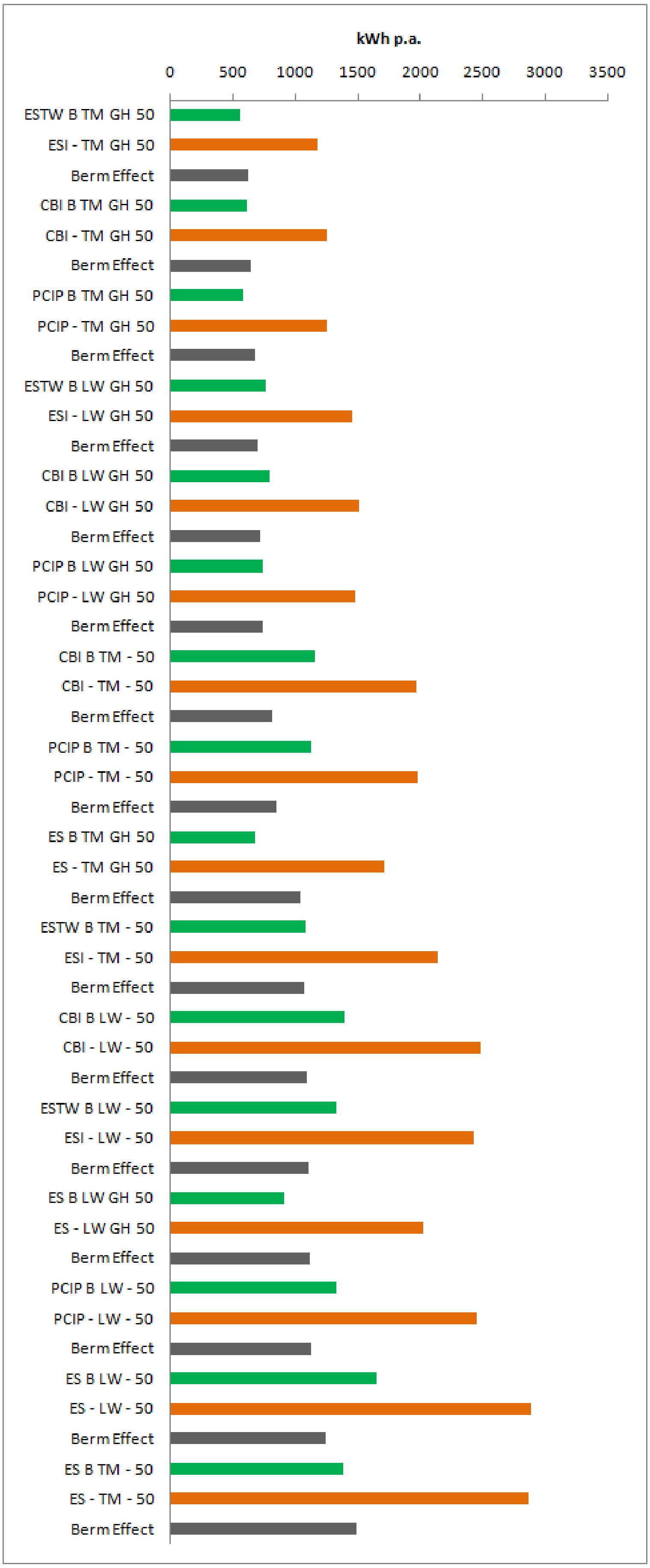

Figure 4.12 - Energy Saving due to Berm

4.2.4.6 Rammed Earth Material Properties Study

The results already presented for rammed earth envelopes, assume certain thermal properties for rammed earth by Taylor (2005, pp. 7-6) as these were calculated in the context of a temperate Australian climate; however, due to the variable nature of earth and earth construction methods further simulations were conducted to establish the effects of various assumptions regarding the thermal properties. A review of the literature was undertaken and two more sets of values were selected (CIBSE, 2006; Goodhew & Griffiths, 2005), one with higher conductivity and one with lower conductivity than that reported by Taylor. The thermal properties of rammed earth from these three studies are shown in Table 4.10.

Table 4.10 - Rammed Earth Property Variations

Material	Density kg/m3	Specific Heat J/kg.K	Conductivity W/m.K
Earth, rammed (CIBSE, UK)	1960	840	1.210
Earth, rammed (Goodhew)	1800	630	0.55
Earth, rammed (Taylor)	2050	600	1.000

These variations of the properties of a rammed earth external wall were simulated in a thermal envelope with thermal mass internal walls , no greenhouse (and no berm)(RE-TM).The results for various glazed areas are shown in Figure 4.13. The results were as expected; the higher conductivity assumption (CIBSE) led to reduced energy efficiency. The graph shows this as higher energy use for heating and cooling, in kWh pa. Further modelling and research would be valuable, however it was decided that Taylor's properties provided useful data for this study. This discussion is also relevant to the thermal performance of other earth construction types such as Earthship and mudbrick, however for the purposes of this study the values used in the simulations (as reported in Table 4.4) are deemed to be sufficiently accurate.

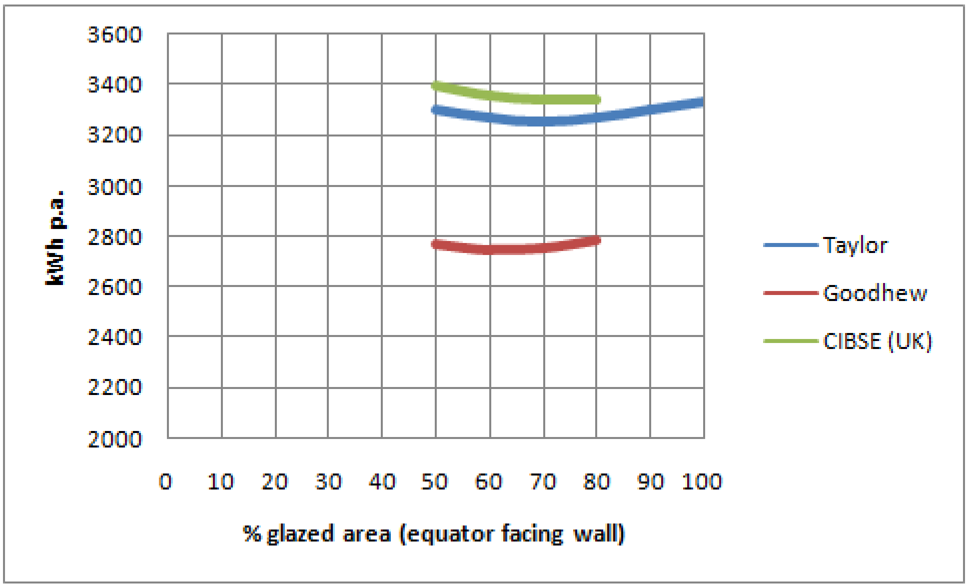

Figure 4.13 - Rammed Earth properties, sensitivity study

4.2.4.7 Effect of Insulation Versus No Insulation

The following graph shows the effect of insulation for the 50 percent glazed envelopes. It compares a thermal envelope with insulation (refer to Table 4.3 for the quantity and type of insulation used) to the same envelope without insulation (not all envelope types had this pairing). Results are ordered from least energy saving (due to insulation) to most energy saving.

As discussed elsewhere the positive effect of the Earthship's "thermal wrap" insulation is evident but is not great. The greatest benefit is gained by the rammed earth and mudbrick constructions which save in the order of 900-1200 kWh pa, almost halving their total heating and cooling load in some cases.

Figure 4.15 shows the effect of the thermal wrap in terms of the effect on the cooling load and the heating load (rather than the total heating and cooling load) in two types of Earthships; one with and one without a greenhouse. Both have thermal mass internal walls. The thermal wrap significantly reduces the heating load and increases the cooling load slightly in both Earthships (with and without greenhouse). This result indicates that the thermal wrap is beneficial overall, reducing the total heating and cooling energy, yet in the summer it is detrimental as it increases the indoor temperature.

Figure 4.14 - Effect of Insulation on total heating and cooling load

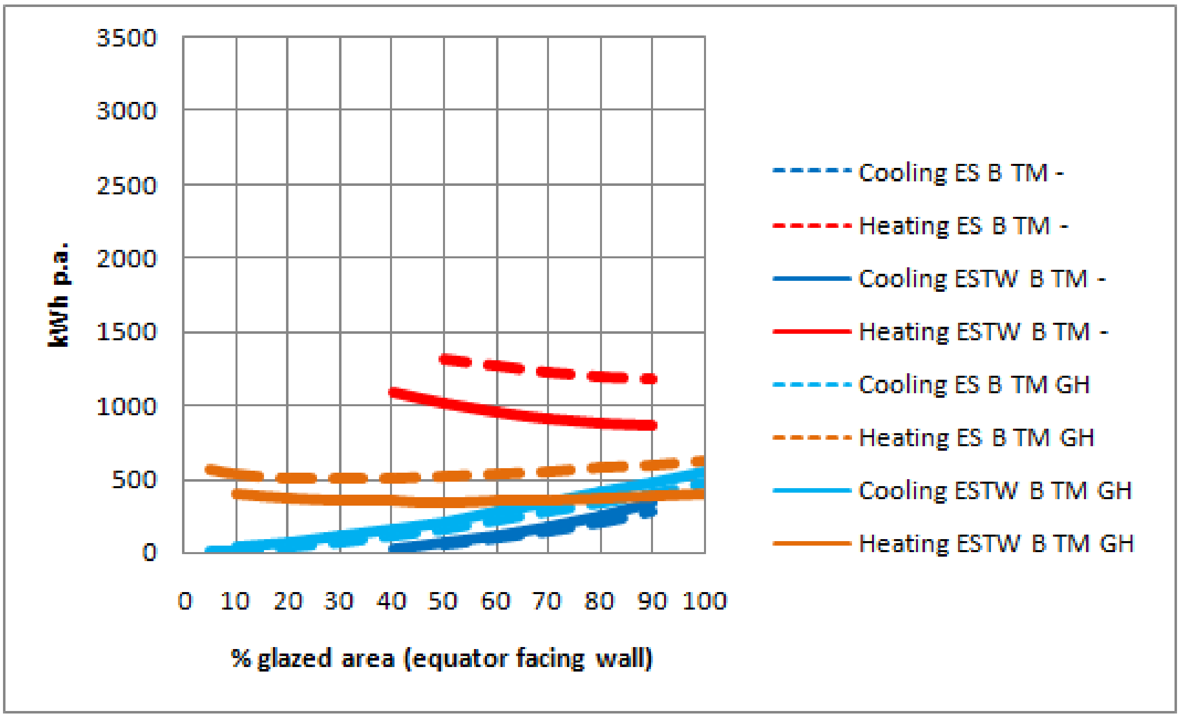

Figure 4.15 - Effect of thermal wrap (insulation in berm) on heating and cooling loads in Earthships with thermal mass internal walls

4.2.4.8 Effect of External wall Material

The effect of the external wall construction has been analysed by categorising the optimal heating and cooling load results according to the configuration of the thermal envelope. Categories used for the analysis are shown in Table 4.11.

Table 4.11- Categories of Thermal Envelope Configurations

Category	Berm	Internal wall Type	Greenhouse
1	Included	Thermal mass	Included
2	Included	Light weight	Included
3	Included	Thermal mass	Not included
4	Included	Light weight	Not included
5	Not included	Thermal mass	Included
6	Not included	Light weight	Included
7	Not included	Thermal mass	Not included
8	Not included	Light weight	Not included

Table 4.12 presents the results for a 50 percent glazed area thermal envelope. For clarity, categories without greenhouse are highlighted and all lightweight internal wall categories are listed in the right column, thermal mass internal wall categories in the left column. This analysis shows that in each category there is a similar pattern in terms of the order of the external wall types, based on energy demand. For example it can be seen that for the bermed envelopes (categories 1,2,3,4) the Thermal Wrap Earthship (ESTW B) and the Precast Concrete Insulated Panel (PCIP B) perform best, whereas the Insulated Concrete Block (CBI B) and the Earthship without the Thermal Wrap (ES B) are consistently ranked third and fourth respectively. Thus, the energy demand ranking is largely determined by external wall type.

Likewise, when comparing the non-bermed envelopes (categories 5,6,7,8), regardless of the greenhouse and the internal wall type, a similar pattern emerges, the energy demand ranking is determined by external wall type. Strawbale, Insulated Earthship, Insulated Rammed Earth, Precast Concrete Insulated Panels, Insulated Mudbrick tend to perform best, whereas Rammed Earth, Mudbrick and Timber Frame tend to perform less well. This is not surprising as the external wall represents a substantial component of the thermal envelope where heat exchange occurs between outdoor and indoor air. In the absence of more influential factors such as the greenhouse and the berm, the external wall type plays a significant role.

Table 4.12 - Analysis of effects of External wall type

Wall Abrv With thermal mass internal walls	Total heating & cooling load kWh p.a.	Cat. from Table 4.11	Wall Abrv With lightweight internal walls	Total heating & cooling load kWh p.a.	Cat. from Table 4.11
ESTW B TM GH 50	558	1	PCIP B LW GH 50	739	2
PCIP B TM GH 50	575	1	ESTW B LW GH 50	756	2
CBI B TM GH 50	605	1	CBI B LW GH 50	795	2
ES B TM GH 50	678	1	ES B LW GH 50	908	2
ESTW B TM - 50	1076	3	PCIP B LW - 50	1321	4
PCIP B TM - 50	1127	3	ESTW B LW - 50	1323	4
CBI B TM - 50	1156	3	CBI B LW - 50	1388	4
ES B TM - 50	1380	3	ES B LW - 50	1647	4
ESI - TM GH 50	1178	5	ESI - LW GH 50	1448	6
SB - TM GH 50	1196	5	PCIP - LW GH 50	1477	6
REI - TM GH 50	1229	5	SB - LW GH 50	1483	6
MBI - TM GH 50	1230	5	REI - LW GH 50	1494	6
PCIP - TM GH 50	1246	5	MBI - LW GH 50	1503	6
CBI - TM GH 50	1248	5	CBI - LW GH 50	1509	6
RBV - TM GH 50	1307	5	RBV - LW GH 50	1599	6
TCSI - TM GH 50	1338	5	TCSI - LW GH 50	1688	6
DB - TM GH 50	1396	5	DB - LW GH 50	1691	6
BV - TM GH 50	1522	5	BV - LW GH 50	2004	6
TF - TM GH 50	1572	5	ES - LW GH 50	2021	6
ES - TM GH 50	1710	5	COB - LW GH 50	2166	6
COB - TM GH 50	1869	5	TF - LW GH 50	2221	6
MB - TM GH 50	2157	5	MB - LW GH 50	2486	6
RE - TM GH 50	2350	5	RE - LW GH 50	2693	6
CBI - TM - 50	1966	7	SB - LW - 50	2382	8
PCIP - TM - 50	1972	7	ESI - LW - 50	2426	8
RBV - TM - 50	2021	7	PCIP - LW - 50	2446	8
TCSI - TM - 50	2027	7	REI - LW - 50	2461	8
SB - TM - 50	2080	7	CBI - LW - 50	2479	8
DB - TM - 50	2122	7	MBI - LW - 50	2485	8
ESI - TM - 50	2141	7	RBV - LW - 50	2567	8
REI - TM - 50	2188	7	TCSI - LW - 50	2647	8
MBI - TM - 50	2199	7	DB - LW - 50	2662	8
BV - TM - 50	2530	7	ES - LW - 50	2887	8
TF - TM - 50	2647	7	COB - LW - 50	3063	8
COB - TM - 50	2797	7	BV - LW - 50	3135	8
ES - TM - 50	2863	7	TF - LW - 50	3314	8
MB - TM - 50	3134	7	MB - LW - 50	3418	8
RE - TM - 50	3304	7	RE - LW - 50	3595	8

4.2.4.9 Earthship Variations Analysis

This analysis compares the results of various Earthship wall envelopes so that the effect on energy demand of design features such as the thermal wrap, and attached greenhouse can be seen clearly, and to explore the effects of non-bermed Earthships - with and without insulation – which would more easily fit within a suburban context. Total heating and cooling load per annum for eight variations of the Earthship wall are presented in Figure 4.16.

The effect of the berm, greenhouse, wall insulation and internal walls has been discussed previously so this will not be repeated; however, in summary, assuming a 50 percent glazed equator facing wall with thermal mass internal walls, the ranking (by energy demand) from best performance to poorest performance is as follows:

- Berm with insulation, with greenhouse (ESTW B GH)
- Berm (without insulation in berm), with greenhouse (ES B GH)
- Berm with insulation, without greenhouse (ESTW B)
- Unbermed, insulated with greenhouse (ESI GH)
- Berm (without insulation in berm), without greenhouse (ES B).
- Unbermed, uninsulated, with greenhouse (ES- GH).
- Unbermed, insulated, without greenhouse (ESI) i.e. adding a layer of insulation (100mm thick expanded polystyrene) and render to the exterior of the tyre wall.
- Unbermed, uninsulated, without greenhouse (ES-).

Not surprisingly, the best performing Earthship envelope includes the berm, insulation in the berm (thermal wrap), thermal mass internal walls, and a greenhouse (ESTW B TM GH). This is the configuration employed by the Global Model Earthship. These results suggest that Reynolds' thermal wrap innovation, and his use of thermal mass internal walls would work well in the Adelaide climate.

Regardless of the internal wall type, the insulated non-bermed Earthship with greenhouse (ESI – GH) performs well – better than the "original" Earthship design (ES B). This indicates that a compact design for the suburbs is feasible, although a significant floor space penalty would still occur due to the width of the insulated tyre wall (approximately 800mm).

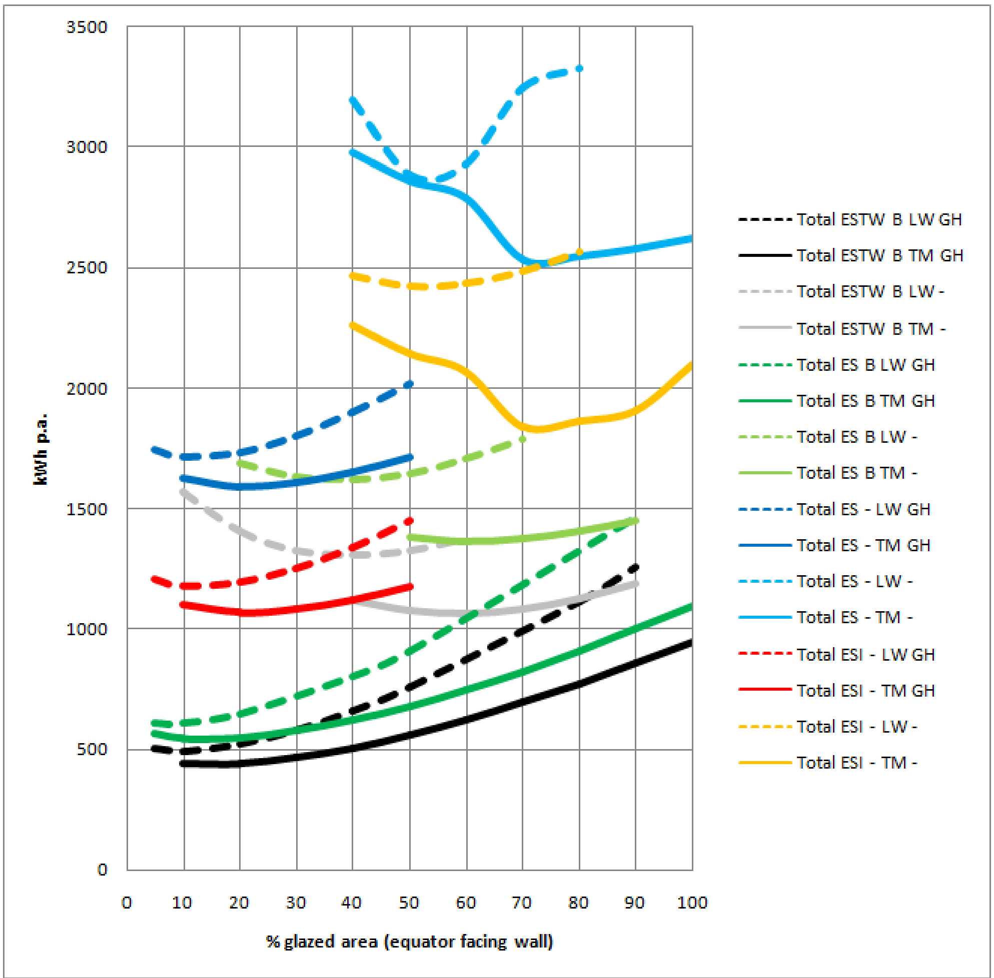

Figure 4.16 - Total Heating & Cooling Load of Earthship Variants

4.2.4.10 Conventional House Study

The main focus of this main thermal modelling study was a passive solar home based on the Earthship and the effect of variations in the materials used to construct the thermal envelope. To make a comparison to a conventional house design a brief modelling exercise was conducted in which the floor plan and glazing arrangement was altered to approximate a more conventional home. The design and construction of the "conventional house" is described in 4.2.2.4

The study found that the thermal performance of the "conventional design" was comparable to the two worst performing passive solar envelopes: Mudbrick with lightweight internal walls (MB LW) and Rammed Earth with lightweight internal walls (RE LW). Compared to the passive solar envelope constructed with exactly the same materials (Timber Frame external walls and lightweight internal walls) it requires approximately 13% more energy for heating and cooling. Compared to the Earthship with Berm, thermal wrap (insulation) and greenhouse (ESTW B GH) it requires approximately 6 times more energy for heating and cooling.

4.2.4.11 Heating and cooling load ranking

Figure 4.17 presents heating and cooling energy loads as well as the total in kWh p.a. for the whole house (e.g. not per m^2) for each thermal envelope with 50 percent glazed area. The results are ranked in terms of total energy load.

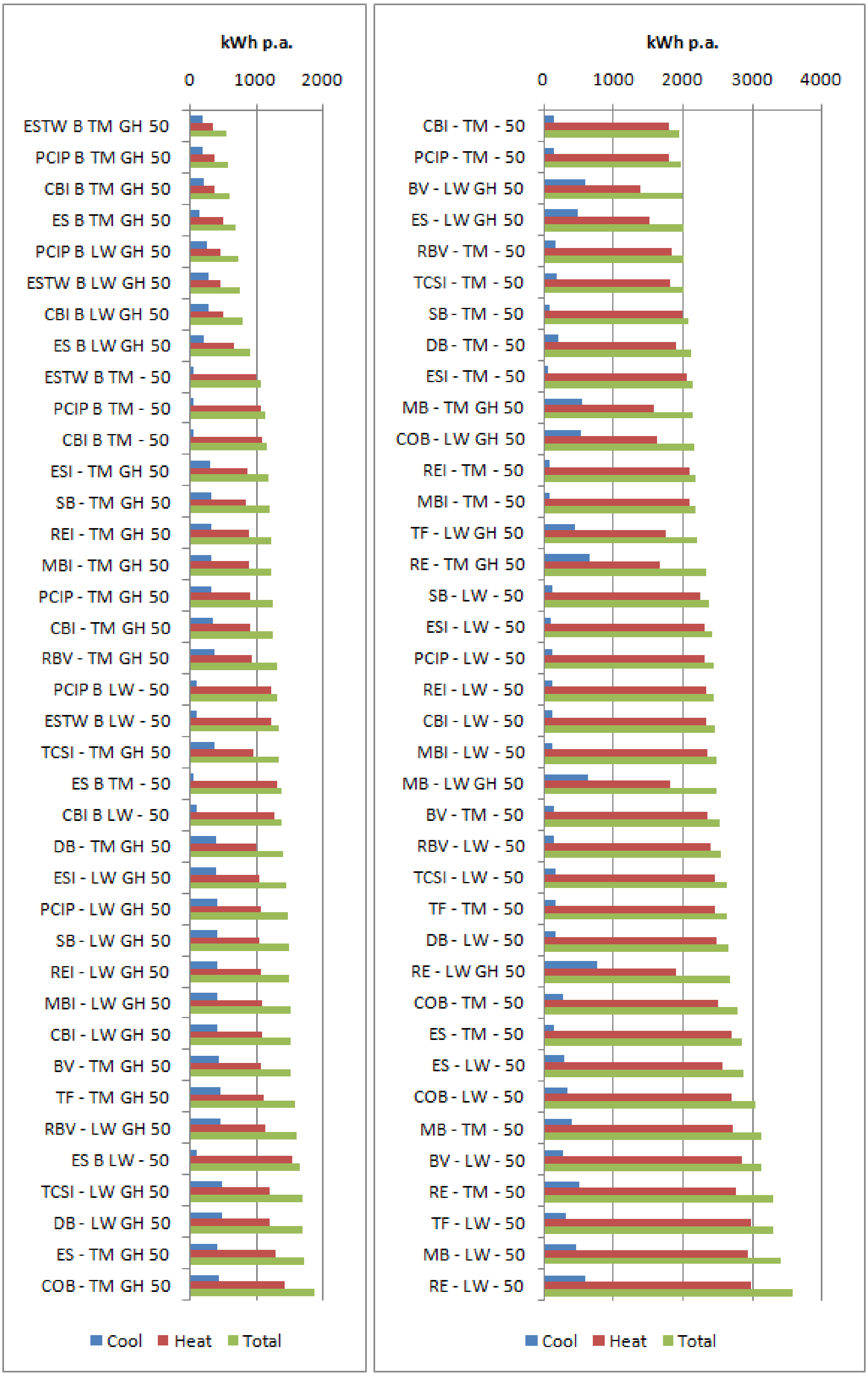

Figure 4.17 - Heating & Cooling Load Results for 50 percent glazed area

The results show that the most energy efficient designs include a berm, greenhouse and thermal mass internal walls. The Global Model Earthship envelope ESTW B TM GH has the least energy load of all; however, similar thermal performance is achievable with concrete block or concrete insulated panel construction, if both have a berm, greenhouse and thermal mass internal walls.

The least energy efficient designs are those without a berm or greenhouse and generally feature lightweight internal walls. The least efficient envelope is Rammed Earth, lightweight internal wall (RE LW). It is interesting to note that when a layer of 100mm expanded polystyrene insulation is added to the exterior of the rammed earth wall and thermal mass internal walls are incorporated (REI TM) the energy use decreases by approximately a third.

4.2.5 Summary

This study supports the common wisdom regarding energy efficient buildings: heating and cooling loads in a temperate climate such as Adelaide can be minimised by ensuring that windows are appropriately sized, oriented, shaded, and (preferably) double glazed, and that thermal mass is positioned inside a well-insulated shell, either by inner leaves of thermal mass in the main walls, or by thermal mass internal walls. It also supports the literature on earth sheltered/covered architecture which cites minimal (or zero) need for heating and cooling due to the beneficial ground temperature cycles (Baggs, Baggs & Baggs, 1985). The reported benefit of attached greenhouses (Mazria, 1979) is also supported by the study.

Anecdotal evidence from Earthship dwellers and from the author’s observations and research (Freney, 2009) is that standard Earthship designs require little, if any, heating and cooling to remain comfortable. The results presented above support this claim, and the general agreement between current knowledge and this study’s results give confidence that the results are credible and suitable for informing the LCA study.

Studies of various options for constructing Earthship walls investigated the suitability of an unbermed tyre wall for suburban contexts where the size and appearance of the berm may be problematic. It found that a non-bermed, insulated Earthship design, is comparable to other energy efficient designs such as Strawbale. These studies also reveal that the use of the thermal wrap has somewhat marginal energy benefits in the Adelaide climate (which does not experience the extremely cold winters that Taos does). In Adelaide the thermal wrap decreases the winter heating load but increases the cooling load. This finding indicates that in temperate climates, the thermal wrap may become less important for reducing operational energy.

4.3 Study 2: Simulation and Calibration of the Earthship home in Taos

Subsequent to Study 1, a field trip to Taos, New Mexico, USA, was conducted to undertake a post occupancy evaluation of Earthship homes, not only to evaluate the actual performance of these homes as already discussed in Chapter 3, but also to collect data to enable calibration of the thermal simulation model of an Earthship home. This Section describes the calibration method and simulation results. This calibration process is necessary to ensure that the way the Earthship design was modelled was correct so that the model can be used for further analyses, including to test the suitability of an Earthship design in climates other than in its origin, New Mexico, USA.

4.3.1 Introduction

The method used to monitor indoor and outdoor conditions of various Earthships in Taos, New Mexico, USA, has been described in Chapter 3 Post Occupancy Evaluation. Study 2 uses the data collected in one of the monitored Earthships - the Global Model Earthship referred to as House #1 in Chapter 3 - to calibrate a simulation model of the building, using DesignBuilder®/EnergyPlus® (DesignBuilder, 2013b). Particular effort was invested in developing an improved method for estimating the ground temperature, a factor that has great bearing on indoor comfort conditions in an earth sheltered design such as the Earthship.

The weather data that were collected in the POE study were augmented in this study by a third party supplier; solar radiation and wind speed were obtained via Weather Analytics and combined into an EPW file format with the outdoor temperature and relative humidity data collected in the POE study. The Weather Analytics system uses the Global Data Assimilation System (GDAS) which "orchestrates the collection, quality control and preprocessing of raw in situ and remote sensor data from a wide array of sensor systems including ground stations, satellites, buoys, balloons, aircraft and ships" producing data at 35km grid resolution (Keller & Khuen, 2012).

The calibration process involved a series of simulations in which key parameters were incrementally altered, and statistical analysis was used to compare the simulated results to the measured results from the POE study. Hourly air temperature results were the focus of the comparison, which used a statistical method (Bou-Saada & Haberl, 1995; International Performance Measurement & Verification Protocol Committee, 2002) to assess the similarity between the two data sets: the coefficient of variance of the root mean square error "CV (RMSE)" between the simulated hourly and measured air temperature was calculated for the 12 month monitoring period.

$$CV(RMSE)\ \% = \frac{\sqrt{\frac{\sum_{i=i}^{n}(y_{pred,i} - y_{data,i})^2}{n-p}}}{\bar{y}_{data}}\ x\ 100$$

By experimenting with key variables in the thermal model and evaluating the CV (RMSE) the simulations became more accurate.

It became clear that two factors were highly influential to the simulation results: the ground temperature and air infiltration rates. The influence of the "under-slab" ground temperature came as no surprise given the earth sheltered design of the Earthship. The model *TgroundS* (Williamson, 1994) for calculating ground temperatures was further evolved in this study to account for the peculiar slab edge condition in an Earthship arising from the presence of the greenhouse. A relationship between measured temperatures in the bedroom, greenhouse and outdoors was used to predict ground temperatures and the heat flow path (length) was increased to account for the modelling assumption that insulation was positioned vertically in the berm and that there was zero (adiabatic) heat flow at the outside surface of the wall. Also, by testing various assumptions regarding the ground temperature such as conductivity of the soil in the berm and under-floor, the ground temperatures were recalculated, producing more accurate simulation results.

A range of air infiltration rates that were deemed to be applicable to the Earthship were established on the basis of design and construction elements and natural ventilation schedules that had been observed and reported in the POE study; however, very little data was available regarding the occupancy of the home, although there were some records of when the building was unoccupied, so these periods were the focus of attempts to calibrate the model.

Iterative simulations of a range of air infiltration rates helped establish the rates which produced the most accurate simulation results.

4.3.2 Assumptions & Study Design

The modelling assumptions were as follows: Occupancy was modelled as zero. Heating and cooling were not used ("free running"). Natural ventilation was scheduled to occur from May to October (all hours) when the indoor air temperature was greater than 21°C, and when outdoor air temperature was lower than indoor temperature. This was calculated based on opening and crack sizes, buoyancy and wind pressures. All external windows were modelled as closed all the time. Earth tubes were not modelled due to inadequate data regarding critical parameters such as air flow rate, soil type, soil moisture content and user behaviour. Furthermore EnergyPlus's® "ZoneEarthtube" object only allows for a fixed rate of airflow throughout the year whereas in an Earthship this would be constantly modulated by the thermodynamics of the greenhouse (and user behaviour). The heavy weight internal wall was modelled as a 50mm thick concrete wall to approximate the amount of thermal mass in the wall (i.e. air filled aluminium cans ignored; only their mortar was accounted for by the 50mm assumption). Similarly, the greenhouse floor was modelled as being only half as thick as actual to approximate the volume of thermal mass as the software was not capable of modelling the soil and foliage "floor" of the garden area. Air infiltration was assumed to be zero in the living spaces and "excellent" (as defined in DesignBuilder®) in the greenhouse. This air infiltration regime is a very high standard and may seem unlikely; however the earth-sheltering and very tight connection between the roof and walls in the living spaces and air tight seals throughout the building, especially in the greenhouse windows and vents, gives this assumption some credibility. Moreover, simulation experiments in which air infiltration rates were increased to more conventional levels lead to greater deviations from the measured air temperature, and therefore the "tighter" values were adopted.

4.3.3 Design & Construction Details

The DesignBuilder® model was created using data from the architectural drawings of the Earthship, a two bedroom Global Model design completed in 2010 with thermal envelope properties as described in Table 4.13. Construction materials for each type of building element are listed from the outside to inside layers. U-values are reported with no bridging effects.

Table 4.13 - Study One: Construction Layers and Thermal Properties

Type	Description	U-Value (W/m2-K)
Floor, living	100mm concrete (uninsulated)	3.355
Floor, greenhouse	25mm sand, 25mm flagstone	3.904
Glazing, external/internal	Double glazed, 4mm clear, 16mm air, 4mm clear	2.715
Roof	0.4mm steel, 200mm Polyisocyanurate (PIR), 25mm softwood	0.110
External wall	1600mm earth, 25mm adobe render	0.613*
"Can" internal wall	50mm concrete	3.382

* does not include effect of berm

As built, the Earthship external wall construction is made from tyres filled with rammed earth. A layer of polystyrene is positioned vertically in the berm about 1200mm from the tyres (the "thermal wrap"). Such a construction poses some challenges to heat transfer modelling necessitating a series of simulations aimed at assessing the validity of various approximations of this wall construction. EnergyPlus® uses one-dimensional heat transfer functions through "layers" of materials (US Department of Energy, 2012) and is therefore not capable of modelling the heat flow through an earth filled tyre due to its (toroid) geometry. One solution is to model the tyre as two layers of 10mm thick rubber positioned approximately 650mm apart, with compacted earth between the rubber layers (Kruis & Heun, 2007). This was the initial approach adopted in Study 1; however, a simplified method was developed in this study which yielded comparable results. It was found that the insulated, bermed tyre wall could be accurately represented as a 1600mm layer of compacted earth (density 1900kg/m3) with adiabatic (zero heat flow) conditions at the outside surface of the wall, and by calculating ground temperatures using assumptions consistent with the assumptions regarding the construction of the berm and floor.

4.3.4 Results & Discussion

The simulated results indicate an acceptable level of accuracy of the model despite the uncertainties outlined above.

For the bedroom a CV (RMSE) of 6.3% was obtained and for the greenhouse 13.7%. This is considered to be an acceptable result as previous work showed that the best hourly empirical models were only capable of producing CV (RMSE) in the 10% to 20% range (Bou-Saada & Haberl, 1995), thus the accuracy of simulation for the bedroom is better than expected.

Figure 4.18 - Figure 4.20 compare results for measured indoor (Tint meas), greenhouse (Tghmeas) and outdoor air temperature (Tout) with the simulated indoor (Tint sim) and greenhouse (Tgh sim) for three selected weeks of the twelve month monitoring period.

4.3.4.1 Winter

During the winter week (Figure 4.18) the simulated indoor temperature (in the bedroom) was often 2°C higher than measured. An incorrect ground temperature assumption was the likely cause of this small discrepancy, and experiments in which ground temperatures were adjusted for the winter months confirmed this suspicion; however, for the rest of the year simulated temperatures in the bedroom were remarkably similar to the measured data indicating that the calculated ground temperatures and other assumptions were credible.

On one of the few cloudy days during the monitoring period (Figure 4.18, day 2) the greenhouse only heated up to 18.7°C. The daytime outdoor maximum was only 2.5°C, and the bedroom temperature was very stable dropping only 1.2°C over the following night, as predicted by the simulation.

In the greenhouse, the simulated minimum temperatures are generally 2-4°C higher than measured in the winter, and the maximums were too low by up to 6°C. In the summer, simulated greenhouse temperatures are more accurate. Where the measured temperature is less than the simulated temperature the discrepancy may be explained by the possibility that the occupants had opened the outside windows and greenhouse roof vents to exhaust excessive hot air (Figure 4.19, days 2-4).

4.3.4.2 Spring

Figure 4.19 shows the close match between measured and simulated temperatures for this week in spring.

4.3.4.3 Summer

During the summer week (Figure 4.20) the measured indoor air temperature is very stable ranging from 22.3 to 24.4°C as predicted by the simulation.

4.3.4.4 The Whole Year

Throughout the 12 month monitoring period, the overall picture is that of extreme outdoor temperatures which ranged from -22.1 to 34.8°C while a very stable indoor temperature range prevails even without employing heating or cooling. The coldest indoor air temperature measured was 16.7°C and the warmest 27.7°C. It is noteworthy that the maximum occurred in February (winter) when the outdoor temperature was only 5.5°C and this high indoor temperature could have been avoided by ventilating the overheated greenhouse. The lowest minimum occurred in January at 7am one morning; however by 9am it had increased to 17.9°C and by 10am it was 19.5°C demonstrating that low temperatures are short lived, and that the passive solar, earth sheltered design is very effective in the Taos climate.

In the greenhouse the results show that the diurnal temperature fluctuates most in winter (∆26°C) when the extreme maximums and minimums occur, whereas in the summer the diurnal swing is not as great (∆20°C) despite the greater outside temperature range in summer. This is most likely due to increased solar gains in the winter caused by the angled greenhouse glazing which is optimised for winter gain.

Figure 4.21 presents measured indoor and greenhouse air temperature, and Figure 4.22, the corresponding simulated results. The results are presented in terms of the average maximum and minimum temperature for indoors and the greenhouse ("Tint ave max", "Tint ave min", "Tghave max" and "Tghave min" respectively) and the 96th percentile indoor temperature extremes ("Tint 96%ile max" and "Tint 96%ile min). The shaded background to these plots indicates the acceptable temperature range in a naturally ventilated building based on the Adaptive Comfort Standard (ACS), as per ASHRAE 55-2010, addendum D (ASHRAE, 2012). This standard takes into account the prevailing mean outside air temperature to calculate the upper and lower limits for the indoor temperature range that would be acceptable to 80% of the population. Section 5.3 of this Standard describes a method for determining thermal conditions in occupant-controlled naturally conditioned spaces. One of the criteria for using this method is that the prevailing mean outdoor temperature is greater than 10°C and less than 33.5°C. Unfortunately the Standard does not specify how to determine the thermal comfort range when the prevailing mean outdoor temperature is outside this range, as it is for the colder half of the year in Taos. Consequently the graphs show the thermal comfort acceptability limits that adhere to this criterion in dark grey shaded area ("T80%adapt"), however, a light grey shaded area ("T80%extrap") has been used to indicate an extrapolation of the acceptability limits for the purposes of discussing the results of this study. This has been done by plotting the minimum and maximum limits for a 10°C mean monthly outdoor temperature for months with mean temperatures less than 10°C.

In the warmer months the results for the bedroom are very similar although the simulation tends to underestimate the maximum 96 percentile extreme and overestimate the minimum 96 percentile extreme. In the cooler months the simulation is towards the warmer side of the acceptability limits whereas the measured data indicate that in reality there is a wider range of temperatures which are slightly inclined towards the cooler side of the limits.

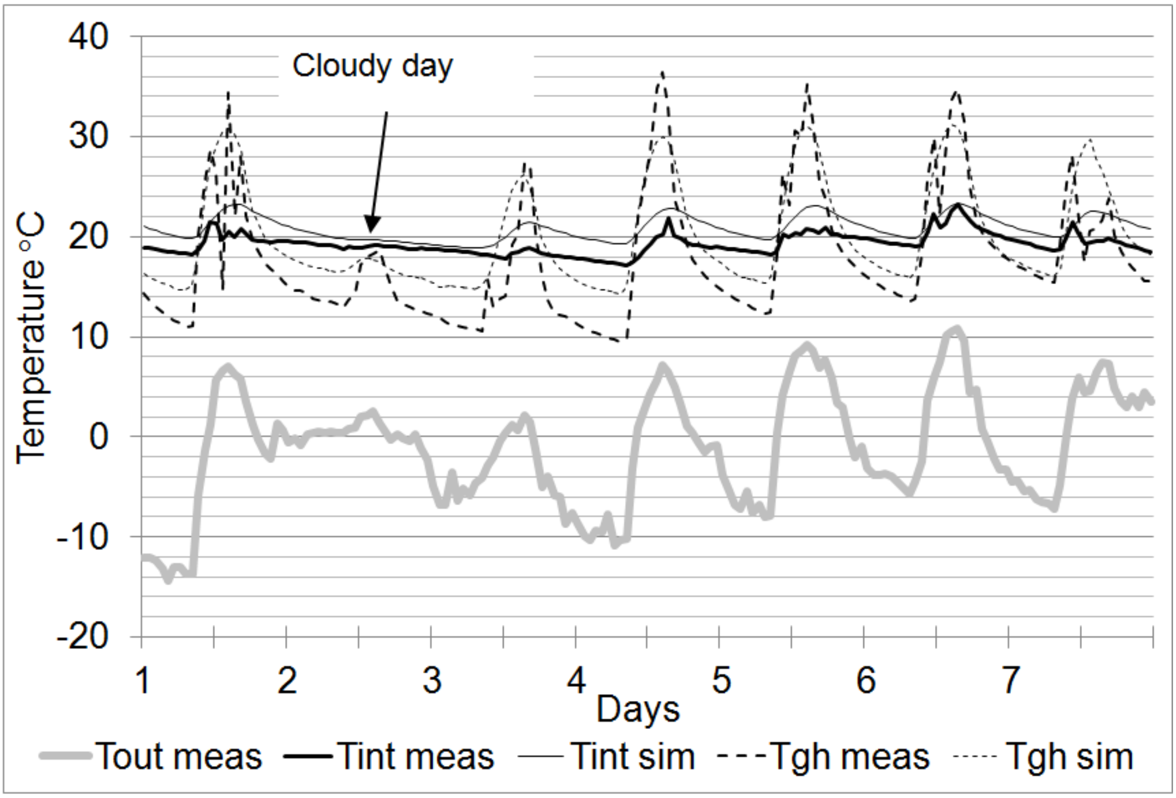

Figure 4.18 - 15/1/12-21/1/12 One week in Winter

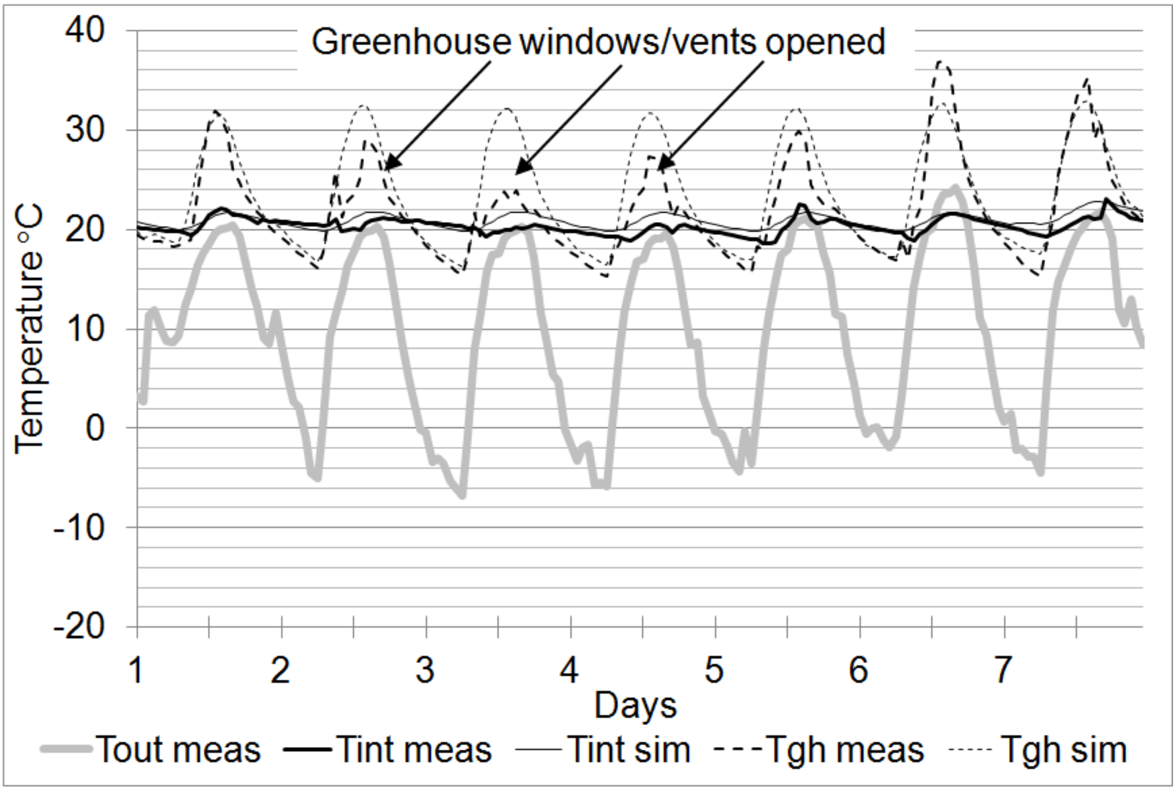

Figure 4.19 - 26/3/12-1/4/12 One week in Spring

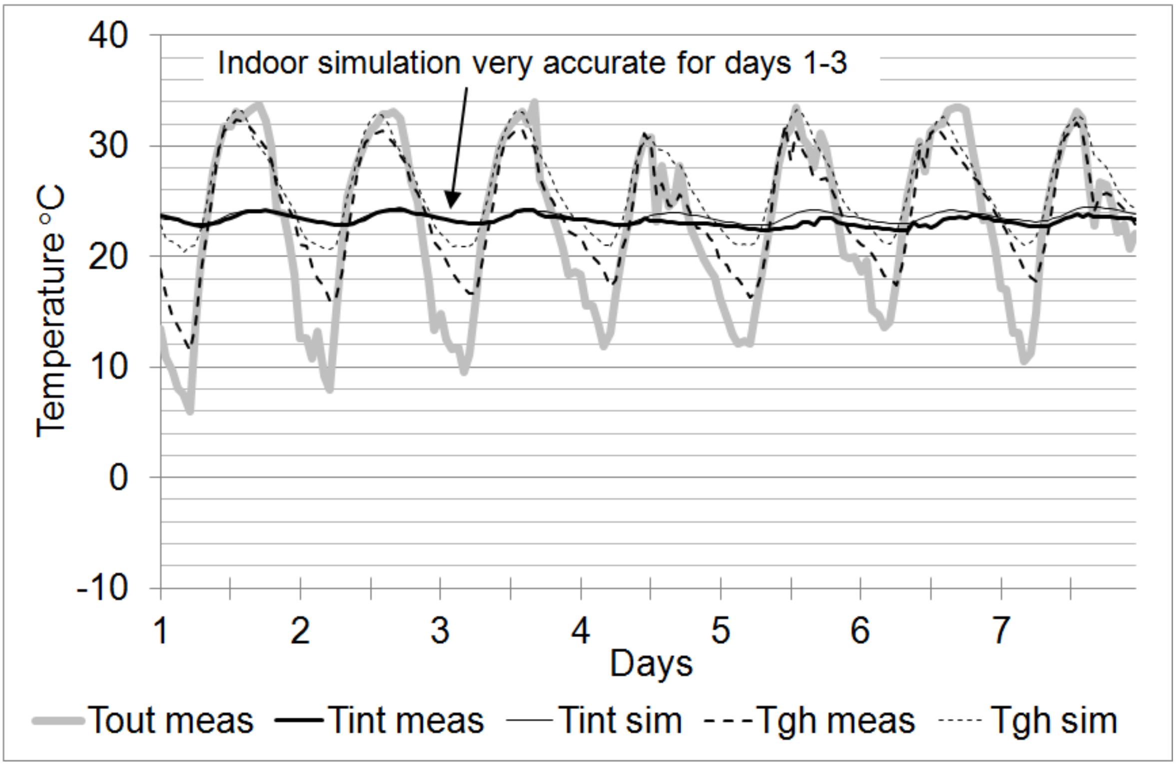

Figure 4.20 - 25/6/12-1/7/12 One week in Summer

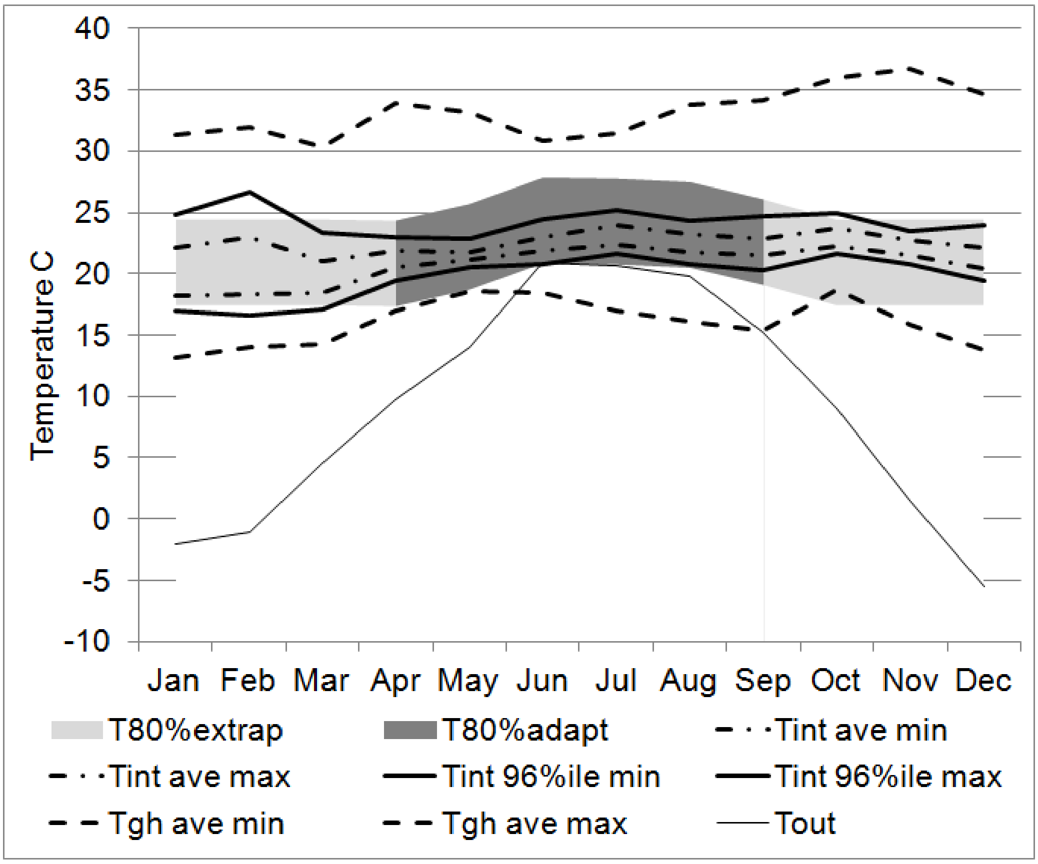

Figure 4.21 - Measured indoor temperature versus ASHRAE acceptability limits

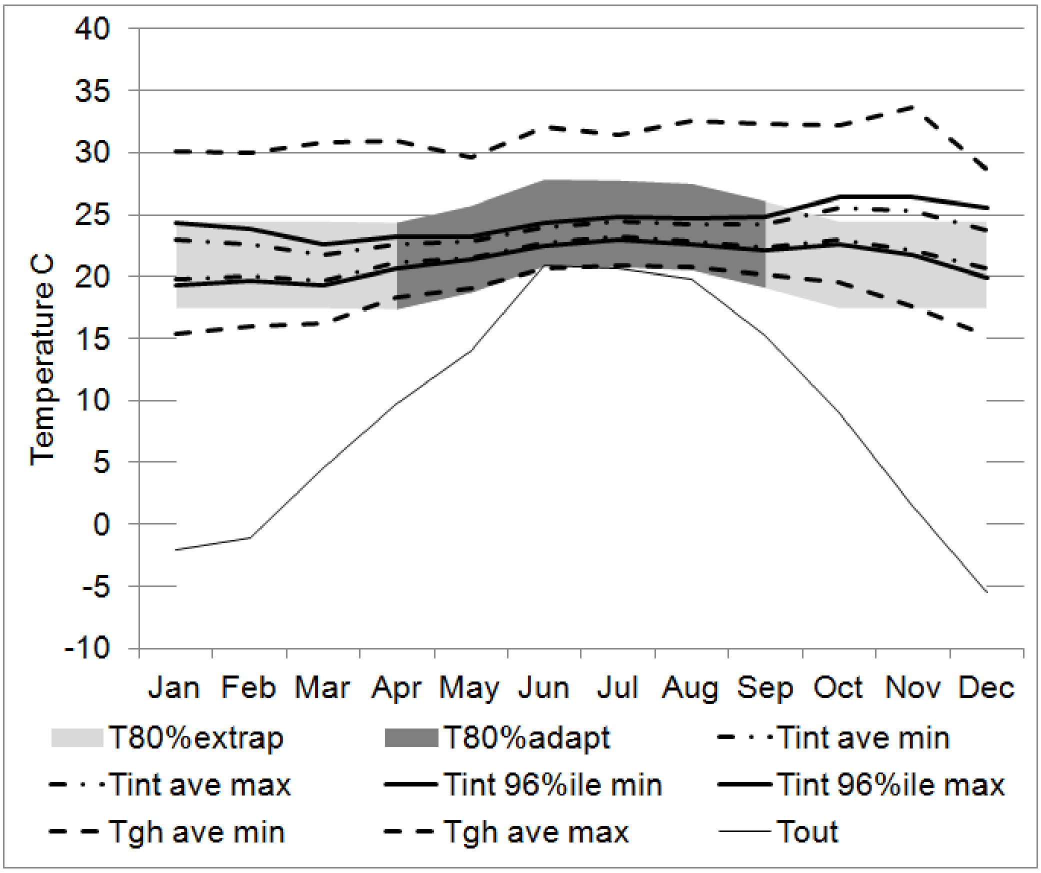

Figure 4.22 - Simulated indoor temperature versus ASHRAE 55-2010 acceptability limits for naturally-ventilated buildings

To improve the accuracy, further work is required to develop more accurate ground temperature predictions. A study by Ip and Miller (2009) has begun this research in the Brighton, England climate, in which monitoring of the under-slab and in-berm temperature of an Earthship has been measured. Aside from measuring under-floor temperatures, data regarding earth type and moisture content throughout the year would also be very useful.

Furthermore, to achieve more accurate and reliable simulations of Earthships and similar earth sheltered designs, it is suggested that improvements are needed to EnergyPlus® and DesignBuilder®. Although EnergyPlus's "slab" utility is capable of generating ground temperatures based on differing core and edge slab parameters, this is not sufficient to model the unusual construction of an Earthship wall. Such walls often have rainwater tanks within them with water levels that vary on a daily basis. The tapering shape of the berm provides for far greater earth sheltering at the base of the wall than the top of the wall, and the characteristics of the earth in the berm may vary in terms of density, and moisture content, the latter on a daily basis according to snowmelt, rainfall, irrigation et cetera thereby effecting the conductivity of the berm. The geometry of the tyre which is non-planar has already been noted as being problematic for EnergyPlus® heat transfer calculations. The inclusion of a layer of polystyrene in the berm is also problematic for EnergyPlus®: an error message encountered while experimenting with Earthship wall simulations stated "Highly conductive or highly resistive layers that are alternated with high mass layers may also result in problems."

Despite these limitations of the tools and the information available, the simulations have shown a high degree of agreement with the measured results. Furthermore, the comparison to the adaptive thermal comfort acceptability limits indicate similar results for both the measured and simulated results and therefore give some confidence that further simulations in other climates are likely to be reasonably reliable for predicting the performance of an Earthship built in these locations.

The overall assessment of the calibrated model's results is that they are very accurate in predicting the indoor air temperature during the warmer months; however, in the cooler months they tend to overestimate the indoor air temperature by roughly 2°C on average.

4.3.5 Summary

The calibration study highlighted the importance of key factors such as ground temperature and air infiltration rates, and once these parameters had been fine-tuned the simulation results were quite accurate and certainly well within the commonly accepted range.

In terms of calculating energy use of the Earthship in other climates, the model is a best practice approach, although validation through a POE monitoring exercise would need to be conducted to verify its validity in other climates. However, for the purposes of the LCA study in which the energy use of the Earthship in the Adelaide climate is of interest, the model is likely to produce more accurate results compared to the first study which did not feature a calibration exercise; and so the calibrated model is the basis for the following study.

4.4 Study 3: Adelaide Climate using Calibrated Model

4.4.1 Introduction

In Study 1, air infiltration rates were assumed to be "average" and the method used for calculating and implementing ground temperatures was a basic initial approach. Variables that might influence the heating/cooling load were investigated such as indoor wall construction, and glazed area.

In Study 2, a thermal model of the Earthship in the Taos climate was calibrated producing reasonably accurate results of indoor air temperature. Through this process of calibration, key variables that drove the results were discovered: air infiltration rates and ground temperature. The *Tground* software used in Study 1 was developed and fine-tuned to address the effect of the greenhouse, producing slightly different ground temperature results which resulted in more accurate indoor air temperature simulations.

The aim of Study 3 was to find out how the heating and cooling energy in the Adelaide climate, for the Earthship and the other buildings studied in the LCA, was affected by the new assumptions for issues such as air infiltration and ground temperature which had been found to be highly influential during the calibration exercise of the Global Model Earthship in Study 2.

The same simulation model used in Study 1 was adapted and updated based on the lessons learned in simulating the building in the Taos study (Study 2).

The study was designed to estimate the energy use for passive solar designed homes based on the Earthship model in the Adelaide climate (Temperate/Mediterranean climate) subject to two key variables; the external wall construction and inclusion/exclusion of the greenhouse although there were other departures from the original parameters used in Study 1 which are noted where applicable below.

4.4.2 Assumptions & Study Design

Occupancy assumptions were identical to Study 1, i.e. 3.6 people (0.03 people/m2) approximating two adults with two children. It was assumed that the occupants would be at home from 3pm to 10am on the next day, every day.

The temperature at which the heater and cooler would be turned on was established by using the ASHRAE adaptive comfort relationship (ASHRAE, 2012). As the minimum winter mean monthly temperature in Adelaide is 11.4°C (July) and the maximum summer mean monthly temperature is 23.3°C (January and February) (Bureau of Meteorology, 2012) the lower and upper acceptability limit based on the ASHRAE adaptive model is 17.8°C and 28.5°C (ASHRAE, 2012). DesignBuilder® allows half degree increments for thermostat settings therefore 17.8°C was rounded up to 18°C to be conservative (i.e. more energy use). Note that in Study 1 the cooling set point temperature differed: it was 26C, and therefore cooling load in this study can be expected to be somewhat less.

Natural ventilation was set to occur at 3 air changes per hour (3 ACH) in the living space and 12 ACH in the greenhouse (Study 1 used 3ACH in both living and greenhouse), any time throughout the year when the indoor temperature was above 21°C, and the outside air temperature was below 21°C. These natural ventilation rates were based on an estimation of the amount of outside air coming through the earth tubes, doors and windows into the living spaces, and through the windows and vents in the greenhouse.

Internal windows (i.e. the glazed partition wall between the greenhouse and the living space) were assumed to be left open at 1% of their area to simulate constant air mixing between the living and greenhouse spaces due to air infiltration through cracks in doors and windows (Study 1 assumed 30% open between 11am and 4pm from May to Sept).

Some Earthships in Taos employ blinds on the inside of the greenhouse glazing to block summer heat, and this seemed applicable in Adelaide which gets even hotter than Taos. Experiments were conducted to establish the most energy efficient schedule for their operation and it was found that leaving them open in the winter, and closing them automatically when the indoor air temperature was above 21°C during the rest of the year, reduced the heating/cooling load the most (Study 1 assumed solar radiation control of 200W/m2 - above this level the blinds closed).

Ground temperatures were calculated using a new version of *TgroundS* (Williamson, 1994) which factored in the effect of the greenhouse and insulation in the berm, whereas in Study 1, the effect of the greenhouse upon ground temperatures was not taken into account.

Air infiltration was assumed to be quite a high standard, in both the greenhouse and living space based on the assumption that the earth-sheltered design, and measures such as weather seals and caulking would minimise air infiltration. A setting of 5 ACH at a pressure of 50 Pa was used (unit of ACH at 50 Pa is consistent with blower door test procedures and should not be confused with the natural ventilation rates quoted above). Study 1 assumed higher "default" rates of air infiltration.

4.4.3 Design & Construction Details

Dimensions of the house were identical to Study 1 including "with" and "without greenhouse" configurations. Construction layers and thermal properties are identical to those used in Study 1 with the exception of the Earthship bermed walls which were modelled slightly differently as this has been shown to increase accuracy of the model during the calibration exercise in Study 2: the bermed Earthship walls were modelled as "adiabatic" (zero heat flow) as described in Study 2 whereas in Study 1 they were not. Construction material details are given in Table 4.14.

A value of 50 percent glazed area (of the equator facing wall) was assumed as this had been established as an appropriate quantity, apropos the LCA, in Study 1.

External walls that were structurally capable of being bermed (i.e. Earthship and Concrete Block) were simulated with and without the berm and likewise external wall constructions that might benefit from additional insulation were simulated with and without an additional exterior insulation layer.

Internal walls were modelled as thermal mass as this has been shown to decrease the heating and cooling load substantially in Study 1. The exception to this was the "conventional" home modelled with a square floor plan - it was modelled with lightweight internal walls to represent conventional construction methods.

Table 4.14 - Construction Materials

Type	Description (dimensions in mm)	U-value (W/m^2-K)
Floor	100 thick concrete, uninsulated	3.355
Glazing, external and internal	Double glazed, 4 clear, 6 air, 4 clear	3.146
Roof	0.4 steel, 196 cellulose, 13 plasterboard	0.196
Brick Veneer	110 brick, 40 air gap with reflective foil, 70 glass fibre, 10 plasterboard	0.337
Concrete Block bermed insulated	1000 earth, 300 concrete block (hollow heavyweight)	0.816*
Concrete Block Insulated unbermed	100 EPS, 300 concrete blocks (hollow, heavyweight)	0.346
Double Brick	110 brick, 50 glass fibre, 110 brick, 10 plasterboard	0.512
Earthship, bermed, insulated	1600 earth, 25 lime render	0.613*
Earthship, unbermed, insulated	25 lime render, 100 EPS, 10 rubber, 630 earth, 10 rubber, 25 lime render	0.299

Type	Description (dimensions in mm)	U-value (W/m^2-K)
Earthship unbermed uninsul.	25 lime render, 10 rubber, 630 earth, 10 rubber, 25 lime render	1.143
Heavy-weight internal wall	110 mudbrick (adobe). Note: this wall type also used for Glazed Partition Wall 275 thk	3.158 (110mm)2.727 (275mm)
Light-weight internal wall	10 plasterboard, 90 air gap, 10 plasterboard	2.246
Rammed Earth	300 rammed earth	2.128
Rammed Earth Insulated	25 lime render, 100 EPS, 300 rammed earth	0.333
Reverse Brick Veneer	8 Cement fibreboard, 70 glass fibre, 40 air gap with reflective foil, 110 brick, 10 plasterboard	0.322
Strawbale	50 lime render, 450 strawbale, 50 lime render	0.108
Timber Frame cement board clad	10 cement fibreboard, air gap with reflective foil, 90 glass fibre batt, 10 plasterboard.	0.285
Timber Frame, steel clad	0.4 steel cladding, 100 glass fibre batt, 10 plasterboard.	0.405

* does not include effect of berm

4.4.4 Results & Discussion

Consistent with Study 1, it was found that for all external wall types, the heating and cooling load was less when heavy weight internal walls (mudbrick) were employed rather than light weight (plaster board on timber stud).

Thus for brevity Figure 4.23 only shows the results for heavy weight internal wall building envelope configurations. Results are shown in megajoules per metre square (MJ/m^2) of living space floor area (greenhouse excluded) per annum and kWh/121m^2 p.a. to show the total for the whole house per annum. For each external wall type results are shown for heating and cooling loads both with the greenhouse ("GH") and without the greenhouse. Results are listed in the order of total energy load (i.e. heating plus cooling) of the configuration including the greenhouse.

The results indicate that when a greenhouse (with thermostat controlled blinds) is attached to the equator facing side of the home, there are energy savings for all external wall types especially in terms of reducing the heating load, although cooling load increases minimally for the more energy efficient constructions. Those that benefit the most are Timber Frame, Rammed Earth, and Brick Veneer. Compared to the other wall types, Earthship (Insulated &Bermed) and Concrete Block (Insulated &Bermed) have the least to gain from a greenhouse, although energy use is approximately halved when a greenhouse is added. It should be noted that the effect of the greenhouse may not only be attributed to the glazing. The inclusion of a substantial 275mm thick adobe wall partitioning the greenhouse from the living space is adding thermal mass to both spaces and enhancing the effect of the greenhouse due to its capacity to store heat and regulate indoor temperatures. Therefore in greenhouse retrofits to lightweight walls it may not be sufficient to simply add a glazed greenhouse: additional thermal mass must also be included.

The result that winter heating is reduced by the use of a greenhouse is not surprising given Adelaide's cold, yet often sunny winter weather which necessitates heating, and opens the possibility for passive solar gains via design features such as a greenhouse. The inconsistent effect of the greenhouse on cooling can be explained by the quantities of thermal mass in the external wall constructions. High thermal mass constructions required more cooling when a greenhouse was included, whereas light weight constructions required less, indicating that the thermal mass's storage capacity was a slight liability, although the savings on heating compensated for this many times over. All wall construction types benefit from the addition of a greenhouse which reduces energy consumption by approximately 50-80%.

The Earthship Insulated Bermed with Greenhouse (i.e. the Global Model design) has the least heating and cooling load of all the building envelopes that were simulated (0.1MJ/m2). In comparison, PassivHaus is assumed to have an energy load of approximately 15MJ/m2 (Feist, Peper, Kah & von Oesen, 2001) while a 10-Star house located in Adelaide and rated in accordance with the Australian Nationwide House Energy Rating Scheme (NatHERS), would have a maximum load of 3MJ/m2 (NatHERS, 2013). Similar performance was achieved by the Concrete Block Insulated Bermed with Greenhouse construction indicating that this wall type offers an alternative to a tyre wall with similar thermal performance. Without the berm, the Earthship Insulated and Concrete Block Insulated external walls perform similarly to Strawbale and Rammed Earth Insulated. The addition of insulation to the outside of a Rammed Earth wall results in a drop in heating and cooling load from 34.5MJ/m2 to only 6.5MJ/m2. This energy saving construction technique (which can be retrofitted) may help the earth building industry regain their environmental credentials (Thomas, 2011) in relation to heating and cooling energy use. Similarly, when a tyre wall is built with no berm or insulation (Earthship, no Insulation, no Berm) its performance is worse than the Timber Frame Insulated wall, whereas if a 100mm layer of polystyrene is added to the outside of the tyre wall the performance increases dramatically, comparable to a Strawbale wall. The results indicate that traditional wall construction methods used in Australia such as Double Brick, Brick Veneer, and Timber Frame, when coupled with passive solar design principles and a high level of air tightness will also lead to low heating and cooling energy, although their performance is still exceeded by that of an insulated bermed Earthship.

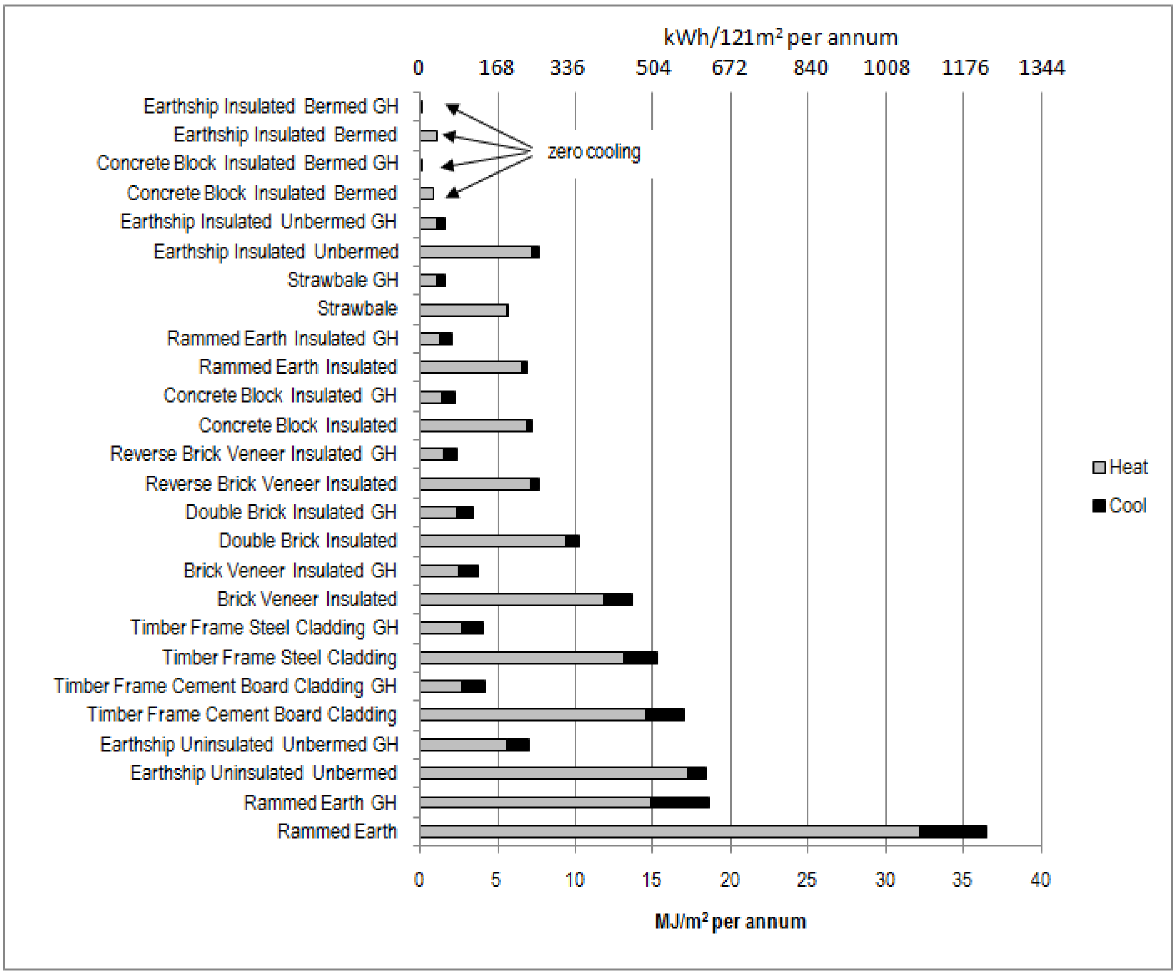

Figure 4.23 - Heating and Cooling Load in Adelaide Climate

Table 4.15 compares the total heating and cooling load between Study 1 and Study 3 for selected envelopes - those selected for the LCA study. The average of the these two studies is also given and this is the order in which the results are listed.

Each set of results, including the derived average results, is ranked; a rank of 1 indicating the lowest energy use. Highlighted cells in the table indicate identical rankings across the studies.

The ranking indicates that there is a fairly consistent order in the performance of the envelopes despite the large difference in absolute results: The Global Model Earthship (ESTW B TM GH) is consistently ranked first, the bermed Earthship without the greenhouse (ESTW B TM) is always ranked second, Brick Veneer eighth and Timber Frame ninth. The largest discrepancy is with the Rammed Earth Insulated envelope which is ranked seventh in Study 1 and fourth in Study 3.

The results of Study 1 can be viewed as a high estimate of energy use where air infiltration may be quite typical whereas Study 3 can be seen as a best case low estimate where air infiltration is negligible and occupants tolerate higher indoor temperatures. It was decided that the LCA study would use the average values to represent a conservative middle ground.

Table 4.15 - Comparison of Results of Thermal Performance Studies

	Energy load kWh p.a.					
	Study 1		Study 3 (calibrated)		Average	
Description	kWh pa	rank	kWh pa	rank	kWh pa	rank
ESTW B TM GH	557.5	1	3.4	1	280.4	1
ESTW B TM	1075.7	2	37.7	2	556.7	2
CBI TM	1248.5	3	242.9	5	745.7	3
SB TM	2079.6	5	189.2	3	1134.4	4
RBV TM	2021.2	4	255.0	6	1138.1	5
ESI TM	2141.0	6	256.3	7	1198.6	6
REI TM	2187.8	7	231.8	4	1209.8	7
BV TM	2530.3	8	457.9	8	1494.1	8
TF TM	2647.4	9	571.7	9	1609.5	9
MB TM	3134.1	10	1067.8	12	2101.0	10
TF LW	3314.1	12	1018.9	11	2166.5	11
BV LW square floor plan	3569.0	13	884.0	10	2226.5	12
RE TM	3304.0	11	1225.0	13	2264.5	13

4.4.5 Summary

In comparison to Study 1 these results are consistently more favourable. This is probably due to the comparatively lower ("tighter") air infiltration rate, warmer ground temperatures and higher cooling set-point assumed in Study 3.

Despite the large difference in results between the two studies, the relative performance of the thermal envelopes is consistent i.e. the ranking of the thermal envelopes is very similar, for example the Global Model Earthship (insulated and bermed, with greenhouse) ranks as the most energy efficient, and uninsulated Rammed Earth being the least energy efficient; the greenhouse produces significant energy savings as do the bermed designs when compared to their un-bermed counterparts. This indicates the potential for energy savings via improved air tightness of building envelopes, and it highlights the need for accurate ground temperature modelling. Finally, although a significant effort was made to develop an accurate, calibrated, simulation model, without more detailed information regarding key parameters such as ground temperature and air infiltration, the results must be treated as relative and not absolute.

In summary the results give confidence that the fundamental Global Model Earthship design would perform better than other designs in the Adelaide climate.

4.5 Study 4: Earthships in Europe

Although the context of the LCA study presented in this thesis is Adelaide, Australia, Earthship performance in other climates was of interest as it is claimed that Earthships would require minimal or zero active heating or cooling in almost any climatic condition (Earthship Biotecture, 2012e). Few scientific studies have tested this claim, and on the contrary, recent monitoring and anecdotal evidence from Earthships built in Europe and the UK question the claim (Hewitt & Telfer, 2012).

This section evaluated the thermal performance in a variety of European climates using the calibrated model from Taos. Simulations were conducted in: Paris, France (maritime temperate), Albacete, Spain (arid/semi arid), Seville, Spain (warm summer Mediterranean), Valladolid, Spain (hot summer Mediterranean) and London (marine west coastal). The Köppen classifications stated in the EnergyPlus weather data STAT files used for the simulations were Cfb, BSk, Csb, Csa, and Cfb respectively. Note that the study has recently been published (Freney, Soebarto & Williamson, 2013b) so only a brief summary of results are presented here.

The thermal model used for this study was basically the same as the model used in Study 3. It was based on the Global Model Earthship and used the same assumptions regarding occupancy and construction materials, but it used different weather files (applicable to the European climates) which were sourced from the EnergyPlus website (U.S. Department of Energy, 2013).

The heating and cooling energy use of the Global Model Earthship in the European locations was generally very low with no need for cooling in the study locations with the exception of Valladolid which required cooling during June-September although this small cooling load (0.9kWh/m^2/yr) might be met by the effect of earth tubes which were not modelled. Backup heating was indicated for Paris (12.6kWh/m^2/yr) and London (14.3kWh/m^2/yr) during the colder months. Valladolid also required small amounts of backup heating (4kWh/m^2/yr) although far less than London and Paris. Albacete's heating load was negligible (0.06kWh/m^2/yr). Seville required no heating or cooling whatsoever.

For comparison to existing standards and aspirations, in France the *Réglementation Thermique 2012* specifies a "primary energy consumption" maximum for French homes of 50kWh/m^2/yr (65 in the north east, 45 in the Mediterranean and 45 in the south west) (French-property.com, 2013). In the UK a low-carbon strategy to reduce UK housing emissions (Boardman, 2007) quotes household energy use as 21-22,000 kWh/yr of which roughly 65% is for space heating. Even the "Passivhaus" concept requires up to 15kWh/m^2/yr of energy for its heat recovery ventilation system and backup heating (Feist, Peper, Kah & von Oesen, 2001) putting it on par with the Global Earthship for energy use in cold, overcast climates. For further information about this study refer to Appendix B which contains a copy of the paper (Freney, Soebarto & Williamson, 2013b) where this research was first published.

This study indicates that backup heating systems are necessary in cold and cloudy climates; however, the energy use is likely to be extremely minimal, on a par with Passivhaus heating energy requirements, due to the Earthship's capacity to store and release heat. In summer, over-heating reported by other studies may be mitigated by natural ventilation of the greenhouse, and shading.

4.6 Summary

The four thermal modelling studies described in this Chapter have explored a wide range of issues relating to the thermal performance of Earthships and other housing types, providing useful data for the LCA study, and documenting improved methods for simulating Earthship thermal performance and recommendations for further research.

The results tell a consistent story: thermal modelling predicts extremely low heating and cooling loads for the Global Model Earthship in a wide variety of climates and variations of the Earthship external wall construction, for example an insulated tyre wall without a berm, also performs very well. The "extreme" passive solar design of the Earthship, which positions all the main rooms adjacent the equator facing side so that they receive abundant solar radiation (in winter), lowers heating and cooling loads no matter what the external wall construction type, indicating that this layout, and passive solar design in general, is universally applicable to many construction types as a potent sustainable design strategy.

Study 1 demonstrated that in the Adelaide climate, the Global Model Earthship (earth-sheltered with greenhouse) would be superior to the other constructions according to thermal modelling. This was due to the earth-sheltering and the greenhouse in particular, and it was found that other external wall constructions, when coupled with a greenhouse and earth-sheltering (if applicable), also achieved much lower energy use indicating that these Earthship design features are excellent for the Adelaide climate. In particular the greenhouse showed great potential to reduce energy use for all the constructions it was modelled with, provided it is designed with adequate thermal mass integrated into its design and with consideration given to shading it in the summer.

Study 2 demonstrated that it was possible to accurately predict indoor air temperature of a Global Model Earthship despite many challenges arising from limitations of thermal modelling software, and lack of detailed data regarding important issues such as the conductivity of the earth-berm. This study confirmed the results of the POE study: that the Global Model Earthships built in Taos provide comfortable indoor air temperatures despite the extreme outdoor weather conditions.

Study 3 implemented the findings of the calibration exercise (Study 2) to re-examine the performance of a variety of construction types in the Adelaide climate - the basis of Study 1. Although the results were quantitatively different to Study 1, in relative terms, it had very similar overall findings and showed that the Global Model Earthship design was superior, and that the greenhouse was effective in reducing overall heating and cooling loads for all construction types.

Study 4 showed that in cold and overcast climates i.e. Paris and London, minimal amounts of backup heating would be necessary to maintain comfortable indoor conditions, corroborating the anecdotal evidence that some Earthships built in cold European climates have not performed as hoped.

These studies give confidence that the basic Global Model Earthship design is suitable to a wide variety of climates; however, it is important to evaluate climate specific issues such as the solar radiation resource and make minor adjustments to the fundamental design. For example, in warm to hot climates, shading of the greenhouse and or additional earth tubes may be necessary, and in cold overcast climates backup heating devices may be needed. In the suburbs, where a berm may not be practical due to its size and aesthetic, variations of the Earthship rammed earth tyre wall construction, which use insulation instead of a berm, also proved to be very energy efficient and compared favourably with other wall types such as strawbale.

5 Life Cycle Assessment Method

5.1 Introduction

Since the outcome of Life Cycle Assessment (LCA) is very dependent upon many issues used to define the study, the following sections explain assumptions and approaches taken in some detail. The study has been guided by the standards regarding LCA published by the International Organisation for Standardisation (ISO) which produces a range of standards (including the 14040 series) (ISO, 1997) which cover many, although not all, aspects of LCA practices.

ISO describes a four-stage process;

- Stage 1: The goal and scope of the study is defined which leads to the establishment of a "system boundary" which defines what will and will not be included in the study.
- Stage 2: Life Cycle Inventory (LCI) data are developed based on the inputs (e.g. materials, energy use) and outputs (e.g. emissions to air, water, soil) of the system throughout all stages of the system's lifecycle.
- Stage 3: Life Cycle Impact Assessment (LCIA) is used to analyse the data collected in the previous stage. Environmental impact "indicators" (e.g. global warming, land use, water use) are used to predict potential impacts to human health and the environment.
- Stage 4: Interpretation is the final phase of LCA in which the LCI and LCIA data is scrutinised and critiqued. Systematic processes for evaluating assumptions are conducted, limitations discussed, and conclusions drawn (ISO, 1997, p. 4).

This Chapter details the rationale for assumptions and procedures adopted in this study for each of these stages outlined above.

5.2 Overview of LCA of Buildings

5.2.1 Functional Unit

In the field of building and construction two types of LCA have been articulated: "whole building" and "components/materials of buildings" or "Whole B/Cs" and "Building materials component combination" (BMCC) (Kotaji, Schuurmans & Edwards, 2003, p. 11).

Although attempts have been made to develop a standardised functional unit for whole buildings and for building components and materials, none have eventuated as yet (Kotaji, Schuurmans & Edwards, 2003, pp. 14-15). Therefore LCA practitioners must establish an appropriate functional unit based on the goal and scope of the study to ensure functional equivalence between the systems being compared.

In general, whole building LCA uses the whole structure, over its whole life, with consideration to the performance characteristics of the building (Kotaji, Schuurmans & Edwards, 2003, p. 14). For example the service life of the buildings being compared may vary considerably due to construction materials or weather conditions and therefore it would be necessary to use time as a factor in the functional unit.

Whereas if weather conditions and the service life of the buildings was the same but the floor area was different then the functional unit should be based on floor area, or volume.

In terms of building material and component combinations (BMCC) the functional unit is defined by an appropriate metric that may be typically used in product standards where products are compared. Kotaji gives the following examples. In comparing insulation as this is related to the area being insulated and the thermal resistance to heat transfer an appropriate functional unit will be m^2K/W (which is the unit for thermal resistance) per $1m^2$ of installed insulation, or for mortar, per tonne (assuming that other factors such as strength and durability of the mortar are equivalent) (p. 14).

It is important to also consider other elements of the building that are relevant to the component being studied to ensure parity between the systems being compared. For example when comparing wall systems, Kotaji says, "to assess the overall impact of one wall compared to another, the study should also include, for example, the environmental load associated with more or less concrete foundation required to achieve the required building stability and durability..." (2003, p. 15).

The literature review showed that the most common basis for comparison was a unit of floor area per year i.e. one metre squared per year, while other studies used the "whole house" per year as the basis of comparison. Provided the floor area is given when a "whole house" functional unit is used, results can easily be converted to m^2/yr.

Another important issue that somewhat confounds LCA studies is the life expectancy of a building. A range of 50-100 years was typical with some studies testing various life expectancies with a sensitivity study.

The functional unit for this study is defined as the "whole house" for a lifespan of 50 years. This life expectancy was chosen to be somewhat conservative and to fit in with the current status quo of continual economic growth in which housing construction, and demolition, play a significant role. In Australia, it is current practice to demolish old homes that may be less than 50 years old and build new, more fashionable homes, so although many construction types are physically capable of lifespans of much longer than 50 years, there are social and economic factors that determine the lifespan of buildings. The effect this assumption has on the results is discussed in Chapter 8.

5.3 Stage 1 - Goal, Scope, Functional Unit and Approach

As outlined in Chapter 4, the goal of the LCA study in this research was to estimate the potential environmental impacts of building and living in an off-grid Earthship compared to various grid connected homes built with a variety of wall constructions (including strawbale, rammed earth, and brick veneer).

The International Reference Life Cycle Data System Handbook (ILCD) specifies that six aspects of the goal definition should be documented;

- "Intended application(s) of the deliverables/results
- Limitations due to the method, assumptions, and impact coverage
- Reasons for carrying out the study and decision-context
- Target audience of the deliverables/results
- Comparative studies to be disclosed to the public
- Commissioner of the study and other influential actors" (European Commission, 2010, p. 29)

5.3.1 Intended Applications

The results of this LCA study will contribute to the body of knowledge regarding the environmental credentials of wall construction materials and processes and of the merits of the archetypical Earthship features: the berm and the greenhouse. The study is, however, not intended to be used for any commercial purposes.

5.3.2 Limitations

The following assumptions and conditions delimit this LCA study;

Climate zone: Adelaide (temperate Australian climate)

The study is based on thermal envelope construction appropriate to the Adelaide climate and conditions which are characterised by the following conditions;

- No snow, few frosts, therefore the soil rarely freezes. This affects the design of footings and avoids the need to insulate footings.
- Presence of termites (insects that eat timber structures). This affects the types of materials used in wall construction. Stainless steel mesh, poison impregnated fabric and granulated granite, are typical termite barrier systems in Australia.
- Infrequent seismic events. This affects the design of walls and footings, in particular the amount of steel typically used for reinforcement.
- Infrequent storm events (e.g. hurricanes and cyclones do not occur in this region). This is more relevant to roof design; however, it has some impact on wall design. More bracing and reinforcement is needed in cyclonic areas.
- Footing design is for reactive clay soils (Site Class H1 as per AS2870-2011) which is a non-conservative average in the Adelaide region (Wittmann, 2010).

5.3.3 Reasons for carrying out the study, and decision context

The study was conducted primarily for academic purposes and the primary objective was to compare the environmental impacts of the Earthship to other housing types.

5.3.4 Target Audience

The target audience is potential home owners, builders, designers, planners and academics.

5.3.5 Comparisons intended to be disclosed to the public

ISO 14044:2006 requires that studies disclosed to the public should not use weighting factors for reporting results because they are “based on value-choices and are not scientifically based” (ISO, 2006, p. 22). Nevertheless weighting factors tend to aid in the comprehension of the results and as this thesis is purely for academic purposes the use of weighting factors will be included in the interpretation of results.

5.3.6 Commissioner of the study and other influential actors

The study was initiated by the author. (Note: this has been made explicit to address the recommendations of the International Reference Life Cycle Data System Handbook quoted previously)

5.3.7 Scope

The scope of this LCA study is “cradle to grave” defined as follows;

- Procurement of raw materials including extraction, manufacture and transport.

- Construction impacts of energy used by heavy machinery included, energy used by hand tools e.g. drills, excluded, equipment/plant manufacture not included. Transport of materials to the building site included.
- Energy used in the operation of heating and cooling systems, domestic appliances, hot water, and lighting.
- Water used during the operation of the home.
- Wastewater treatment.
- Maintenance of external and internal (painted) walls only (but not roof, floor etc).
- Food grown in and around the home.
- Demolition and recycling.

The following types of walls form the basis of the comparative study:

- Brick veneer
- Concrete block
- Earthship (and variations of the tyre wall)
- Mudbrick
- Rammed earth
- Rammed earth with external insulation
- Reverse brick veneer
- Strawbale
- Timber frame

Brick veneer, concrete block, timber frame and to some extent, reverse brick veneer, were chosen for the study as they represent the most common construction materials and systems for domestic scale buildings. Strawbale, mudbrick and rammed earth were analysed as they have become the preferred constructions particularly for "green" buildings.

5.3.7.1 System Boundary

The system boundary for the LCA study is presented in Figure 5.1. Raw materials, manufacturing processes, major construction processes (minor processes such as use of electric hand tools were omitted) and end-of-life waste treatment processes are included for major building elements used to construct the thermal envelope of the building (e.g. footings, floor, roof, walls). Others have been omitted such as the majority of the plumbing and electrical componentry, although where there is additional componentry required by the Earthship's off-grid systems, these extras have been included. Operational energy and some significant components/materials required for maintenance have been included.

The system boundary directs the focus of the study towards the key issues being evaluated, that is, the thermal performance and the construction materials of the thermal envelope and performance of the off-grid systems (compared to grid infrastructure), whereas other elements such as furniture, window coverings and outdoor paving have not been included as these are not unique features of any particular construction type being assessed by this study.

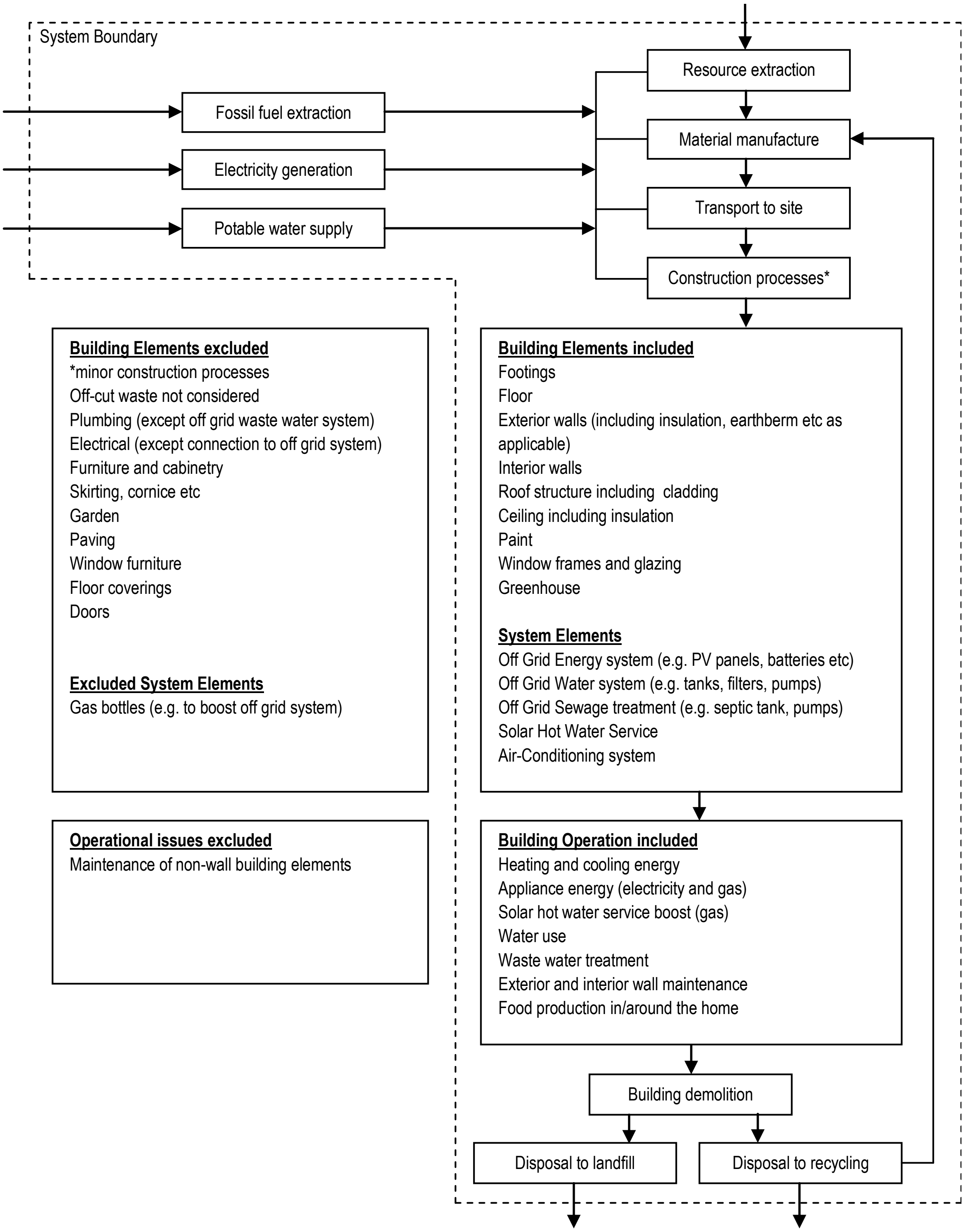

Figure 5.1 - System Boundary Diagram

5.3.8 Functional Unit

The design of the house representing the functional unit was based on the basic dimensions and proportions of the floor plan of the "Global Model" Earthship design. As the study focuses on Earthship, and because the Earthship floor plan (arguably) represents a highly effective passive solar design (in which all rooms obtain direct solar gains from the equator facing side) using one standardised floor plan enabled the effects of wall construction, rather than floor plan design, to dictate the results.

Likewise, for the Thermal Modelling Study the standardised floor plan meant that orientation and shading were identical for all the thermal envelopes being assessed and differences in the heating and cooling load were attributable to the wall materials and other elements such as the greenhouse and berm because other factors such as orientation, shading and glazing did not vary. One exception to this general scheme is the inclusion of a house based on a more conventional floor plan and glazing arrangement, traditional construction materials and grid connected utilities.

These assumptions are designed to answer the questions: (1) how are the environmental impacts arising from heating/cooling energy in a passive solar design home based on the Earthship Global Model floor plan effected due to changing wall materials, using or not using earth sheltering (the berm), and using or not using a greenhouse, and (2) how does this compare to a more “conventional” home?

5.3.8.1 Functional Unit Definition

The functional unit is defined as the whole house with the following properties/elements;

- $121m^2$ floor area of internal dimensions either;
- The Passive Solar design of 22m x 5.5m, oriented with glazing facing the equator (i.e. north for Adelaide) (refer to Figure 5.2) The outer dimensions vary according the External Wall type.
- The Conventional design of 11m x 11m (refer to Figure 5.3)
- An attached greenhouse and berm (refer to Figure 5.2) is also considered as part of the functional unit (floor area $46m^2$) for some “Earthship” configurations, whereas other homes are assumed to have no greenhouse and no berm.
- Ceiling height 2.7m.
- Footing designs vary for each External Wall type and are compliant with Australian Standards for footings AS2870 based on a non-conservative (worst case) soil type for Adelaide i.e. highly reactive deep clay - class H1.
- Glazed area of 29.7m2, double glazed, equator facing for Passive Solar design (refer to Figure 5.2) or, for the Conventional design (refer to Figure 5.3), double glazing is distributed equally on all external walls.
- Roof.
- Floor.
- Standardised thermal comfort level based on the assumptions of the thermal modelling study (see Chapter 4).
- Daylighting based on a glazed area of 50% of the north facing wall area.
- 50 year life span.
- Energy, water, and sewage treatment systems designed to fulfil the needs of a family of four.

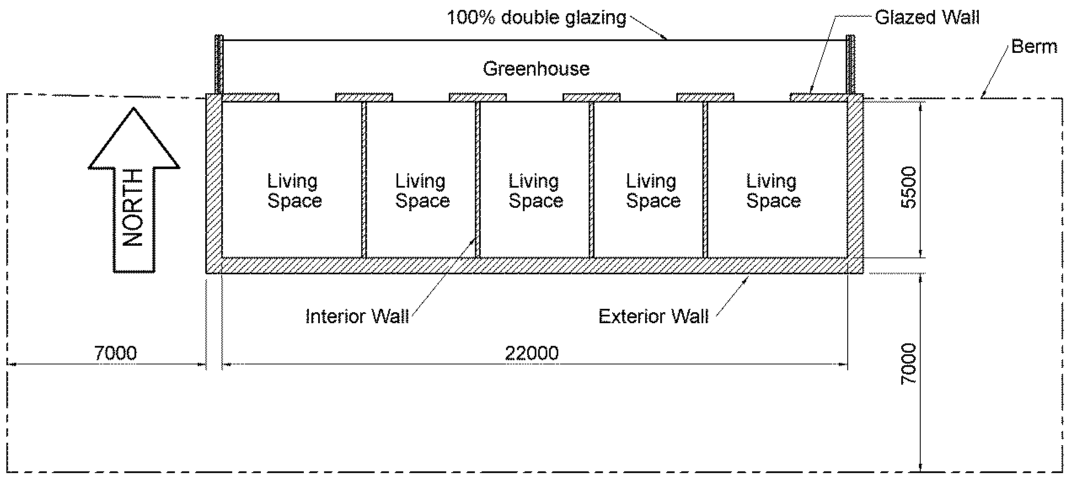

Figure 5.2 - Functional Unit Floor Plan for Passive Solar Design (with Greenhouse and Berm).

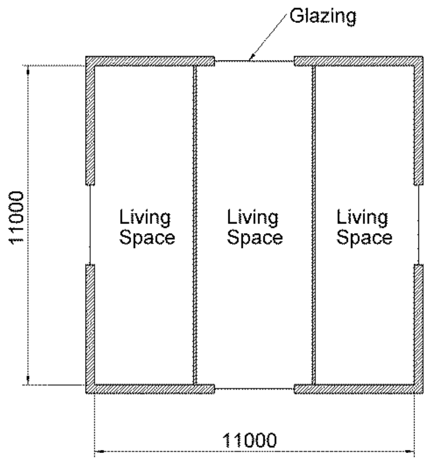

Figure 5.3 - Conventional Functional Unit Floor Plan

5.3.9 Approach

ISO 14044 details three main types of LCA questions;

> *"Micro-level decision support":Life cycle based decision support on micro-level, i.e. typically for questions related to specific products. "Micro-level decisions" are assumed to have limited and no structural consequences outside the decision-context, i.e. they are supposed not to change available production capacity.*
>
> *"Meso/macro-level decision support":Life cycle based decision support at a strategic level (e.g. raw materials strategies, technology scenarios, policy options). "Meso/macro-level decisions" are assumed to have structural consequences outside the decision-context, i.e. they are supposed to change available production capacity.*
>
> *"Accounting":Purely descriptive documentation of the system's life cycle under analysis (e.g. a product, sector, or country), without being interested in any potential additional consequences on other parts of the economy." (European Commission, 2010, p. v)*

The International Reference Life Cycle Data Handbook (ILCD) lists "comparison of specific goods or services" and "benchmarking of specific products against the product group's average" as relevant applications of the Micro-level decision support approach to LCA modelling (European Commission, 2010, p. 38). These match the aims of this study in which comparisons are being made and therefore a Micro-level decision support approach is appropriate.

Advice on how to model this approach ("Situation A" – Micro-level decision support) is documented in the ILCD. It recommends attributional modelling, using system expansion to solve multifunctionality problems (arising from co-products) although where system expansion is not possible allocation may be used. (European Commission, 2010, p. 82). Allocation was handled using the default ratios for allocating impacts to multi-output process in the Australasian database supplied with SimaPro™ 7.3.3 (Goedkoop, Oele, de Schryver & Vieira, 2008). For example it uses economic allocation to attribute impacts to the various co-products of timber production (wood chips, sawdust, etc) and it uses energy content to assign impacts to the various products arising from oil refineries such as petrol and diesel.

Recycled material was assumed to be closed loop (recycled material goes back into the original product) with the virgin material assumed to be substituted by recycled material, with an allowance for losses and/or degradation in the recycling process. The environmental impacts of recycling are therefore driven by the avoided production of raw materials and material lost in the recycling process.

Reused materials that could potentially be recycled, (or disposed of) after the reuse phase, for example, car tyres used to build the Earthship walls were assumed to have impacts equal to the impacts associated with the transport process needed to deliver them to the building site and away from the building site at end-of-life, plus the impacts of end-of-life processes such as recycling or land-filling.

5.4 Stage 2 - Life Cycle Inventory Analysis (LCI)

Life Cycle Inventory Analysis (LCI) refers to the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle." (ISO, 2006, p. 2). This section describes the process used to establish the inventory of inputs and outputs to the system arising from the lifecycle of the various buildings being analysed.

There are two levels of inventory: the LCI databases relating to materials and processes generated by industry and researchers, and the data developed in this study regarding the construction materials, products, and processes that have been used in the construction elements of the houses being analysed. The latter is referred to, in this study, as the Building Elements Inventory.

Another important LCI item is the operational energy used by the house during its "use" phase. The method for generating this data has been described in Chapter 4, which investigates thermal performance in the Adelaide climate.

Having identified these inputs for house construction and operation, SimaPro LCA software is used to implement the primary data contained in the LCI databases. Assumptions regarding recycling rates and disposal methods are also entered into the software completing the process of defining assumptions regarding the life cycle of the home. Using this information the LCA software generates a very detailed inventory (LCI) which can be analysed to assess environmental impacts using a variety of environmental "indicators" (described in Section 5.5).

5.4.1.1 LCI Databases

Where possible the LCI data used in this study are from "Australasian Unit Process LCI" (RMIT Centre for Design, CRC for Waste Management and Pollution Control & Life Cycle Strategies, 1998-2007) 2013 edition. These data were originally developed during the late 1990s by the RMIT Centre for Design from data originally developed by the CRC for Waste Management and Pollution Control (Carre, 2011). It is updated by Tim Grant of Life Cycle Strategies (Life Cycle Strategies, 2014).

Currently the Australian Life Cycle Assessment Society (ALCAS) is developing an Australian Life Cycle Inventory Database Initiative (AusLCI), which will "provide and maintain a national, publicly-accessible database with easy access to authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services over their entire life cycle" (AusLCI, 2013). However at this stage preliminary ("beta release") electricity data is the only inventory that has been published and the associated report is pending.

Australian LCI data developed by BPIC (Building Products Innovation Council) are available via the BPIC website, however these data were not used due to concerns that the methodology of this study may not adhere to their protocol (Howard & Sharp, 2010) which may result in BPIC members taking action "...to enforce correct use of the data. A full range of remedies to misrepresentations or consequential damages may be pursued..." (p. 12).LCI data tends to be confidential as it has the potential to seriously damage the viability of industries by exposing their environmental credentials. Likewise, the use of the data is a sensitive issue because if used improperly, false conclusions will be made regarding the environmental attributes of products and industries. Therefore it is not surprising BPIC have explicitly warned users of the data about the potential for recourse should their protocol not be adhered to.

Consequently the Australasian Unit Process LCI provides the most "open source" freely available, liability-free dataset; however, it has the disadvantage of being somewhat limited in scope and therefore other datasets must be used such as the European EcoInvent (Ecoinvent, 2013). In such cases these data were adapted to Australian conditions as much as practicable, generally by changing energy (electricity and gas) and transport processes from European processes to Australian processes – generally South Australian processes.

5.4.1.2 Validation

Life Cycle Impact Assessment results for major building products such as bricks, concrete, timber are presented with a comparison to similar studies and a discussion about the quality of the LCI data used in this study.

5.4.1.3 Building Elements Inventory - Method

The general approach for calculating the Building Elements Inventory was as follows;

1. Research typical construction methods to establish the materials required and how they are assembled.

- Calculate the volume of each material via either:

- a computer model (hereby referred to as a CAD model) using 3D parametric solid modelling software (SolidWorks) as a means to calculate material quantities and document the assumptions made regarding materials and construction.
- or, for components with very basic geometry, simple calculations.

2. Create a drawing to document the assumptions regarding the material volumes and the overall structure under analysis and establish the volumes of all relevant components.
3. Calculate the mass using the known material densities which were sourced from product specification sheets or, for more generic materials via online sources such as the SI Metric website (SI Metric, 2012).
4. In some cases a second stage of calculations were performed to calculate the volume of “sub-components” for example, the “render” component was calculated firstly as a gross volume of render. Secondly, the volume of sand, cement, and water were calculated based on volumetric mixing ratios for the render. Likewise for the tyre wall, the gross volume of the wall was calculated first and then the volume of its sub-components (such as tyres, cardboard, and earth) were calculated.
5. Use the mass/volume of every significant element of the wall construction in the LCA modelling software (SimaPro™ 7.3.3) to establish the environmental impacts arising from the materials used in the wall construction. The results of this are covered in Chapter 6 Life Cycle Inventory Analysis.

For calculating wall material quantities a “wall module” of certain dimensions was established based on the nature of the wall construction and this module was used to establish the quantities per linear metre of wall. For example the Earthship wall module was 0.65m long based on a tyre diameter of 0.65m, Strawbale wall module was 900mm long based on bales 900mm long etc. Results for the module length were then multiplied by the calculated linear length of external wall to determine the total quantities of materials for the Functional Unit of each particular envelope thereby enabling comparison in terms of a linear metre of external wall or the total amount of external wall.

The approach for calculating the environmental impacts of processes (as opposed to materials) used to construct the various structures being studied was;

1. Research typical construction methods to establish the processes involved.
2. Research fuel/energy consumption of machinery/tools.
3. Estimate and calculate approximate fuel/energy use for each machine/tool. Where possible discussions with builders informed these estimates.
4. Document the research findings and calculations.
5. Input the results into the LCA software to establish the environmental impacts arising from the processes used in the wall construction.

The parameters (used in SimaPro™ LCA modelling software) and assumptions regarding the materials and processes used in the construction of the internal walls are defined in this section. The level of documentation of the assumptions and values used in the modelling is limited by the extreme detail contained in SimaPro™'s Life Cycle Inventories databases. As such, each construction is only documented to the level where the reader can understand the main inputs, without getting bogged down in the minutiae. Typically this entails a quantities list of the main building products (e.g. bricks, concrete, timber, glass) and/or raw materials (e.g. sand) plus the transport type required to deliver the product/material to the construction site.

5.4.1.4 Off-Grid Systems Inventory

To establish quantities of materials used to manufacture the off-grid systems (energy, water, waste water and food production) suppliers were contacted to request this information and where information was missing assumptions were made. All assumptions are listed under the appropriate "systems" headings in the LCI section.

5.5 Stage 3 - Life Cycle Impact Assessment (LCIA)

5.5.1.1 Introduction

Life Cycle Impact Assessment (LCIA) is the third stage of LCA with the aim of "understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO, 2006) p. 2. It translates the results of the LCI (life cycle inventory analysis) into "indicators" or "impact categories" such as "global warming potential", "photochemical smog", "ozone depletion" and "eco toxicity".

This section gives a brief account of global LCIA practice, Australian best practice, and describes the method selected for this study.

ISO describes the mandatory elements of this stage as:

- "selection of impact categories[1], category indicators[2] and characterisation models;
- assignment of LCI results to the selected impact categories (classification) and
- calculation of category indicator results (characterisation)" (ISO, 2006) p. 16.

Optional elements of LCIA include normalisation and weighting. Normalisation is used to report results in the context of worldwide or region totals and weighting attempts to assign relative importance to the various impact categories such that an overall result can be clearly communicated. Note, however, that this is not recommended for LCA studies that are intended for publication, due to the subjective nature of assigning weighting factors which are subject to public opinion – this is "arguably the most controversial and debated step of the LCIA" (Bengtsson & Howard, 2010a) p. 11.

5.5.1.2 Choice of Impact Categories & Characterisation Models

Selection of impact categories is not prescribed by any standard and consequently many "Methods" have been developed to cater to differing environmental and technical conditions which exist in different countries and regions. An LCIA "Method" is essentially a set of impact categories, each of which is configured to tally quantities for a given list of substances, and then reports the impact in the common unit for that impact category. For example greenhouse gases (e.g. CO_2, CO, CH4) are listed for the "global warming" indicator with corresponding factors which define their relative impacts. For global warming the common unit is kgCO_2 equivalents; CO_2 has a factor of 1, whereas CH4 has a factor of 21, and these factors can vary based on assumptions defined by international agreements (e.g. Kyoto Protocol) or the LCA methodology applied.

Although some impact categories are applicable globally, others are more sensitive to geographic location due to various factors such as differences in the way energy is produced, land is utilised and availability of water. Furthermore the impact categories must be consistent with and sensitive to the inventory data. A common LCIA method used in Europe is Eco Indicator 99 developed by Goedkoop and Spriensma (Goedkoop & Spriensma, 1999) and others have been developed such as CML (Centre of Environmental Science of Leiden University in the Netherlands), and IMPACT 2002+ (a combination

[1] "Impact Category: Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned" (ISO, 2006) p. 5

[2] "Category Indicator: Quantifiable representation of an impact category" (ISO, 2006) p. 6

of four methods; CML, IPCC, Eco Indicator 99 and IMPACT 2002. Each attempts to address some kind of methodological problem with LCA; it may present the results in a different way, or it may focus on a particular type of impact.

In Australia best practice guidelines (Grant & Peters, 2008) have been developed and reviewed by members of the Australian Life Cycle Assessment Society (ALCAS) to provide guidance on the selection of impact categories in the Australian context. These guidelines are grouped into global and regional categories and classified as "ready to use" or "provisional – needs development". Table 5.1 presents these impact categories and discusses their relevance to this study.

Another study significant to LCIA in Australia was conducted on behalf of the Building Products Innovation Council and AusIndustry (the "BPIC/ICIP Project") by Bengtsson and Howard (Bengtsson & Howard, 2010a) with the objective of proposing "an LCIA method to allow for consistent level playing field comparison between LCA studies" conducted in Australia. In general this report agrees with the guidelines developed by Grant and Peters (2008) and furthermore it identifies 14 "midpoint impact categories" which, when normalised and weighted, lead to four "endpoint damage categories" (refer Figure 5.4).

Table 5.1 - Recommended Australian Impact Categories

Category & status	Description and Discussion
Global Impact Categories	
Global Warming *Ready to use*	Measurement of the emission of greenhouse gases (GHG) into the atmosphere. These gases increase the amount of heat (infrared radiation) that is trapped in the atmosphere. Category Indicator: kilograms of Carbon Dioxide equivalents. GHG emissions are suspected to be the key factor driving climate change however it is also related to human health, ecological quality and resource depletion. The IPCCs fourth assessment report defines the main greenhouse gases and their causes as, a) carbon dioxide caused by burning carbon based fuels and land-use change, b) methane caused by agriculture and fossil fuel use, and c) nitrous oxide caused by agriculture (IPCC, 2007). Characterisation factors for GHG have been defined by various agencies and certain contexts and these vary due to assumptions such as the timeframe over which a gas is assumed to have an influence on global warming and the gases' global warming potential (potency). For this study GHG characterisation factors are as per the National Greenhouse Accounts (Department of Climate Change and Energy Efficiency, 2012) which assume the GHG impacts are averaged over a 100 year time frame. The DCC figures were chosen as this is the method used by the Australian Government for reporting greenhouse gas emissions.
Stratospheric ozone depletion *Ready to use*	Measurement of the emission of gases that deplete the ozone layer. Category Indicator: kilograms of Chlorinated Fluorocarbon 11 equivalents. The Montreal Protocol established an internationally agreed model for assessing the relative ozone depletion potential for a problematic group of chemicals: namely chlorofluorocarbons (CFCs) and hydrochloroflurocarbons (HCFCs). In Australia, most of these chemicals are no longer in use and hence this impact category is only applicable if significant quantities of ozone depleting chemicals are used. CFSs, HCFCs and Hydrofluorocarbons (HFCs) which replaced CFCs and HCFCs are also extremely potent (thousands of times more potent than CO_2) greenhouse gases and their impact on global warming is counted in the Global Warming impact category. In the construction and use of a home (in Australia) it is highly unlikely that any ozone depleting chemicals are employed.
Minerals and/or fossil fuel depletion (abiotic resource depletion) *Ready to use*	Measurement of the additional energy needed to mine diminishing resources. As non renewable resources are depleted the energy required to find them and extract them increases. Category Indicator: Mega joules of surplus energy. This category is relevant to this study in which homes constructed with non renewable minerals versus homes constructed with renewable materials are compared.
Regional Impact Categories	
Human and eco-toxicity *Ready to use*	Measurement of the effects of industrial process pollutants on humans and ecosystems. Category Indicator: Disability Adjusted Life Years (DALY), a measure of the burden of disease and is the sum of the years of life lost due to premature death and the years spent with disability. The guidelines recommend that this category is only necessary where the systems in question have direct interaction with significant toxic substances such as in waste management systems or agriculture where toxins may be involved in the form of herbicides, pesticides and fertilisers.

	This category is applicable to this study which includes the use of agricultural residues (straw) for Strawbale wall construction and as an ingredient in adobe render which is used in Earthship and Strawbale construction.
Water use *Provisional*	Measurement of water use including water used in manufacturing processes and for potable domestic water use. Category Indicator: kilolitres of water. This category is provisional because of significant uncertainty regarding an appropriate evaluation method arising from the variable impact of water scarcity in different regions. LCI data generally contains only volumetric data which will have differing consequences depending on the availability of water in each region and the sensitivity of the environment to water extraction. Many different approaches are currently being developed in Australia (Bengtsson & Howard, 2010a, p. 37) and overseas however this rough volumetric indicator can be used with caution to draw tentative conclusions. Water use is a significant issue in the production of construction materials and in the operation of a home.
Land use *Provisional*	Measurement of land use for a period of time. This encompasses the use of land for industrial, agricultural, forestry and domestic purposes. Category Indicator: hectares per year. Similar to Water Use, this category also involves significant uncertainty and various models have been developed to evaluate the impact of land use. Some models take into account the level of disturbance of the natural environment whereas others focus on the effect upon species populations (Grant & Peters, 2008, p. 9). At this stage the common practice in Australia is to simply total the land area used by all processes. Due to this indiscriminate addition of various types of land use only tentative conclusions can be drawn. Land use is a significant issue in the production of construction materials and in the operation of a home this category will be included.
Eutrophication *Provisional*	Measurement of nitrogen and phosphorous to air, water and soil. Category Indicator: kilograms of PO_4 equivalents. Grant warns that results must be “treated with care with sources of nitrogen being investigated to determine if they are directly released to aquatic environments or may be attenuated by airborne transport. Overestimation of environmental burdens is likely in Australia doe to the deposition of nitrogen oxide (NOx) emissions in insensitive environments.” (Grant & Peters, 2008, p. 10). This may be relevant to Earthship and Strawbale constructions.
Photochemical oxidation (smog) *Ready to use*	Measurement of photochemical smog causing gases such as nitrogen oxides, volatile organic compounds and peroxyacyl nitrates, aldehydes and ozone. Category Indicator: kilograms of C_2H_4 equivalents. (Ethylene) In Australia smog incidents are fairly low and are related mainly to NOx emissions from vehicles which have improved due to more modern engine technology. Grant suggests that it can be omitted from routine LCA (Grant & Peters, 2008, p. 10). This could be relevant due to the need for transporting significant quantities of materials to the construction site.
Soil salinisation *Ready to use*	Measurement of the accumulation of soluble salts of sodium, magnesium and calcium in the soil causing reduced soil fertility. Category Indicator: salinisation potential. This category is only relevant for irrigated agriculture (Grant & Peters, 2008, p. 11). This impact category could be omitted for this study.

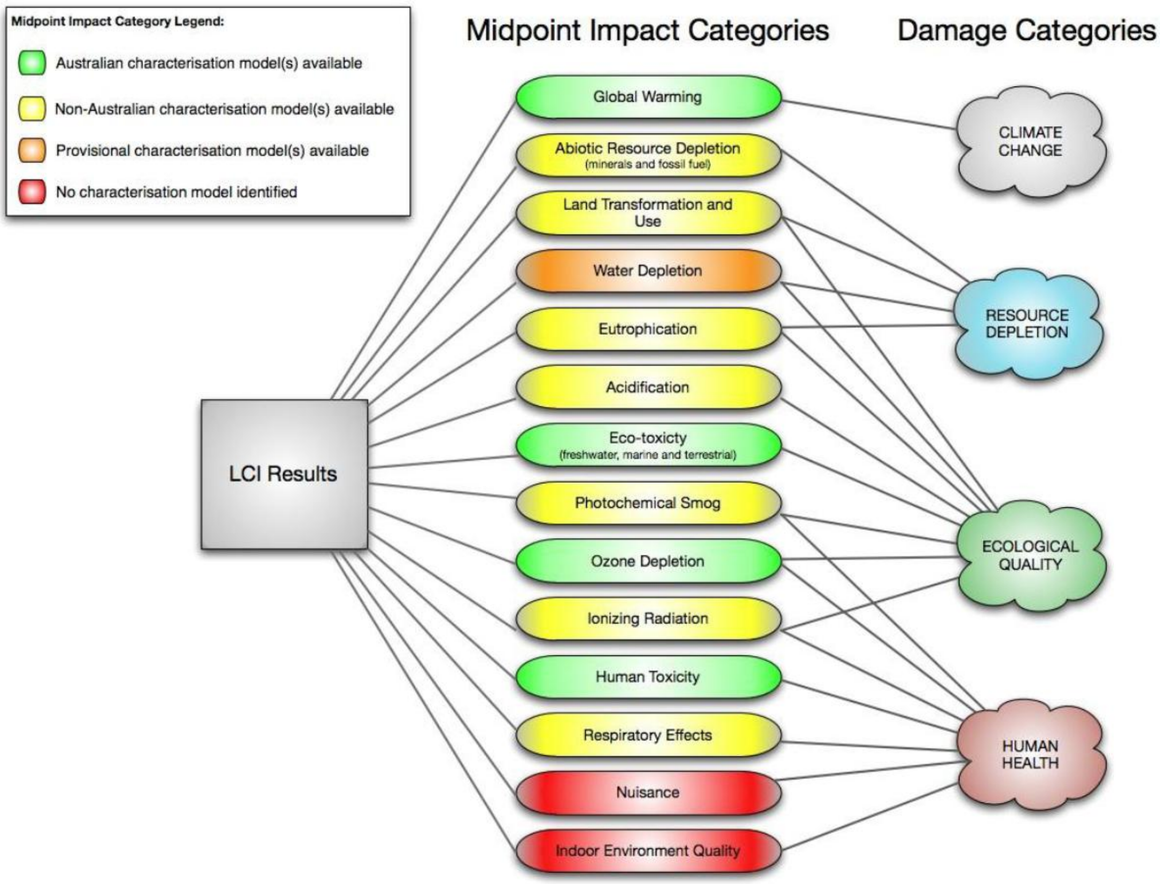

Figure 5.4 - BPIC/ICIP Project's recommended LCIA method (Bengtsson & Howard, 2010a) p. 8

This raises the issue of another potentially problematic aspect of impact assessment methods: normalising the results against a known baseline. This is not problematic for well understood impact categories such as global warming because data is readily available and the characterisation results can be normalised against global, national or per capita emissions for example. However other impact categories with obscure category indicators (common units) can create difficulties for normalisation, especially in the Australian context where the development of LCIA methods is ongoing. This is especially the case in terms of human and eco toxicity and this was borne out by initial results of this study in which the internal wall constructions were analysed with various methods. Minute quantities of toxics were reported for all internal wall types, for all Methods used, but without data regarding what level of toxics constituted a tangible threat to human or eco system health, (i.e. without a credible figure to use for normalisation) it was difficult to interpret the data.

The final and most controversial aspect of the LCIA Method is that of weighting. Having normalised the characterisation results (thus creating a unit-less result) the weighting process assigns relative importance to the various impact/damage categories. The weighted results of each category can then be totalled to present a single number, overall “score” for the summated impacts of the system/product. ISO expressly prohibits this for studies that are for publication.

The LCA study by Carre (2011) for the Forest and Wood Products Australia adopted Grant’s indicators with the exception that the toxicity indicators were not used on the grounds that Australian LCI data was not adequate, and it included two other categories which have been historically used, especially in the construction industry: embodied energy (or “cumulative energy demand”) and solid waste. Carre’s study notes that these are “not true measures of environmental impact, but rather track issues that are likely to be precursors to environmental impact” (Carre, 2011, p. 16). They also provide a means for comparing results with previous studies.

Embodied energy, which is also known as cumulative energy demand, is often used as a measure of potential environmental impacts from constructing a building as well as the energy required for manufacturing the heating and cooling equipment, and to a lesser extent is a measure of solid waste produced during those processes. Thus despite them not being “true measures” of environmental impact, they can be useful for comparing results with other studies, although in time they may become redundant. This is certainly the view of the BPIC/ICIP project which recommends that the Solid Waste indicator be omitted as it overlaps with other mid-point categories: resources depletion, land transformation and use, eco-toxicity and human toxicity (Bengtsson & Howard, 2010a, p. 39-40). Grant’s guidelines do not include Solid Waste (Grant & Peters, 2008) but Carre, on the other hand, included the Solid Waste indicator because it indicates potential landfill requirements, a concept which is interesting, and easily understood by the layperson.

In Carre’s study Cumulative Energy Demand was based on a European impact assessment method “CML 92 V2.04” with changes to reflect Australian energy production (Carre, 2011, p. 16). It included fossil, renewable, electrical, and feedstock (energy expending in manufacture of materials/products). However the BPIC/ICIP report suggests that Embodied Energy be considered as part of Abiotic Resource Depletion, otherwise impacts arising from fossil fuel burning would be double counted (p. 39). Furthermore it suggests that renewable energy not be counted as it is “free of burden in terms of depleting resources”.

In summary, the framework proposed by the BPIC/ICIP project seems highly applicable to this project, yet few if any published studies have used this system and an Australian Method is yet to be configured for SimaPro™ LCA software for widespread use by LCA practitioners. Although Carre’s method omits toxics, this is justified by concerns about data quality, and its use of (arguably) out of date indicators (Solid Waste and Embodied Energy) are nonetheless still relevant and useful especially in the context of building LCA.

In conclusion, it seemed reasonable and practical to adopt the majority of indicators used by Carre but to also investigate some additional methods for assessing the impacts on human and ecosystem health (toxics). Grant suggested the USEtox™ method (Grant, 2013) was worth experimenting with. Further, Grant suggested the use of this method in analysing “resource depletion”, to avoid “double counting” of fossil fuel, which is counted in Embodied Energy.

The indicators comprising the Method used in this study are outlined in Table 5.2.

Table 5.2 - Indicators comprising the Method used in this Study

Indicators	Method source/comments
Global Warming Potential	Greenhouse impacts are 100 year impacts based on 1990 IPCC characterisation figures (Bengtsson & Howard, 2010a, p. 25).
Ozone Depletion	Ozone depletion based on CML2001 (Center of Environmental Science of Leiden University) (Goedkoop, Oele, de Schryver & Vieira, 2008, p. 9) from Australasian Unit Process LCI (adaptation by Life Cycle Strategies).
Photochemical Oxidation	CML2001 (Goedkoop, Oele, de Schryver & Vieira, 2008, p. 5).
Eutrophication	Based on CML2001 (adaptation by Life Cycle Strategies).
Land Use & Transformation	Addition of land use without any weighting.
Water Use/Depletion	Addition of water use without any weighting.
Solid Waste	Addition of all waste inventories.
Embodied Energy	Australasian Unit Process LCI V2.02 (RMIT Centre for Design, CRC for Waste Management and Pollution Control & Life Cycle Strategies, 1998-2007)
Human Toxicity (Carcinogens)	USEtox (Rosenbaum et al., 2008)
Human Toxicity (Non-carcinogenic)	USEtox (Rosenbaum et al., 2008)
Eco Toxicity	USEtox (Rosenbaum et al., 2008)

For the toxics indicators, Grant's guidelines suggest the use of a method that uses Disability-Adjusted Life Year (DALY) as the common unit; however, for this study Grant suggested (Grant, 2013) the USEtox™ method (Rosenbaum et al., 2008) which uses units called Comparative Toxic Unit specific to human or eco system toxicity thus the unit abbreviations are CTUh and CTUe. All other indicators are as per Table 5.1 which describes the best practice Australian indicators.

Characterisation factors used in this study are tabled in Appendix D.

5.5.2 Normalisation

Normalisation factors were derived from the BPIC/ICIP report (Bengtsson & Howard, 2010b) and, Carre (2011, p. 119) as tabled below. Normalisation factors for a 50 year time frame are also given as this is the standard assumption for the life span of the functional unit in this study.

Table 5.3 - Normalisation Factors Comparison

	Source	BPIC part 2		Carre	Carre	This Study	This Study	This Study for 50 yr
Impact Category	Unit	AU Total	per capita	AU tot*	per capita	AU tot	per capita	per capita
global warming	kg CO_2 eq	6.21E+11	2.87E+04	1.24E-03	2.61E+04	6.21E+11	2.87E+04	1.43E+06
ozone layer depletion	kg CFC-11 eq	4.17E+04	2.00E-03			4.17E+04	2.00E-03	1.00E-01
photo-chemical oxidation	NMVOC eq (kg C_2H_4 Carre and this study)	1.61E+09	7.50E+01	3.43E-07	7.19E+00	1.61E+09	7.50E+01	3.75E+03
eutrophication	kg PO4 eq	4.16E+08	1.90E+01	6.75E-07	1.42E+01	4.17E+08	1.90E+01	9.50E+02
land transformation	Ha a		2.60E+01	1.14E-06	2.39E+01	4.95E+08	2.60E+01	1.30E+03
water consumption	kl H2O		9.30E+02	4.33E-05	9.09E+02	9.09E+10	9.30E+02	4.65E+04
solid waste				6.61E-05	1.39E+03	6.62E-05	1.39E+03	6.94E+04
embodied energy lhv				3.66E-02	7.69E+05	3.66E-02	7.69E+05	3.85E+07
abiotic depletion	kg Sb eq	6.50E+09	3.00E+02					
acidification	kg SO2 eq	2.67E+09	1.23E+02					

*calculated

5.5.3 Weighting

Weighting factors were calculated based on the BPIC Weighting report (Bengtsson, Howard & Kneppers, 2010). Table 5.4 reports the Australian average demographically adjusted figures given in the BPIC/ICIP report, and the figures used in this study. Embodied Energy was assigned a relatively high weighting as it is directly related to Global Warming which has a high weighting. Resource Depletion was based on the Non Renewable Fuels weighting and Solid Waste was assigned a low weighting as this is an issue that does not generally cause alarm.

As some of the BPIC/ICIP impact categories were not adopted by this study it was necessary to assume that the weightings could be interpreted as being relative e.g. Global Warming is seven times more important than Photochemical Smog. The weighting factors were derived from this assumption using Global Warming as a reference/baseline. These weighting factors were then used to calculate a theoretical Australian “EcoPoint” score using the normalised results. Note that toxicity indicators do not contribute to the EcoPoint score due to unreliable data and lack of normalisation data for the USEtox method.

Table 5.4 - Weighting Factor

BPIC/ICIP LCIA Impact Category	Australian Average Demographically Adjusted	This Study	Weighting Factor
Global Warming	21	21	1
Acidification	4	NA	
Ozone Layer Depletion	4	4	0.19
Marine Aquatic Ecotoxicity	12	NA	
Terrestrial Ecotoxicity	6	NA	
Abiotic Depletion: Non Renewable Fuels	3	NA	
Abiotic Depletion: Minerals	4	NA	
Human Toxicity	3	NA	
Ionizing Radiation	2	NA	
Land Transformation and Use	17	17	0.81
Respiratory Effects	3	NA	
Photochemical Smog	3	3	0.14
Freshwater Aquatic Ecotoxicity	10	NA	
Eutrophication	3	3	0.14
Water Depletion	6	6	0.29
Other Impact Categories used in this study			
Solid Waste	NA	3	0.14
Embodied Energy	NA	15	0.71

5.6 Stage 4 - Interpretation

Life cycle interpretation refers to “phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations. (ISO, 2006, p. 2). It includes identification of significant issues arising from the LCI and LCIA stages, an evaluation of the data and method in terms of completeness, sensitivity and consistency, and limitations, recommendations and conclusions (p. 23).

In essence, the interpretation stage of the LCA presents the final results with discussion about assumptions that may have affected the results and where appropriate, further sensitivity studies are used to demonstrate how important or uncertain assumptions affected the results. For each building element and the overall thermal envelope results are reported for each life cycle stage: construction, operation, and end-of-life, plus an overall result for the full life cycle. This enables conclusions to be drawn about the relative impacts of the various building elements (roof, wall etc) and the relative impacts of one thermal envelope type versus another.

5.6.1.1 Sensitivity Studies

Sensitivity studies or sensitivity analysis refers to “systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study” (ISO, 2006) p. 5.

In this study, the following assumptions have been tested;

- Some building codes require concrete footings for all wall types including tyre walls (e.g. Gubb Earthship in New Zealand (Gubb, 2012)) due to seismic conditions or problematic soil conditions. Therefore the effect of including a concrete footing in the Earthship design has been investigated.
- Assumptions about how Earthship internal “can walls” are constructed and disposed of at end-of-life have been explored. This relates to whether or not the aluminium cans are recycled and the type of mortar used (cement based or mud based) to make the walls.
- The effect of not counting the benefits of carbon sequestration of timber products in landfill was briefly investigated in terms of the impacts associated with external wall construction.

- The effect of altering the weightings of impact categories was explored in terms of the final results of the LCA study as this is a contentious issue.

5.7 Summary

The four stages presented in this Chapter have been used to analyse the environmental impacts of a typical off-grid Earthship dwelling compared to buildings of the same dimensions and design but which have different wall construction methods and which are serviced by conventional energy, water and wastewater infrastructure. These will be discussed in the following Chapter.

6 Life Cycle Inventory Analysis

6.1 Introduction

Life Cycle Inventory Analysis (LCI) is the second stage of LCA in which an inventory of inputs and outputs of the system are compiled. This section presents the results of calculations regarding quantities of materials and energy use throughout the lifecycle of the systems (buildings) under analysis. The calculation method has been described in Chapter 5.

The calculation results are presented here in terms of assumptions which are described in the following order:

- assumptions regarding process energy to include diesel fuel, earth moving, excavation, transport and concrete/render mixing.
- assumptions regarding end-of-life scenarios for various materials.
- assumptions regarding heating/cooling energy (as per the Thermal Performance Study findings presented in Chapter 4).
- other operational energy use assumptions.
- assumptions regarding material thicknesses and material densities.
- assumptions and data sources for common building materials such as timber, concrete, bricks, steel and double glazing.
- energy emission factors for South Australia which are presented and compared to the SimaPro™ data.
- assumptions regarding the construction of walls, and the resulting material quantities for each wall type under analysis in the LCA: Earthship, Mudbrick, Rammed Earth, Rammed Earth Insulated, Strawbale, Concrete Block Insulated, Brick Veneer, Reverse Brick Veneer, Timber Frame (cement fibre board clad) and Timber Frame (steel clad).
- assumptions regarding common elements, and the resulting material quantities for; render, roof & ceiling, floor, internal walls, partition wall, and greenhouse.
- assumptions regarding the systems for energy, wastewater and water collection/storage.
- assumptions regarding maintenance of the walls and systems.
- assumptions regarding land occupation (the area needed to site the home and wastewater system).

6.1.1 Building Elements Definitions

Before presenting the assumptions for the various lifecycle stages, a description of each major element of the thermal envelope is described below.

6.1.1.1 External Walls

The materials inventory for all external wall types was based on the functional unit of inside dimensions 22m x 5.5m x 2.7m ceiling height and includes materials for the top plate assembly and footings as appropriate for each wall type. The term "external wall" refers to the south, east and west walls, and due to the use of glazing and other variables associated with the equator facing wall, the equator facing wall is classified and described separately (below).

Further assumptions are detailed later under headings for each external wall type.

6.1.1.2 Internal Partition Walls

In the thermal modelling study internal partition walls were either "lightweight" timber frame with plasterboard lining (total 110mm thick) or "thermal mass" adobe bricks (110mm thick). Both will be evaluated in the LCA plus the Earthship "can walls" that are typically used for internal Earthship walls. The "can wall" is modelled in two configurations, one "low embodied energy" (low EE) version which assumes a clay based mortar and recycling of the aluminium cans at end-of-life, and the standard Earthship construction method of using a cement based mortar. The latter configuration assumes landfill at the end-of-life of the aluminium cans.

6.1.1.3 Equator Facing Wall / Greenhouse Partition Wall

The glazed wall bounding the northern side of the living space is termed the "Equator Facing Wall" in the context of a thermal envelope with no greenhouse, whereas it is termed "Greenhouse Partition Wall" when a greenhouse is included in the thermal envelope. The Equator Facing Wall is an external wall, whereas the Greenhouse Partition Wall is an internal wall. Collectively these walls are referred to as the Glazed Wall.

The materials used to construct the Glazed Wall are generally the same as the external wall type; however, an exception to this is the Earthship. In an Earthship the Glazed Wall is not made from tyres - it is almost entirely glazed, whereas other house construction methods tend to use the same construction method for all walls. Therefore the Earthship "Without Greenhouse" envelopes utilise a steel clad insulated timber frame wall (TFS) similar to actual Earthship constructions in Taos.

6.1.1.4 Key Dimensions of External Walls

Based on the assumptions regarding the External Walls and Glazed Wall key dimensions for each envelope are presented in Table 6.1. For the Earthship, the External Wall bounds the south, east and west sides of the house whereas the other external wall types are assumed to include the north wall ("Glazed Wall") which is assumed to have a glazed area of 50% (of the Equator Facing wall area).

Wall lengths are calculated using the mid-line (centre axis) of the wall which helps to account for inaccuracies arising from the wall corners, i.e. if the inner length of the wall was used for calculations the corners would not be counted and if the outer length was used the corners would be double counted. The length of the Equator Facing Wall is 22m long; however, as it is 50% glazed, for the purposes of calculating the quantity (linear metres) of External Wall materials, calculations are based on half this length (11m) to take into account the glazed area.

Table 6.1 gives the dimensions of the External Wall and Equator Facing Wall for the various external wall construction types. Although the internal dimensions of the thermal envelope are constant, the External Wall length varies slightly due to differing thicknesses of the external wall. An exception to this is Brick Veneer Conventional which is based on a square floor plan (11m x 11m) of the same area as the functional unit (121m^2).

Table 6.1 - Linear metres of external wall and footing based on wall width and functional unit dimensions

External Wall Type	Wall length	Wall depth	Wall thick	Glz Wall thick	Footing length	External Wall length	Glz Wall length	Total Ext wall length	Glz Wall type
	m	m	m	m	lm	lm	lm	lm	
Earthship / ESI	22	5.5	0.675	0.1	56.55	34.55	11		TF steel clad
Rammed Earth / REI	22	5.5	0.3	0.3	55.60			44.60	as per ext wall
Strawbale	22	5.5	0.55	0.55	56.10			45.10	as per ext wall
Concrete Block Insulated	22	5.5	0.305	0.305	55.61			44.61	as per ext wall
Reverse Brick Veneer	22	5.5	0.256	0.256	55.51			44.51	as per ext wall
Brick Veneer	22	5.5	0.263	0.263	55.53			44.53	as per ext wall
Brick Veneer Conventional	11	11	0.263	0.263	44.53			34.05	as per ext wall
Timber Frame CemFib clad	22	5.5	0.115	0.115	55.23			44.23	as per ext wall
Timber Frame Steel clad	22	5.5	0.104	0.104	55.21			44.21	as per ext wall
Mudbrick	22	5.5	0.275	0.275	55.55			44.55	as per ext wall

6.1.1.5 Greenhouse

The greenhouse is a 46m^2 space adjoining the living areas on the equator facing side of the building. The equator facing side is assumed to be 100% glazed with double glazing units. Two configurations of the greenhouse were modelled, one assuming the use of the cement mortar “can wall” and landfill of the aluminium cans at end-of-life, and another assuming a clay mortar “can wall” and recycling of the aluminium cans at end-of-life.

6.1.1.6 Roof

The roof is a highly insulated (R5.1), timber truss, steel clad structure based on the geometry of the Global Model Earthship. R5.1 is also the minimum roof assembly insulation value for an Earthship built in the colder climes of Adelaide region (BCA climate category 6 in the Adelaide Hills). A “conventional” roof was also modelled based on a gable roof design with similar amounts of insulation and roof area.

6.1.1.7 Floor

The thermal modelling study used a concrete slab floor, although in reality Earthship floors are often made of mud, brick, flagstone or concrete slab. In terms of the thermal modelling, concrete and mud offer comparable thermal properties; however, in terms of embodied energy (and therefore environmental impacts) they are poles apart. To establish the relative impacts of a concrete floor versus a mud floor inventories were developed for each type of floor.

6.1.2 Systems Description

The autonomous systems used by the Earthship include renewable energy with battery storage, rain water collection, storage, filtration and pressurisation, and on-site wastewater treatment. This study compares these systems to conventional systems as outlined in Table 6.2. Further details are given in the Systems heading. As food is a by-product of the wastewater treatment system of the Earthship this is compared to supermarket purchased food.

Table 6.2 - Autonomous and Conventional Systems

Service	Autonomous Earthship	Grid connected Conventional
Energy	Renewable energy system, typically solar panels, with battery bank for storage, and inverter/charge controller. This supplies electricity for appliances and lighting. Energy for heating and cooling is not necessary. Bottled gas is used for solar hot water backup and cooking fuel.	Electricity and gas delivered by the grid. Electricity is assumed for general appliances, lighting, and heating and cooling and gas is assumed for solar hot water backup and cooking fuel.
Water	Rain water tanks are used to store roof run-off. A "water organisation module" (WOM) is used to filter and pressurise the water for delivery to appliances and outlets in the house.	Water is supplied via infrastructure including dams, pumping/sterilisation stations and pipe networks.
Wastewater treatment	Biological filters are used to treat greywater and blackwater. Treated greywater is used for toilet flushing and irrigation of food crops. Treated blackwater is used for irrigation of landscape.	Wastewater is pumped to treatment station via sewer pipe network. Fresh water is used to flush toilet.
Food	Food is grown in the greywater planter, reducing the quantity of food required from other food systems (farms, supermarket etc)	Food is not grown on site, but is obtained from other sources such as the supermarket.

6.2 Assumptions of Process Energy

Process energy is often not included in building life cycle assessment due to lack of data, and previous findings that process energy is insignificant (Gustavsson & Joelsson, 2010; Kellenberger & Althaus, 2009). However in this study an attempt has been made to include process energy as the Earthship relies heavily on earth moving machinery, so this should be investigated.

6.2.1 Diesel Fuel – Process Energy

It is assumed that diesel fuel has an energy density of 35MJ/L (Nektalova, 2008). This is relevant to Earth Moving and Excavation processes described below.

6.2.2 Earth Moving – Process Energy

Based on discussions with the operator of a 5 tonne track excavator (Mumford, 2012) the estimated rate of excavation for soft earth (e.g. earth that was previously excavated and stockpiled) is 80m3/hr and for hard earth (i.e. digging into virgin ground) 40m3/hr. The fuel consumption of the excavator is assumed to be 6L/hr (diesel) based on discussion with same operator. Assuming an energy density of 35MJ/L for diesel fuel this equates to 210MJ per hour for use of the excavator in "soft earth".

6.2.3 Excavation – Process Energy

Excavation generally assumes digging into hard, compacted, "virgin" ground and therefore it takes more time and energy for an excavator to perform it's task compared to "earth moving" which involves digging "soft earth" as explained above. Therefore when "digging in hard earth" a value of 40m3/hr is applicable (Mumford, 2012).

6.2.4 Transport of Materials & Products

Environmental impacts arising from transport were modelled using the assumptions below:

- Materials/Products manufactured in a factory, were transported 50km to a retailer and another 50km to the site.
- If delivery of raw material to the factory was required (e.g. plastic granules to the rotational moulder) it was assumed to be transported 50km to the factory.
- Materials/products delivered directly from the manufacturer (e.g. a quarry) to the site were transported 50km.
- Earth that was hauled to site (e.g. to build an Earthship berm) was transported 20km on the grounds that it is usually supplied for free as a waste material from a local excavation site.

- Materials/products obtained locally and transported directly to site (e.g. used tyres) were modelled as being transported 20km in total assuming an owner-builder travelling 10km to collect reused materials and then returning 10km to the site.
- At end-of-life, waste is assumed to be transported 50km to the landfill site.

6.2.5 Render Mixing – Process Energy

It is assumed that all render (internal and external) is mixed onsite using a petrol powered cement mixer. Using fuel consumption values for a Honda GX120 engine (Honda Motor Co., 1990) powering a mixer which has a 102L volume mixing bowl, it is estimated that at a rate of 8 mixes per hour at half load (so as not to overfill the mixer bowl), 960kg of concrete render could be mixed, with 0.8kg of petrol and 1 tonne of concrete render would require 0.833kg of petrol. Using the same rate of batches per hour and fuel consumption, adobe render, due to its lower density, will be mixed at a rate of 700kg per hour using the same rate of fuel consumption, thus 1.143 kg of petrol per tonne of adobe render.

Transportation of cement is by road from plant to retailer plus another journey from retailer to construction site. Transportation of sand is directly from the quarry to the site.

6.2.6 Process Energy of Constructions

Unless stated otherwise, zero process energy is assumed for construction processes associated with construction of the thermal envelope, for example, energy used for powering electric hand tools is not counted.

6.3 Building Materials Standard Assumptions

Unless otherwise noted, these are the assumptions made for the building materials/products used in the materials inventory for each construction type.

Table 6.3 - Standard Assumptions for Building Materials & Products

Description	Abbreviation	Material	Size	Standard/Ref.	Trade Name examples
damp proof course under wall	DPC	polyethylene film	0.5mm thick		viscourse, b course, damp course
damp proof course under footing	DPC	polyethylene film	0.2mm thick		Fortecon
plasterboard			13mm thick		ECO8 Gyprock
cement fibre board			6mm thick		Hardiflex sheets
bricks		Fired clay	230 x 110 x 75mm	AS1618-2003	
mortar, for brick		Cement based	10mm thick	AS2350.12-2006 p. 6	
insulation wall batt		glass wool	90mm thick		

Table 6.4 - Density of Materials

Material/Product	Density	Density Range	Density	Vol for 1kg	Reference Source
	kg/m3	kg/m3	kg/m^2	m3	
aluminium	2700				http://en.wikipedia.org/wiki/Aluminium
brick, clay, fired	2403				http://www.simetric.co.uk/si_materials.htm
building paper #30 (aka kraft paper)			0.976		http://www.greenbuildingadvisor.com/blogs/dept/musings/all-about-water-resistive-barriers
butyl rubber	920				http://physics.nist.gov/cgi-bin/Star/compos.pl?matno=242
cardboard, used	689				http://www.simetric.co.uk/si_materials.htm
cement, Portland	1506				http://www.simetric.co.uk/si_materials.htm
clay, dry excavated	1089				http://www.simetric.co.uk/si_materials.htm
compressed cement sheet	1298				http://www.jameshardie.com.au/products/download/file/Hardiflex_Sheets_Certificate_of_Phys._Prop.pdf
concrete	2400			0.00041	http://hypertextbook.com/facts/1999/KatrinaJones.shtml
earth, compacted in berm	1522				http://www.simetric.co.uk/si_materials.htm
earth, infill (interstices)	1900				Assumes same density as earth packed in tyre
earth, packed in tyre	1900				Engineered to get the weight of a rammed earth tyre to be approx 140kg.
earth, rammed, RE wall	2000				Approximate average of values cited by various sources (CIBSE, 2006; Goodhew & Griffiths, 2005; Taylor, 2005)
expanded polystyrene EPS	37	29-45			http://www.rmax.com.au/twp-technical.html
fibreglass	1280				http://en.wikipedia.org/wiki/Fibre_glass#Properties
geofabric	120				http://www.geofabrics.com.au/documents/2-Maxjute-Thick-Feb12.pdf
glass	2579				http://www.simetric.co.uk/si_materials.htm
glass wool batts	20				http://www.upadirect.com.au/files/UPA%20Insulation%20Batt.pdf
glass wool batts, Bradford R2.7 wall	34				personal communication with Benjamin of CSR, 23 October 2012.
glass wool batts, Bradford R5 ceiling	28				personal communication with CSR, 30 October 2012.
glass wool batts, Bradford R2.5 ceiling	7				personal communication with CSR, 30 October 2012.
glue	1100				estimate
gravel, dry 1/4 to 2 inch	1682				http://www.simetric.co.uk/si_materials.htm
Gyprock	715				Calculated from data on material specification sheet
Hardiflex	1298				http://www.jameshardie.com.au/products/download/file/Hardiflex_Sheets_Certificate_of_Phys._Prop.pdf
LDPE film	940				http://en.wikipedia.org/wiki/Polyethylene
lime, hydrated	481				http://www.simetric.co.uk/si_materials.htm
Mudbrick	1600				(Heathcote & Sri Ravindrarajah, n.d.)
mortar, wet	2403				http://www.simetric.co.uk/si_materials.htm
pinus radiata	510	460-560			http://www.nzwood.co.nz/images/uploads/file/Info%20Sheets%20Species/NZW13611%20Species-RadiataPine.pdf
plaster board	715	650-880			http://www.lafargeplasterboard.com.au/products/Plasterboard-sizes-and-weights-table.htm
ply wood, 19mm thk	600			0.00166	http://www.australply.com.au/ti_char.html
polyethylene	940				http://en.wikipedia.org/wiki/Polyethylene
polyiso	27				http://www.fpcfoam.com/polyiso-tech.html
render, external (cement)	2000				http://www.heidelbergcement.com/uk/en/hanson/products/mortars/bagged/sandcement_mortar_technical_information.htm
render, internal (clay based)	1700				http://www.strawtec.com.au/page.php?id=39
render, lime (lime wet or mortar)	1540				http://www.simetric.co.uk/si_materials.htm

Material/Product	Density	Density Range	Density	Vol for 1kg	Reference Source
	kg/m3	kg/m3	kg/m^2	m3	
sand, dry	1602				http://www.simetric.co.uk/si_materials.htm
sand, rammed	1682				http://www.simetric.co.uk/si_materials.htm
Sarking (reflective Al foil)	790				calculated
steel	7800				http://wiki.answers.com/Q/What_is_the_density_of_low_grade_steel
stone, common generic	2515				http://www.simetric.co.uk/si_materials.htm
straw	116				http://vzj.geoscienceworld.org/cgi/content/full/3/2/714#BIB19
tyre, used	1150				(Amoozegar & Robarge, n.d.)
water	1000				http://www.simetric.co.uk/si_materials.htm

6.4 LCI data of key Materials, Products & Processes

6.4.1 Timber - Softwood

The timber LCI used in this study is based on data from 2 mills in Tasmania, collected circa 2005 (RMIT Centre for Design, CRC for Waste Management and Pollution Control & Life Cycle Strategies, 1998-2007). Only softwood has been used in this study and it is assumed to be untreated. Due to the co-products arising from the manufacture of structural timber such as wood chips and pulp logs, allocation has been used to share the environmental impacts. The basis for allocation is mass.

6.4.2 Carbon in wood products in landfills

Data published by The Department of Climate Change and Energy Efficiency (Department of Climate Change and Energy Efficiency, 2010) regarding the storage of carbon in landfills were used to update the Australasian LCI Unit Process, "Landfill, Wood AU". Key assumptions are: the decomposition of carbon fraction is 0.23 (this is the value updated); proportion of methane oxidation occurring in the landfill cap is 0.1; fraction of methane recovered is 0.55; and the fraction of landfill gas which is methane is 0.5.

6.4.3 Concrete

The Australasian LCI Unit Process, "Concrete, 20MPa AU" was adapted to use energy from the South Australian grid. It assumes general purpose Portland cement, fly ash, sands, coarse aggregates, water and chemical admixtures in the following amounts for 1kg of concrete;

- Portland cement 83.1g
- Sand: 350g
- Gravel: 740g
- Blast furnace slag: 16.6g
- Water: 89.6L

6.4.4 Bricks

EcoInvent LCI data for clay bricks was adapted to use energy (electricity and gas) from the South Australian grid.

6.4.5 Steel

Various steel inventories from the Australasian library were used according to the type of steel needed:

- "Steel, electric arc furnace, at plant" was used for fasteners such as nails and screws, and for steel reinforcing in concrete. 100% recycled content is assumed with only the collection impact of the scrap steel included.
- "Rolled steel, structural, at regional store" was used to model sheet steel for roofing and flashing. 10% recycled content is assumed and blast furnace slag is credited with avoided cement production.

6.4.6 Double Glazing

The EcoInvent unit process "Glazing, double (2-IV), U<1.1 W/m^{2}K, at plant/RER U" was adapted to Australian conditions by changing processes of European origin to Australian where possible. This process included: water (completely softened), aluminium extruding (process), aluminium production, polybutadine (used in the seal), transport, and electricity. Mass of the glass was also updated to reflect assumptions regarding the glass panes weight assumed to be 12.5kg/m^2 for each sheet of glass (Viridian Glass, 2008).

6.4.7 Paint

Paint was assumed to be acrylic based and coverage was 16m^2 per litre (Dulux, 2013). EcoInvent LCI data was used.

6.5 Energy Emission Factors

6.5.1 Natural Gas

Emissions from natural gas distributed in a pipeline are tabled below showing values from the Department of Climate Change and Energy Efficiency (Department of Climate Change and Energy Efficiency, 2012) and from the Australasian LCI Unit Process data. The values for carbon dioxide and methane are practically identical however there is a large difference for dinitrogen monoxide indicating that there may be an error in one of the data sets.

Table 6.5 - Natural Gas Emission Factors

Source	CO_2	CH_4	N_2O
SimaPro™ Australasian LCI Unit Process	51.16 g/MJ	1.072 mg/MJ	0.1099 mg/MJ
SimaPro™ Australasian LCI Unit Process **converted to kg/GJ**	51.16 kg/GJ	0.001072 kg/GJ	0.00011 kg/GJ
DCCEE	51.2 kg CO_2-e/GJ	0.1 kg CO_2-e/GJ	0.03 kg CO_2-e/GJ

6.5.2 Electricity

Emissions for 100,000kWh of electricity from the SA grid were analysed in SimaPro™ resulting in 74.6 tonnes of CO_2-e. In contrast the *Australian national greenhouse accounts: national greenhouse accounts factors*(Department of Climate Change and Energy Efficiency, 2012, p. 19) indicates that the emissions for 100,000kWh of SA grid energy would emit 65 tonnes of CO_2-e. According to the National Greenhouse Accounts, SimaPro™ data is modelling South Australian electricity more like Northern Territory electricity.

6.6 Earthship Wall Assumptions

This section gives an overview of the Earthship tyre wall construction method, it describes the method used to calculate the quantities of materials and processes used (the "materials inventory") and it presents the results of these calculations, listing the mass of each material used to construct an Earthship tyre wall and the energy used by various potentially significant processes such as fuel used for excavation.

6.6.1 Overview of Earthship Wall Construction

The main components of the Earthship external tyre walls are;

- Tyre "modules" rammed with earth
- Bond beam
- Buttresses
- Internal render (not water proof – clay based "adobe")
- External render (water proof – cement based, applicable to wing walls only)
- Thermal wrap (insulation contained in the berm)
- Water proofing membrane and drainage system at base of wall (i.e. French drain)
- Berm
- Reinforced Concrete Footing. NOTE: only required in extreme Earthquake zones e.g. New Zealand, Japan, however it has been modelled as part of the sensitivity study to understand its impacts, if built.

The main walls to the east, west and south serve as a load bearing retaining walls to which the roof is mounted via a bond beam assembly. Earthship Biotecture typically (re)uses old car tyres as the basic building block of these walls. The tyres are filled with earth excavated from the site, and compacted using manual labour – people with sledge hammers. These walls are bermed with many tonnes of earth which is generally sourced onsite avoiding the need for transporting the earth. Within the berm expanded polystyrene (EPS) insulation is positioned to improve the thermal performance of the building. This is called the "thermal wrap". The walls are rendered with an adobe render or a cement render where waterproofing is required.

A similar tyre wall is built to the north however it is only about 600mm high and on this the greenhouse structure is constructed. In this study a bond beam on top of this low tyre wall has been included to represent a worst case, conservative engineering solution. Earthship Biotecture typically use treated wood, or plastic wood, as a method for anchoring the greenhouse framing to the tyre wall however other Earthship builders take a more conservative approach and use a concrete bond beam similar to that used on the main tyre wall.

The bond beam is made primarily from concrete, (re)used aluminium cans and steel rebar (reinforcing bar) which is skewered through the top three courses of tyres to ensure good connection between the tyre wall and the bond beam. Steel anchor bolts are set into the bond beam to attach the top plate assembly which is typically a simple timber plate to which the roof trusses can be nailed.

The buttresses are spaced as evenly as possible along the inside of the rear (south) wall to resist the forces exerted by the berm. They are constructed with reinforced concrete, using plywood and softwood timber as formwork.

The materials inventories have been developed based on the main construction assemblies so that the impacts of each can be understood. The main "assemblies" of the Earthship wall have been classified as Tyre Wall which includes the bond beam, Buttresses, and Berm. The following sections describe these assemblies in more detail.

6.6.2 Tyre Wall Material Quantities

Volumes for components numbered 1-6 above were calculated based on a quantity per linear metre of tyre wall whereas the berm and thermal wrap were calculated based on their actual overall dimensions. It was assumed that the tyres used were 650mm in (rolling/outside) diameter (a common size in Australia) with 25mm of render applied to one side (internal) after being "packed out" with adobe render mixture thus making the wall 675mm in thickness. The height of the tyre wall was assumed to be 2420mm requiring 11 tyres each "pounded" to 220mm in height, plus a 280mm concrete bond beam taking the overall height of the wall 2700mm.

Using these basic dimensions as the basis for one "module" of tyre wall i.e. 11 tyres stacked on top of each other, packed out and rendered on the inside and with a bond beam atop, a CAD model was used to calculate the volume of materials/products in the module which represents 0.65lm (the diameter of the tyre) of wall. Refer to Figure 6.1.

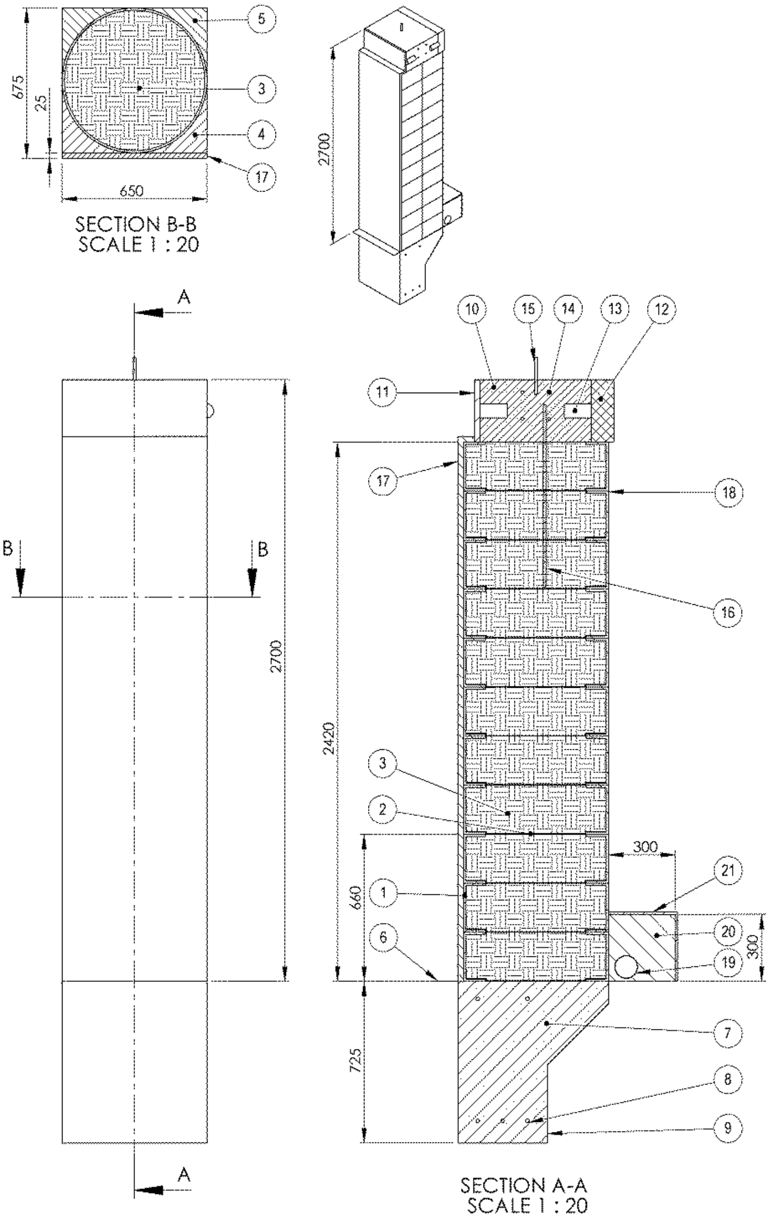

Figure 6.1 - Tyre Wall with 11 Tyre Modules

Having established the quantities of materials for 0.65lm of wall this was normalised to 1lm of wall and again for the total length of tyre wall = 34.55 linear metres (lm) (ref Table 6.1). To this the volume of the tyre wing wall (the tapering walls at the east and west end of the Earthship) must be added; however, it was assumed that no bond beam was built on this part of the tyre wall so this has been omitted from the wing wall list of components. The volume of both wing walls is assumed to be equivalent to the volume of one full height wing wall due to their triangular shape which tapers to nothing at the extremity furthest from the main tyre wall. The length of the wing walls is assumed to be 7.0m.

Thus it is assumed that the functional unit contains a total length of tyre wall is 34.55m + 7m = 41.55m, of which 7.0m does not have a bond beam. Items 7-9 detail materials for construction of a footing with is NOT necessary for construction of tyre walls under typical circumstances and these items have not been included in the LCI however it has been tabled so that the impact of this optional (technically redundant, but perhaps bureaucratically necessary) footing can be calculated. This is discussed elsewhere. Item 22 (external render) is interchanged with Item 17 (internal render) as necessary to provide weatherproof render on the Wing Walls.

The following table lists the materials inventory results based on 0.65lm of wall as drawn in Figure 6.1. The mass of materials is given for 1lm, for the main wall, wing walls and low greenhouse wall (which is only three tyres high but is otherwise the same).

Table 6.6 - Materials for 1lm and functional unit of Earthship External Wall

			Linear Metre	Main Wall	Wing Walls	Total	GH Tyre Wall	Grand Total
Item	Description	Material	Mass (kg/lm)	Mass (kg)	Mass (kg)	Mass (kg)	Mass FU (kg)	Mass FU (kg)
1	tyre	tyre	145.51	5,027.5	1,018.6	6,046.1	912.8	6,958.9
2	cardboard	cardboard	11.39	393.6	79.7	473.3	71.5	544.8
3	earth, rammed	earth rammed	2075.47	71,707.4	14,528.3	86,235.6	13,018.8	99,254.5
4	pack out material	assembly	287.00	9,915.9	2,009.0	11,924.9	1,800.3	13,725.2
5	earth berm, interstices	earth, packed	260.61	9,004.0	1,824.3	10,828.3	1,634.7	12,463.0
6	dpc, under tyre	low density polyethylene	0.42	14.6	3.0	17.6	9.7	27.3
7	footing	concrete	852.75	29,462.5	5,969.2	35,431.7	19,613.2	55,045.0
8	rebar, footing	plain carbon steel	7.84	270.7	54.9	325.6	180.2	505.8
9	dpc, under footing	low density polyethylene	0.55	19.1	3.9	23.0	12.7	35.8
10	bond beam	concrete	265.82	9,184.0	NA	9,184.0	6,113.8	15,297.7
11	render, bond beam	clay based	11.90	411.1	NA	411.1	273.7	684.8
12	insulation, bond beam	EPS	1.04	35.8	NA	35.8	23.8	59.6
13	can, aluminium	aluminium	1.00	34.4	NA	34.4	22.9	57.4
14	rebar bond beam module	plain carbon steel	4.13	142.6	NA	142.6	94.9	237.6
15	anchor bolt	plain carbon steel	0.32	11.2	NA	11.2	7.5	18.6
16	rebar skewer tyres	plain carbon steel	1.50	51.8	NA	51.8	34.5	86.3
17	render internal	adobe render	106.04	3,663.6	NA	3,663.6	NA	3,663.6
18	damp course vertical	low density polyethylene	0.68	23.6	4.8	28.4	15.7	44.1
19	ag pipe dia 100mm	low density polyethylene	0.30	10.3	2.1	12.4	6.9	19.2
20	gravel wall drainage	gravel	137.64	4,755	963	5,718	3,165	8,884
21	geofabric for tyre wall	jute	0.73	25.3	5.1	30.4	16.8	47.3
22	render external 12.5mm thk	concrete render	62.38	NA	742.3	742.3	782.5	1,524.8

In summary, it is assumed that the main material “flows” in the bermed tyre walls are (approximately): 810 used tyres weighing almost 7 tonnes, half a tonne of reused cardboard, and almost 100 tonnes of compacted earth to fill the tyres, 13.7 tonnes of adobe mixture to pack out the interstices between the tyres. 12.5 tonnes of earth has been counted for the interstices on the outside of the tyre wall – to this the mass of the berm must be added (this is calculated and discussed later) - and 18kg of damp proof course (plastic sheet) is used under the first course of tyres. Not counting the concrete footing (which is generally unnecessary unless building in areas with severe Earthquake danger e.g. New Zealand, Japan) 15.3 tonnes of concrete is used in the bond beams (i.e. one bond beam for the main tyre wall and one for the greenhouse wall – and note, this is an extreme example representing very conservative engineering: Earthship Biotecture usually does not build a bond beam on the greenhouse tyre wall). 4250 used aluminium beverage containers are used weighing 57kg (13.5g is assumed weight of each can). 342.5kg of steel is used in the construction of the bond beams. 4348kg of adobe render (assumed 25mm thick) is used to plaster the inside of the wall including the inside face of the bond beam, and 1500kg of concrete render (assumed 12.5mm thick) is used to plaster the exposed faces of the wing walls and the greenhouse low tyre wall (which must be waterproof). 19kg of plastic (LDPE) pipe is used for a French drain plus almost 9 tonnes of gravel, 47kg of geofabric and 44kg of plastic sheet to assist with drainage and waterproofing (note: Earthship Biotecture do not use a French Drain as it is not necessary in Taos's arid climate).

6.6.3 Buttress Material Quantities

Due to the long straight tyre wall at the rear of the Global Model Earthship buttresses (columns) are used to help stabilise the wall against the forces exerted by the berm. The drawing below shows a CAD model for one Buttress; however, for the functional unit being studied four buttresses would be needed, thereby supporting the rear (south) tyre wall every 4.4m (22/5 = 4.4).

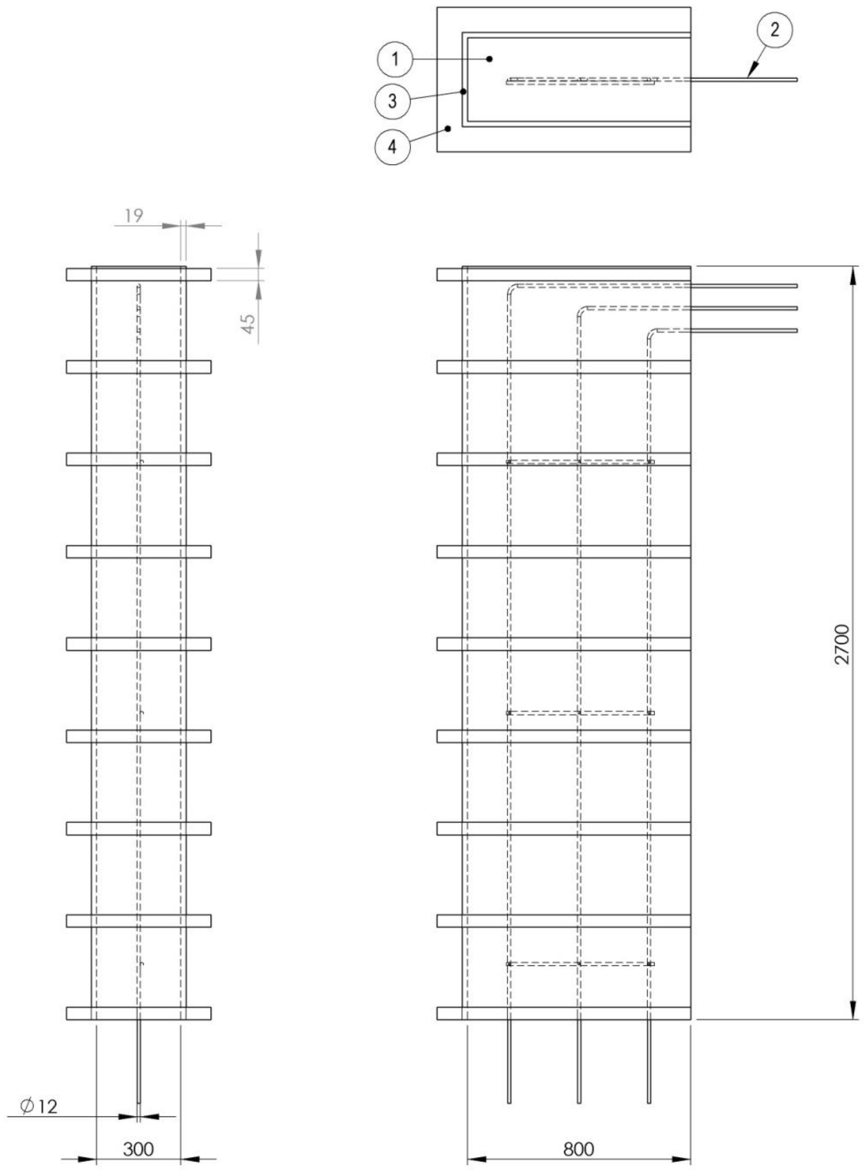

Figure 6.2 - Buttress, Earthship Wall

The following table shows the final quantities of materials for the Buttress for a single buttress and for all four buttresses required for the functional unit. Note that the plywood and pine is formwork that is assumed to be disposed of after one use. Refer to Section 6.23 for assumptions regarding recycling and end-of-life for all material types.

Table 6.7 - Buttress Earthship Wall, Materials Inventory

Item	Description	Material	Mass (kg)
1	Concrete	concrete	6,220.8
2	Rebar	steel	43.68
3	Plywood (formwork)	plywood	240.0
4	Timber, Pine (formwork)	pine	163.2

Note that other Earthship designs either avoid the need for reinforced concrete buttresses due to the arch shape inherent in their design, or they may use buttresses formed with rammed earth tyres, - this was modelled in the “lowEE” Earthship configuration assuming 8 linear metres of tyre wall (i.e. buttresses are three tyres long by 11 tyres high) with double the amount of render to account for render on both sides of the wall.

6.6.4 Berm Material Quantities

The berm is illustrated in Figure 6.3. It is assumed to extend horizontally 7m from the external face of the external walls and wing walls, with a height of 2.7m tapering away at the extremities. There is also a low berm at the front of the Earthship which extends the length and height of the greenhouse tyre wall.

The berms consist mainly of earth dug from site and are constructed with an excavator. It is assumed the density of the earth in the berm is 1522 kg/m3, somewhat less than compacted earth e.g. within the tyres which is assumed to be 1900kg/m3.

Expanded Polystyrene insulation board is installed in the berm and five steel earth tubes are located horizontally in the berm extending from the internal living spaces to the outside air. Timber hatches are located at each end of the earth tubes.

The components for the French drain (which is more correctly part of the berm than part of the tyre wall) are given in Table 6.6 where the tyre wall materials are listed, rather than being duplicated here. The French Drain components/materials are labelled 19, 20 & 21 in Table 6.6.

The volume of berms (main and front) have been calculated based on the dimensions of the berm plus the “earth berm, interstices” (refer Table 6.6) which calculates the volume of berm material that extends into the interstices between the tyres.

In summary the berm requires approximately 642 tonnes of earth, 469kg of EPS for insulation, 87kg of steel for the earth tubes, and 38kg of pine for the inner and outer earth tube hatches. The small berm against the greenhouse wall requires 15.2 tonnes of earth. A diagram of the berm and the materials inventory are given below.

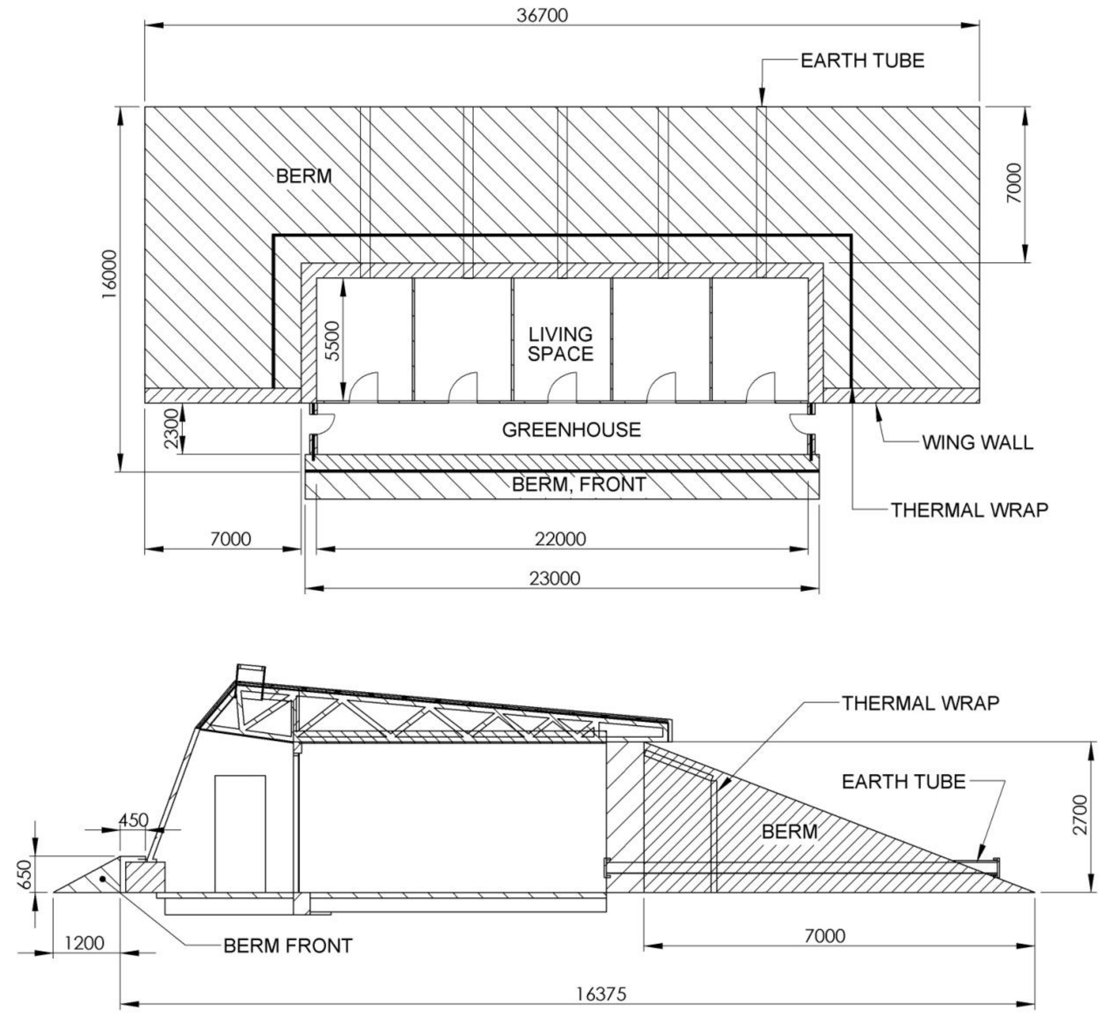

Figure 6.3 - Berm dimensions

Table 6.8 - Berm, main, with Earth Tubes, Materials Inventory

Description	Material	Mass (kg)
berm	earth, compacted	631,420*
insulation thermal wrap	EPS	468.7
earth tube, steel pipe	steel	87.3
hatch, earth tube, timber	pine	37.6

*assumes tyre wall is planar (flat), therefore add “earth berm interstices” value from 6.6.2.

Table 6.9 - Berm, front, Materials Inventory

Description	Material	Mass (kg)
Berm, front	earth, compacted	13,652*

*assumes tyre wall is planar (flat), therefore add “earth berm interstices” value from 6.6.2.

6.6.5 Process Energy

6.6.5.1 Earth Moving – Process Energy

Using the assumption stated previously, for the main berm of 421.9m3 (414.8m3 main berm plus 7.11m3 for the interstices between tyres), assuming digging in soft earth (80m3/hr), 5.27hr of excavator use is required, and at 6L per hour this equates to 31.62L of fuel. Diesel fuel is assumed to have an energy density of 35MJ/L, thus the energy use needed to build the main berm by excavator is 31.62L x 35MJ/L = 1106.7MJ

Using the same assumptions the energy needed to build the front berm 10.04m3 (8.97m3 berm plus 1.07 interstices) is 0.125hr x 6L x 35MJ = 26.25MJ.

6.6.5.2 Excavation – Process Energy

The component "earth, rammed" represents the amount of the earth that is used to fill the tyres. Although there is no process energy used to ram the earth into the tyres (human physical labour is used), energy is used in creating the earth which must be excavated and also possibly trucked in, although this will depend on the topography of the site. The usual method employed by Earthship Biotecture is to "equalise the cut and fill", that is, to estimate how much earth will be needed for berm construction and filling the tyres, thereby indicating how much excavation is necessary to prepare the site and supply earth for these other purposes. This avoids the need to organise and pay for earth to be trucked in.

The total volume of earth required is given by the sum of the various "berm", "berm interstices" and "earth, rammed" components as tabled below. Excavation duration, fuel use, and energy use are derived from the total volumes for each wall.

In total 72.6L of fuel which represents 2542.2MJ of energy is required to excavate the earth required for construction.

Table 6.10 - Earthship Wall Process Energy

Description	Main & Wing Walls	Low Front Wall	Total
berm (m3)	414.86	8.97	423.83
berm, interstices (m3)	7.11	1.07	8.18
earth, rammed (m3)	45.38	6.85	52.23
Total (m3)	467.35	16.89	484.24
Excavation duration (hrs) @ 40m3/hr	11.68	0.42	12.10
Excavation fuel use (L) @ 6L/hr	70.10	2.53	72.63
Excavation energy use (MJ) @ 35MJ/L	2453.6	88.6	2542.2

6.7 Tyre Wall Insulated

This wall construction is assumed to be identical to Tyre Wall Bermed with the exception that materials related to the berm materials are not included (i.e. items 5, 12, 18-21). Item 12 Bond Beam Insulation is replaced by a full height (2700mm) sheet of 100mm thick EPS insulation which is coated with a 5mm layer of cement based render. The EPS is assumed to be glued to the tyre wall with a 0.5mm thick coat of glue on the inside face of the EPS. Table 6.11 presents the quantities of these materials for one linear metre of wall and the total assumed for the functional unit.

Table 6.11 - Additional Materials for Tyre Wall Insulated

Description	Material	Mass per lm (kg)	Mass FU (kg)
Insulation	EPS	9.99	345.2
Render 12.5mm thk	cement based	67.5	2,332.1
Adhesive	acrylic based	1.485	51.3

6.8 Tyre Wall Uninsulated

This wall construction is assumed to be identical to the Tyre Wall Insulated; however, the rendered insulation is replaced by additional "pack out" material (Item 4 is doubled to duplicate the pack out material on the outside face of the wall) to create a flat outer face, and a 12.5mm thick layer of cement based render is used as a finishing weather proof coat. The additional materials are tabled below in Table 6.12.

Table 6.12 - Additional Materials for Tyre Wall Uninsulated

Description	Material	Mass per lm (kg)	Mass FU (kg)
Pack Out Material	adobe	287.0	9,915.9
Render 12.5mm thk	cement based	67.5	2,332.1

6.9 Mudbrick Wall Assumptions

6.9.1 Overview of Mudbrick Construction

Mudbrick construction burgeoned in Victoria, Australia in the 1960s, with many people attracted to the do-it-yourself construction method (Archer & Archer, 1980).

They are typically built on a reinforced concrete footing and may use a post and beam structure to support the roof, or they are load bearing (Middleton & Young, 1986, p. 53), thereby avoiding extra materials, although some type of top plate assembly, for connecting the roof, is required (Middleton & Young, 1986, p. 46). This latter option (load bearing) has been used in this study.

The mudbricks are typically made on site using materials sourced on site, although sand, gravel, clay and cement may need to be imported depending on the "recipe" used and the materials available on site. Simple moulds made of timber are used to form the "mud" mixture into a brick which is then dried in the sun for an extended period.

6.9.2 Mudbrick Wall Material Quantities

The main components of the mudbrick wall are;

1. Reinforced Concrete Footings
2. Mudbricks
3. Timber Top plate
4. External render

Volumes for the wall components were based on the Mudbrick wall "module" length which is defined in this study as 1000mm long x 2700mm high x 275mm wide. It was assumed that the wall was 275mm wide, representing the average of two common sizes used in Australia 250mm and 300mm (Bakes, 2013; Middleton & Young, 1986). Assumptions regarding design of the reinforced concrete footing and structural pine top plate, held down by steel reinforcing bar, are given in Figure 6.4 below which shows one linear metre of wall. Quantities of materials for one linear metre of wall and for the functional unit are given in Table 6.13.

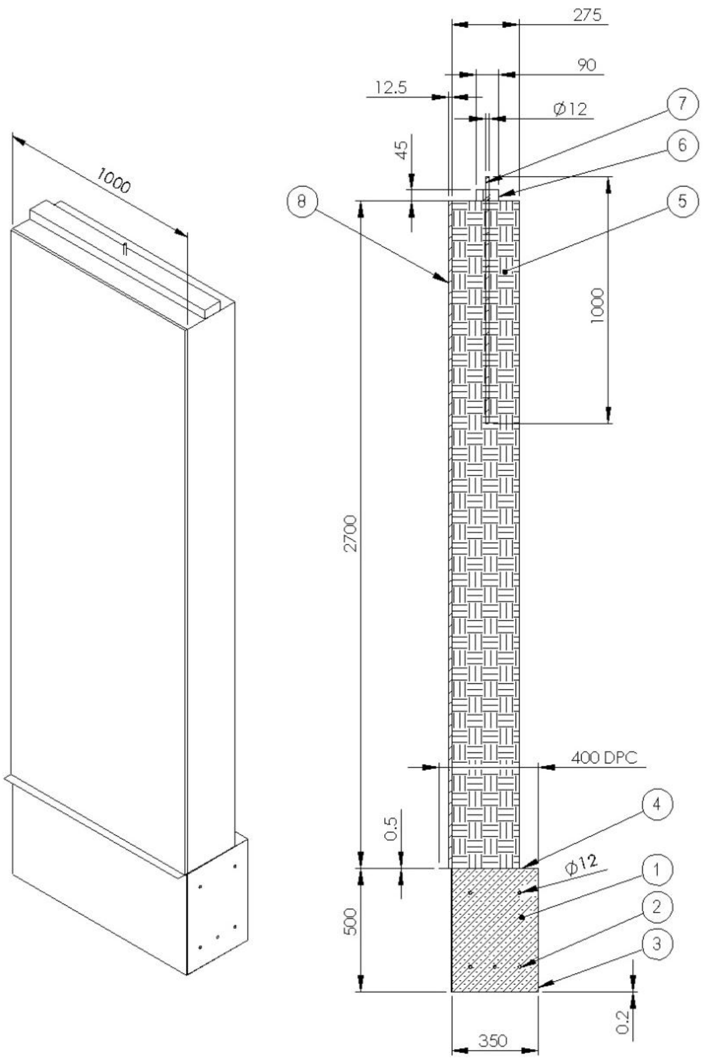

Figure 6.4 - Mudbrick Wall Module

Table 6.13 - Materials for 1lm and functional unit of Mudbrick wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	footing	concrete	420.0	18,695
2	Rebar, footing dia12mm	steel	4.4	196
3	DPC under footing 0.2mm	polyethylene	0.25	11
4	DPC under wall 0.5mm	polyethylene	0.188	8
5	Mudbricks	adobe	1188.0	52,880
		earth from site 80%	1053.1	46,878
		sand 10%	100.9	4,495
		straw 10%	0.68	31
		water 20%	1.188	53
6	Top plate	MGP12 pine	2.06	92
7	Tie down	steel	0.88	39
8	Render, cement	cement render	67.50	3,005

6.9.3 Process Energy

It is assumed that the mudbricks are manufactured with no process energy as it is possible to mix the mud manually (Middleton & Young, 1986, p. 62); however, it is assumed that the render used to water proof the wall and provide durability is mixed in a petrol powered mixer as per the standard assumptions used in this study for cement based render.

6.10 Rammed Earth Wall Assumptions

6.10.1 Overview of Rammed Earth Construction

Rammed Earth walls are generally constructed on a concrete footing (Easton & Wright, 2007, p. 87). Formwork made from steel or timber is set up over the footing to receive the wall material, which differs from site to site depending on soil type. It is likely that sand or clay will need to be imported and added to the soil available on site to ensure the proper consistency, or if the on-site soil is inappropriate, soil will need to be imported (Easton & Wright, 2007, p. 110). A small quantity of cement – for example six to eight percent (Middleton & Young, 1986, p. 81) – is usually added as a waterproofing agent and to improve strength. The cement is referred to as a "stabiliser" and the resulting wall a "stabilised rammed earth wall". In some cases cement is not used at all however modern rammed earth walls typically use some cement to ensure good longevity.

The soil mixture is mixed on site by machinery; usually a bucket on a tractor or a small skid steer loader (e.g. a "Bob Cat") is used to mix the materials in a large pile known as the "mix pad" on the ground (Easton & Wright, 2007, p. 143). Water is added to facilitate compaction of the mixture into the formwork. Prior to mechanisation compaction was done with a special wooden tamping device however nowadays a pneumatic tamper is used (Easton & Wright, 2007, p. 151-154). The wall is poured and tamped in small sections and, as the wall sets, the formwork is removed and reassembled to pour the next section or layer above and this process is repeated until the wall is complete. While the top layer of the wall is poured, means for fixing a top plate are installed, for example steel reinforcing bar. The wall does not require rendering or painting.

6.10.2 Rammed Earth Wall Material Quantities

The main components of the rammed earth wall are;

1. Reinforced Concrete Footings
2. Rammed Earth Wall
3. Timber Top plate

Volumes for the wall components were based on the Rammed Earth wall "module" length which is defined in this study as 1000mm long x 2700mm high x 300mm wide. These results were then normalised to volumes of materials per linear metre of wall. It was assumed that the wall was 300mm wide, a common width for external rammed earth walls built in Australia (though internal and non load-bearing walls may be thinner). Assumptions regarding design of the reinforced concrete footing and structural pine top plate, held down by steel reinforcing bar, are given in Figure 6.5 which shows one linear metre of wall. Quantities of materials for one linear metre of wall and for the functional unit are given in Table 6.14.

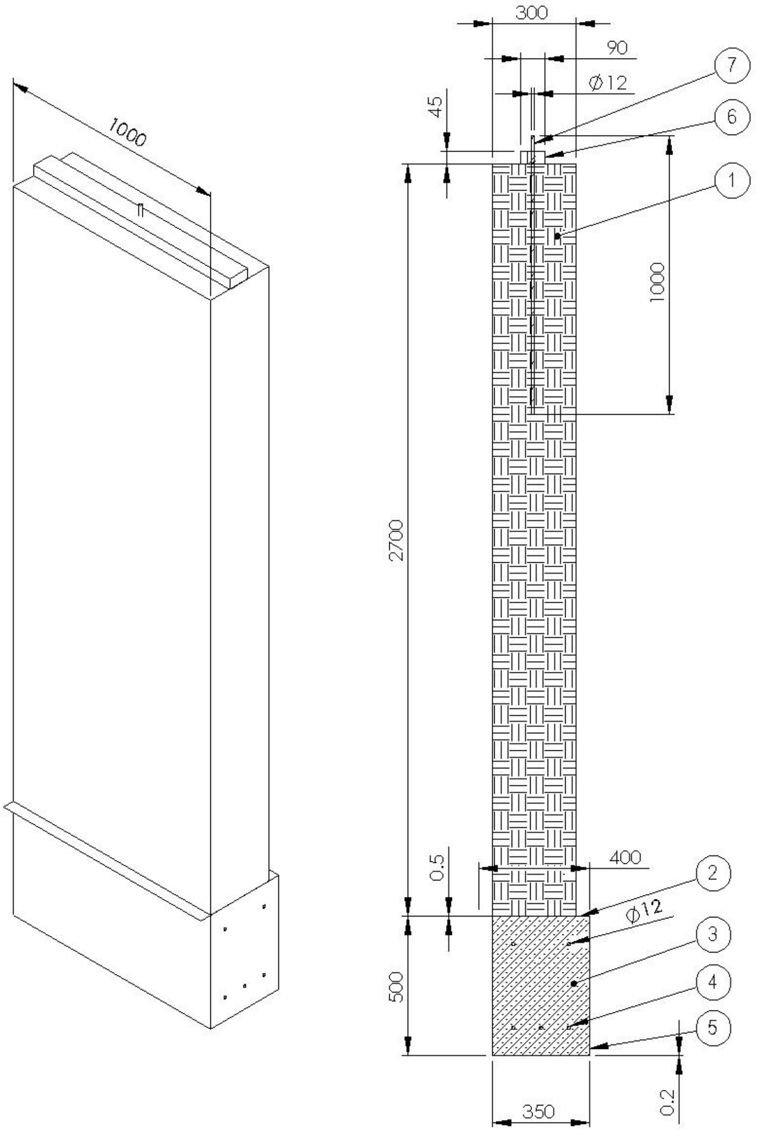

Figure 6.5 - Rammed Earth Wall Module

Table 6.14 - Materials for 1lm and functional unit of Rammed Earth wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	wall	earth rammed	1620	73,224.00
2	DPC	PE Low Density Film	0.1128	6.34
3	footing concrete	concrete	420	23,604.00
4	rebar footings	Plain Carbon Steel	4.407	247.67
5	DPC under footing	PE Low Density Film	0.3807	21.40
6	top plate	Pine	2.0655	116.08
7	tie down top plate	Plain Carbon Steel	0.8814	39.84

Assumptions regarding the composition and quantities of materials comprising one tonne of rammed earth are given in the table below. The amount of soil (“earth, from site”) is half of the mix and to this sand and five percent cement (by volume) is added to obtain an appropriate mixture.

The quantity of water was calculated based on discussion with a rammed earth wall builder, Stephen Dobson, a leading practitioner in Australia (Dobson, 2011). Dobson reported water consumption in rammed earth construction for 6m² of 300mm thick wall is 500 litres in summer and 300 litres in the winter. Using 400 litres as the average this equates to 400 litres per 1.8m3 or 222 litres/m3. Assuming a density for rammed earth wall of 2000kg/m3 this equates to 111 litres/tonne. Compacted density values are given for sand and soil in the table below to reflect that the compaction process increases the quantity of these materials. It is assumed that about 11 litres of water is "stored" in one linear metre of wall whereas the rest of the water (100L) evaporates during the wall drying/curing process. It should be noted that no data was available regarding the exact rate of water absorption by the wall materials however 11 litres would be about the right amount of water to bond with 38kg of Portland cement.

Table 6.15 - Material quantities in 1 tonne of rammed earth material

Description	Material	% by Vol	Vol per tonne	Density	Compacted Density	Mass 1 tonne
		%	m^3	kg/m^3	kg/m^3	kg
wall	earth rammed		0.5	2000	2000	1000
earth, from site	soil	50	0.25	1522	2275	569
sand	sand	45	0.225	1602	1700	383
cement	Portland cement	5	0.025	1506	1506	38
water	water	22	0.11	1000	1000	111
TOTAL						1100

6.10.3 Process Energy

During construction of the rammed earth wall diesel fuel is used to power a Bob Cat (for mixing the wall material) and a compressor for powering a pneumatic tamper. The following information regarding fuel use of this equipment was provided by an experienced rammed earth builder (Dobson, 2011), as follows.

20 litres of diesel is used to power the compressor for the tampers each week (5 days) which equals 4L/day. Each day 4.5m³ of wall is built (15m² of wall face area per day, 300mm thick walls), thus 1m³ of wall requires 0.89L and 0.5m³ (1 tonne) requires 0.44L. Assuming 35MJ per litre of diesel fuel the energy used by the Bob Cat for one tonne of wall is 15.56MJ. Multiplying by 65.45 tonnes to represent the functional unit, the total Bob Cat energy use is 1,018MJ.

70 litres of diesel is used to power the Bob Cat for an average of 3.5hrs per day for one week (5 days). Thus 14L is used per day during which 4.5m³ of wall is built, therefore 3.11L is used per m³ or 1.56L is used per tonne. Assuming 35MJ per litre of diesel fuel the energy used by the Bob Cat for one tonne of wall is 54.4MJ. Multiplying by 65.45 tonnes to represent the functional unit, the total Bob Cat energy use is 3,563MJ. The total process energy for the functional unit is therefore 1,018MJ + 3,563MJ = 4,581MJ

6.11 Rammed Earth Insulated

The materials assumed in the Rammed Earth Insulated wall are the same as the Rammed Earth wall with the addition of a 100mm thick layer of expanded polystyrene (EPS) and a layer of cement based render (5mm thick) applied to the outer surface of the EPS to protect it from the weather and improve aesthetics. Adhesive is also needed to glue the EPS to the Rammed Earth wall. The footing is assumed to be the same dimensions as the weight of the additional materials is minimal.

Additional materials are presented in Table 6.16.

Table 6.16 - Additional Materials for Rammed Earth Insulated Wall

Description	Material	Linear Metre	Functional Unit
		Mass (kg)	Mass (kg)
Insulation	EPS 100mm thk	9.99	451.55
Render	Concrete render 5mm thk	27	1,220.40
Adhesive	water based	1.485	67.12

6.12 Strawbale Wall Assumptions

6.12.1 Overview

Although Strawbale walls can be built as load bearing structures, for various practical reasons the vast majority of them tend to utilise a timber or steel frame to support the roof load (Downton, 2010). This LCI assumes a timber frame structure with strawbales used as non-structural infill (for insulation). The main components of the non load-bearing Strawbale wall are;

- Reinforced Concrete Footings
- Timber framing
- Strawbale infill
- Top plate assembly
- Tie down/stabilising system

6.12.2 Straw Life Cycle Assumptions

In this study, straw was assumed to be a waste product from wheat farming. In Australia a common agricultural practice is to burn this waste straw, so, if this waste was converted to a strawbale, the avoided impacts of burning straw should be counted in the LCA.

Data regarding emissions of particulates when burning straw was sourced from Li et al. (2007). Straw was assumed to biodegrade on site at the end of the life, with a neutral carbon cycle i.e. the same quantity of carbon sequestered during its growth stage is released during the end-of-life composting process.

6.12.3 Material Quantities

Volumes for the framing components were calculated based on a unit of wall equal to the spacing of the timber posts, whereas the other components (strawbales, render, footings etc) were based on the Strawbale wall “module” length which is assumed to be 900mm long x 2700mm high x 550mm wide. These results were then normalised to volumes/masses of materials per linear metre of wall.

It was assumed that the wall used bales of 350mm high x 450mm wide by 900mm long. This is a common size in Australia although other sizes are available (Thomas, 2013). The top plate assembly is assumed to be made from steel trench mesh and is tied down to the concrete footing using high tensile fencing wire and a “Gripple” tensioning device, at 0.45m centres (spacing) i.e. two per module. Polyethylene tubing located in the concrete footing is used to form an anchor for the tensioning wire. A 50mm thick layer of render is assumed and this includes a 10mm thick layer of lime render on one side of the wall to provide water proofing for the external side of the wall - this was the system used by the author in his own home, designed by architect Bohdan Dorniak (Bohdan Dorniak & Co, 2014).

Figure 6.6 illustrates the various materials assumed to be used in the construction of one module (900mm long) of wall.

Figure 6.7 illustrates a module of the structural frame that was assumed to be used in conjunction with the wall module. One frame module was assumed for every three wall modules resulting in a post at centres of 2.7m. Expanded metal lath is included, and as drawn appears to be oversize; however, this is the area (quantity) required to cover all the straw to timber connections i.e. adjacent the post and the mounting rail which is needed for mounting a picture rail, cupboards, shelves et cetera.

Quantities of materials for one linear metre of wall and for the functional unit are given in Table 6.17.

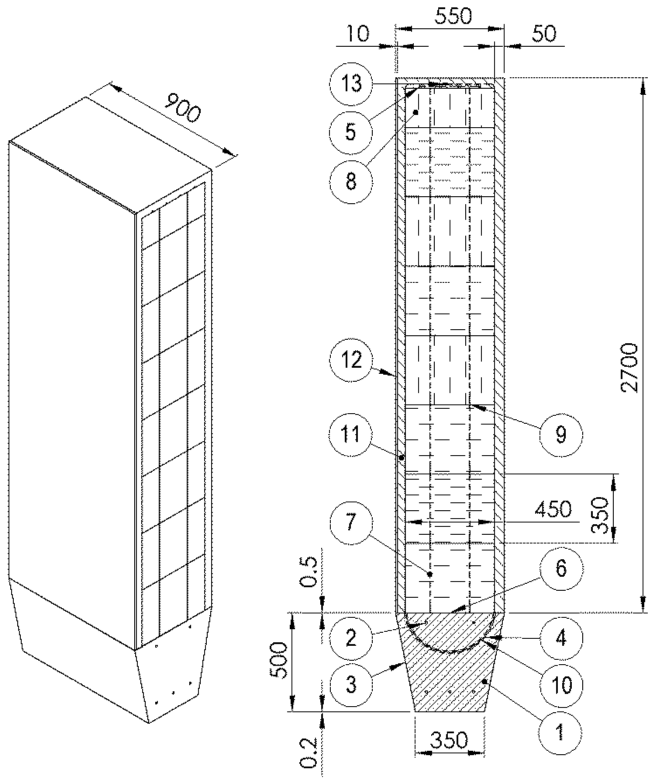

Figure 6.6 - Materials In Strawbale Wall Module

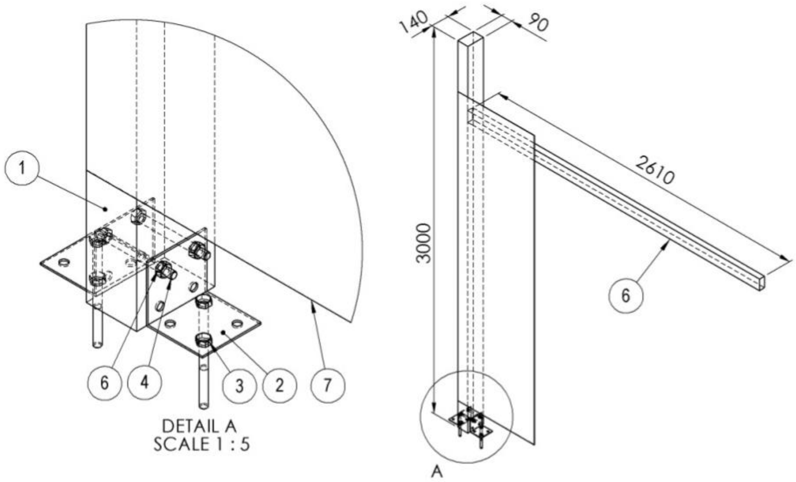

Figure 6.7 - Materials in Strawbale Framing Module

Table 6.17 - Materials for 1lm and functional unit of Strawbale Wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	footing	concrete	540	30888.0
2	Rebar Footings	steel	4.41	252.3
3	DPC under footing 0.2mm	polyethylene	0.25	14.8
4	Polypipe anchor for wire	polyethylene	0.05	2.4
5	Trench mesh, top plate	steel	1.79	82.9
6	DPC under wall 0.5mm	polyethylene	0.25	12.0
7	Straw, baled	straw	127.89	5908.5
8	straw half bale	straw	10.41	481.1
9	twine strawbale	polyethylene	0.36	17.0
10	Wire	steel	0.55	25.6
11	render, adobe	render, clay	451.27	20848.8
12	Render, Lime 10mm thk	render, lime	41.57	1920.7
13	Tensioner, wire	steel	0.05	2.4

Table 6.18 - Strawbale Wall Framing Material Quantities

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	post pine 140x90x3000	Pine	6.42	296.88
2	Bracket steel	Steel	0.30	7.09
3	Hex Bolt M12 x 100	Steel	0.13	1.56
4	Hex Bolt M12 x 120	Steel	0.08	1.92
5	Hex Nut Plain M12	Steel	0.01	0.24
6	rail mounting pine 90x45x2610	Pine	1.79	83.02
7	expanded metal lath	Steel	1.00	46.37

6.12.4 Process Energy

Process energy for Strawbale wall construction has been assumed for mixing render. Fuel used for render mixing is described under the Common Element heading.

6.13 Concrete Block Insulated Wall Assumptions

6.13.1 Construction Overview

Concrete blocks are assumed to be 200mm wide and 200mm high, hollow and filled with concrete mortar and reinforcing bar as specified by the manufacturer (Boral, 2013). This entails N16 (diameter 16mm) reinforcing bar positioned vertically at 400mm centres and N16 horizontal reinforcing bar positioned every other block i.e. 400mm centres. A 10mm thick cement based render is applied to the outer face of the 100mm thick EPS insulation layer.

Concrete used to manufacture the blocks was assumed to be lightweight, density: 1750 kg/m^3(Jones, 1999).

6.13.2 Material Quantities

Figure 6.8 and Table 6.19 illustrate and table the material quantities assumed for the Concrete Block wall.

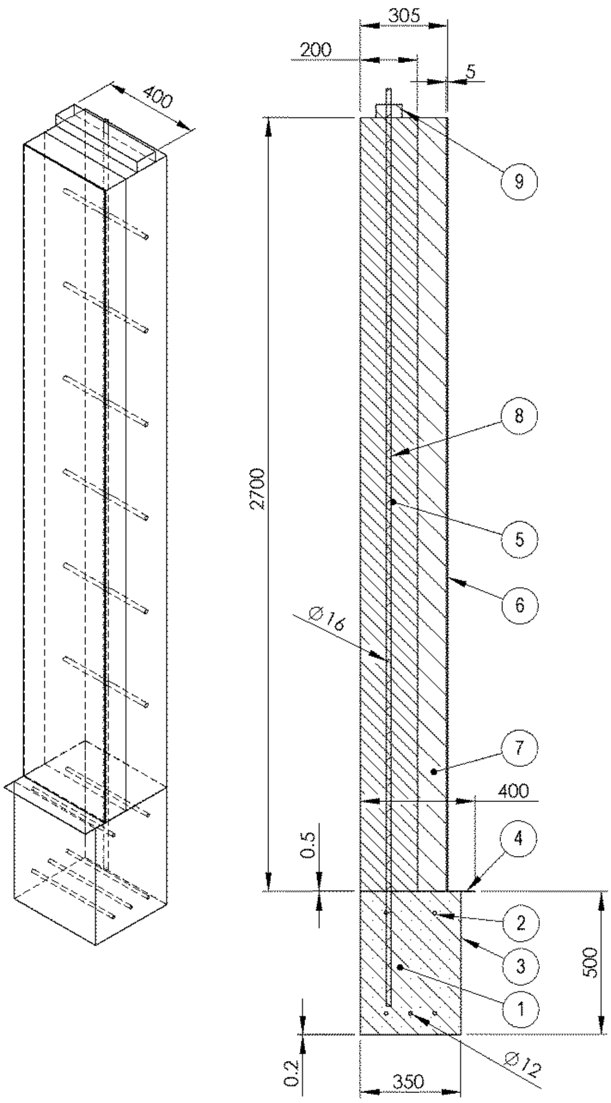

Figure 6.8 - Concrete Block Wall Module

Table 6.19 - Materials for 1lm and functional unit of Concrete Block wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	footing	concrete	420.00	23,612.4
2	Rebar, footing dia12mm	steel	4.41	247.8
3	DPC under footing 0.2mm	LDPE	0.25	14.3
4	DPC under wall 0.5mm	LDPE	0.19	8.5
5	Concrete blocks and mortar	concrete and mortar		
	concrete blocks 20%	cast concrete	189.00	8546.6
	concrete mortar 80%	poured concrete	1036.80	46,884.1
6	Render 5mm	cement based	27.00	1,220.9
7	Insulation 100mm	EPS	9.99	451.7
8	Rebar in blocks	steel	21.65	978.8
9	Top plate	pine	2.07	93.4
10	Adhesive	Acrylic based	1.485	51.3

6.13.3 Process Energy

Process energy is accounted for in the concrete process.

6.14 Brick Veneer Wall Assumptions

6.14.1 Construction Overview

Brick veneer is a common form of wall construction in Australia. It is usually constructed with a plasterboard lining (Inglis & Downton, 2010) on either a steel or timber frame, the latter being the most common. A reinforced concrete footing is constructed first and it features a rebate on which the brick outer leaf is constructed. This assists with water proofing. Damp proof course is placed on top of the footing to prevent rising damp. The framed wall is generally insulated with fibreglass or rockwool batts and a layer of "sarking" (aluminium backed kraftpaper) is used in conjunction with an air gap between the inner framed wall and outer brick wall to improve thermal performance.

6.14.2 Material Quantities

It was assumed the framing was timber and therefore the insulated Brick Veneer wall was modelled with reference to AS1684.4-2010 Residential timber-framed construction (non-cyclonic) (Standards Australia, 2010) and the ICANZ Insulation handbook (Insulation Council of Australia and New Zealand, 2010). It was assumed the wall had an outer leaf of brick 110mm thick with a timber frame of 35 x 90mm MGP12 pine, studs at 450 centres (based on Table A10, for wall height 2700mm, sheet roof type, truss span 6000mm - (Standards Australia, 2010)) and 45 x 90 bottom and top plates (based on Tables A21 and A23). Insulation was assumed to be R2.7 Bradford wall batt 90mm thick, density of 34kg/m^3 (CSR, 2012a). A reflective foil sheet was included. Footings were as per discussion with a structural engineer (Wittmann, 2010). Lining was assumed to be 13mm thick plasterboard and the wall finish, an acrylic based paint.

The material quantities were calculated based on a wall module length of 450mm as this is one of the standard designs of stud frame in Australia (600mm is the other). These values were then scaled up for 1 linear metre of wall and then multiplied by the wall length of the functional unit.

Figure 6.9 and Table 6.20 illustrate and table the material quantities assumed for the Brick Veneer wall.

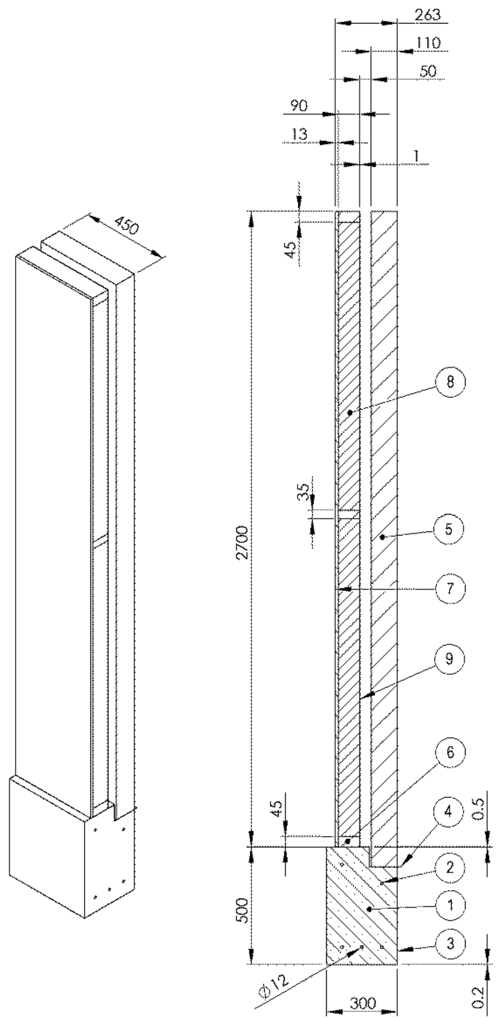

Figure 6.9 - Brick Veneer Wall components

Table 6.20 - Materials for 1lm and functional unit of Brick veneer wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	footing	concrete	335.52	18,630
2	Rebar, footing dia12mm	steel	4.40	244
3	DPC under footing 0.2mm	polyethylene	0.23	13
4	DPC under wall 0.5mm	polyethylene	0.19	8
5	Bricks and mortar	bricks and mortar	736.16	32,779
		bricks (85%)	625.74	27,861
		mortar (15%)	110.42	4,917
6	Timber Framing	MGP12 pine	14.93	665
7	Lining Plasterboard 13mm	Gyprock ECO8	25.10	1,117
8	Insulation	glass wool batt	7.27	324
9	Sarking (reflective foil)	aluminium and kraft paper	2.13	95
10	Nails framing	steel	0.22	9
11	Nails line/clad	steel	0.03	1.3
12	Adhesive line/clad	acrylic	0.11	5
13	Paint (litres) two coats	acrylic	0.3L	15L

The volume was calculated for bricks and mortar combined, therefore this value needed to be separated into the constituent quantities. The assumptions were that the brick was 230mm long and 75mm high and 110mm wide (this is a typical size in Australia) (Standards Australia, 2003) and the mortar is 10mm thick on top, bottom and ends of the brick, and it extends the full width of the brick i.e. 110mm. Hence for each brick the wall surface area is 17,250mm^2 whereas when the mortar is added it increases to 20,400mm^2. By percentage of the exposed face of the brick wall this represents 85% brick and 15% mortar. As both the brick and mortar were assumed to be the same width (110mm) this ratio also applies volumetrically i.e. 85% of the volume of the wall is composed of brick and 15% mortar and thus quantities of these components can be calculated accordingly.

The quantity of nails has been calculated based on installation instructions for Gyprock: the quantity of nails used for fastening lining to the frame was 1kg per 100m^2 of Gyprock (CSR, 2010, p. 18). Quantity and specification of nails used to assemble the framing was based on AS1684.4 2010 p 98-100. Adhesive quantities for fastening the lining/cladding to the frame were as per Gyprock installation instructions: 4.2kg of adhesive per 100m^2 of Gyprock (CSR, 2010, p. 18).

For the reflective foil (commonly termed “sarking” in Australia), it was assumed that it was 1mm thick and was composed of 95% kraft paper, and 5% aluminium foil by weight.

6.14.3 Process Energy

Process energy is accounted for in the mortar process. It assumes mixing of mortar on site (refer to Section 6.18.2)

6.15 Reverse Brick Veneer Wall Assumptions

6.15.1 Construction Overview

Reverse brick veneer is similar to brick veneer but the main elements (brick and framed wall) are reversed with the brick on the inside of the envelope rather than on the outside. This takes advantage of the thermal mass properties of the brick and improves thermal performance (Inglis & Downton, 2010). This arrangement necessitates the use of lightweight sheeting for the wall cladding material. In this study, cement fibreboard was used to reduce its embodied energy content, although other materials such as corrugated steel sheets are commonly used.

It was assumed that the Reverse Brick Veneer wall was insulated with the same materials as the Brick Veneer wall.

6.15.2 Material Quantities

Figure 6.10 and Table 6.21 illustrate and table the material quantities assumed for the Reverse Brick Veneer wall.

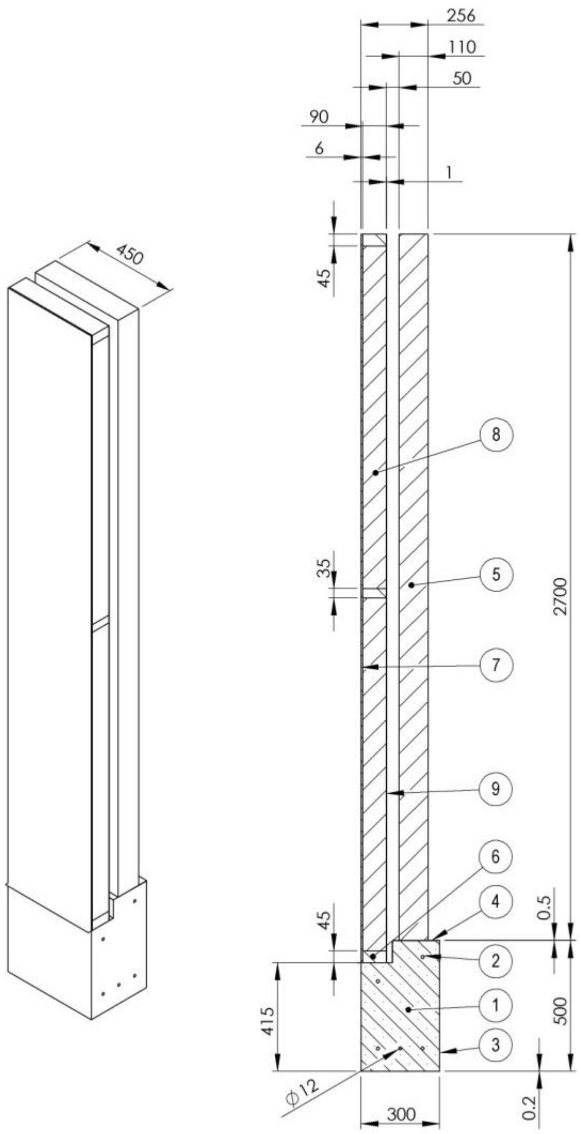

Figure 6.10 - Reverse Brick Veneer wall module

Table 6.21 - Materials for 1lm and functional unit of Reverse Brick Veneer wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	footing	concrete	335.520	18,625
2	Rebar, footing dia12mm	steel	4.403	245
3	DPC under footing 0.2mm	polyethylene	0.228	13
4	DPC under wall 0.5mm	polyethylene	0.188	8
5	Bricks and mortar	bricks and mortar	713.691	31,768
		bricks (85%)	606.637	27,003
		mortar (15%)	107.054	4,766
6	Timber Framing	MGP12 pine	15.235	679
7	Cement Fibreboard 6mm	Hardiplank	21.694	966
8	Insulation	glass wool batt	7.508	335
9	Sarking (reflective foil)	aluminium and kraft paper	2.200	98
10	Nails framing	steel	0.222	9
11	Nails line/clad	steel	0.027	1
12	Adhesive line/clad	acrylic	0.105	5
13	Paint (litres) two coats	acrylic	0.338	15

6.15.3 Process Energy

Process energy is accounted for in the mortar process. It assumes hand mixing of mortar on site (refer 6.18.2)

6.16 Timber Frame Cement Fibreboard Clad Assumptions

6.16.1 Construction Overview

Light weight timber framed homes are the most common form of domestic wall construction in Australia (Davis & Downton, 2010). Specifications for timber framing for this wall construction are given in accordance with Australian Standards for non-cyclonic areas (Standards Australia, 2010). The stud frames are made of timber (35mm x 90mm), spaced at 450mm centres and lined with plasterboard, clad with cement fibreboard and insulated between studs with glasswool batt insulation.

6.16.2 Material Quantities

Figure 6.11 and Table 6.22 illustrate and table the material quantities assumed for the Timber Frame Cement Fibreboard Clad wall.

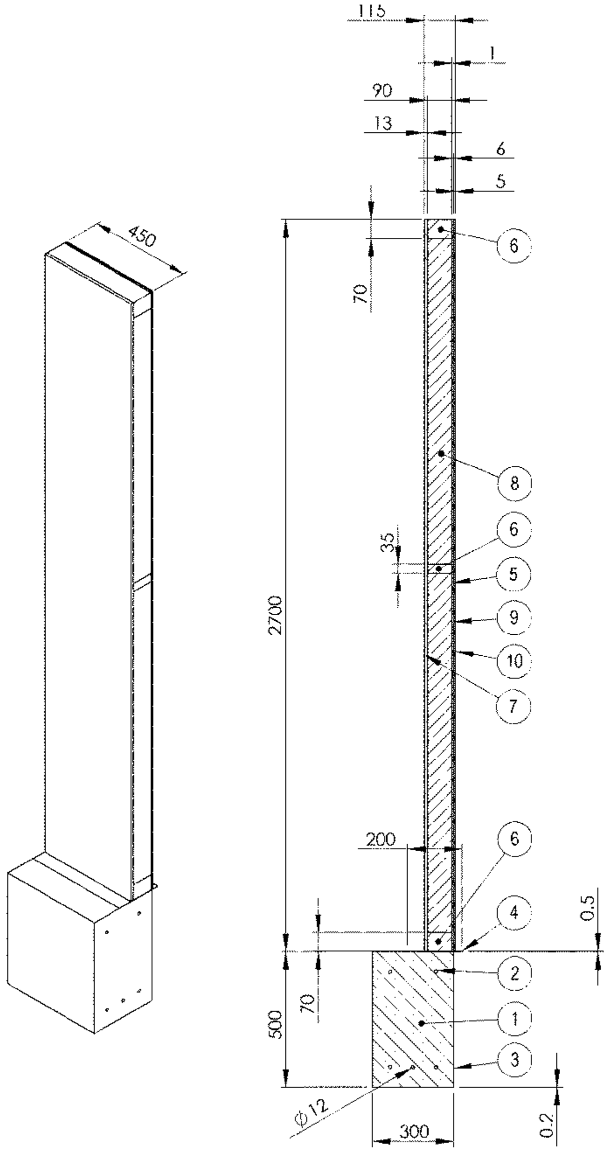

Figure 6.11 - Timber Frame Cement Fibreboard Clad Wall Module

Table 6.22 - Materials for 1lm and functional unit of Timber Frame Cement Fibreboard Clad wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	Footing	Concrete	360.00	19,965.6
2	Rebar, footing dia12mm	Steel	4.40	244.2
3	DPC under footing 0.2mm	LDPE	0.24	13.6
4	DPC under wall 0.5mm	LDPE	0.09	4.2
5	Foil	Aluminium and kraft paper	0.0027	0.120
6	Timber framing	Mgp10 pine 35x90	17.05	757.8
7	Lining Plasterboard 13mm	Plasterboard	25.09	1,115.6
8	Insulation	Glass wool wall batt 90mm thick	7.12	316.7
9	Cement fibreboard 6mm thk	Cement fibreboard	21.03	934.9
10	Render 5mm thk	Cement render	27.00	1,200.4
11	Nails framing	Steel	0.22	9.9
12	Nails line/clad	Steel	0.03	1.2
13	Adhesive line/clad	Acrylic	0.23	10.1
14	Paint (litres) two coats	Acrylic	0.676	30

Quantities of nails and adhesive (items 9-11) have been calculated in the same way as the Brick Veneer wall with the exception that nails used for fixing the lining/cladding were doubled to account for the cladding used in this construction. Likewise the quantity of adhesive was doubled. It is assumed that the amount of nails and adhesive for fixing Gyprock is the same as for fixing cement fibreboard. Two coats of paint are assumed for the lining and the cladding.

6.17 Timber Frame Steel Clad Wall Assumptions

6.17.1 Construction Overview

This wall construction was used for the Equator Facing Wall in the Earthship without Greenhouse envelopes. It was assumed to be identical to the Timber Frame Cement Fibreboard Clad wall construction with the exception that the cladding was different: it has a layer of steel instead of cement fibreboard, adhesive and render.

6.17.2 Material Quantities

Figure 6.12 and Table 6.23 illustrate and table the material quantities assumed for the Timber Frame Cement Fibreboard Clad wall.

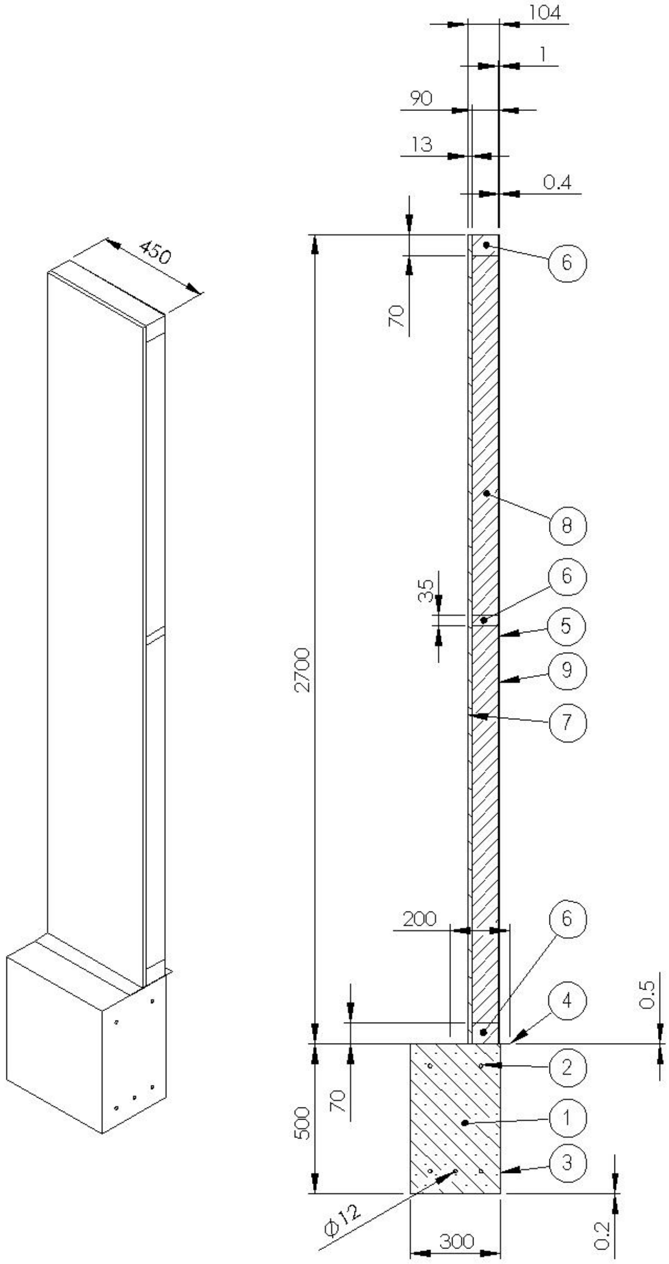

Figure 6.12 - Timber Frame Steel Clad wall module

Table 6.23 - Materials for 1lm and functional unit of Timber Frame Steel Clad wall

Item	Description	Material	Linear Metre	Functional Unit
			Mass (kg)	Mass (kg)
1	Footing	Concrete	360.00	19,965.6
2	Rebar, footing dia12mm	Steel	4.40	244.2
3	DPC under footing 0.2mm	LDPE	0.24	13.6
4	DPC under wall 0.5mm	LDPE	0.09	4.2
5	Foil	Aluminium and kraft paper	0.0027	0.120
6	Timber framing	Mgp10 pine 35x90	17.05	757.8
7	Lining Plasterboard 13mm	Plasterboard	25.09	1,115.6
8	Insulation	Glass wool wall batt 90mm thick	7.12	316.7
9	Steel cladding	Steel 0.4mm thk	11.70	520.12
10	Nails framing	Steel	0.22	9.9
11	Nails line/clad	Steel	0.03	1.2
13	Paint (litres) two coats	Acrylic	0.338	15

6.17.3 Process Energy

No process energy was assumed for this wall construction other than that accounted for in the concrete process.

6.18 Common Element Assumptions

6.18.1 Render, Internal

The sub-components (ingredients) of the internal render are shown below. Volume and mass are calculated for 1m3 of render materials (not including water). Adobe render is usually made on site with the local soil which is augmented with extra sand or clay to obtain the correct consistency (Steen, Steen, Bainbridge & Eisenberg, 1994, p. 212). For the purposes of this LCA a worst case scenario is assumed in which sand and clay are imported to the site rather than the local soil being used. The quantities were calculated using a ratio (by volume) based approximately on guidelines by Steen for rendering strawbale walls.

Material	Density	Ratio by vol	Percentage	Volume	Mass	Mass/kg of render
	kg/m3		%	m3	kg	
Sand	1602	4	67%	0.667	1068.0	0.757
Clay	1089	1	17%	0.167	181.5	0.129
Straw	116	1	17%	0.167	19.3	0.014
Water	1000	1	14%	0.143	142.9	0.101
Total Solids		6	100%	1.000	1268.8	
Total inc water		7	114%	1.143	1411.7	1

6.18.2 Render, External

The volume/mass of the external render ingredients was calculated as per the internal render as per AS2350.12-2006 p.6 (Standards Australia, 2006) which gives quantities of sand, cement and water for mixing cement mortar in the ratio of 3 parts sand to one part cement to half a part of water.

Table 6.24 - Material quantities for 1kg of cement render (excluding wire netting)

Material	Density	Ratio by vol	Percentage	Volume	Mass	Mass/kg of render
	kg/m3		%	m3	kg	kg
Sand	1602	3	75%	0.750	1201.5	0.706
Cement	1506	1	25%	0.250	376.5	0.221
Water	1000	0.5	13%	0.125	125.0	0.073
Total Solids		4	100%	1.000	1578.0	
Total inc water		4.5	113%	1.125	1703.0	1

Another component of the external render is wire netting which provides extra strength to the render and a “key” for the render to grip. In the case of Earthship tyre walls, it is nailed or screwed into the tyres and for strawbale walls it is fastened to the bales with baling twine which passes all the way through the bales.

Assuming a render thickness of 25mm, 1m3 will cover 40m^2. Assuming wire netting weighs 0.29kg/m^2(Hurricane Wire Products, 2006), 1m3 of render will require 40 x 0.29 = 11.6kg of steel wire netting or 1kg of render will require 11.6 / 1578 (the weight of 1m3 of render) = 0.00735kg of steel wire netting.

6.18.3 Roof & Ceiling

Two rooves were modelled, one based on the Earthship Global Model design and the other a more conventional truss gable roof.

6.18.3.1 Earthship Roof

Figure 6.13 shows the basic roof construction for the Global Model Earthship. The roof and ceiling materials are timber (Radiata pine) trusses, timber purlins, plywood, building paper, steel roof cladding, timber ceiling, EPS insulation directly above the ceiling, and EPS insulation below the steel cladding. Nails and screws were calculated using an estimate of 100g per m^2 roof area.

This design was slightly modified to reflect Australian materials and roof construction practices while maintaining an insulative value of R5.1 ($5.1m^2K/W$ of thermal resistance).1mm thickness of reflective foil or “sarking” was assumed instead of 2mm building paper; glass wool insulation was assumed instead of polyiso, and insulation under roof cladding layer was omitted. Table 6.25 lists the material quantities assumed for the Australian version of the Earthship roof.

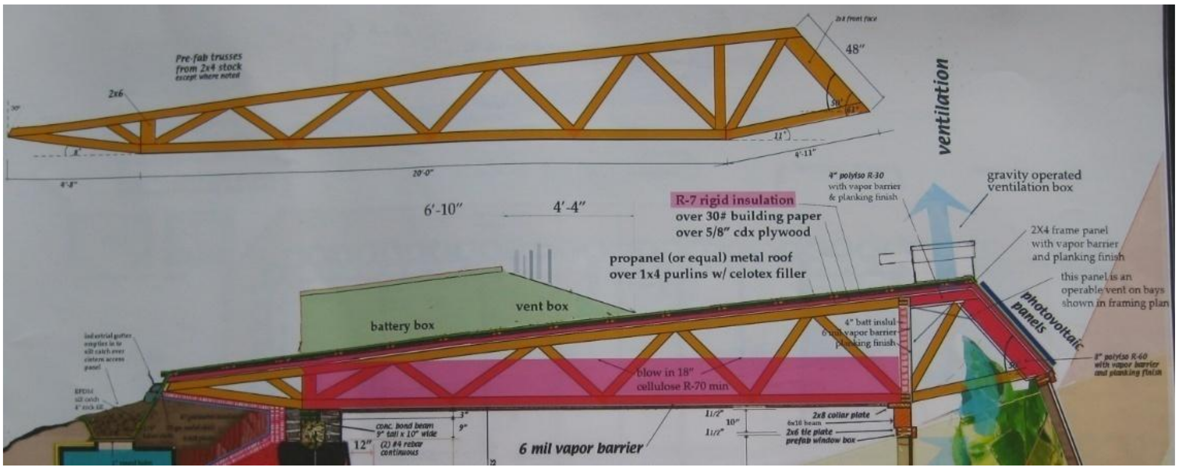

Figure 6.13 - Global Model Roof design (copyright Earthship Biotecture)

Table 6.25 - Materials for functional unit of Global Model Roof Adapted for typical Australian Materials

Description	Material	Mass (kg)
truss roof	Pine 45 x 90	2,104.5
plywood roof	Ply 16 thk	197.66
sarking	Sarking 1mm thk	16.3
roof cladding	Steel 0.4 thk	969.11
ceiling	pine 25 thk	1,542.8
insulation ceiling	Glass wool ceiling batt R5 200 thk	637.6
purlins	Pine 25 x 90	421.3
Nails and screws	Steel	17.7

6.18.3.2 Conventional Roof

A gable roof was the basis for a conventional roof. It was assumed to overhang the north and south walls by 0.9m and the east and west walls by 0.6m. The northern overhang is intended to provide shading in the summer while still admitting radiation in the winter (and is the same overhang assumed in the thermal modelling). The roof is constructed using a truss design ((University of Maryland, 1963) using materials similar to the Earthship roof (timber truss with steel cladding); however, the ceiling is made from plasterboard instead of pine and EPS insulation has been replaced by fibre glass ceiling batts (100mm thick) and reflective foil sarking to reflect common Australian building practice. Nails and screws were calculated using the same estimate as the Earthship roof.

Figure 6.14 and Table 6.26 illustrate the dimensions and material quantities assumed for the conventional roof.

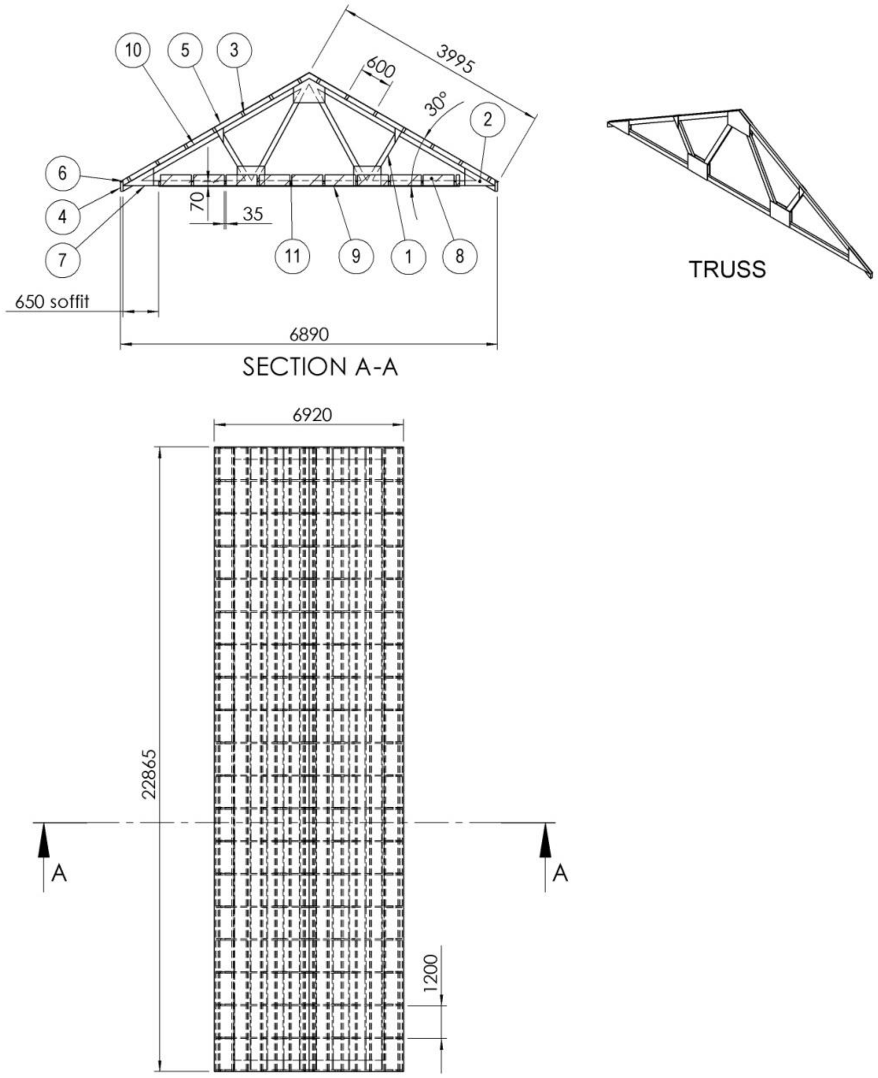

Figure 6.14 - Conventional Roof

Table 6.26 - Materials for functional unit of Conventional Roof

Item	Description	Material	Mass (kg)
1	truss roof conventional	pine 45 x 90mm	826.8
2	Brace Roof Truss	ply 10mm thk	186.6
3	purlins	pine 45 x 90mm	660.6
4	barge board	pine 45 x 170mm	178.2
5	roof cladding	steel 0.42mm thk	792.3
6	gable cladding steel	steel 0.42mm thk	63.9
7	soffit	steel 0.42mm thk	149.43
8	insulation above ceiling	fibreglass ceiling batt 200mm thk R5	610.9
9	ceiling, plasterboard	plasterboard 13mm thk	1122.5
10	Sarking	kraft paper w aluminium foil 1mm thk	135.4
11	Ceiling battens	pine 35 x 70	274.1
	Nails and screws	Steel	17.7

6.18.4 Floor

Two types of floor were modelled. A conventional concrete slab floor comprising damp proof course, and reinforced concrete slab 100mm thick was compared to a rammed earth "mud" floor (often used in Earthship construction) assumed to have the same damp proof course as the concrete slab, plus a 100mm thick layer of sand and a 100mm layer of cement reinforced rammed earth. The floor is assumed to be 22m x 5.5m x 0.1m thick and in the greenhouse it is of the same dimensions except the width is 2.4m instead of 5.5m. This is in accordance with the functional unit dimensions.

Material quantities for each floor are tabled below.

Table 6.27 - Living Area Floors - Concrete Slab

Material	Material Specification	Mass(kg)
Concrete	100mm thk	29,040
Steel	REO MESH SL62 (dia 6mm x 200mm spacing)	267
Low Density Polyethylene (LDPE)	0.3mm thk	34.1

Table 6.28 - Living Area Floors - Mud

Material	Material Specification	Mass(kg)
Rammed Earth	Assumed density of 2000kg/m3	24,200
Sand	100mm thk (under damp course)	20,352
Low Density Polyethylene (LDPE)	0.3mm thk	34.1

Table 6.29 - Greenhouse Floor - Concrete Slab

Material	Material Specification	Mass(kg)
Concrete	100mm thk	6,336
Steel	REO MESH SL62 (dia 6mm x 200mm spacing)	58.3
Low Density Polyethylene (LDPE)	0.3mm thk	7.4

Table 6.30 - Greenhouse Floor - Mud

Material	Material Specification	Mass(kg)
Rammed Earth	Assumed density of 2000kg/m3	5,280
Sand	100mm thk (under damp course)	4,440
Low Density Polyethylene (LDPE)	0.3mm thk	7.4

6.18.5 Internal Partition Walls

Five types of internal partition walls were modelled.

- "Clay Brick" with cement mortar (as per "Thermal Mass" internal wall in Thermal Performance Study),
- "Timber Frame" with plasterboard lining (as per "Light Weight internal wall in the Thermal Performance Study),
- "Can Wall" as per Earthship designs, made from aluminium beverage cans with cement mortar.
- "Rammed Earth"
- "Mudbrick"

Clay brick is a typical internal wall type for conventional homes with thermal mass internal walls, although it is more common that conventional homes have lightweight stud walls that are timber framed with a plasterboard lining, hence the inclusion of the "Timber Frame" internal wall type. The can wall is typical of Earthship constructions. It is quick and easy to build using “waste” aluminium beverage cans. Rammed earth internal walls are often built in homes with rammed earth external walls and likewise, homes with mudbrick external walls often feature mudbrick internal walls.

Footing dimensions varied according to the wall type and were assumed to be integral with the concrete slab or in the case of the mud floor, a separate sub-floor “footing” structure. The footing width was assumed to be 0.3m for the clay brick, rammed earth and mudbrick walls on account of their mass and width, in contrast to the “can” and light weight timber frame walls which were assumed to have footings 0.2m wide due to their lighter weight. The depth of the footing was assumed to be 0.3m for all internal wall types with the exception the light weight timber frame wall which was assumed to require only a 0.2m deep footing on account of the light weight. Two lengths of 12mm diameter steel reinforcing bar were assumed in all internal wall footings. Note that these dimensions were estimates by the author, whereas the footing specifications for the external walls were given by an engineer.

6.18.5.1 Fired Clay Brick

The internal thermal mass clay brick wall was assumed to be constructed using the same bricks and mortar as the external wall. It was assumed that the wall was painted.

The material quantities for the functional unit (4 internal walls 2.7m high x 5.5m long) and for one metre square of wall area (FU value divided by 59.4m^2) are shown in Table 6.31.

Table 6.31 - Fired clay brick internal wall material quantities

Material	Assumptions	Mass/FU (kg)	Mass/m^2 wall area (kg)
Bricks	Brick size 230 x 115 x 75 mm	13,953	234.9
Cement Mortar	10 mm thick	2,215	37.3

6.18.5.2 Timber Frame

The light weight timber frame wall is assumed to be non-load-bearing and is constructed from 35 x 70mm Radiata pine with plasterboard lining and glass wool batt insulation and was designed in accordance to the relevant Australian Standards for timber framing (Standards Australia, 2010). Nails and adhesive are also included as per the manufacturer’s recommendations.

The material quantities for the functional unit are shown in Table 6.32.

Table 6.32 - Timber frame internal wall material quantities

Material	Assumptions	Mass/FU (kg)	Mass/m^2 wall area (kg)
Timber frame	Radiata pine 35 x 70mm	288.8 kg	4.86 kg
Plaster Board	10mm thick “ECO8”, density 9.3kg/m^2(CSR, 2012b)	1104.8 kg	2.01 kg
Insulation	Glass wool batt 70 thick, density 25kg/m^3	110.5 kg	18.6 kg
Nails	Steel (quantities as per Australian Standards and suppliers recommendations) (CSR, 2010)	1.8 kg	0.03 kg
Adhesive	Acrylic based (quantities as per suppliers recommendations) (CSR, 2010)	4.2 kg	0.07 kg
Paint	Acrylic, coverage 8m^2/L	14.9 L	0.25 L

6.18.5.3 Can Wall

Two variations of the Can Wall were modelled in the LCA study: the traditional version which uses a cement mortar and assumes that the aluminium cans are landfilled at end-of-life, and a “low embodied energy” (lowEE) version which instead uses an adobe mortar, and assumes that 90 percent of the aluminium cans are recycled at the end-of-life.

The Can Wall is assumed to be 150mm thick due to the aluminium beverage container (“can”) being 135mm long and 7.5mm of render being applied to each end of the can. Its height is assumed to be the standard 2.7m high; however the length is assumed to be only 4.7m on account of a buttressing structure adjacent the tyre wall which causes the internal wall to be 800mm less than if the buttress was not included.

To establish the quantity of mortar and aluminium cans required to build the wall a 3D CAD model was generated (see Figure 6.15) as per the construction drawings given by Reynolds, which calls for 19mm of mortar between each can (Reynolds, 1990, pp. 158-159). The CAD model assumed cylindrical cans whereas Reynolds recommends pinching the walls of the can to make a vee shape to aid with laying in the mortar, hence an additional 15% volume in cement render was estimated and factored into the results.

An aluminium beverage can was weighed (the traditional type of diameter 65mm x 135mm height) to establish the amount of aluminium used in the wall. Its weight was 14g, and assuming 1980 cans per wall (as per the CAD model) the total weight of aluminium was 27.72kg for each wall.

The total mass of cement mortar, cement render, and aluminium cans for all four walls of the functional unit are shown in Table 6.33.

Table 6.33 - "Can wall" internal wall material quantities (4 walls 4.7m x 2.7m x 0.135m)

Material	Assumptions	Total mass (kg)	Mass / wall area (kg/m^2)
Cement mortar		9120.8	179.7
Aluminium (Can)	Can mass 14g	110.9	2.18
Cement render	7.5mm thick each side of wall	1827.3	36

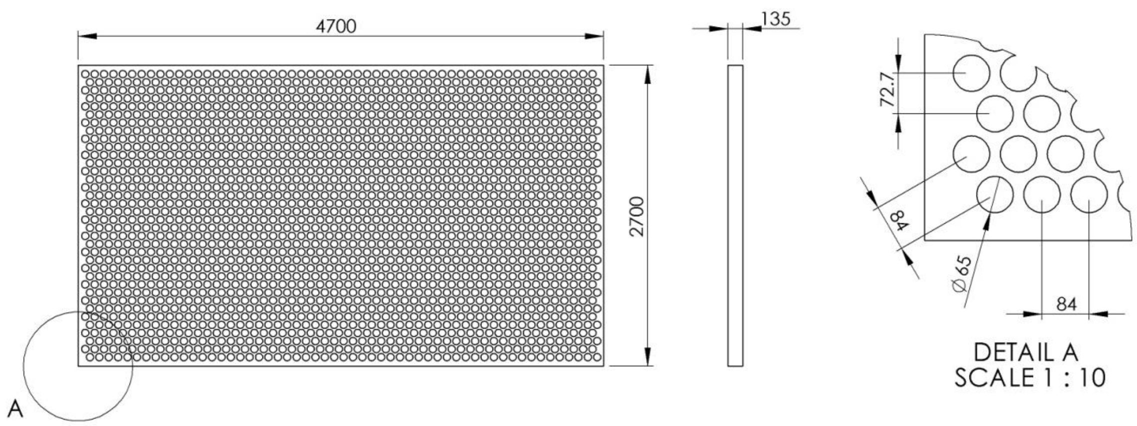

Figure 6.15 - "Can wall" CAD model calculations

6.18.5.4 Can Wall with Adobe Mortar (lowEE Earthship)

When adobe mortar is used instead of cement mortar, the quantity of adobe mortar is 127.7kg per m^2 of wall area (assuming 1700kg/m^3 density of adobe mortar).

6.18.5.5 Rammed Earth Internal wall

The rammed earth internal wall was assumed to be as thin as possible to minimise loss of internal floor space. A minimum of 200mm thick is recommended (Ramtec, 2008). At a density of 2000kg/m^3 the mass is 400kg/m^2 of wall.

6.18.5.6 Mudbrick Internal wall

The mudbrick internal wall was assumed to be 200mm thick. At a density of 1600kg/m^3, the mass is 320kg/m^2 of wall.

6.18.6 Equator Facing Wall & Greenhouse Partition Wall

The Equator Facing Wall and the Greenhouse Partition Wall were both assumed to be 50% glazed. In the case of the Equator Facing Wall (i.e. no greenhouse included in the envelope) the unglazed portion of the wall was assumed to be the External Wall construction however in the case of Earthship External

Wall constructions, rather than a tyre wall, a steel clad insulated timber frame wall was assumed i.e. Timber Frame Steel Clad (TFS).

For the Greenhouse Partition Wall (i.e. greenhouse included) the unglazed portion of the wall was assumed to be a "can wall" of thickness 150mm as per the internal wall described previously.

The windows were assumed to be double glazed units consisting of two layers of 5mm clear uncoated glass separated by a 12mm air gap. A butyl seal which incorporates an aluminium extrusion and desiccant was also included. Timber window frames 50mm x 50mm were also counted. Dimensions of the windows were 2.7m high x 2.2m wide including frames (Figure 6.16). The Functional Unit included 5 windows thus the total area of double glazed area, including frames, was 29.7m^2 and 28.5m^2 not including frames (glazed units only). A structural beam of pine which acts as a lintel for all windows was assumed to be 23m long x 0.3m high x 0.15m wide.

The following tables document the materials assumed for the Equator Facing Wall and the Greenhouse Partition Wall.

Table 6.34 - Window Frames and Glazing - applicable to all Equator Facing Walls / Greenhouse Partition Walls

Description	Material	Total Area (m^2)	Mass (kg)
Window frame	Pine	1.2	69.9
Double glazing	Double glazed unit	28.5	808.5

Table 6.35 - Earthship, Equator Facing Wall 50% Glazed, Timber Framed Steel Clad (i.e. for Earthship Without Greenhouse)

Description	Material	Total Area (m^2)	Mass (kg)
Foil (Sarking)	aluminium and kraft paper		23.5
Timber Framing 35 x 90	MGP10 pine 35x90		187.5
Lining Plasterboard 13mm	plasterboard		276.0
Insulation	glass wool batt 90mm		78.4
Steel cladding	steel 0.4mm thick		321.2
Nails, framing	steel		2.4
Nails, line/clad	steel		0.3
Paint (litres) two coats	acrylic		3.3
Footing	concrete		7,920
Rebar, footing dia12mm	steel		96.8
DPC under footing 0.2mm	polyethylene		5.3
DPC under wall 0.5mm	polyethylene		2
Top plate (structural beam)	MGP12 pine		527.9

Table 6.36 - Base Case Earthship, Greenhouse Partition Wall 50% Glazed

Description	Material	Total Area (m^2)	Mass (kg)
Walls, Can, Cement, Greenhouse	See indented list below	29.7	
cement mortar	Cement mortar		5336.8
aluminium cans	Aluminium		64.8
cement render	Cement mortar		1069.2
paint	Acrylic paint		18.56
footing	concrete		7,920
Rebar, footing dia12mm	steel		96.8
DPC under footing 0.2mm	polyethylene		5.3
DPC under wall 0.5mm	polyethylene		2
Top plate (structural beam)	MGP12 pine		527.9

Table 6.37 - LowEE Earthship, Greenhouse Partition Wall 50% Glazed

Description	Material	Total Area (m^2)	Mass (kg)
Walls, Can, Adobe, Greenhouse	See indented list below	29.7	
adobe mortar	Adobe mortar		4361.7
aluminium cans	Aluminium (not recycled)		6.4
adobe render	adobe mortar		2019.6*
paint	Acrylic paint		0
footing	concrete		7,920
Rebar, footing dia12mm	steel		96.8
DPC under footing 0.2mm	polyethylene		5.3
DPC under wall 0.5mm	polyethylene		2
Top plate (structural beam)	MGP12 pine		527.9

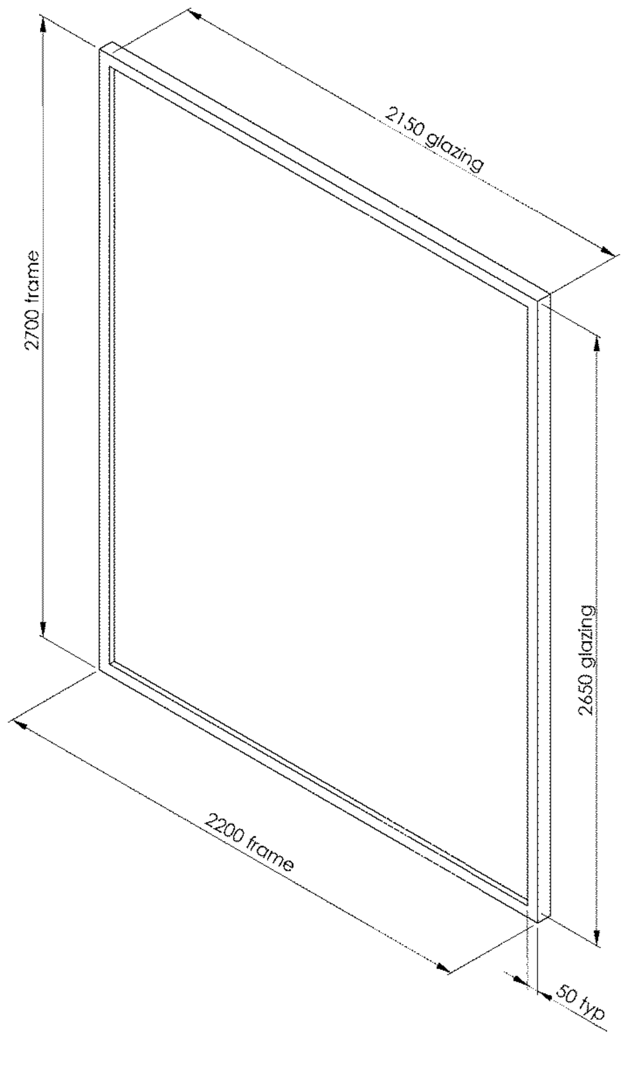

Figure 6.16 - Window frame and double glazed unit dimensions

6.18.7 Greenhouse

As was the case with the internal Can Walls, two variations of the greenhouse were modelled: one based on traditional Earthship methods and another “low embodied energy” version which substituted adobe mortar for the usual cement mortar in all the Can Walls.

6.18.7.1 Earthship Greenhouse LCI

The results for the low tyre wall at the front of the greenhouse have already been given in the External wall section (Table 6.6).

Table 6.38 lists the remainder of the materials assumed in the construction of the greenhouse.

This includes the can walls (which use the Internal Wall calculations to calculate the quantities of cement render and aluminium cans), the insulation within the can walls, concrete footings for the can walls, timber framing and metal flashing for the angled glazed greenhouse facade, ceiling insulation (polyurethane), and a vent box assembly which forms part of the greenhouse roof.

Table 6.38 - Greenhouse material quantities

Description	Material	Tot Area (m^2)	Mass (kg)
Walls, Can, External Greenhouse	See indented list below	35.4	
cement mortar*	Cement mortar		6361.0*
adobe mortar (alternative to cement mortar)*	Adobe mortar		5198.8*
aluminium cans	aluminium		77.2
cement render	Cement mortar		1274.4
paint	Acrylic paint		22.1
Insulation Greenhouse walls	polyurethane		47.8
Footings Greenhouse east/west walls	See indented list below		
concrete	concrete		1457.3
rebar	steel		20.3
dpc	LDPE		0.6
Framing, Glazed Greenhouse	pine		638.0
lining ceiling greenhouse	pine		358.3
Insulation Greenhouse Ceiling	polyiso		211.7
Flashing Greenhouse	steel		56.1
vent box	ply		47.4
frame, vent lid, timber	pine		8.4
cladding, vent box and lid, steel	steel		11.2
Insulated Glazed Units	Double glazed units	42.5	1140

* the Base Case Earthship was assumed to use cement mortar whereas the “LowEE Earthship” was assumed to use adobe mortar.

6.19 Systems Assumptions

To compare the Earthship’s off-grid systems to conventional “grid connected” services for energy, water and wastewater treatment (sewer) it was necessary to develop estimates for the quantities of energy, water and wastewater that would be used by each type of household, and then define these systems.

The following sections detail the rationale and calculations for these assumptions.

6.19.1 Energy System including Solar Hot Water

Energy was assumed to be provided by electricity for heating and cooling, lighting and other household appliances, and gas was assumed for energy intensive tasks such as cooking and solar hot water boosting.

Energy was considered, and modelled, in four discrete categories:

- Heating and cooling electricity
- Other household electricity (lighting and electrical appliances)
- Gas for hot water boost
- Gas for cooking

Heating and cooling electricity was modelled as per the results of the Thermal Performance Study and this is discussed further under Section 6.20. Although the Earthship can be assumed to require zero heating or cooling, and is able to provide for its energy needs via the off-grid energy system, to be absolutely fair in the comparison with the grid connected homes which typically require heating and cooling, the Earthship was modelled with grid supplied energy, sufficient to meet the minimal heating/cooling load dictated by the results of the Thermal Performance study (Chapter 4).

It was assumed that other household electricity use - for appliances and lighting - would be a maximum of 5kWh/day. This was met by the off-grid electricity system for the Earthship and for the Mudbrick home, whereas the other homes were assumed to use grid electricity. Although it seemed unlikely that a grid connected home would use such a small amount of electricity, this same quantity of grid electricity was compared to the off-grid electricity to gain an understanding of how the two systems compare on an equal basis. However, to investigate the effect of more typical home energy use in Adelaide (Commonwealth of Australia, 2013a), a scenario in which 20kWh/day of electricity was used was also modelled.

Calculations and assumptions for energy use are presented below.

6.19.2 Electricity Use Estimate

An off-grid renewable electricity system designed to deliver up to 5kWh/day in Adelaide conditions was designed by a local company, Natural Technology Systems (specifications of system in Appendix D). To check that this would be adequate, a schedule of lighting and appliance usage was developed (Table 6.39) indicating that at least 2.3kWh/day would be needed, hence the 5kWh/day system provides for significant additional energy use, and represents an over estimate of the capacity of the system.

Although larger than a typical Taos Earthship system this system is sized to be suitable for frugal energy use in the Adelaide climate. Additional batteries and PV panels (1.52kW) were necessary due to Adelaide's higher number of overcast winter days compared to Taos. In Taos, Earthship energy systems are approximately 720-1000W PV systems with approx 8 batteries totalling approximately 700 amp hours storage capacity (refer Chapter 3).

Quantities and masses of the system components with assumptions regarding replacement intervals and the resultant total lifecycle mass are shown in Table 6.40. Heating and cooling energy was calculated separately using the results of the Thermal Performance study (refer Chapter 4).

As the off-grid energy system can provide up to 5kWh/day for lighting and appliances this figure was also adopted for grid connected energy. This correlates with generic energy use data for Australian households which quotes 33% of energy use for lights, standby, refrigeration, lifestyle appliances and washing and drying (AGL Energy, 2013). Using an average electricity use for a four person household in Adelaide (postcode 5000) of 19.2kWh/day (Commonwealth of Australia, 2013a) this equates to 6.4kWh/day indicating that the 5kWh/day assumption is realistic, especially for frugal energy use.

As it is assumed that natural daylighting, lighting and appliances are standardised for all house types the result of this modelling approach is that the heating/cooling energy, which was determined by the physical properties of the external wall type (and in the case of the Earthship, the greenhouse and berm), is the only variable affecting energy use.

6.19.3 Gas Use Estimate

In Australia it is fairly common practice for grid connected homes to use gas for cooking and for boosting solar hot water systems as does the Earthship. This study assumed that the gas energy use for a grid connected home was identical to an Earthship because similar amounts of SHW boosting and cooking activities are likely to take place in both types of home – although it could be argued that the off-grid Earthship will drive more frugal gas use (e.g. shorter showers) than a grid connected home where gas and water is seemingly never ending, apart from this, there is nothing inherent in the Earthship design that tends to reduce gas use.

The average annual gas use was calculated based on responses to a question regarding expenses related to gas use in the Earthship Occupants' Questionnaire. As the bulk of responses to the questionnaire were from the US, all respondents' answers were converted to US dollars and averaged. This gave a result of US$185 per annum per household. This equates to 3650kWh per annum or 10kWh per day per household assuming $0.35/litre of gas, the average price of natural gas in America in 2012 (EIA, 2014) and 6.9kWh per litre (ELGAS, 2014).

This value was compared to other information published by the Commonwealth of Australia: a RHEEM instantaneous gas heater available in New Zealand quotes 18,674MJ gas energy use per annum although details about volume of water is not clear (Commonwealth of Australia, 2012). Information was not available for gas cookers as these are not included in the Australian Governments' energy efficiency labelling scheme or the Minimum Energy Performance Standards.

South Australian architect, Emilis Prelgauskas estimates approximately 45kg of LPG per annum per person for cooking and SHWS boost (Prelgauskas, 2013). Assuming 50MJ/kg for LPG energy density (Envestra Limited, 2007) this equates to 9000MJ per annum for four people.

The author's personal experience is that approximately 0.7kg of LPG/week is used by a family of four for cooking purposes only (electric oven, with gas cooktop) i.e. one 9kg bottle per quarter. Scaling this up by approximately 40% to reflect gas oven use, 1kg LPG/week is assumed. This equates to 2,600MJ of energy per annum. This estimate is similar to survey results from a study conducted by the independent regulator for energy prices in New South Wales. This study quotes 2000MJ per annum for households that use gas only for cooking (Independent Pricing & Regulatory Tribunal, 2014).

For solar hot water it was assumed 60% of the energy was supplied by the sun and 40% by gas based on a discussion from a sales representative of SHWS in Adelaide (Ward, 2013b). Using the energy consumption for the RHEEM system mentioned above, this equates to 7,470MJ per annum gas use. Adding the RHEEM system gas use (less solar component) to the cooking gas use reported by the author closely approximates the gas use reported by Prelgauskas, however this anecdotal evidence from Australia is substantially less that that reported by the Earthship occupants. This may be due to differences in climate, hot water usage, cooking practices, and appliance efficiency.

It was decided to use the Australian estimates:

Cooking gas: 2,600MJ

SHWS boost gas: 7,470MJ (RHEEM system providing 40% of hot water, solar 60%)

Total: 2,600 + 7,470 = 10,070MJ/yr

For off-grid systems, bottled gas was assumed to be LPG, whereas grid connected gas type was assumed to be natural gas as per current gas infrastructure in South Australia (Government of South Australia, 2011).

Off-Grid Energy System Specifications

Table 6.39 - Electrical appliances assumed in sizing of off-grid energy system

Electrical Appliance	Qty	Watts	Total Watts	Hr/Day use	Wh/day	kWh/yr	notes/refs
Lights	8	5	40	5	200	73	Quantity of lights turned on simultaneously
Stereo	1	40	40	5	200	73	
Fridge/Freezer	1				480	175	average consumption at 21C (Sun Frost, 2013)
Microwave	1	1000	1000	0.3	300	110	
Range Hood	1	62	62	1	62	23	
Food Processor	1	600	600	0.1	60	22	
exhaust fan	1	30	30	0.5	15	6	

Electrical Appliance	Qty	Watts	Total Watts	Hr/Day use	Wh/day	kWh/yr	notes/refs
computer	2	50	100	5	500	183	laptop
water pump	1	60	60	0.5	30	11	
washing machine	1				164.38	60	four cold washes per week based on 105kWh/365 uses (Commonwealth of Australia, 2013c)
television	1				273.97	100	Estimate based energy efficient TV (AU data)
TOTAL					2285.36	836	

Table 6.40 - Specifications of Renewable Energy System

Description	Qty	Mass each (kg)	Total Mass (kg)	Replacement interval (yr)	Total Qty over 50 (yr)	Total Mass (kg)
Batteries, deep cycle, gel cell	12	66.00	792	15 (Exide Technologies, 2012)	40	2640
190 Watt Solar PV Modules (total 1.52kW)	8	18.85	150.8	25	16	302
Solar Regulator system controller	1	1.12	1.12	15	3.3	4
3.5kW inverter/charger	1	37	37	15	3.3	123
Solar Array Frame for Roof or Ground mount	1	40	40	25	2	80
TOTAL (for freight calculation)						3149

6.19.3.1 LCI Assumptions & Data

Energy

Australasian LCI Unit Processes for South Australia were used to model electricity and gas use. For the purposes of calculating impacts arising from transportation of the gas to a remote location (off-grid home), it was assumed the gas was delivered in a 50kg bottle by a rigid truck travelling 50km, once per year for the lifecycle duration (base case: 50yr).

Off-Grid Electricity System Components

The Australasian LCI Unit Process database does not include data for the inverter, solar panels, batteries or regulator, necessitating the use of alternative data. In the case of the inverter, solar panels and regulator, Ecoinvent (European) data was used. It includes LCI data for a 18.5kg, 2.5kW inverter, which was scaled to 37kg, 5kW for this study to approximate the mass of the inverter specified for the Adelaide Earthship system.

Likewise, data for poly crystalline silicon 72 cell modules was available in the Ecoinvent data although at a slightly reduced wattage of 166W per panel therefore the quantity of solar panels was scaled up (14%) to approximate190W output.

To model the regulator, the inverter data was used as a proxy for electronic hardware, scaled down according to mass i.e. 1.12kg/18.5kg = 0.061 inverters.

LCI data for lead acid batteries was not available in any datasets supplied with SimaPro™ so a review of the literature was undertaken. A recent literature review of LCI data of battery technology by Sullivan and Gaines (2010) quotes the cradle to gate energy of lead acid batteries as 23.4 to 38 MJ/kg. It reports their composition as 25% lead, 35% lead oxides, 10% polypropylene, 10% sulphuric acid, 16% water, 2% glass, 1% antimony. These proportions were used to model the battery where possible; however, due to lack of LCI data for lead oxides, lead was used as a proxy with 30% being primary and 70% secondary (recycled) lead as per Sullivan and Gaines (2010) p. 8.

The weight of each battery specified is 66kg multiplied by 12 batteries which comprise the battery bank for the system = total of 792kg.

The electricity used to manufacture the battery (assemble the materials) was assumed to be 8.4MJ/kg of battery (Sullivan and Gaines, 2010) and this was assumed to be supplied by a German gas power plant (EcoInvent LCI data) as the batteries specified (Sonnenschein) are manufactured by a company based in Germany (Exide Technologies, 2012).

It was assumed that 98% of the batteries' lead was recycled (Battery Council International, 2012). The energy to recycle the lead was assumed to be 5.3MJ/kg Sullivan and Gaines (2010) p. 9 and the heat energy was supplied by natural gas.

Recycling of photovoltaic panels, which is technically possible (Energy Matters, 2013) was not modelled due to lack of LCI data.

The panel mounting equipment was assumed to be steel weighing 40kg. Cable requirements were assumed to be 50m of electrical cable to connect panels to each other, to the inverter, batteries et cetera. This was modelled using Swiss data from the Ecoinvent LCI database. Freight of the renewable energy system was assumed to be 3093.5kg of equipment from Germany to Australia by 25,000km of transoceanic freight (boat) plus 100km of transport by an articulated truck within Australia.

Space Heating & Cooling Equipment

A reverse cycle "split" system was assumed to be used in the house as this is a common heating and cooling system used in Australian homes. This was assumed for all scenarios, even the Earthships which typically do not include mechanical heating/cooling systems. The rationale for this was to be conservative and model a worst case scenario for the Earthships in which the occupants install air conditioning to maintain stringent comfort levels, although in reality the majority of Earthship occupants would simply tolerate slight discomfort.

The total weight of a split system unit is assumed to be 33.5kg and composed primarily of steel (66%) and a motor and pump assembly (34%) (Advameg Inc., 2013). This is the weight quoted for a single split system unit manufactured by Toshiba (Toshiba, 2014, p. 19). It is assumed that five such units would be required, one for each room and that they would need to be replaced every 10 years. As LCI data for manufacturing processes/energy was not available, modelling of the HVAC plant was limited to the raw materials.

Solar Hot Water System

Quantities of materials used to manufacture the SHWS were supplied by a representative of Edwards Pty Ltd (Ward, 2013a) and are presented in Table 6.41. Transport for the total mass was included. As LCI data for manufacturing processes/energy was not available modelling of the SHWS was limited to the raw materials.

Table 6.41 - Material Quantities of SHWS

Material	Mass (kg)
Colourbond Steel	42.5
Stainless Steel	39
Glass	31.2
Copper	9.1
Polyurethane	6.75
Aluminium	5.52
Brass	1.5
Total	135.57

6.19.4 Wastewater System

6.19.4.1 Earthship Greywater System and Food Production*

The wastewater system used in this analysis is based on the typical Taos Earthship design as, unlike the energy system, it does not require alteration due to geographic conditions in Adelaide. The greywater system has been modelled using the following major components: plastic liner, rubber liner, PVC waste drain (plumbing), gravel and sand (the growing medium/substrate), and a small water pump. Fuel use (1 hr of excavator use – diesel fuel) has been included for excavation of the trench.

It has been assumed the pump used to transport the treated greywater from the planter to the toilet cistern will need to be replaced every five years, and that these pumps are recycled at the end-of-life. The pump LCI data is scaled down from a 5.5kW water pump weighing 60kg to a pump weighing 3kg which is more appropriate for simulating the small DC "GWOM" pump used in the Earthship.

Material quantities for the greywater planter are based on a size of 22m x 0.9m x 0.7m deep. Other assumptions are shown in the table below. Credits for food production in the greywater planter have been included in the modelling. It is assumed that, on average, each year the harvest is: 10kg of bananas, 20kg of tomatoes and 20kg of leafy vegetables, based on the author's observations of quantities of produce from Earthship greenhouses in Taos during both summer and winter seasons - these quantities are conservative estimate. Following from this, it is assumed that this avoids annual "food miles" of: 30,000kgkm of transport for bananas (which would typically be transported from Queensland to Adelaide), 2000kgkm for tomatoes and 2000kgkm for leafy vegetables the latter two assumed to be supplied locally (transported only 100km). The LCI data used for the food crops also includes use of farm machinery, fertiliser, pesticide, chemicals, water use and land use, so these are assumed to be avoided when this produce is grown in the Earthship greenhouse.

Impacts arising from the area of land the greywater system occupies have been allocated to the greenhouse rather than the greywater system itself.

Table 6.42 - Earthship Greywater System – Assumptions and Material Quantities

Description	Material	Length (m)	Width (m)	Depth/Dia (m)	Thk (m)	Tot Vol (m^3)	Tot Area (m^2)	Density (kg/m^3)	Mass (kg)
Liner, plastic	LDPE film	22	0.9	0.7	0.0002	0.0104	51.86	940	9.7
Liner, rubber	Synthetic rubber	22	0.9	0.7	0.001	0.0519	51.86	920	47.7
Plumbing	PVC pipe	12		0.1	0.003				19.0
Substrate	Gravel	22	0.9	0.35				1682	11,656
Substrate	Sand	22	0.9	0.35				1602	11,102
Pump (5 units)									15

6.19.4.2 Blackwater System

The blackwater system has the same material quantities as the greywater system with regard to the plastic and rubber liners and the growing substrate (gravel and sand). The Blackwater system is assumed to have half the amount of PVC pipe, no pump, and a 215kg plastic, roto-moulded septic tank of 3000L capacity. The mass for the septic tank was supplied by a local manufacturer (Team Poly, 2012). To account for extra excavation needed for the septic tank the blackwater system includes modelling of 12 litres of diesel fuel (2hr excavator use) - double the amount of the greywater system.

Due to the extensive area of biological filters (the indoor greywater planter and the external blackwater planter) it is unlikely that there would be any outflow from the system requiring "disposal" to the landscape e.g. via subsurface irrigation. However, to be conservative, and in keeping with current regulations for on-site wastewater treatment systems in South Australia, it has been assumed that the system would encompass $200m^2$ of arable land. Water that the system might theoretically "produce", which could be utilised for irrigation, has not been modelled.

Table 6.43 - Earthship Blackwater System - Assumptions and Material Quantities

Description	Material	Length (m)	Width (m)	Depth/Dia (m)	Thk (m)	Tot Vol (m^3)	Tot Area (m^2)	Density (kg/m^3)	Mass (kg)
Liner, plastic	LDPE film	22	0.9	0.7	0.0002	0.0104	51.86	940	9.7
Liner, rubber	Synthetic rubber	22	0.9	0.7	0.001	0.0519	51.86	920	47.7
Plumbing	PVC pipe	6		0.1	0.003				9.5
Substrate	Gravel	22	0.9	0.35				1682	11,656
Substrate	Sand	22	0.9	0.35				1602	11,102
Tank, septic, 3000L	HDPE	2.3	1.6	1.7					215

6.19.4.3 Conventional Wastewater System (Sewer)

In a conventional home, serviced by sewage infrastructure, the environmental impacts arising from wastewater are directly proportional to the volume of water that enters the sewer. According to SA Water, the South Australian Government's water authority, "wastewater treatment is a complex and expensive operation" and in the South Australian metropolitan area there are 8700km of sewer pipes (SA Water, 2014a). For comparison, Australia is approximately 4100km across from eastern most point to western most point. The sewer system requires energy for pumping stations, aeration tanks and for powering various other aspects of the treatment process. Captured gases (methane) generated by the wastewater treatment process can be used to deliver energy to the plant, or the electricity grid; however, this does not avoid the need for other inputs such as chemicals (for example chlorine) to treat the wastewater to a standard suitable for recycling. In South Australia approximately 26% of wastewater was recycled in 2011-12 (SA Water, 2014b) meaning that of the 100,000 megalitres of wastewater collected each year, 74,000 megalitres is discharged to the environment as "waste".

Documentation published by the South Australian Health Commission (South Australian Health Commission, 1995) prescribes a wastewater discharge of 150 litres per person per day for a home with reticulated (mains) water. Assuming a 4 person household, this amounts to 219kL per annum (note: 250kL is the volume of an Olympic swimming pool) and over 50 years, 10,950kL of wastewater.

The "wastewater treatment, Adelaide" unit process in the Australasian LCI Unit Process data uses energy from natural gas, petrol, LPG, diesel, wind power, and wastewater gas.

6.19.5 Water Collection System

6.19.5.1 Earthship Water Collection System

In Taos, the new Global Model Earthships at the Greater World community are typically built with 4 x 1400 gallon cisterns, hence 5300L x 4 = 21,200L. Reynolds calculates 19.3 gallons of water use per day per person in an Earthship (Reynolds, 2005, p. 18) which equates to 73.1 litres/person/day or 106.58kL per annum per 4 person household, or 5,329kL over 50 years. These homes have approximately 2000 sq ft roof area (185m^2).

Water storage capacity needs to be calculated in accordance with the size of the roof, rainfall patterns, and water use in the home. If the annual rainfall occurred all on one day then the water storage capacity required would be equal to the water use of the whole year, hence a very large tank. On the other hand, if there was enough rainfall every day to supply the daily water use the tank could be very small – the same capacity as the daily water use; however, rainfall tends to be distributed throughout the year albeit with concentrations in certain seasons. To establish the requirements for water storage capacity in Adelaide an online tool for calculating tank size developed by the Alternative Technology Association was used (Alternative Technology Association, 2010). This tool uses historical rainfall data for the selected area, in this case Kent Town, Adelaide, combined with user input to calculate various parameters related to tank water supply. It has various options regarding roof material type, and allows input for "first flush" (diverted water) volume, daily water use, roof area and tank size. Based on these inputs it calculates the number of days when tank water is available, days when the tank is overflowing (and how much water overflows), volume of tank water used per annum, and the volume of water required from an alternate source. A similar tool developed by Williamson (2009) was used as a comparison and both sets of results were in general agreement.

Various options were investigated to find an optimal tank size and roof area for the given consumption rate using both calculators. The results are presented and compared in Table 6.44 below.

It became evident that the roof area of the function unit used in this study (175m^2) was not adequate to provide sufficient water for three or four people (scenario 3 and 1 respectively – refer to Table 6.44) based on the previously quoted usage rate of 73L per day per person claimed by Reynolds (Reynolds, 2005). Assuming water consumption could not be lowered any further, to solve this problem extra roof space could be added via an additional roof catchment such as a car port, shed, et cetera, or extra water could be supplied by other means such as a tanker truck, or pumped from an aquifer. As the Earthship aims to be self-sufficient the option of extra roof space (in the form of a shed) seemed to be most applicable and therefore this was modelled in the LCA.

Another assumption is that the tanks are filled initially by a tanker truck i.e. a once off delivery of 30kL of water. This would not be necessary if there was sufficient time and rainfall for the tanks to fill prior to occupancy, however to be conservative the once off delivery of water seemed reasonable.

Table 6.44 - Rainwater tank sizing calculations

Tankulator Results								Williamson
Scenario	water use (no. People) (L/day & no. people)	roof area (m^2)	tank size (kL)	days when tank water available (no. of days / %)	days of overflowing tank (days)	tank water used (L)	water from alternate supply (L)	percent days when tank water available (%)
1	292 (4)	175	20	243 (67%)	0	70,956	35,624	71.7
2	292 (4)	206	20	290 (79%)	0	84,680	21,900	84.3
3	219 (3)	175	20	333 (91%)	0	72,982	6,953	95.5
4	219 (3)	206	20	362 (99%)	10	79,278	657	100
5	219 (3)	250	15	356 (98%)	23	77,964	1,971	100
6	219 (3)	250	20	365 (100%)	22	79,935	0	100
7	219 (3)	250	25	365 (100%)	22	79,935	0	100
8	219 (3)	250	30	365 (100%)	22	79,935	0	100
9	292 (4)	250	30	359 (98%)	0	104,682	1,898	100
10	292 (4)	260	30	365 (100%)	5	106,580	0	100

An Australian made, 5000L, underground, polyethylene rainwater tank similar to those used by Earthship Biotecture has been assumed in this study and is quoted as weighing 375kg (Rainwater tanks direct, 2012). To provide adequate water storage for 4 people's water use, based on the results of calculations tabled above, 6 tanks giving total storage of 30kL would be required plus 85m^2 of extra roof space (scenario 10).

The extra roof catchment area was provided by means of a steel framed, steel clad shed. It was assumed the shed consisted of 1600 kg of steel (Turner, 2012). Half the steel was assumed to be sheet steel (cladding), and the other structural steel (posts, trusses, girts, et cetera).

As the Earthship typically incorporates filters and a pump to provide clean pressurised water throughout the home, some maintenance is required: in this study it is assumed that the filter is replaced every six months and the pump is replaced every 5 years.

6.19.5.2 Conventional Water Supply

SA Health, the regulatory body in South Australia concerned with the treatment of wastewater, quotes 150L per person per day for "sanitary fixtures" which includes basins (7L), bath/shower (32L), dishwashing machine/kitchen sink (30L), laundry trough/washing machine (31L) and water closet pan

(50L) (South Australian Health Commission, 1995). Assuming 5L used per person per day for drinking and cooking, this gives a total of 155L of mains supplied water per person per day. Thus 4 people, would use 226.3kL per annum, and over a duration of 50 years, would use 11,315kL.

However, these figures do not take into account garden irrigation. A report by the ABS on water use in SA shows per capita water use as approximately 390L per day (Australian Bureau of Statistics, 2011). As this is the total water use per person this can be assumed to include garden irrigation. Using this figure a 4 person household would use 569.4kL per annum, and over a duration of 50 years, would use 28,470kL. The Earthship uses approximately one fifth this quantity and also provides sufficient water for garden irrigation, hence this last figure of 28,470kL was used as the basis for comparing the conventional water supply with the Earthship's self sufficient water supply.

6.20 Operational Energy Assumptions

6.20.1 Heating and Cooling Energy

Table 6.45 lists assumptions for the heating and cooling load (per annum) for each thermal envelope modelled in the LCA in accordance with the results of the Thermal Performance study which calculated the energy "load" for each thermal envelope.

It also lists the "final" energy use as opposed to the "load". A coefficient of performance (COP) for heating, and energy efficiency ratio (EER) for cooling of 4.25 was assumed, which replicates 4 Star energy performance under the AS3823.2 standard for energy performance of electrical appliances (Standards Australia, 2011, p. 5), thus all the results calculated in the Thermal Performance study were divided by 4.25 to arrive at the "final" result representing the total heating and cooling energy. These values were then used to model the life cycle energy for heating and cooling i.e. they were multiplied by 50 – the number of years defining the LCA's Functional Unit.

Materials required for the manufacture of the heating/cooling plant (i.e. split system air conditioner) have been included in the modelling (refer to Space Heating & Cooling Equipment Section in this Chapter).

Energy other than heating and cooling energy has been accounted for separately and is discussed in the Systems Section in this Chapter.

Table 6.45 - Heating and Cooling Load Assumed in LCA

Thermal Envelope Type			Energy Use per annum	
External walls	Internal walls	Greenhouse	Heat/Cool Load (kWh pa)	Final Heat and Cool elec. (kWh pa)
Brick Veneer (BV)	Timber Frame (LW)	No	Calculated (not modelled)	2,920
Brick Veneer (BV)	Timber Frame (LW)	No	2226.5	524
Brick Veneer (BV)	Brick (TM)	No	1494.1	352
Concrete Block with Insulation (CBI)	Brick (TM)	No	745.7	175
Tyre wall with insulation in berm, cans landfilled (ESIB)	Can (landfilled) and cement (CL)	Yes	280.4	66
Tyre wall with insulation in berm, cans recycled (ESIB lowEE)	Can (recycled) and Adobe (CR)	Yes	280.4	66
Tyre wall with no berm, cans recycled (ESI lowEE)	Can (recycled) and Adobe (CR)	No	1198.6	282
Mudbrick (MB)	Mudbrick (MB)	No	2101.0	494
Reverse Brick Veneer (RBV)	Brick (TM)	No	1138.1	268
Rammed Earth (RE)	RE (RE)	No	2264.5	533
Rammed Earth Insulated (REI)	RE (RE)	No	1209.8	285
Strawbale (SB)	MB (MB)	No	1134.4	267
Timber Frame with cement fibre board cladding (TFC)	Timber Frame (LW)	No	2166.5	510

6.21 Maintenance Assumptions

There are many uncertainties regarding maintenance requirements for different wall materials and assemblies with little research addressing this issue. Maintenance requirements are contingent upon issues such as the original building quality and workmanship, quality of materials, physical properties of materials and products, climate, occupant behaviour, and design details.

Careful design of connections between major building elements, executed by the builder with care and high quality, durable materials may result in negligible maintenance requirements, although materials prone to weathering, for example timber, may require regular maintenance such as painting, oiling or staining; however, if this is done regularly the lifespan of the structure may be comparable to similar structures built with more inherently durable materials. No matter what the material, if a regular maintenance cycle is skipped, or damage that requires urgent repair is not fixed immediately, the consequences may lead to a dramatic reduction in the serviceable life of the structure.

Maintenance requirements may be substantially reduced or avoided altogether if design features are used to negate issues such as weathering, for example wide verandas that keep rain off walls. Likewise, appropriate material selection may also avoid the need for maintenance. In this study external wall constructions were designed to provide a durable finish that would not be prone to weathering, for example, Strawbale walls had a final coat of lime render (over the main adobe render), Mudbrick walls had a final coat of cement render and Rammed Earth walls were stabilised with cement.

Given the lack of information regarding maintenance records of various wall construction types and the likelihood that the impacts of maintenance would be relatively small compared to other aspects of the building's lifecycle , this aspect of the study was limited to;

- Repainting timber cladding of external walls every 10 years.
- Repainting internal walls every 10 years, however only those that require painting (i.e. adobe rendered and rammed earth internal walls were assumed not to need painting).
- Replacement of major components of the renewable energy system. For replacement intervals, see Table 6.40.
- Replacement of pumps (e.g. used in greywater system) – new pump every 5 years.

6.22 Land Occupation Assumptions

The area of land the house occupies is another factor that should be factored into the LCA study especially the Earthship which requires more land for the off-grid wastewater treatment system. This study assumes the building is constructed on arable land.

Table 6.46 gives assumptions regarding the footprint of the home, that is, the outside dimensions of the house based on the wall thickness and the standardised internal dimensions of the functional unit of this study (22m x 5.5m). Assumptions for areas occupied by the Earthship wastewater system, greenhouse and berm are also given.

Table 6.46 - Land area occupied - need to update with all wall types and check data

Building Type	Wall thickness (m)	House Area (m^2)	Greenhouse Area (m^2)	Berm Area (m^2)	Wastewater System Area (m^2)	Total Area (m^2)
Earthship	0.65	146	70	340	200	760
Earthship unbermed	0.65	146	70	NA	200	416
rammed earth	0.3	138	NA	NA	NA	138
mudbrick	0.275	136	NA	NA	200	336
brick veneer	0.27	136	NA	NA	NA	136
reverse brick veneer	0.27	136	NA	NA	NA	136
strawbale	0.55	152	NA	NA	NA	152

6.23 Waste/Disposal Scenario Assumptions

As noted elsewhere, the End-of-life (EOL) stage of building LCA studies has traditionally been neglected due to the assumption that most impacts arise during the use and construction stages of the building lifecycle and the effect of recycling has minimal impact; however, other studies have indicated that reuse and recycling can provide significant benefits (Blengini & Di Carlo, 2010; Thormark, 2002), or, where materials cannot be recycled easily, recycling may cause problems especially for solid waste disposal facilities (Blengini, 2009).

Another reason for glossing over this area of LCA is that data may not be available. Modelling the end-of-life destination (waste treatment) of materials and products requires various data; the rates and types (methods) of reuse, recycling or disposal of all relevant materials; transport distance to the recycling/reprocessing plant; and LCI data such as the amount of energy used during reprocessing, and quantities of "avoided products" produced by the recycling process (for which credits are given – e.g. brick and concrete may be recycled into aggregates for road construction).

Acquisition of this data presents significant challenges for a variety of reasons. Firstly, the fate of materials at the end of a building's life is not well understood, with very little useful data available. Reports from government agencies tend to focus upon "big picture" state averages rather than delve into the finer details required by this study: what proportion of various materials is salvaged from a domestic building site, where does it go and what happens to it. For example, a report by South Australia's waste agency Zero Waste SA (Rawtec, InfraPlan & Life Cycle Strategies, 2012) reports the quantities of various key materials that are recovered from the waste stream and their destination (SA, interstate or overseas), and it reports the gross quantity of all materials disposed to landfill; however, it does not report the quantities of specific materials sent to landfill.

Secondly, salvage, reuse and recycling technology and practices of the future, 50 years from now, is unknown, and the results of current practice is also difficult to predict due to fluctuating economic forces.

Finally, Australian Life Cycle Inventory data regarding reuse, recycling and disposal processes are often out of date or non-existent, and European data (e.g. EcoInvent) are unlikely to accurately model Australian practices.

6.23.1.1 Current EOL Practice in Australia and South Australia

The most recent literature reference was based on a study of "deconstruction" in the Australian construction industry (Crowther, 2000) which reported various EOL salvage rates and destinations (reuse, recycling, landfill): brick 75%, timber 79%, structural steel 78%, iron roofing 88%, concrete 70%, aluminium 90%, and windows (glass) 73%.(Crowther, 2000).

Enquires with agencies such as ZeroWasteSA, the Master Builders Association and the Waste Management Association of Australia did not yield more up-to-date information. However, the site manager of Adelaide's "city dump", the Wingfield Waste & Recycling Centre was able to provide some useful advice: significant quantities of sarking (reflective foil insulation), plasterboard, glass/rock wool insulation, and polystyrene insulation, are landfilled (Mckee, 2013).

A representative of a local waste recovery company that recycles construction waste, particularly concrete and bricks (Adelaide Resource Recovery Pty Ltd, Wingfield SA), reported the following estimates (and comments) for the percentage of material reused, recycled and landfilled for various construction materials (refer Table 6.47). However the problem with this information is that it is does not encompass waste diversion activities occurring before delivery of waste materials at the "dump" or reprocessing plant, perhaps explaining the difference from Crowther's findings for salvage of materials. Further enquiries with a local plastic recovery company (Advanced Plastic Recycling Pty Ltd) revealed that plastic is not usually recovered from a building demolition due to small volumes of plastic which would be uneconomical to collect from individual building sites. Furthermore, plastics recovered from building demolition are usually contaminated by other materials which may be difficult to separate and are therefore not practical to recycle (Lokan, 2013).

Table 6.47 - Destinations of salvaged materials at Adelaide Resource Recovery Pty Ltd

Material	Reuse/ Recycle/ Landfill rate %	Comments ref: (Hocking, 2013)
Concrete	0/99/1	"as we only landfill the bare minimum that comes in concrete loads as the orange DPC plastic, timber etc are still recycled elsewhere."
Steel	0/100/0	
Aluminium	0/100/0	
Brick	0/100/0	
Gyprock	0/20/80	"some Gyprock has been added to timber to produce a mulch product.."
Compressed cement fibre board	0/50/50	"we will crush cement fibreboards with concrete or brick to produce non-critical rubbles when required"
Sarking (reflective foil)	0/0/100	
Polystyrene (insulation)	0/0/100	
Fibreglass wool (insulation)	0/0/100	

6.23.1.2 Waste Scenario Assumptions Rationale

Given the problems outlined above, a "waste scenario" was designed based on current best practice thereby giving results that are reasonably accurate under the current system and could be assumed to be conservative if future systems evolve to be more efficient. Although plastic was not generally recoverable from building demolition this is not likely to be the case for large plastic components such as rain water tanks hence a high recovery rate was used for HDPE, whereas PVC plastic (used in plumbing) was assumed to be landfilled 100 percent, as was reflective foil insulation, polystyrene and glass/rock wool insulation, and plasterboard.

End-of-life destinations, rates and assumptions for all materials are outlined in Table 6.48. LCI data was based on Australasian LCI Unit Process processes and, where these were not available, EcoInvent processes.

Table 6.48 - Treatment types and rates for materials at end-of-life

Material	Re-use	Re-cycle	Land-fill	No treat-ment	Substitution Material & Quantity Recovered	Notes / Reference
Cardboard (i.e. used in Earthship wall)			100		NA	Cardboard is used in Earthship wall types only. It would not be suitable for recycling due to contamination with earth and hence is assumed to be landfilled.
PVC			100		NA	PVC is used for plumbing pipes in the Earthship wastewater system. It is typically landfilled due to the recycling process being highly sensitive to any type of impurity. Collection of low volumes is uneconomical.
PP			100		NA	Polypropylene is used in the Strawbale footings, and the drainage pipe used in the Earthship berm. Although highly recyclable, collection of low volumes is uneconomical.
HDPE		95	10		Recycling avoids 0.87kg HDPE granulate /1kg recovered	Polyethylene is used in the off-grid water catchment system's rain water tanks. Collection of low volumes is uneconomical however it is economical to salvage a whole rainwater tank.
Steel, structural		95	5		Recycling avoids 0.855kg pig iron /1kg recovered	Steel for roofing (steel frame was not investigated in this study). 5% is assumed to be landfilled due to inefficiencies with salvage operations and contamination from other materials adhering to the steel.
Steel, reinforcing		95	5		NA - credit for recycled content modelled in production of reinforcing steel	Steel for reinforcing concrete. 5% is assumed to be landfilled due to inefficiencies with salvage operations and contamination from other materials adhering to the steel.
Aluminium		95 *	5 *		Recycling avoids 0.94kg aluminium /1kg recovered	Aluminium is used primarily in the beverage cans in Earthship "can" walls although some componentry in the SHWS is also aluminium. 5% is landfilled due to contamination from mortar. Recovered aluminium is used as a raw material for new aluminium. *A sensitivity study was included to investigate the impact of 100% landfill of aluminium which may be necessary due to mortar contamination preventing recycling (Mullinger, 2012).

Concrete, concrete render, lime render, stabilised rammed earth		95	5		Recycling avoids 0.9kg quarried aggregates /1kg recovered	Concrete is primarily used in the footings applicable to all walls except Earthship walls; however, Earthship has other reinforced concrete elements. This EOL treatment also applies to cement stabilised rammed earth, cement or lime based renders, cement mortar, and concrete block all of which are assumed to be recycled into aggregate with 5% being sent to landfill due to inefficiency in the salvage operation.
Tyre			100		NA	Tyres are used in the Earthship external walls. All tyres are assumed to be shredded and landfilled at the building's EOL. It was assumed tyres were transported 40km to a landfill site and that 0.067kWh of low voltage South Australian electricity was needed for shredding 1kg of tyres, based on data from EcoInvent for metal shredding.
Pine, structural	20		80 *		Reuse replaces original material 1kg/1kg	Structural pine timber is used mainly in the Brick Veneer and Reverse Brick Veneer wall types however it is also used in other wall types. 20% was assumed to be salvaged and reused e.g. long pieces in good condition: without contaminants such as glue, and the remainder was assumed to be landfilled with the benefit of carbon sequestration counted. *A sensitivity study investigated the effect of not counting carbon sequestration in landfill.
Plywood	20		80 *		Reuse replaces original material 1kg/1kg	Plywood is used mainly for formwork in the Earthship bond beam and concrete buttresses. It was assumed to have the same EOL treatment as structural pine. *A sensitivity study investigated the effect of not counting carbon sequestration in landfill.
Glazing, double	10	80	10		Reuse replaces original material 1kg/1kg Recycling avoids 0.99kg glass cullet / 1kg recovered	Double glazed window units were used in all thermal envelopes. As these are expensive items and there is a market for salvaged building products such as these it was assumed 10% would be reused. Due to inefficiencies 10% were landfilled and the remaining 80% recycled to produce new glass.
Brick	5 *	90 *	5 *		Reuse replaces original material 1kg/1kg Recycling avoids 0.9kg quarried aggregates /1kg recovered	Fired clay bricks were used in the Brick Veneer and Reverse Brick Veneer wall types. Bricks are highly recyclable being used to make rubble or aggregate hence 90% was assumed for this purpose with 5% reused as second hand bricks and 5% landfilled due to contamination and inefficiency. *these assumptions were tested with a sensitivity study.
Battery, Lead		100	0		Recycling avoids 0.98kg lead /1kg recovered	The off-grid energy system assumes lead acid batteries are used for energy storage. The Battery Council International (Battery Council International, 2012) reports that 98% of lead from car batteries is recycled.
Photovoltaic panels (recycling silicon)		0	100		Recycling avoids 0.8kg silicon (solar grade) /1kg recovered	Photovoltaic panels are used in the off-grid energy system. Although they are highly recyclable (Energy Matters, 2010) recycling was not modelled due to lack of LCI data.
Straw				100	NA	Straw is used primarily in the Strawbale wall but is also used in adobe render/mortar. It is assumed the straw is simply left to compost on site and hence no treatment process is necessary. Biogenic CO_2 cycle is assumed to be neutral.
Earth				100	NA	Earth is used primarily in the berm of the Earthship and inside the tyre walls of the Earthship. It is also a major component in adobe render, mudbricks and rammed earth. Where cement has not been incorporated with the earth it can be assumed that these materials will readily disintegrate back into the soil without causing environmental impacts. Where cement is incorporated e.g. a stabilised rammed earth wall this was landfilled (refer concrete).
Water				100	NA	Water is an ingredient in all render mixtures (adobe, lime and cement based) and is used in concrete, rammed earth, and mudbrick. It is also modelled in the use phase of the house for domestic uses. Other than sewage treatment for the domestic use of water, when used in building construction materials it is assumed there is no treatment process necessary as it will simply evaporate or remain chemically bound to the building material e.g. concrete.
Electronics				100	NA	The inverter used in the off-grid energy system was classified as "electronics". Due to lack of Australian LCI data for e-waste disposal and the small volume of materials embodied in the inverter it was assumed to be landfilled.
All other materials			100		NA	All other materials were assumed to be transported 40km to a landfill site.

6.23.1.3 Landfill LCI data assumptions

Australasian data supplied with SimaPro™ was used to model landfill operations: 0.8kWh of low voltage electricity (adapted to SA electricity grid) and 1litre of diesel per tonne of waste.

6.23.2 Transport distances for EOL treatments

Discussions with Adelaide metal recycling companies revealed that salvaged metal components from building components are typically shipped interstate or overseas (Sims Metal Management, 2013).

Transport distances for various EOL processes assumed in this study are given below:

- Aluminium Recycling: Adelaide to Yennora NSW, Alcoa Pty Ltd = 1355km
- Steel Recycling: Adelaide to Port Kembla, BlueScope Steel Pty Ltd = 1340km
- Lead Recycling: Adelaide to Melbourne, Simstar Alloys Pty Ltd = 800km
- Landfill: 40km e.g. from Adelaide's southern suburbs to Wingfield Waste and Recycling Centre (main city dump).
- Concrete recycling: 40km e.g. from Adelaide's southern suburbs to construction and demolition materials recycling facility at Wingfield (i.e. Adelaide Resource Recovery Pty Ltd).

6.24 Chapter Summary

This Chapter has documented assumptions regarding the "flows" of materials, processes and energy throughout the lifecycle of the systems (housing) being studied. The environmental impacts arising from these flows is the subject of the next Chapter.

7 Life Cycle Impact Assessment & Interpretation

7.1 Introduction

This Chapter analyses the Life Cycle Inventory results presented in the previous Chapter. This is known as Life Cycle Impact Assessment (LCIA), the third stage of LCA, and Interpretation, the final stage of LCA. The analysis is conducted in terms of the impact categories (environmental impact "indicators") established in the LCA Method Chapter.

7.2 Structure of LCIA Results

The LCIA for each major "element" or "system" (defined earlier in the LCI section) of the building is presented followed by aggregated LCIA results for the "Whole House". In this way the relative impacts of each element can be better understood, and the holistic, overall impact of the complete building can also be ascertained. Elements comprising the Thermal Envelope and the sub-systems comprising the complete Systems Package are shown in Table 7.1.

Table 7.1 - Elements & Systems Comprising the Whole House

Whole House	
Thermal Envelope	Systems Package
External walls	Energy
Internal walls	Water
Glazed Wall	Waste water (including food production via wastewater system)
Floor	
Roof	
Greenhouse	

The main topics of discussion are the External Walls, Thermal Envelope, all Systems, and the Whole House, each of which has its own major heading in this Chapter. For brevity, other elements such as the Internal Walls are not discussed in isolation although they are included in the discussion of the Thermal Envelope and Whole House.

The discussion in this Chapter centres on the Earthship; however, for comparison, Brick Veneer, and Mudbrick are also discussed routinely to provide a comparison to a conventional and an alternative construction. Furthermore, the construction types showing the greatest and least impacts are also discussed.

For each of the main topics an analysis of the characterisation results for each impact category is given, followed by a discussion of the normalised and weighted "single score" results. Elementary flow data and characterisation data are included in Appendix D1.

Results for the various scenarios and systems being compared are presented in column graph format. For the characterisation results a black diamond is used to show the total impact when the End-of-life (EOL) stage is taken into account, in the legend it is described as "Total inc. EOL". Typically this diamond appears below the top of the column indicating that EOL processes have reduced the overall impact of the system, for example in the "Off-Grid Energy System" in the left column of Figure 7.1. Otherwise, the graphs are self-explanatory.

Characterisation results are also presented in network diagram format (Figure 7.2) for the Earthship component/system to illustrate in some detail where the main impacts arise. To interpret the network diagram it is helpful to understand the meaning of the thickness, colour and direction of the arrows connecting the "process boxes". The thickness (width) of the arrow visually indicates the magnitude of the impact and this correlates with the percentage figure reported in the bottom left corner of each process box. The vertical bar on the right side of the process box also serves as a visual indication of the magnitude of impact. The direction of the arrow indicates the source and "destination" of the impact, and the colour of the arrow indicates either a deleterious environmental impact (red) or a beneficial environmental impact (green), for example, due to an effective recycling process. The "cut off" value quoted in the caption for each network diagram is the value below which processes are not displayed, which is necessary in terms of presenting the results as clearly as possible, and it helps to focus attention on the processes causing the majority of impacts while overlooking insignificant processes with minimal impact.

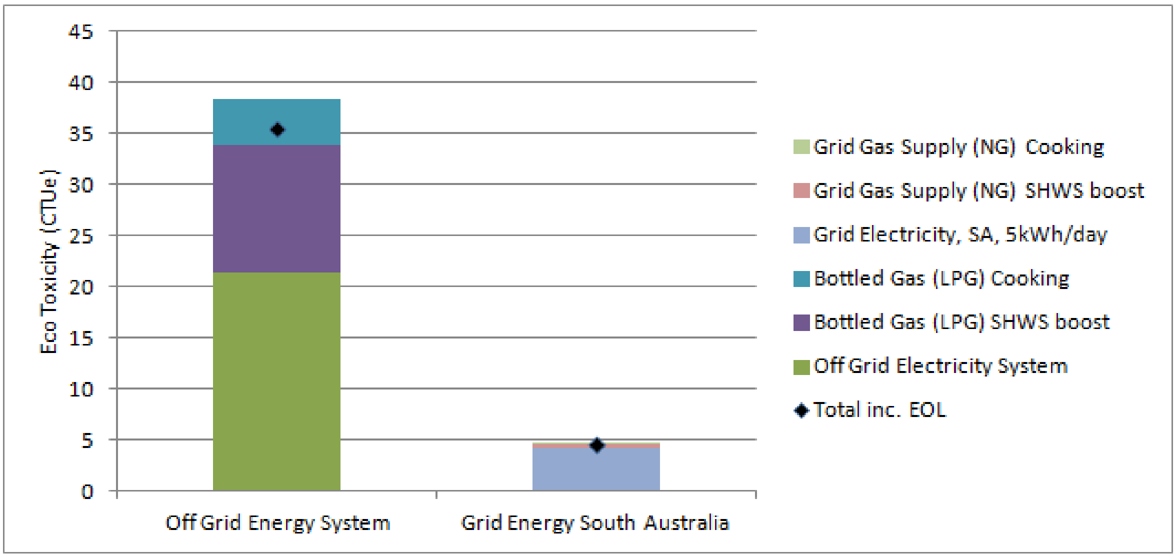

Figure 7.1 - Example of characterisation results

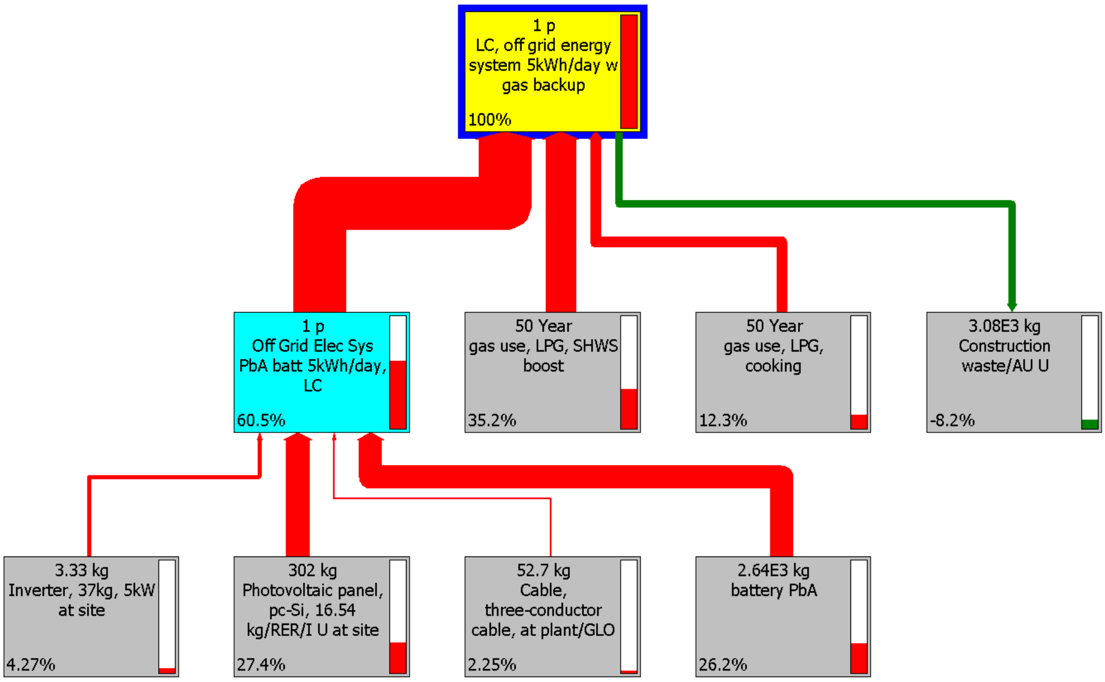

Figure 7.2 - Example of network diagram results

7.2.1 Definition of Whole House: Elements & Systems

Each "Whole House" scenario was defined primarily by the External Wall type which was combined with other elements and either an off-grid or conventional grid connected Systems package.

The External Wall is grouped with an applicable Internal Wall type, that is, the type typically used in combination with that type of external wall construction. In general, internal walls that contain thermal mass have been used due to the findings of the Thermal Modelling Study (see Chapter 4), which found that heating and cooling energy was reduced when thermal mass internal walls were used in preference to lightweight internal walls. The exception to this is the Timber Frame and Conventional Brick Veneer house which have light weight internal walls to reflect typical construction practice. This enables some of the more unusual constructions to be compared to a conventional construction.

The floor plan was based on the long, shallow Earthship floor plan; referred to as the passive solar floor plan; however, the Conventional Brick Veneer house was an exception to this; it was modelled with a square floor plan. This floor plan variation was intended to highlight the difference in energy use and materials use, arising from the different floor plan and glazing orientation (refer to Chapter 4 for details).

The Glazed Wall type was generally the same as the External Wall with the exception of the Earthship where different walling materials are used, similar to typical Earthship design (refer to 6.1.1 for detailed discussion of this).

For the Earthship variants the floor was defined as "rammed earth" (mud) whereas all other floor types were concrete slab on ground. The exception to this was the Mudbrick house type which also had a rammed earth floor.

Earthship roofs were based on an "Australianised" version of the Global Model roof whereas other configurations use a conventional Gable roof.

The greenhouse was included in two of the Earthship scenarios (labelled 4 & 5 in Table 7.2).

Utilities systems were assumed to be "off-grid" for all Earthships and Mudbrick. For the other House Types, conventional "grid" infrastructure has been modelled.

Table 7.2 defines thirteen "Whole House" scenarios analysed in this study.

Table 7.2 - Whole House Scenarios

#	Description of House Type / Scenario (Abbreviation)	Floor plan design	External walls i.e. non equator-facing walls (Abbreviation)	Glazed Wall (Equator Facing)	Internal walls (Abbreviation)	Buttress	Floor	Roof	Greenhouse	Systems	Heat and Cool elec. kWh pa[3]	Other electricity kWh pa[4]	Gas, cook & SHWS kWh pa[5]
1	Conventional brick veneer home with average energy use (20kWh/day) (BV CONV 20)	Conventional (square)	Brick Veneer (BV)	Same as Extnl. wall	Timber Frame (LW)	NA	Slab	Gable	NA	Grid	2,920 = 20kWh/day total	4,380	0
2	Conventional brick veneer home with modelled energy use (BV CONV)	Conventional (square)	Brick Veneer (BV)	Same as Extnl. wall	Timber Frame (LW)	NA	Slab	Gable	NA	Grid	524	1,825	2,797
3	Passive solar brick veneer home with brick internal walls (BV TM)	Passive solar	Brick Veneer (BV)	Same as Extnl. wall	Brick (TM)	NA	Slab	Gable	NA	Grid	352	1,825	2,797
4	Passive solar concrete block insulated home with brick internal walls (CBI TM)	Passive solar	Concrete Block with Insulation (CBI)	Same as Extnl. wall	Brick (TM)	NA	Slab	Gable	NA	Grid	175	1,825	2,797
5	Earthship with greenhouse & insulation in berm, aluminium cans landfilled at EOL (ESIB GH Base Case)	Passive solar	Tyre wall with insulation in berm, cans landfilled at EOL (ESIB)	Can (landfilled) and cement	Can (landfilled) and cement (CL)	Concrete	Rammed Earth	Earthship Aust version	Can and cement walls, insulated	**Off-Grid**	66	1,825	2,797
6	Earthship as above, cement minimised design, aluminium cans recycled at EOL (ESIB GH-lowEE)	Passive solar	Tyre wall with insulation in berm, cans recycled at EOL (ESIB lowEE)	Can (recycled) and Adobe	Can (recycled) and Adobe (CR)	Tyre	Rammed Earth	Earthship Aust version	Can and Adobe walls, insulated	**Off-Grid**	66	1,825	2,797
7	Earthship no berm, no greenhouse, cement minimised, aluminium cans recycled at EOL (ESI lowEE)	Passive solar	Tyre wall with no berm, cans recycled at EOL (ESI lowEE)	TFS (timber frame steel clad)	Can (recycled) and Adobe (CR)	NA	Rammed Earth	Earthship Aust version	NA	**Off-Grid**	282	1,825	2,797
8	Passive solar, off-grid mudbrick home (MB MB)	Passive solar	Mudbrick (MB)	Same as Extnl. wall	Mudbrick (MB)	NA	Rammed Earth	Gable	NA	**Off-Grid**	494	1,825	2,797
9	Passive solar reverse brick veneer home (RBV TM)	Passive solar	Reverse Brick Veneer (RBV)	Same as Extnl. wall	Brick (TM)	NA	Slab	Gable	NA	Grid	268	1,825	2,797
10	Passive solar rammed earth home (no insulation) (RE RE)	Passive solar	Rammed Earth (RE)	Same as Extnl. wall	Rammed Earth (RE)	NA	Slab	Gable	NA	Grid	533	1,825	2,797
11	Passive solar rammed earth insulated home (REI RE)	Passive solar	Rammed Earth Insulated (REI)	Same as Extnl. wall	Rammed Earth (RE)	NA	Slab	Gable	NA	Grid	285	1,825	2,797
12	Passive solar strawbale home (SB TM)	Passive solar	Strawbale (SB)	Same as Extnl. wall	Mudbrick (MB)	NA	Slab	Gable	NA	Grid	267	1,825	2,797
13	Passive solar timber frame home with lightweight internal walls (TFC LW)	Passive solar	Timber Frame with cement fibre board cladding (TFC)	Same as Extnl. wall	Timber Frame (LW)	NA	Slab	Gable	NA	Grid	510	1,825	2,797

[3] Assumes coefficient of performance of 4.25 (“4 star” efficiency) for reverse cycle air conditioner to supply theoretical heating and cooling energy load as per Thermal Modelling Study results. BV CONV 20 assumes 40% of total energy use (20kWh/day) is used for heat/cool energy.

[4] 4380kWh pa = 12kWh per day and 1852kWh pa = 5kWh per day.

[5] Natural gas (NG) assumed for grid connected homes and liquid petroleum gas (LPG) assumed for off-grid homes.

The rationale for configuring the thermal envelopes in this way was to explore the potential environmental impacts of various Earthship designs and compare these with a standard "conventional" brick veneer home, and passive solar designed homes of various wall construction types.

Three variants of the Earthship were explored:

- The Earthship "base case" is the typical Earthship configuration as built in Taos, with a berm and greenhouse (labelled #5 in table above). It has been modelled as per the Earthship Biotecture specifications, although with some occasional deviations appropriate to Australian conditions, most notably the roof materials (refer to LCI Chapter for full definitions of construction elements).
- The "lowEE" Earthship (labelled #6) has "can walls" that employ adobe instead of cement mortar, and the aluminium cans were assumed to be recycled instead of landfilled. This scenario was designed to explore the effect of minimising cement use and recycling aluminium cans at EOL (whereas the Base Case landfills aluminium cans at EOL).
- An Earthship with no berm and no greenhouse (labelled #7) with can walls and aluminium recycling as per the lowEE Earthship described above. This scenario explores the impacts of an Earthship more suited to small suburban sites, and offers a "fairer" functional comparison to the other (non-Earthship) thermal envelopes which do not feature a berm or greenhouse.

The reason for configuring the Mudbrick home with off-grid utilities and a rammed earth ("mud") floor was that these types of homes tend to be built in remote locations where utilities are not available, and as the walls have been made from mud, the same logic applies to the floor: minimising environmental impacts (and expense) by using freely available materials. Although the Mudbrick home doesn't have a greenhouse (nor does the unbermed Earthship #7), the "off-grid" (at home) food production was assumed to be achieved in a conventional garden irrigated with wastewater.

Although these configurations are somewhat arbitrary, for example off-grid systems, food production or mud floors could be combined with any of these house types, they have been configured to represent a range of construction methods and lifestyles (to grow food or not to grow food in one's garden). For a more direct comparison, a sensitivity study is included to demonstrate the effect of all thermal envelopes utilising off grid systems (including food production). Although this is not current practice it is possible.

The results are presented so that the impacts of each element or system can be understood in isolation and therefore the overall impacts of any combination of elements and systems can be deduced.

7.2.2 Limitations: Toxicity

There are many difficulties with assessing toxicity of a product or system throughout its lifecycle and consequently toxicity impacts are often omitted from LCA studies. A significant problem is that different methods used to develop characterisation factors of toxic substances often fail to produce the same results (Rosenbaum et al., 2008). The complex nature of the lifecycle of a toxic substance also causes great uncertainty; its "path" through the environment and its impact upon life forms along the way is dependent on many factors that may be impossible to forecast. Furthermore, secrecy about manufacturing processes and their toxic emissions may also result in inaccurate LCI data.

Nevertheless much research has been conducted with the aim of improving toxicity models and characterisation factors for use in LCIA. As explained in the LCA Method Chapter, this study uses the USEtox model to characterise toxic emissions but stops short of normalising and weighting the results to produce a single score. Therefore, to better understand the scale of toxic emissions in the Australian context the substances causing more than one percent (by weight) of total toxic emissions are identified and discussed in the context of national Australian averages sourced from the National Pollutant Inventory which publishes data regarding emissions of various pollutants (Commonwealth of Australia:

Department of Sustainability, n.d., p. 15). Rather than discuss toxic emissions for each element of the house, aggregated results for the “Whole House” are discussed in comparison to the Australian annual emissions towards the end of this Chapter.

7.3 External Wall

This section presents results and analysis of the External Walls. A sensitivity study regarding the effect of End-of-life (EOL) treatments for Brick Veneer and Timber Frame is included in the results. The default EOL for Bricks is 5% reuse, 90% recycling (into aggregates) and 5% landfilled, whereas the effect of 60% reuse, 15% recycling and 25% landfill (Crowther, 2000) is tested as a sensitivity study scenario.

The default assumption for carbon sequestration in landfill for all timber components is that CO_2 is sequestered and methane is captured from the landfill (refer to Chapter 6 for details); however, a sensitivity study scenario tests the effect of not counting the effect of carbon sequestration during landfill for the Timber Frame wall only as this has the highest proportion of timber content.

The sections following discuss the characterisation results for 1 linear metre (lm) of external wall for each impact category. A network diagram from SimaPro™ is given for the Earthship Base Case (ESIB CL) to illustrate and identify the impact associated with the various elements and construction materials.

Table 7.3 - Descriptions and abbreviations of External Walls

Abbreviation	Description
BV 5/90/5	Brick veneer external wall with footing. End-of-life assumption is that 5% of bricks are reused, 90% are recycled and 5% are landfilled
BV 60/15/25	Brick veneer external wall with footing. End-of-life assumption is that 60% of bricks are reused, 15% are recycled and 25% are landfilled
CBI	Concrete block external wall insulated on the exterior with 100mm expanded polystyrene foam
ESI CanR	Earthship wall (tyre wall) insulated on the exterior with 100mm expanded polystyrene foam, aluminium cans used in the bond beam assumed to be recycled at end-of-life. (no footing).
ESIB CanR	Earthship wall (tyre wall) with a berm and insulated with 100mm expanded polystyrene foam “thermal wrap”, aluminium cans used in the bond beam assumed to be recycled at end-of-life (no footing).
ESIB CanL	Earthship wall (tyre wall) with a berm and insulated with 100mm expanded polystyrene foam “thermal wrap”, aluminium cans used in the bond beam assumed to be landfilled at end-of-life (no footing).
ESIB CanL inc Foot	Earthship wall (tyre wall) with footing, a berm and insulated with 100mm expanded polystyrene foam “thermal wrap”, aluminium cans used in the bond beam assumed to be landfilled at end-of-life.
MB	Mudbrick wall with footing.
RBV	Reverse brick veneer wall with footing.
RE	Rammed earth wall with footing.
REI	Rammed earth wall with footing and insulated on the exterior with 100mm expanded polystyrene foam.
SB	Strawbale wall with footing.
TFC	Timber frame wall with cement fibreboard cladding with footing.

7.3.1 Global Warming Potential for External Wall

Figure 7.3 shows results for Global Warming Potential (GWP) in terms of kilograms of carbon dioxide equivalent emissions for 1 linear metre (1lm) of each external wall type. Carbon storage in landfill at EOL is assumed for all timber components in all wall types with the exception of the "TFC No CO_2 seq" scenario which is a sensitivity study to test the effect of not sequestering carbon in the Timber Frame wall (which has relatively high timber content and is therefore likely to be affected the most).

The results indicate that an external wall made from Mudbrick (with cement based external render) has the lowest GWP, the majority of which is attributed to the steel reinforced concrete footing.

The highest GWP is the insulated, bermed Earthship wall with footing (ESIB CL FOOT); however, it should be noted that footings are only usually necessary (for Earthships) in severe earthquake zones e.g. New Zealand, Japan. When the footing is excluded as per typical Earthship construction, the impact of the insulated, bermed, Earthship wall (ESIB CL) with aluminium cans in the bond beam landfilled (CL) at EOL, is similar to the Rammed Earth Insulated wall (REI). The effect of recycling aluminium cans (ESIB CR) at EOL reduces the lifecycle GWP by approximately 28kg CO_2e per linear metre of wall. The Earthship wall which is insulated, with no berm (ESI) has the second lowest GWP, followed by the Strawbale wall (SB).

The "wall" component of the Earthship wall scenarios has the greatest GWP where insulation has been counted in the wall structure (ESI CR), whereas insulation has been counted in the "berm" component (where it is physically located) in the other Earthship external wall scenarios (refer Figure 7.4).

As Earthship walls are typically buttressed with either reinforced concrete or a "stub" tyre wall with bond beam atop, these two scenarios were modelled. The buttress assembly shows substantial impacts for the reinforced concrete buttress (ESIB CL FOOT and ESIB CL) whereas when a stub tyre wall is used the impacts are reduced by approximately 50kgCO_2e. Impacts from the increase in the length of bond beam required for the stub tyre wall buttresses (extra 5.2lm) is offset by the effect of recycling the aluminium cans (in the bond beam) at EOL.

Figure 7.4 is a network diagram showing the relative impacts (in terms of percentages) of construction elements/materials that contribute more than 5% of the overall GWP impact. Concrete in the bond beam and buttresses, and insulation in the berm are the cause of the majority of impacts for this impact category.

Although it has not been modelled explicitly, it can be deduced, from Figure 7.3and Figure 7.4 that an unbermed, uninsulated Earthship wall would have even lower GWP impact than a Mudbrick wall due to relatively less use of concrete and steel in the bond beam compared to the Mudbrick wall's footing. That is, the lowest GWP impact external wall would be an Earthship (tyre) wall with no footing, no berm and no insulation; however, when the thermal performance of the wall is taken into account over the lifecycle of the home, the lifecycle benefit of a berm and insulation is enormous, far outweighing the GWP of the materials – this is presented and discussed under the Whole House heading at the end of this Chapter.

The Brick Veneer walls scenarios show variable results depending on the EOL assumption. Where there is a large degree of brick reuse, emissions are similar to ESIB CL, whereas for the BV scenario which recycles 90% of the recovered bricks into aggregates, the GWP impacts are only slightly lower than Concrete Block Insulated, and Reverse Brick Veneer. The impacts for BV and RBV arise mainly from the use of fired clay bricks which involves large quantities of energy for firing a kiln.

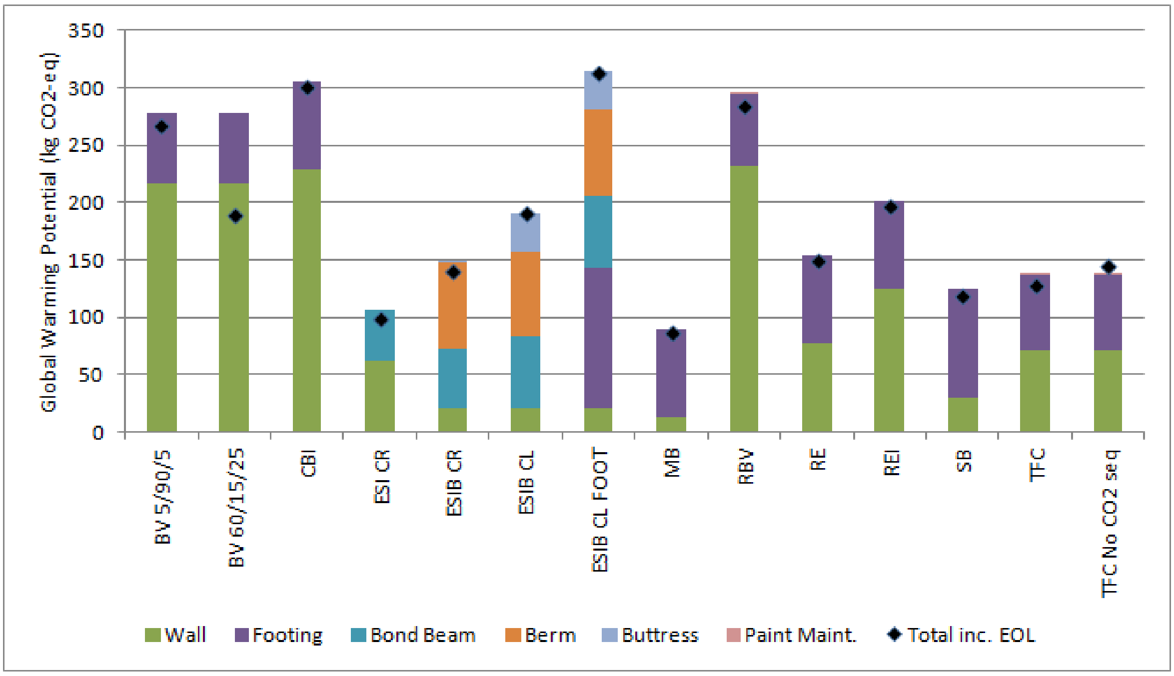

Figure 7.3 - Global Warming Potential, External Walls, Characterisation, 1lm

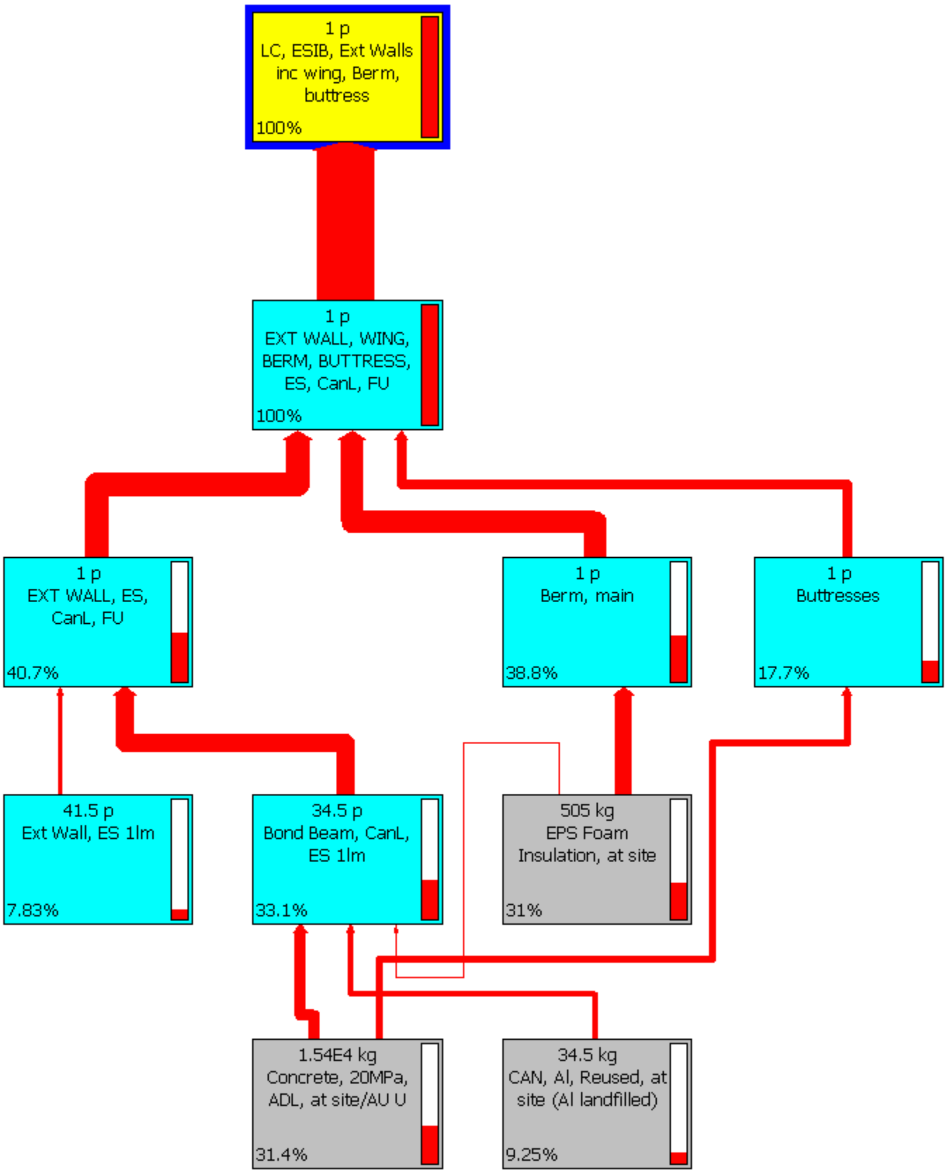

Figure 7.4 - Global warming potential, network diagram 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.2 Ozone Depletion for External Wall

Figure 7.5 shows results for Ozone Depletion potential in terms of kilograms of CFC 11 equivalent emissions for each external wall type, normalised for 1lm of wall.

Reverse Brick Veneer and Timber Frame have the highest impact due to the compressed cement fibreboard manufacturing process (which emits chlorinated hydrocarbons to the air).

Mudbrick has the least emissions, followed by Strawbale and Rammed Earth, their impacts arising mainly from the use of cement (e.g. in the footings).

The use of EPS foam insulation and plywood (formwork for buttresses) contribute approximately 71% of the impact for the Earthship wall scenarios (Figure 7.6).

The production of fired clay bricks leads to the majority of emissions for the Brick Veneer wall scenarios.

End-of-life (EOL) impacts are caused by the emissions of vehicles associated with recycling and landfill processes.

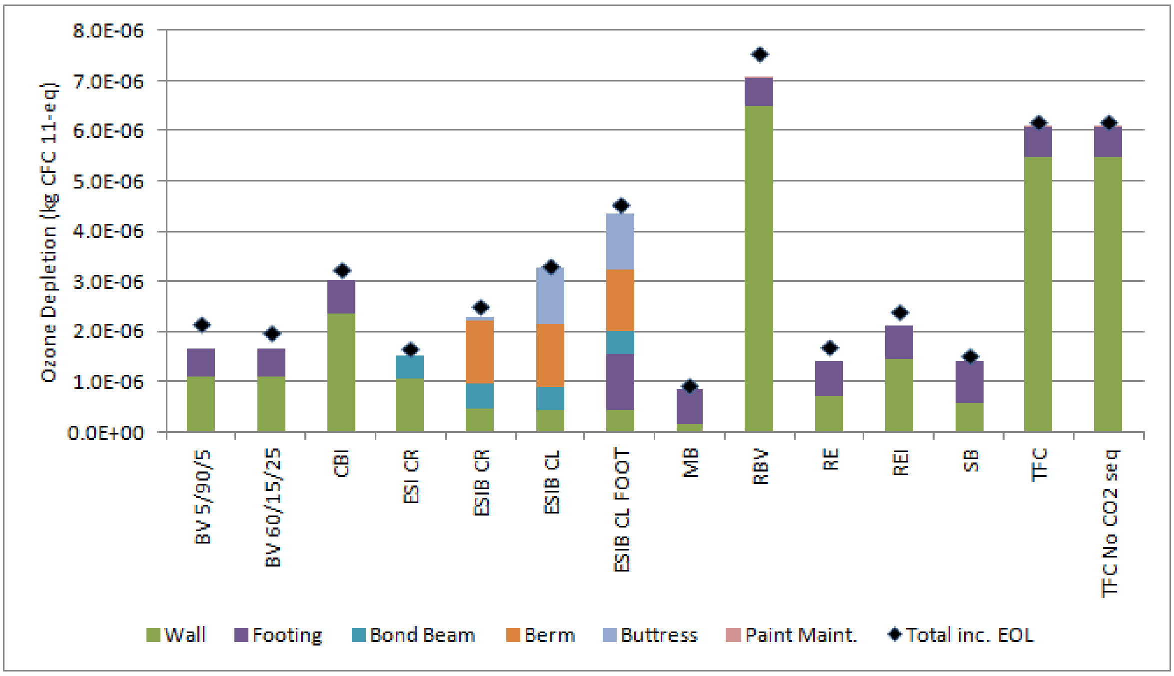

Figure 7.5 - Ozone Depletion, External Walls, Characterisation, 1lm

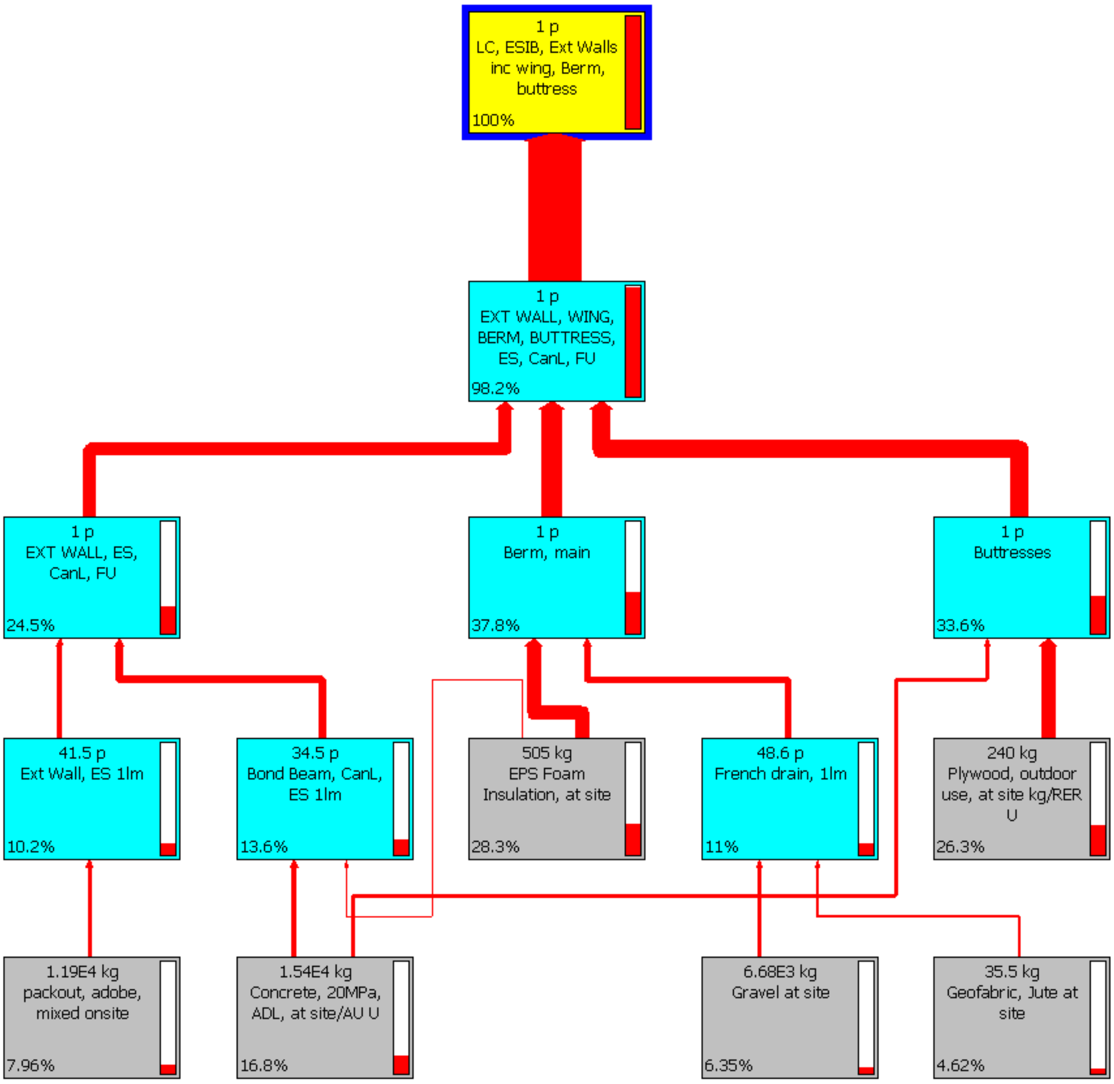

Figure 7.6 - Ozone Depletion, network diagram, 4% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.3 Photochemical oxidation for External Wall

Figure 7.7 shows results for Photochemical Oxidation (smog) in terms of kilograms of C_2H_4 equivalent emissions for each external wall type, normalised for 1lm of wall. Smog is generally caused by emissions from fossil fuelled vehicles especially in cities; however, manufacture of materials that rely heavily upon fossil fuels may also contribute to this environmental impact category.

The bermed Earthship scenarios show the highest emissions and this is due to the manufacture of expanded polystyrene insulation which is used in large quantities in the berm construction (Figure 7.8) and as insulation for ESI CR, the unbermed, insulated Earthship. Steel, though used in the wall footings (and Earthship bond beam and buttresses), is a minor contributor to emissions.

The Brick Veneer wall's emissions are mainly from the fired clay brick manufacturing process and from the use of acrylic paint for painting the plasterboard lining (this includes repainting).

Mudbrick has the lowest emissions due to the lowest use of transport for hauling materials to the job site, plus not inherently energy intensive manufacturing processes, other than use of cement and steel in the footings.

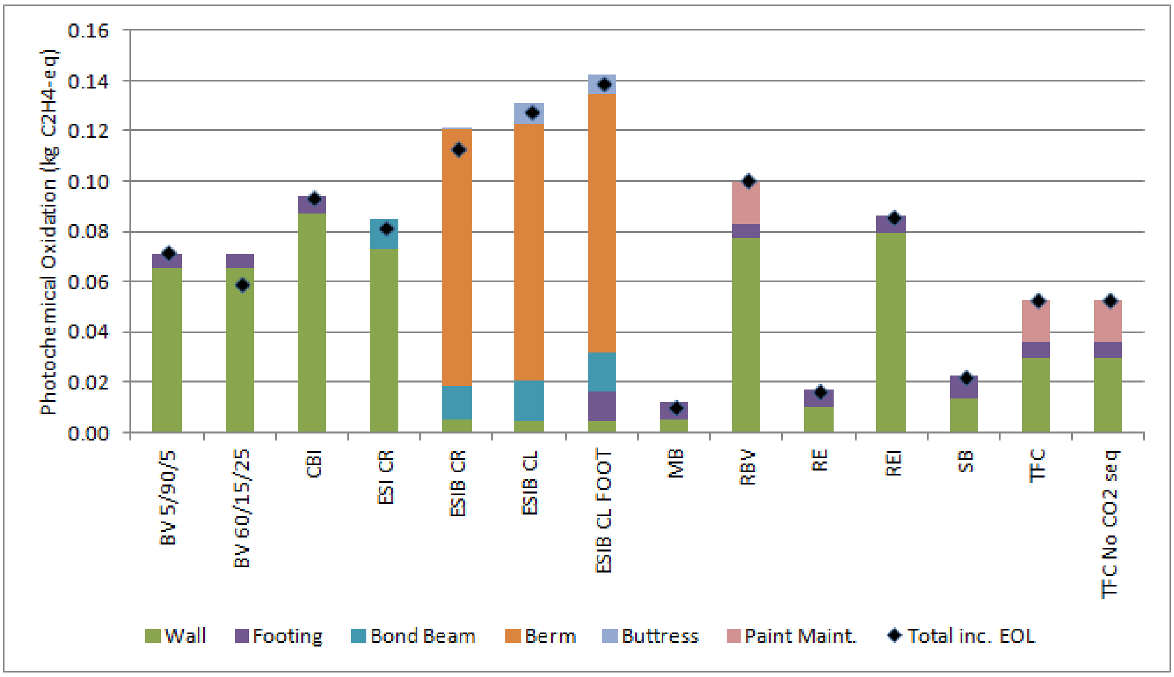

Figure 7.7 - Photochemical Oxidation, External Walls, Characterisation, 1lm

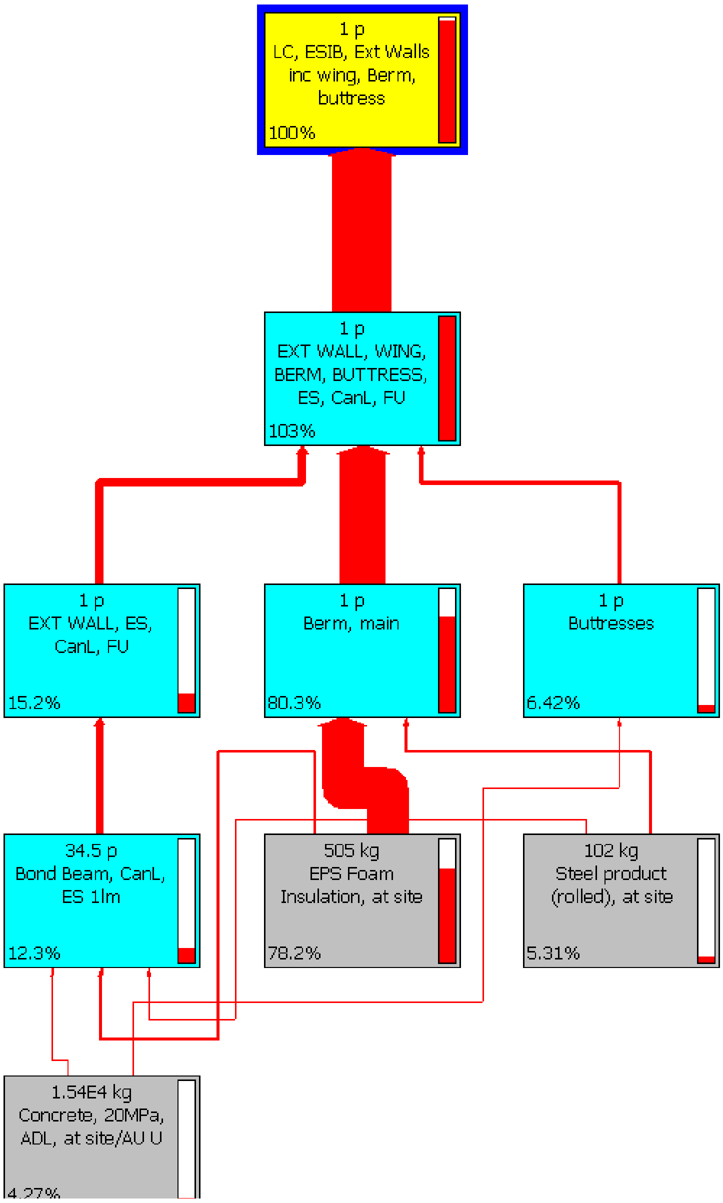

Figure 7.8 - Photochemical Oxidation, network diagram 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.4 Eutrophication for External Wall

Figure 7.9 shows results for Eutrophication potential in terms of kilograms of PO_4 equivalent emissions for each external wall type, normalised for 1lm of wall. Processes involving agriculture generally contribute to this impact category due to fertiliser run-off into waterways.

Figure 7.10 shows a network diagram for ESIB CL (5% cut off) which indicates that the main impacts arise from the use of a jute geofabric (associated with a French drain), EPS insulation (in berm), use of plywood in the buttresses construction (used as formwork), concrete, aluminium and cardboard, the latter two are assumed to be landfilled and therefore removed from the "technosphere" and hence impacts are counted for their replacement by virgin materials in lieu of recycling.

Brick manufacture is the main contributor for the Brick Veneer scenarios and the Reverse Brick Veneer wall. Concrete in the footing is the main contributor for Mudbrick.

The Concrete Block Insulated wall's Eutrophication potential arises from concrete which is used in the footings and to fill the cores of the blocks.

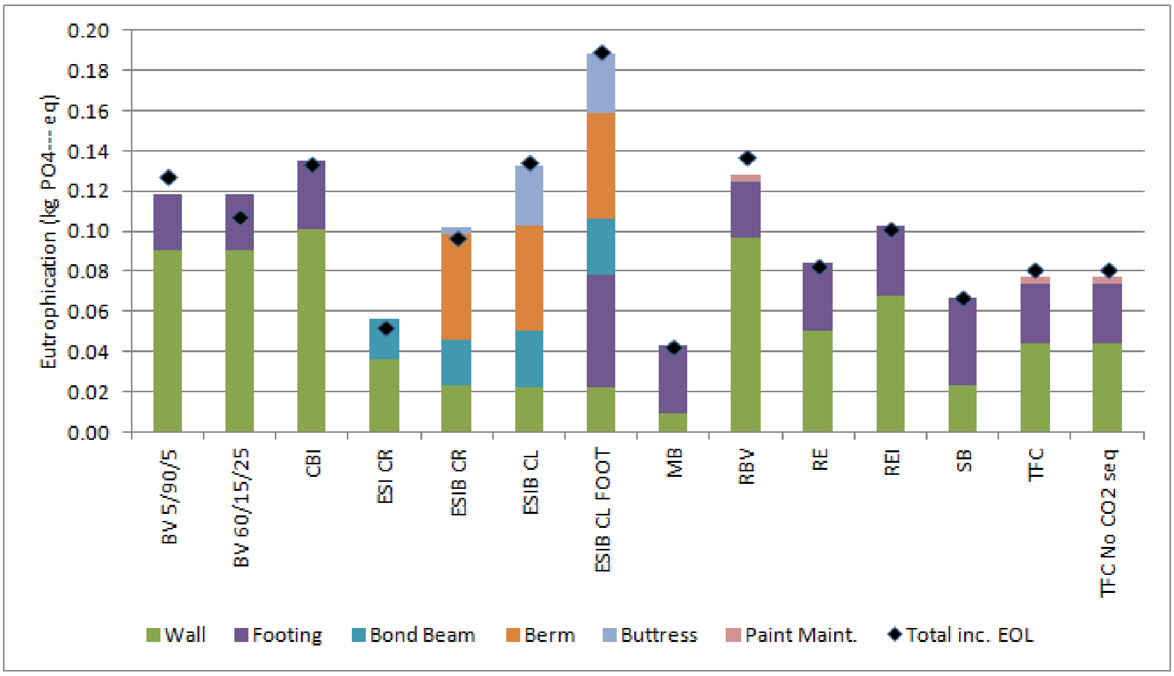

Figure 7.9 - Eutrophication, External Walls, Characterisation, 1lm

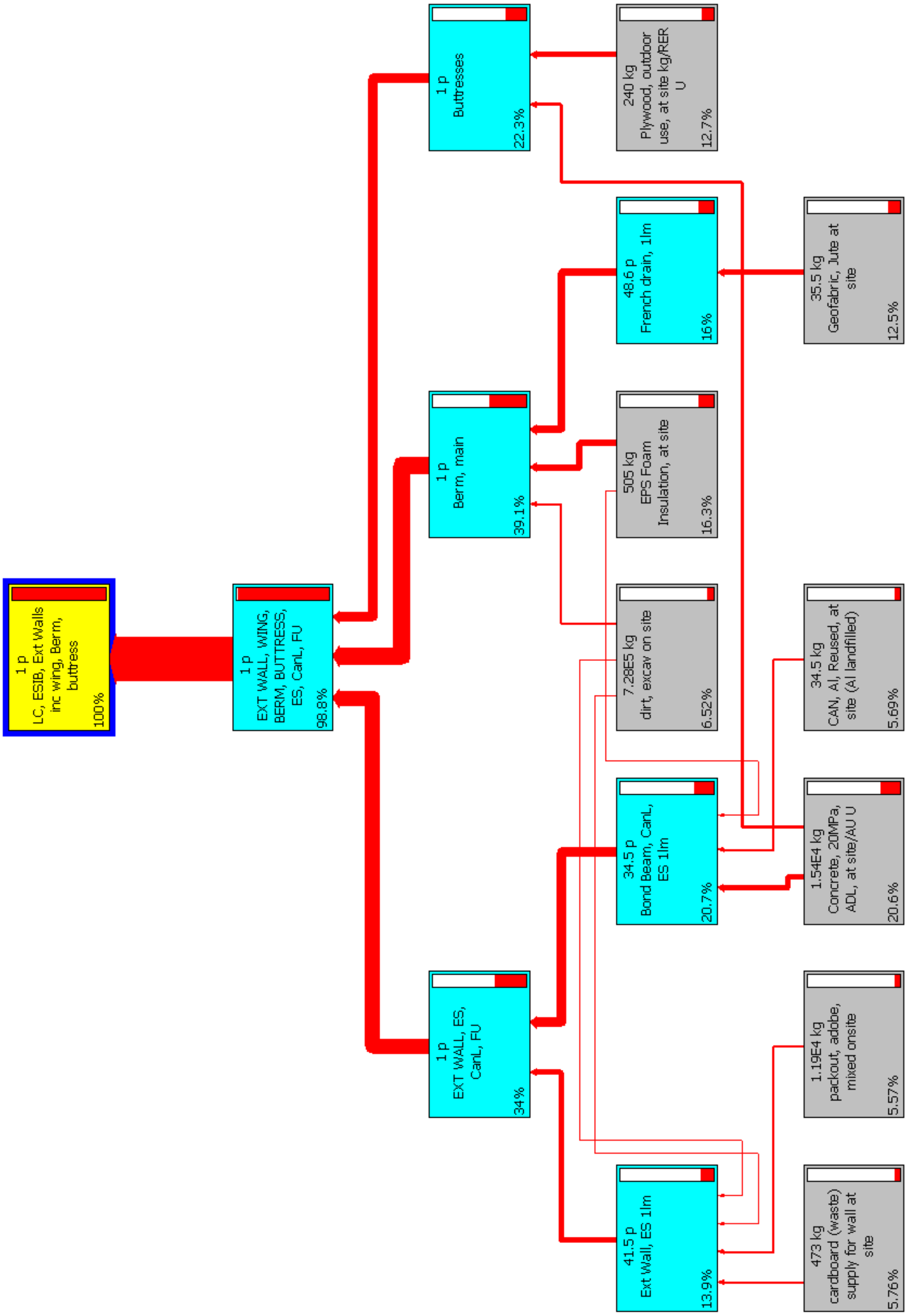

Figure 7.10 - Eutrophication, network diagram 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.5 Land Use & Transformation for External Wall

Figure 7.11 shows results for Land Use & Transformation in terms of hectare years (Ha years) for each external wall type, normalised for 1lm of wall.

The disproportionately large land transformation potential for ESIB is due to plywood (Figure 7.12) which is used as formwork in the construction of the concrete buttresses associated with this wall type. Where plywood is not used in buttress construction i.e. ESIB CR and ESI, the impacts drop significantly.

The use of pine timber leads to the main impacts in Brick Veneer, Reverse Brick Veneer, Strawbale and Timber Frame.

The EOL benefits evident in all wall constructions are mainly due to the assumption that 20% of the plywood and pine is reused.

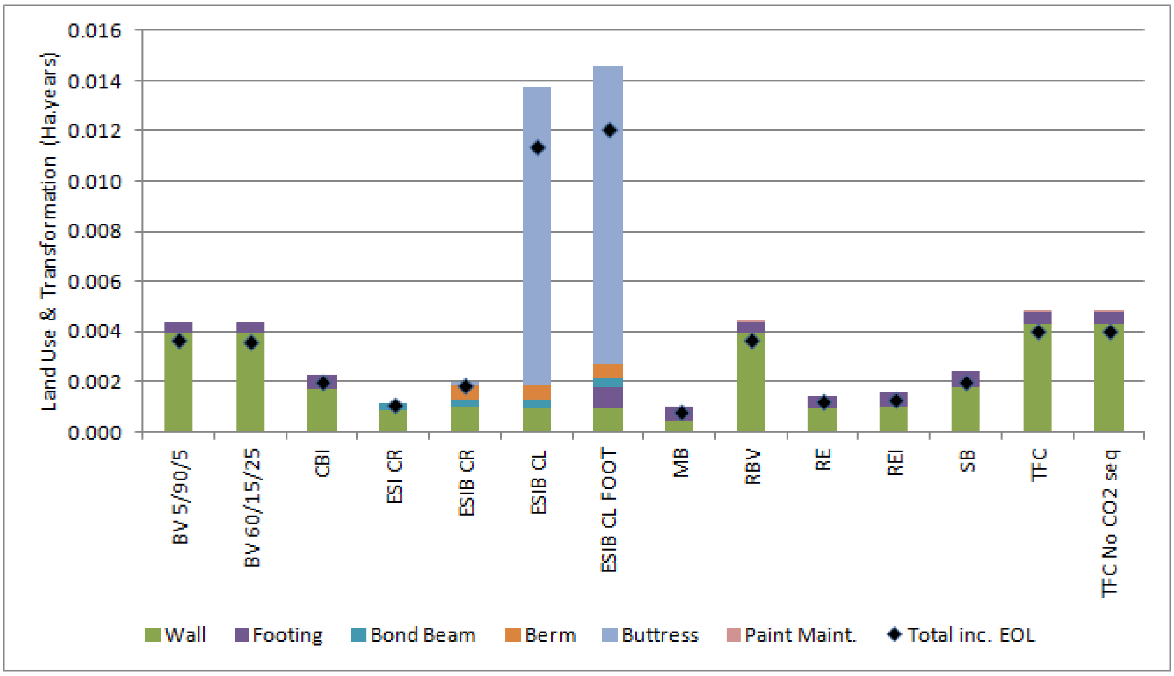

Figure 7.11 - Land Use & Transformation, External Walls, Characterisation, 1lm

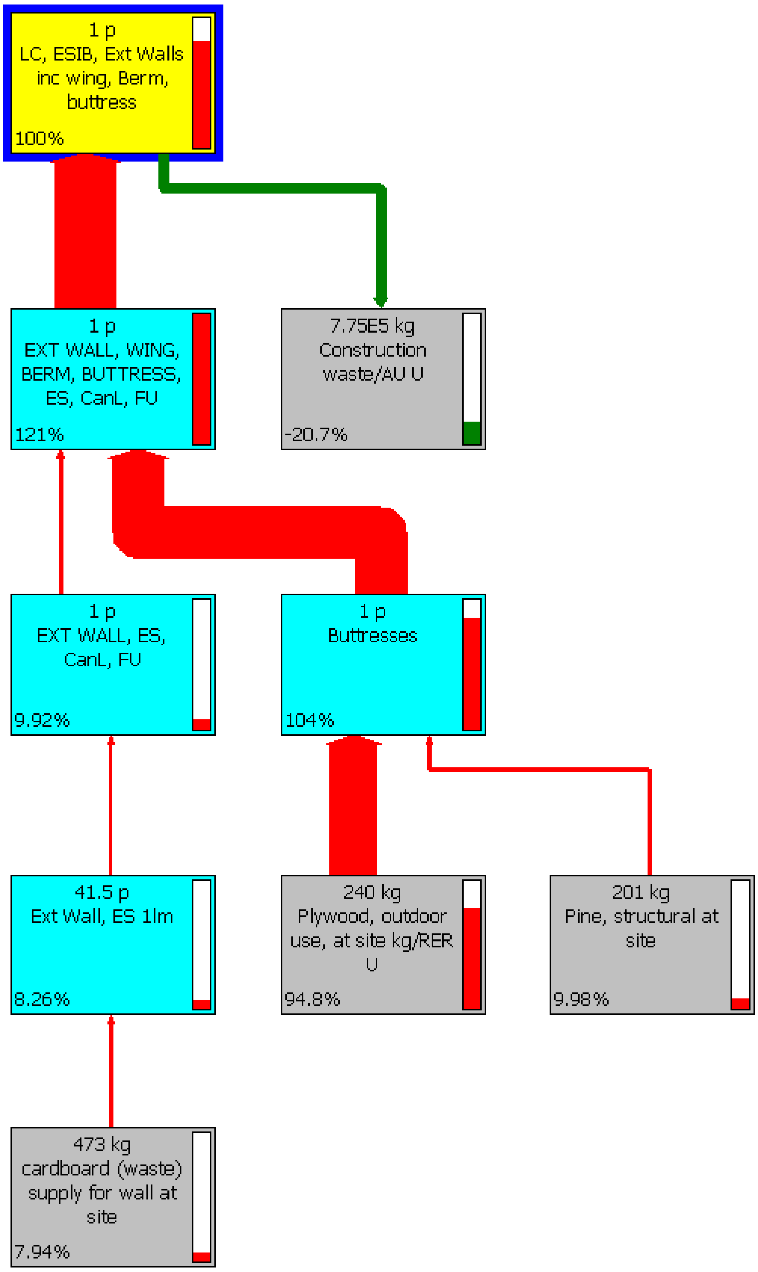

Figure 7.12 - Land Use & Transformation, network diagram 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.6 Water Use & Depletion for External Wall

Figure 7.13 shows results for Water Use & Depletion in terms of cubic metres of water for each external wall type, normalised for 1lm of wall.

EPS foam insulation is the main contributor to the water impacts in the Earthship scenarios. Cement manufacture is water intensive and this is the main contributor for the Concrete Block Insulated wall which is has the highest impact if the Earthship with concrete footings is discounted and if EOL benefits are also discounted. Recycling of concrete reduces lifecycle emissions due to avoided water use in the production of aggregates.

Due to the benefits of recycling bricks, the Brick Veneer 5/90/5 (high recycle rate) scenario has the least water use, although in production it is similar to Timber Frame and Mudbrick.

The main contributor to water depletion for the Earthship Base Case (ESIB CL) is manufacture of expanded polystyrene insulation (EPS) as shown in Figure 7.14.

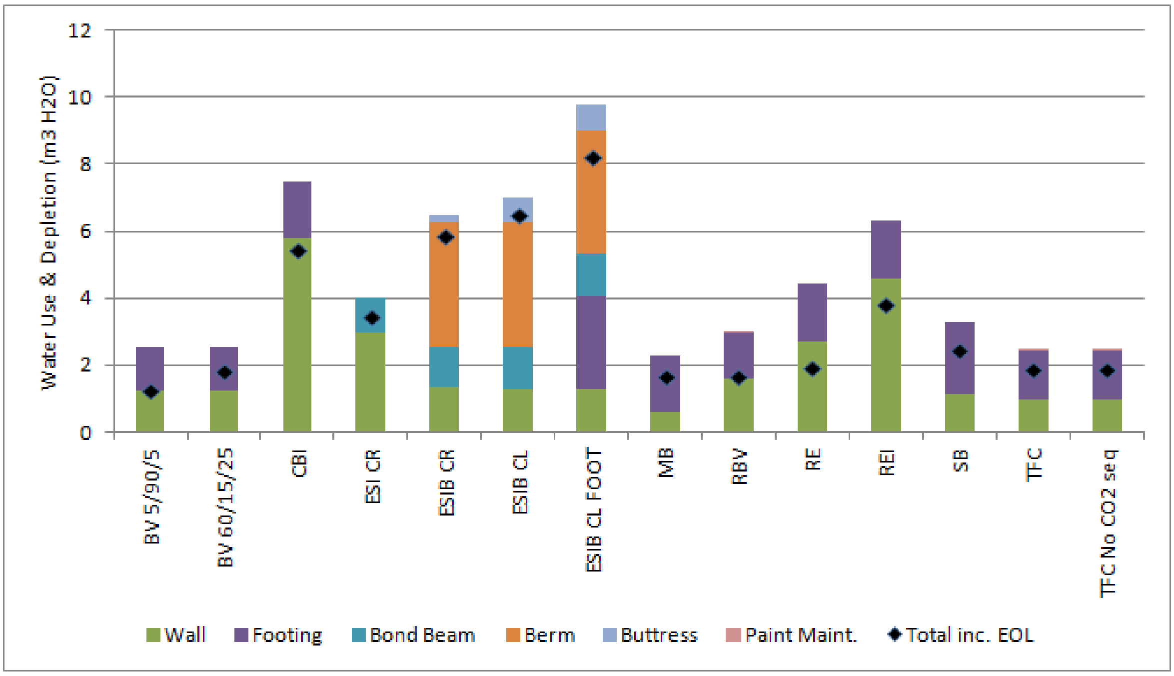

Figure 7.13 - Water Use & Depletion, External Walls, Characterisation, 1lm

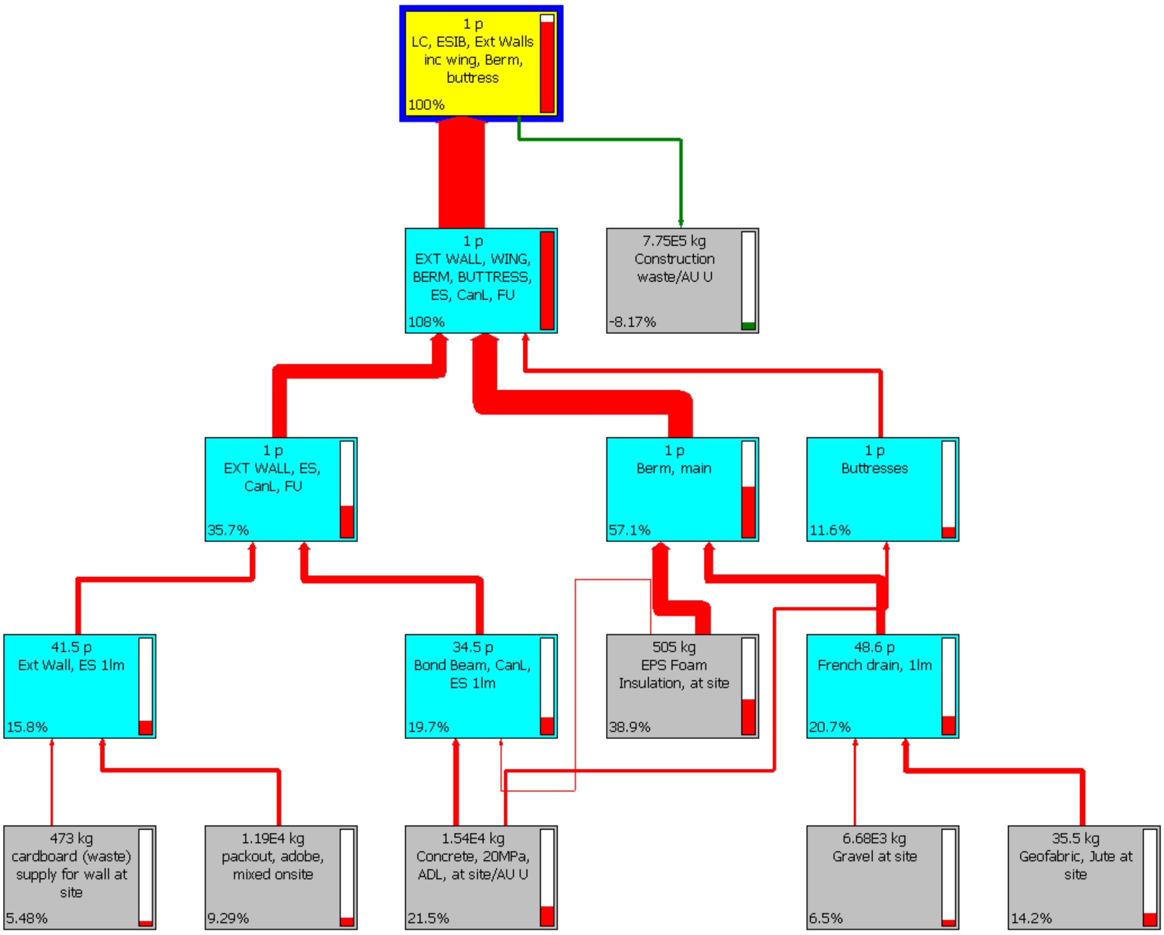

Figure 7.14 - Water Use & Depletion, network diagram, 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.7 Solid Waste for External Wall

Figure 7.15 shows results for Solid Waste impacts in terms of kilograms of waste sent to landfill for each external wall type, normalised for 1lm of wall.

The bulk of waste was generated at the end of the wall's life (EOL), however there were also some manufacturing stage impacts, especially where concrete is used, as its manufacturing process generates waste.

Note that cardboard, and aluminium cans used in the Earthship have not been displayed as an EOL impact although they should have been due to a technical difficulty with modelling. This does not affect the final results but assigns these materials the incorrect lifecycle stage classification: "manufacturing" instead of "EOL".

It is arguable that the cardboard would need to be recycled as it could be left on site and used as compost for a garden hence this models a worst case scenario in which the cardboard is landfilled.

The materials sent to landfill ("construction waste" category) are primarily: steel fasteners, sarking (reflective foil insulation), geofabric, fibreglass insulation batts, EPS foam insulation, drainage pipe, damp proof course (DPC), compressed fibre cement cladding, and aluminium cans (although this was tested with a sensitivity study - "CR" or "CanR" indicates aluminium can recycling).

In addition to these materials, proportions of other materials such as concrete and rammed earth are also sent to landfill. Although it is assumed that most of these materials are recycled, a small proportion is assumed to be sent to landfill (see Waste Scenario Assumptions Rationale in Section 6.23.1.2 for discussion and rates).

When it is assumed that 25% of bricks are landfilled (BV 60/15/25) the solid waste impact is the greatest. The next highest impact is from the bermed Earthship with footing (ESIB CL FOOT) due to the large volume of concrete contained in the footing.

Mudbrick has the fewest waste impacts due to the assumption that the mudbricks disintegrate on site at end-of-life, with only the thin cement based render needing disposal, and a large proportion of this is recycled.

A network diagram is not given for the Earthship Base Case for this impact category because of the modelling issues described above which makes the diagram misleading.

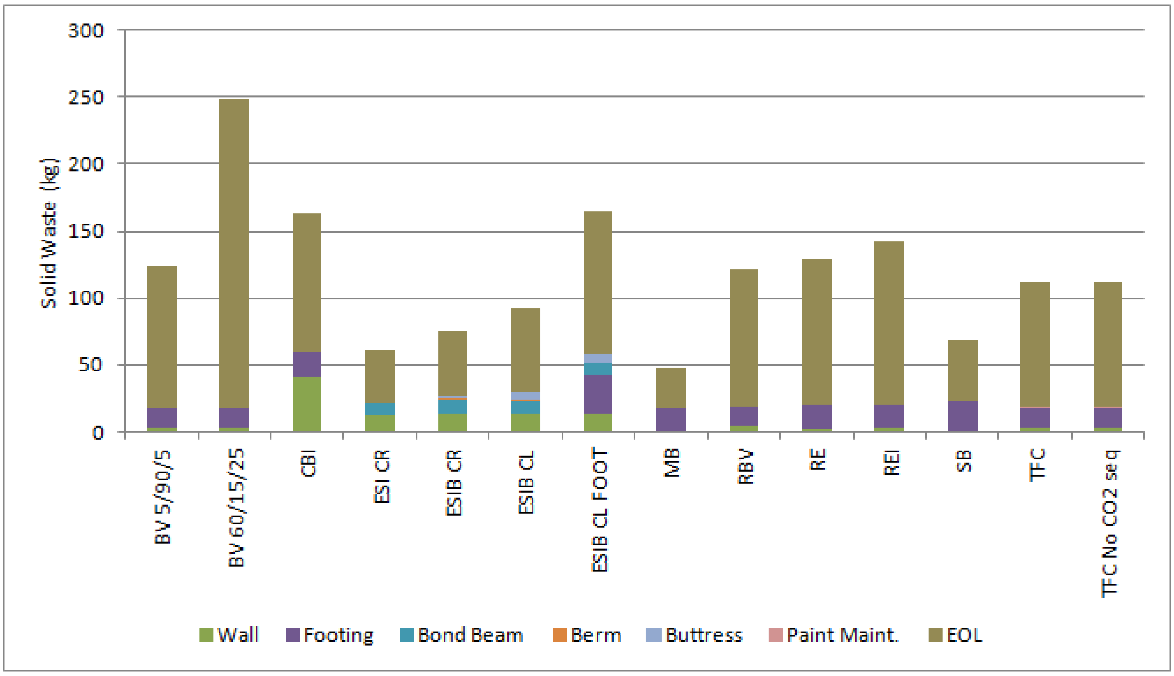

Figure 7.15 - Solid waste, External Walls, Characterisation, 1lm

7.3.8 Embodied energy LHV for External Wall

Figure 7.16 shows results for Embodied Energy (EE) use in terms of megajoules (low heating value - MJ LHV) for each external wall type, normalised for 1lm of wall. The characterisation profile is almost identical to that of the Global Warming Potential (GWP) category with the exception of Concrete Block Insulated, which shows relatively less EE impact. This is due to EE impacts and GWP being driven by fossil fuel use, in this case, in manufacturing processes of construction materials. Refer to the discussion for GWP (Section 7.3.1) as it is also relevant to this impact category.

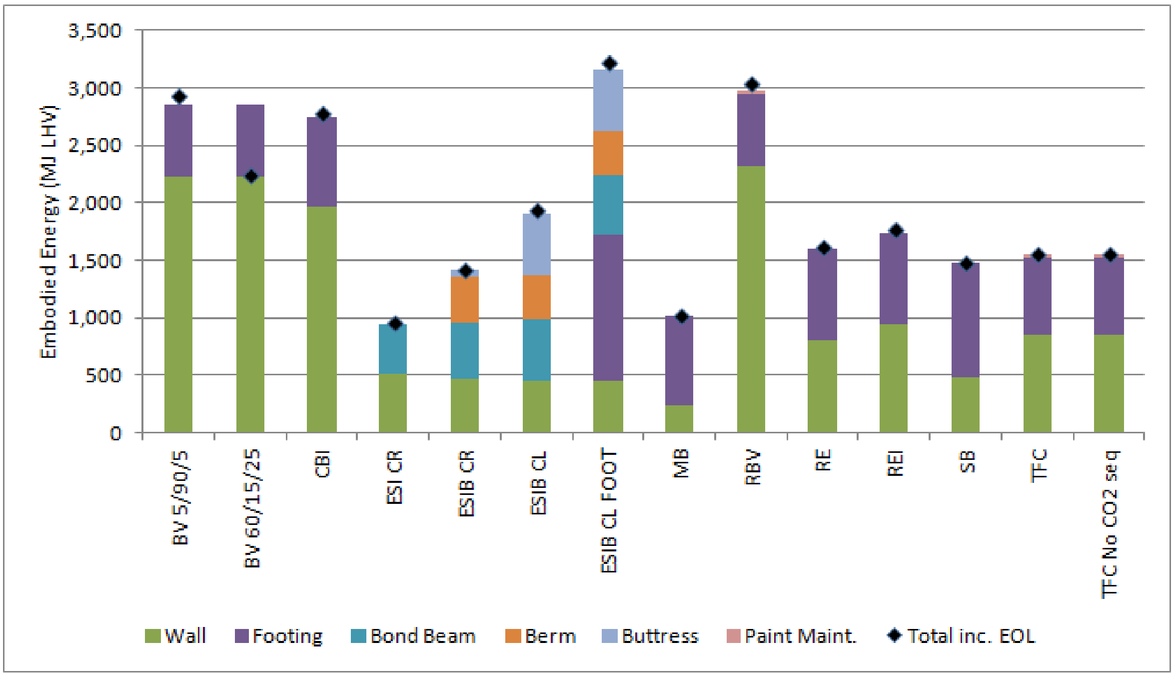

Figure 7.16 - Embodied Energy, External Walls, Characterisation, 1lm

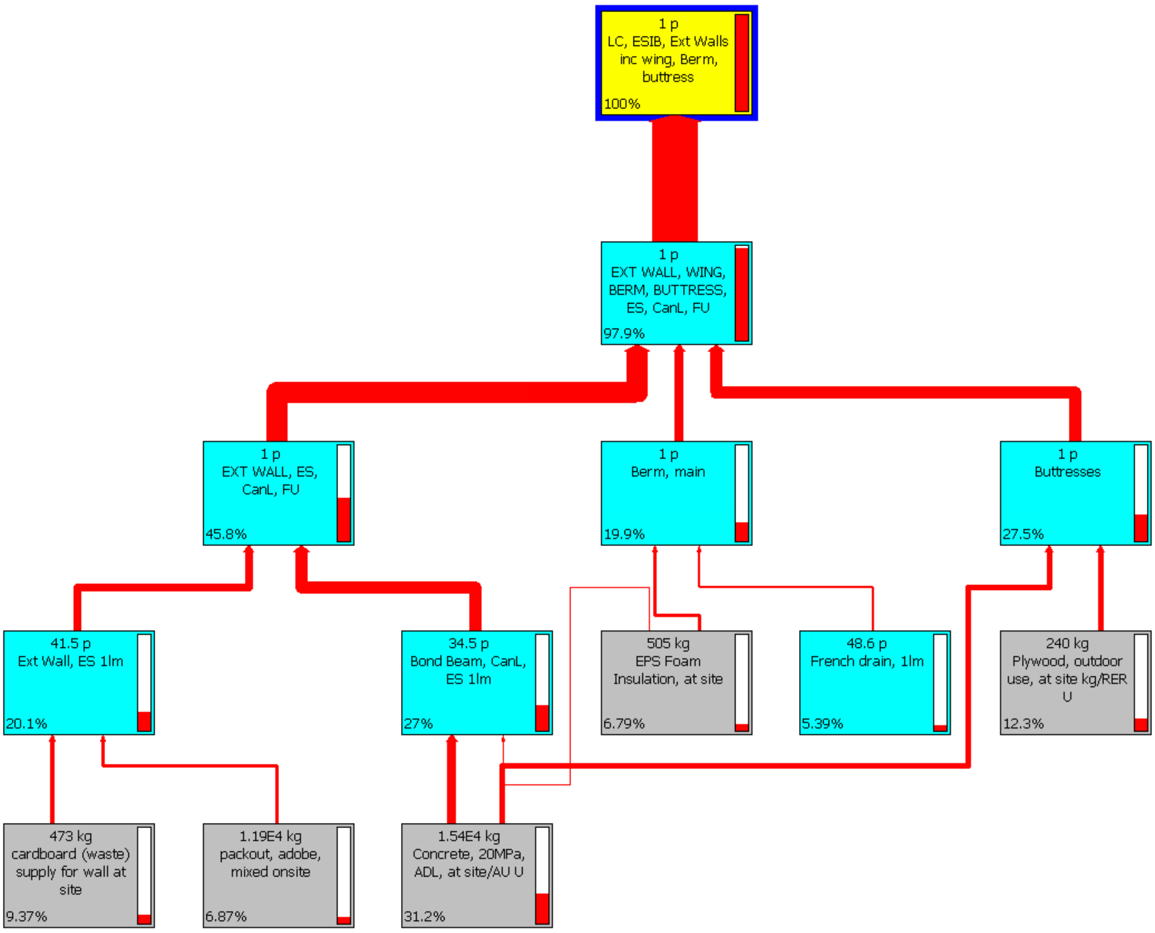

Figure 7.17 - Embodied Energy, network diagram 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.9 Human Toxicity, Carcinogenic, for External Wall

Figure 7.18 shows results for Human Carcinogens in terms of Comparable Toxic Units (Human) (CTUh) for each external wall type, normalised for 1lm of wall. Carcinogenic Human Toxicity potential for the Earthship base case (ESIB CL) is mainly due to the use of plywood which is used as formwork in the construction of the buttresses (Figure 7.19).Plywood contains formaldehyde: the main cause of the toxicity. 76g of formaldehyde are emitted to the air throughout the lifecycle of the plywood although it is likely that the vast majority is emitted during the manufacturing phase at the manufacturing plant.

In the “lowEE” Earthship scenario (ESIB CR), where cans are recycled, tyre buttresses are used and plywood is not necessary, the toxicity potential is virtually zero. Likewise for the unbermed Earthship, which requires no buttress (ESI CR), the toxicity is negligible.

Benzene and formaldehyde emissions are the main cause of toxicity for the constructions incorporating fired clay bricks.

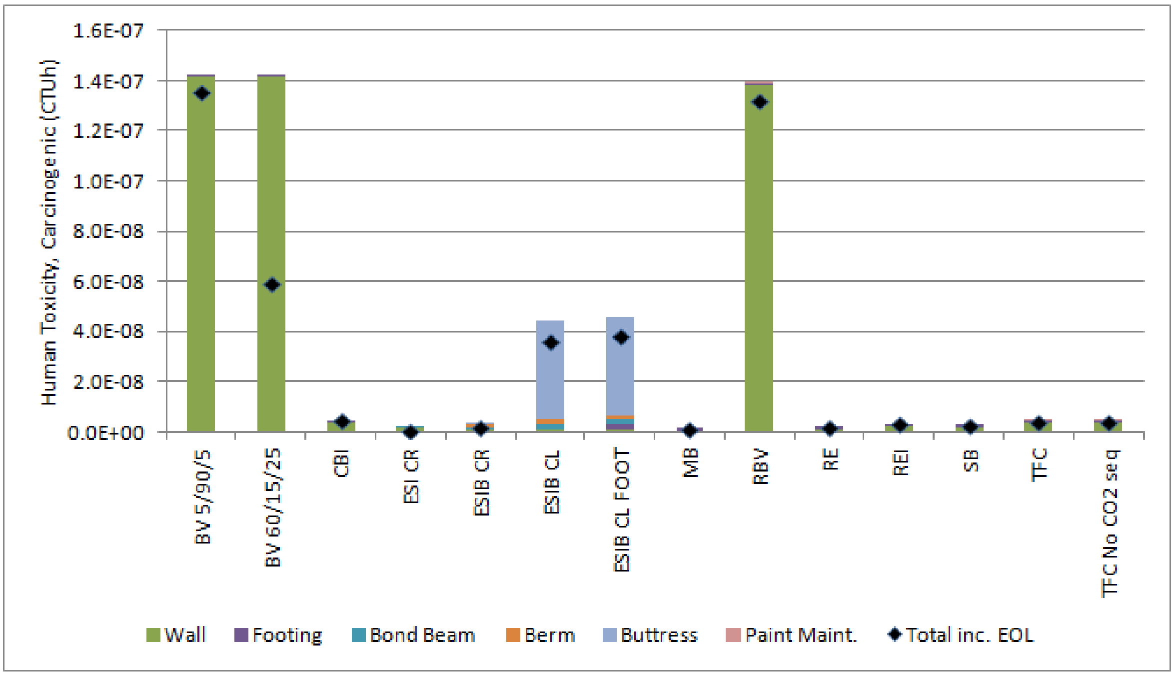

Figure 7.18 - Human Toxicity, Carcinogenic, External Walls, Characterisation, 1lm

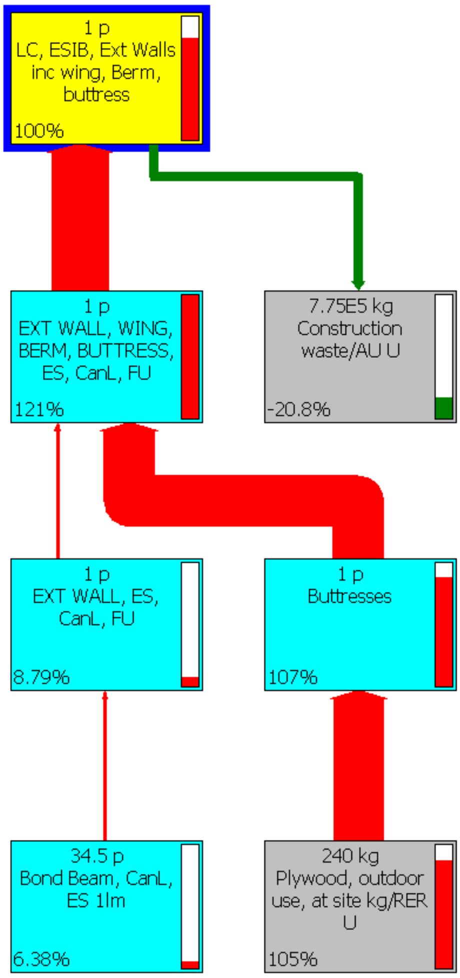

Figure 7.19 - Human Toxicity - Carcinogenic, network diagram 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.10 Human Toxicity, Non-Carcinogenic, for External Wall

Figure 7.20 shows results for Non-Carcinogenic Human Toxicity in terms of Comparable Toxic Units (Human) (CTUh) for each external wall type, normalised for 1lm of wall. Non-Carcinogenic Human Toxicity potential for the Earthship Base Case is mainly due to the use of plywood which is used as formwork in the construction of the buttresses (Figure 7.21).

In the “lowEE” Earthship scenario (ESIB CR), where tyre buttresses are used and plywood is not necessary the toxicity potential is lower. Other contributors to the bermed Earthship scenarios are EPS foam insulation, concrete and jute (geofabric).

The highest emissions are from the wall constructions containing fired clay bricks, emissions of carbon disulphide during the brick manufacturing process being the main cause of non carcinogenic human toxicity.

Mudbrick has the lowest impact, with emissions arising from the use of cement in the footings and cement render. The main substances contributing to the toxicity for cement production being carbon disulfide, benzene, hexane and xylene (emissions to air).

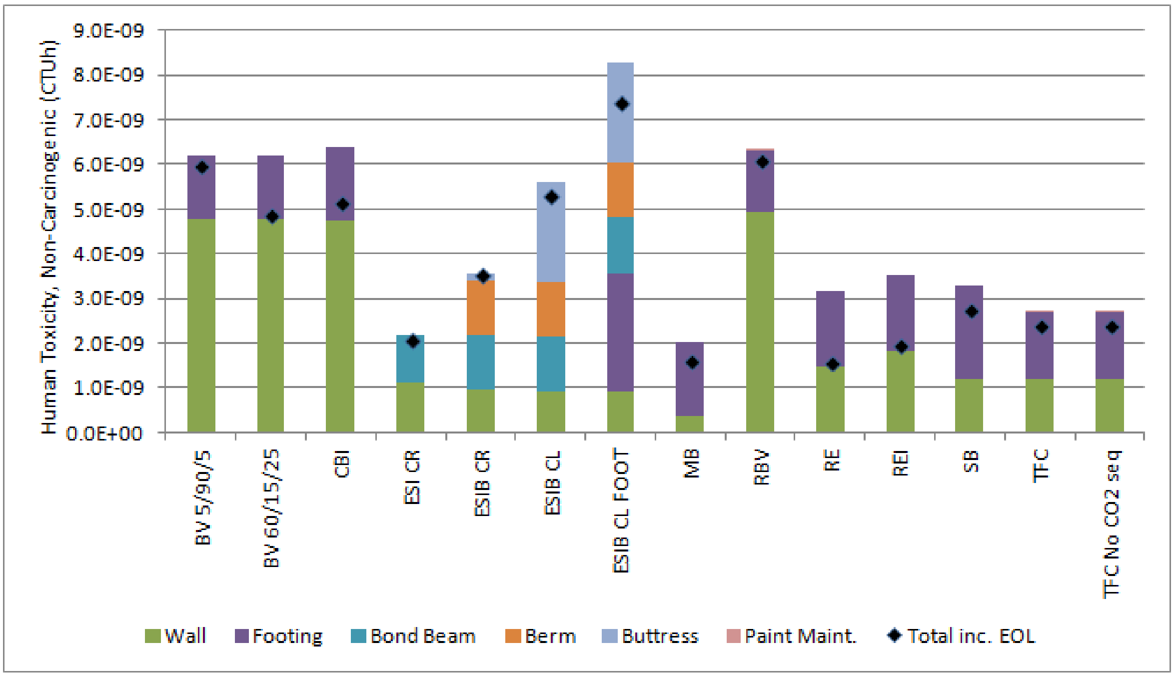

Figure 7.20 - Human Toxicity, Non-Carcinogenic, External Walls, Characterisation, 1lm

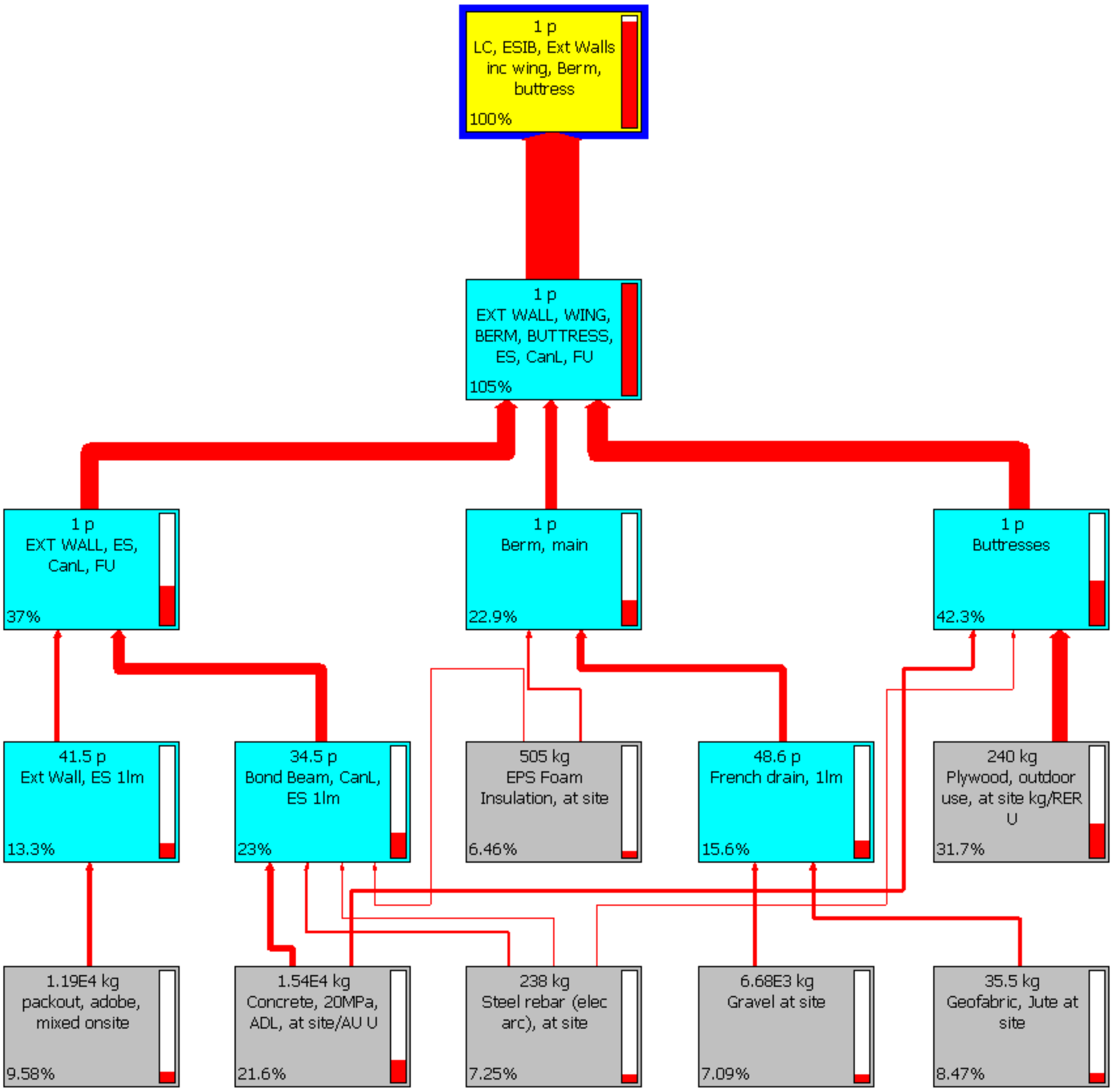

Figure 7.21 - Human Toxicity, Non-Carcinogenic, network diagram, 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.11 Eco Toxicity for External Wall

Figure 7.22 shows results for Eco Toxicity potential in terms of Comparable Toxic Units (Eco) (CTUe) for each external wall type, normalised for 1lm of wall. Eco Toxicity potential is highest for the Earthships that have a berm due to the use of jute as part of the French drain system in the berm (Figure 7.23). The use of chemicals in the growing of jute is the cause of the eco toxicity potential. It should be noted that the Taos Earthships do not use a French drain as it is unnecessary in the dry-arid climate and the relatively flat site that provides for good drainage. It was modelled in this study due to Adelaide's higher rainfall and as per common engineering practice for drainage of retaining walls.

Where a berm is not incorporated into the Earthship (ESI CR) the eco toxicity drops significantly due to geofabric not being used.

Where fired clay bricks are used in the wall construction the eco toxicity arises mainly from phenol emissions to water and formaldehyde emissions to air.

Concrete's impacts are caused mainly by emissions of chlorothalonil and metolachlor to soil and cumene, phenol, benzene and toluene to water.

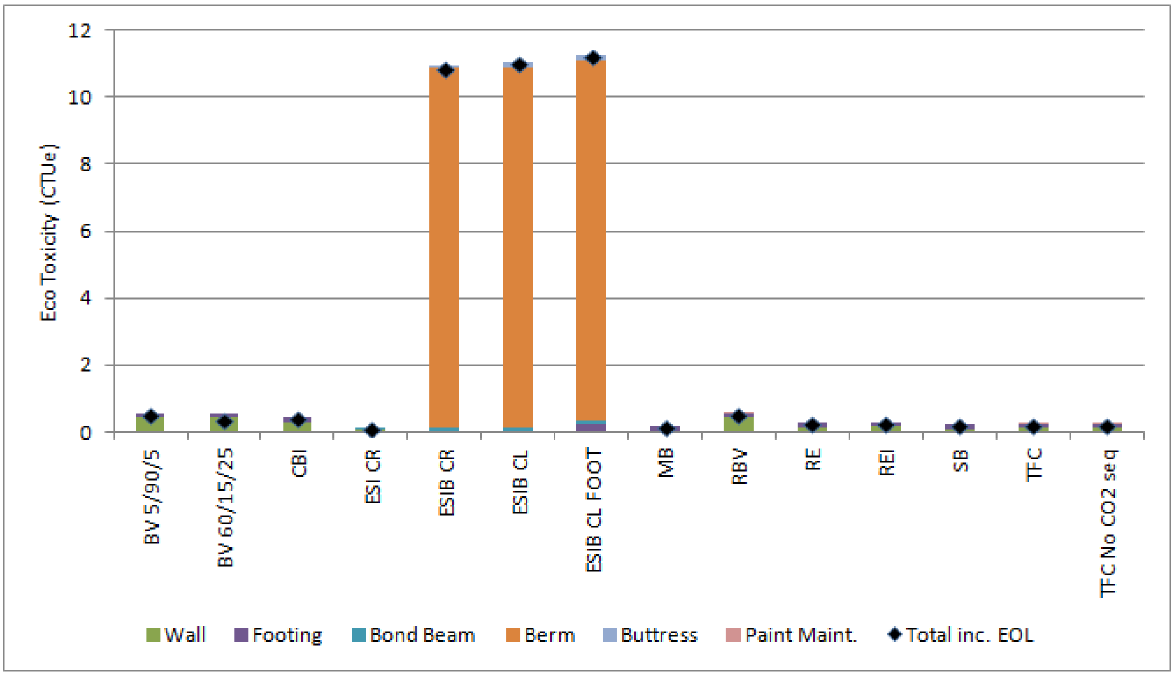

Figure 7.22 - Eco Toxicity, External Walls, Characterisation, 1lm

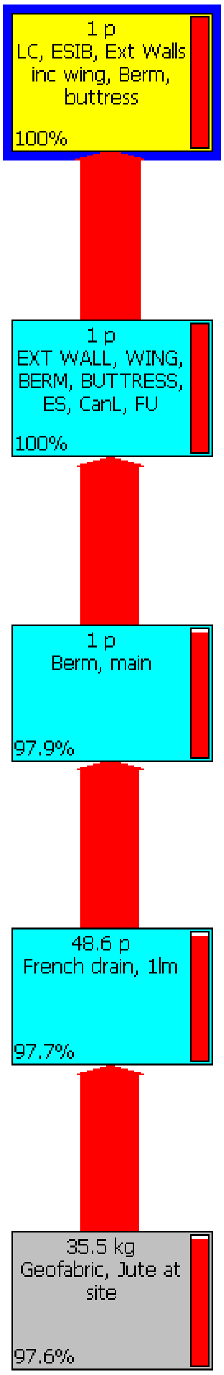

Figure 7.23 - Eco Toxicity, network diagram, 5% cut off, Earthship Base Case external walls inc. berm and buttresses

7.3.12 Normalisation of Impacts for External Wall

To better understand the significance of the various environmental impact metrics, normalisation is used to interpret the characterisation results in terms of a certain baseline, typically national or global averages.

In this study, characterisation results were normalised using the Australian, average, per capita, data, multiplied by 50 – to represent 50 years worth of “impacts” - for each indicator. Normalisation factors were obtained from the BPIC Normalisation Report (Bengtsson & Howard, 2010b) and for Solid Waste and Embodied Energy indicators, figures from an LCA study for the Forestry Forest & Wood Products Australia Limited(Carre, 2011). Normalisation factors are given in Section 5.5.2.

As normalisation factors were not available for the three toxicity indicators which employ the USEtox method, the significance of the toxicity results is discussed separately: refer to Section **Error! eference source not found.**.

Figure 7.24 shows the normalised results for the functional unit of wall (as opposed to 1lm of wall). A value of 1 on the vertical axis represents 50 years of average per capita impacts and 0.02 represents one year.

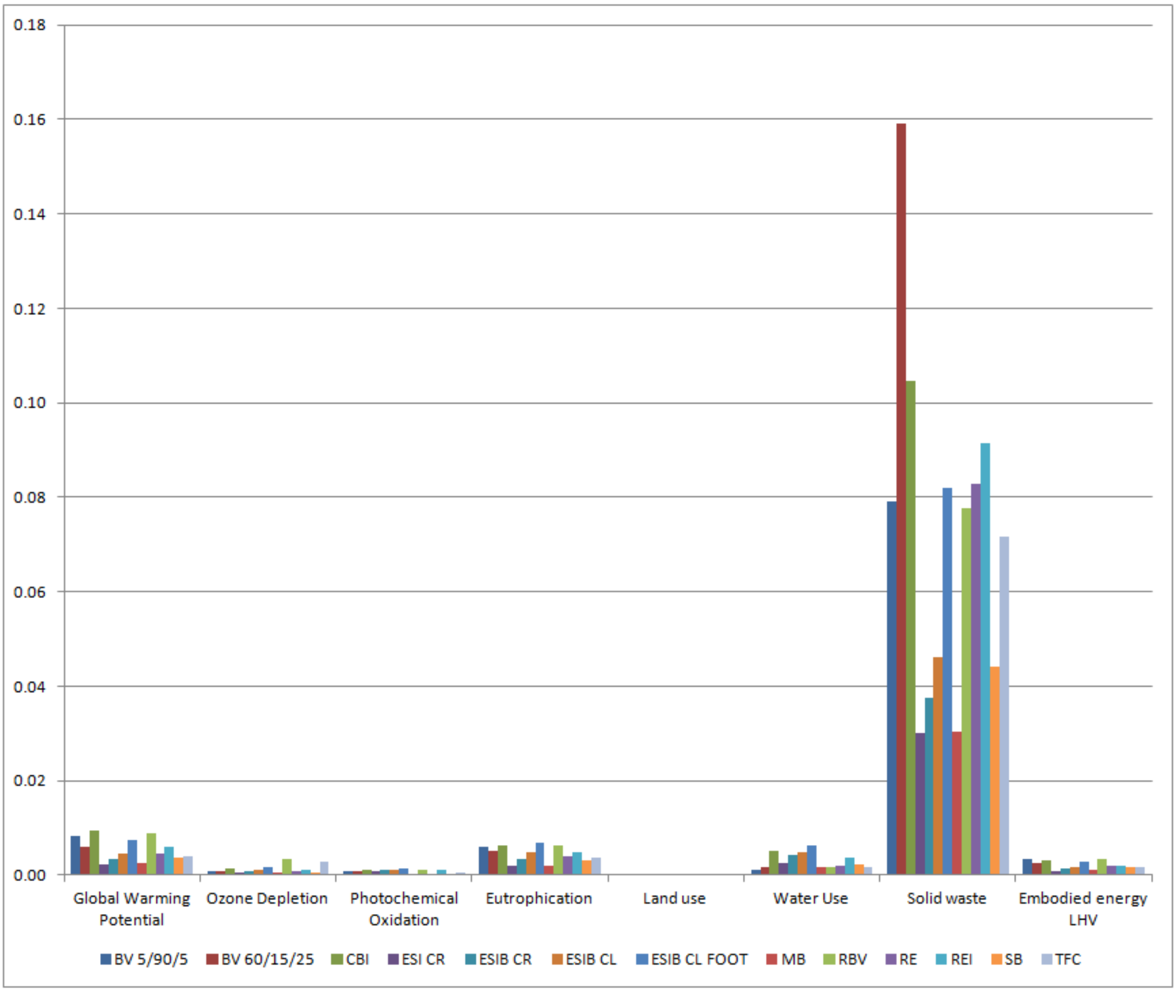

Figure 7.24 - Normalisation results, External Walls (Functional Unit, not 1lm)

Table 7.4 - Normalisation results, External Walls (Functional Unit), data

Impact category	Global Warming Potential	Ozone Depletion	Photochemical Oxidation	Eutrophication	Land use	Water Use	Solid waste	Embodied energy LHV
BV 5/90/5	0.008289	0.000968	0.000851	0.005952	0.000127	0.001195	0.079188	0.003396
BV 60/15/25	0.005863	0.00088	0.000704	0.005019	0.000124	0.001743	0.159151	0.002591
CBI	0.009353	0.001455	0.001111	0.006273	7.00E-05	0.005228	0.104511	0.003213
ESI CR	0.002382	0.000576	0.000748	0.001892	3.02E-05	0.00258	0.030039	0.000855
ESIB CR	0.003392	0.000866	0.001042	0.003526	5.07E-05	0.004387	0.037638	0.001272
ESIB CL	0.004602	0.001147	0.001174	0.004864	0.000303	0.004843	0.046268	0.001743
ESIB CL FOOT	0.007529	0.001566	0.001274	0.006861	0.000323	0.006154	0.081906	0.002887
MB	0.002686	0.00041	0.000122	0.00199	2.97E-05	0.001594	0.030475	0.001171
RBV	0.008806	0.003353	0.001187	0.006404	0.000128	0.001605	0.077607	0.003524
RE	0.004642	0.000756	0.000195	0.003889	4.20E-05	0.001853	0.082988	0.001875
REI	0.006108	0.00108	0.001018	0.004748	4.50E-05	0.003654	0.091424	0.002047
SB	0.003739	0.000686	0.000267	0.00318	7.01E-05	0.002365	0.04425	0.001722
TFC	0.003927	0.00273	0.000624	0.003745	0.000139	0.001786	0.071746	0.001791

Solid Waste has the most significant impact relative to the other impact categories. The analysis uses Carre's (Carre (2011) normalisation figure, an annual per capita average of approximately 1.4 tonnes of solid waste is used as the base line. The walls analysed range from approximately 2 tonnes of waste (Mudbrick) to 11 tonnes of waste (Brick Veneer 60/15/25) representing about 1.5 years and 8 years worth of (per person) waste disposal respectively.

Land Use & Transformation is negligible and Photochemical Oxidation and Ozone Depletion have relatively minor impacts.

Global Warming Potential, Eutrophication, Water Use and to a lesser degree, Embodied Energy all show similar orders of impact in the range of approximately 1 month to 6 months of impact. To give an example, construction of the Concrete Block Insulated wall generates GHG emissions equivalent to about 6 months of GHG emissions and 3 months of water use, of the average Australian.

For a better understanding of the relative importance of these impacts the highly controversial stage of LCA – weighting – is discussed in the next Section.

7.3.13 Weighted Single Score for Impacts, for External Wall

The process of weighting the normalised results is controversial due to its reliance on opinion rather than scientific research. The process necessitates value judgements regarding the relative importance of the impact categories, for example, how much more (or less) important GWP is than Water Use. Nevertheless, research involving surveys of people's opinions is used to quantify these relative impacts so that the normalised results can be weighted and summed to produce a single score.

This study uses weightings in the ratios established by BPIC (Bengtsson, Howard & Kneppers, 2010) and for indicators not canvassed by the BPIC report (Solid Waste and Embodied Energy), weightings were established based on their comparability to other indicators: Solid Waste was assumed to have the same weighting as Eutrophication and Photochemical Oxidation; and Embodied Energy approximately 25% less than GWP. In brief, the BPIC report classifies GWP as the most important (21%), and then Land Transformation (17%), Water Use (6%), Ozone Layer Depletion (4%), Photochemical Oxidation and Eutrophication (3%) et cetera. As this study does not use all the BPIC indicators (e.g. acidification) relative weighting factors were derived from the ratios implied by the BPIC study e.g. Water Use is twice as important as Eutrophication but only approximately a third as important as Global Warming Potential. Weighting factors for this study are given in Table 5.4.

Figure 7.25 shows the weighted results in order of least impact to most impact, the vertical axis being an arbitrary "eco point" (resulting from the weighting process) used for comparison within the context of this study.

It can be seen that Solid Waste is the most influential category, followed closely by Global Warming Potential, the remainder of the impact categories playing minor but not insignificant roles.

The unbermed Earthship with no greenhouse (ESI CR), shows the lowest overall impact followed closely by Mudbrick (MB). The bermed Earthship with greenhouse and recycled aluminium cans (ESIB CR) shows very similar results to the Strawbale wall. Where aluminium cans are not recycled (ESIB CL) the Earthship is approximately in the middle range of the results. The higher impact walls are, in order of low to high impact: Timber Frame, Rammed Earth, Rammed Earth Insulated, Brick Veneer, Reverse Brick Veneer, the Earthship with footings, and finally, the highest, Concrete Block Insulated.

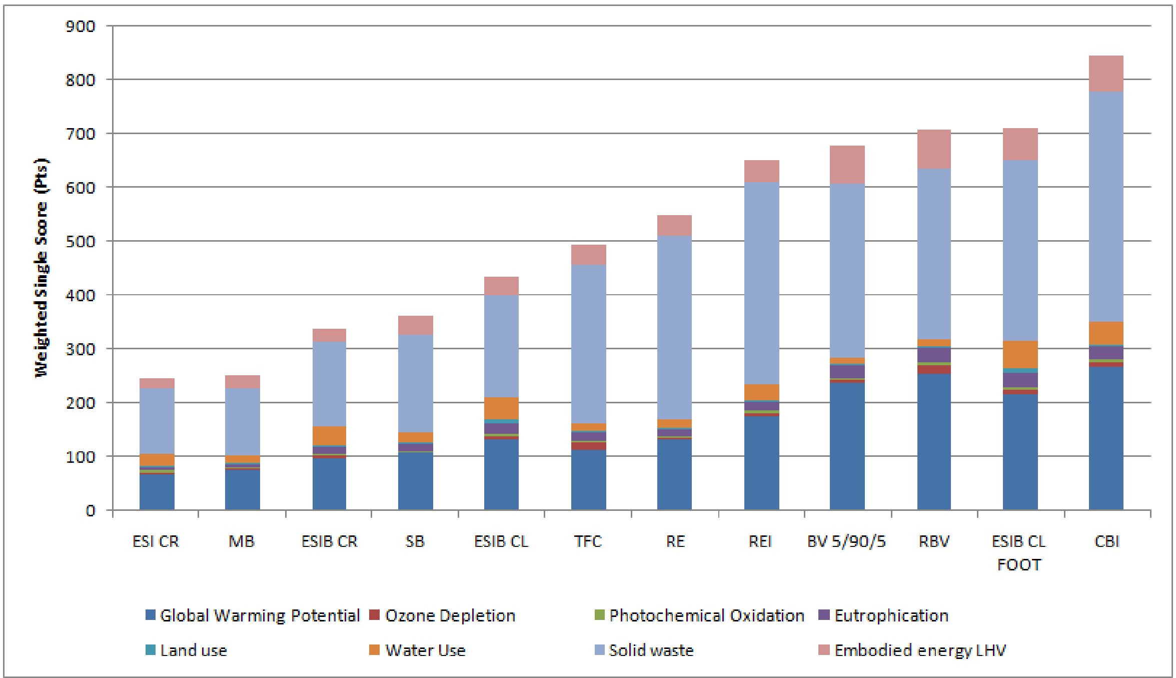

Figure 7.25 - Weighted Single Score, External Walls, All Indicators

As discussed elsewhere, Embodied Energy essentially double counts substances that are accounted for in the GWP category, and Solid Waste, although an interesting and relevant metric, is not technically an environmental impact, and impacts such as GHG emissions associated with hauling waste to a landfill site, and "land use" of the landfill site are already counted in other categories, hence, to a degree, Solid Waste is also double counting other metrics.

Therefore the effect of omitting the Solid Waste and Embodied Energy indicators is investigated via a sensitivity study, shown in Figure 7.26. In this case the "ranking" (order) of the wall constructions changes slightly, some swapping order with the adjacent construction. Black arrows above each column graph show the direction and scale of movement in the ranking, e.g. two arrows indicating a ranking change of two positions. Mudbrick becomes the lowest impact wall type (swapping places with the unbermed Earthship with aluminium can recycling, ESI CR). The various Earthship scenarios are ranked 2nd, 4th, 7th and 10th and the Concrete Block Insulated remains as the highest impact wall type.

Similarly in a second sensitivity study the effect on ranking of increasing the weighting for the non-GWP indicators by 20% is shown in Figure 7.27. Likewise in Figure 7.28 the opposite bias has been applied to the non GWP indicators by reducing the weighting by 20%, thereby increasing the relative importance of GWP. Again, black arrows are used to compare the results with the previous analysis (i.e. previous figure).

The sensitivity studies show how assumptions regarding weighting affect the rankings, though in general the rankings do not change significantly. This indicates that these somewhat arbitrary weighting assumptions do not radically change the results, although this presupposes the validity of the underlying assumption that GWP and Land Transformation are far more significant than the other indicators.

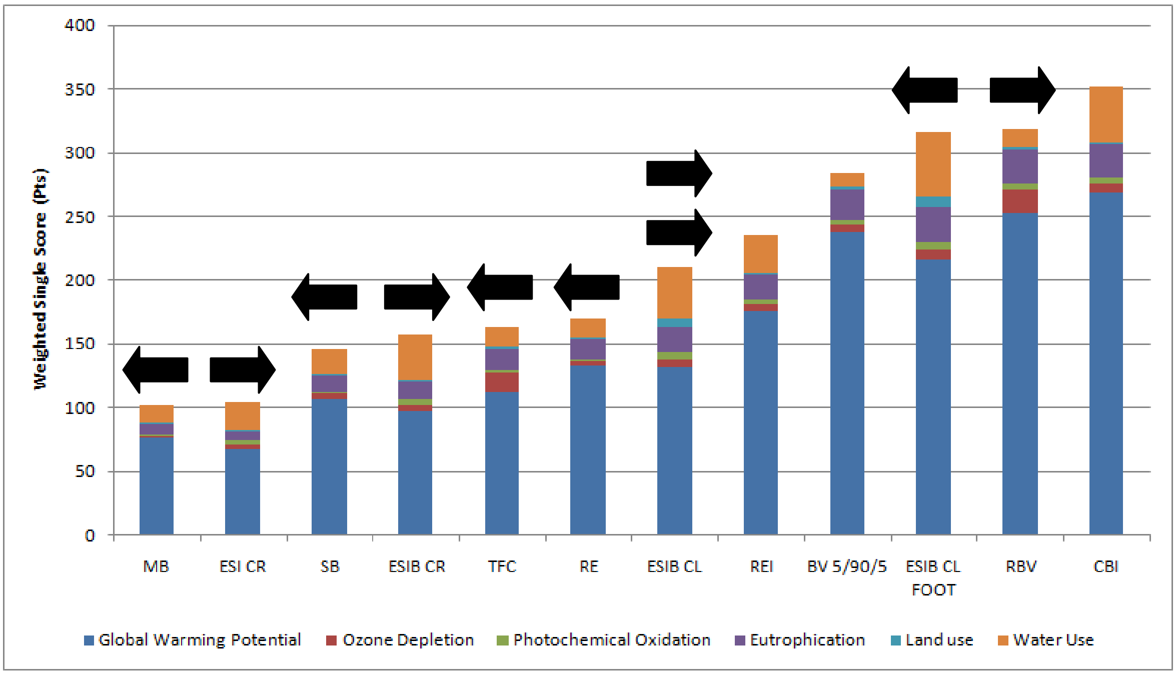

Figure 7.26 - Weighted Single Score, Sensitivity Study: External Walls, Discounting Embodied Energy and Solid Waste

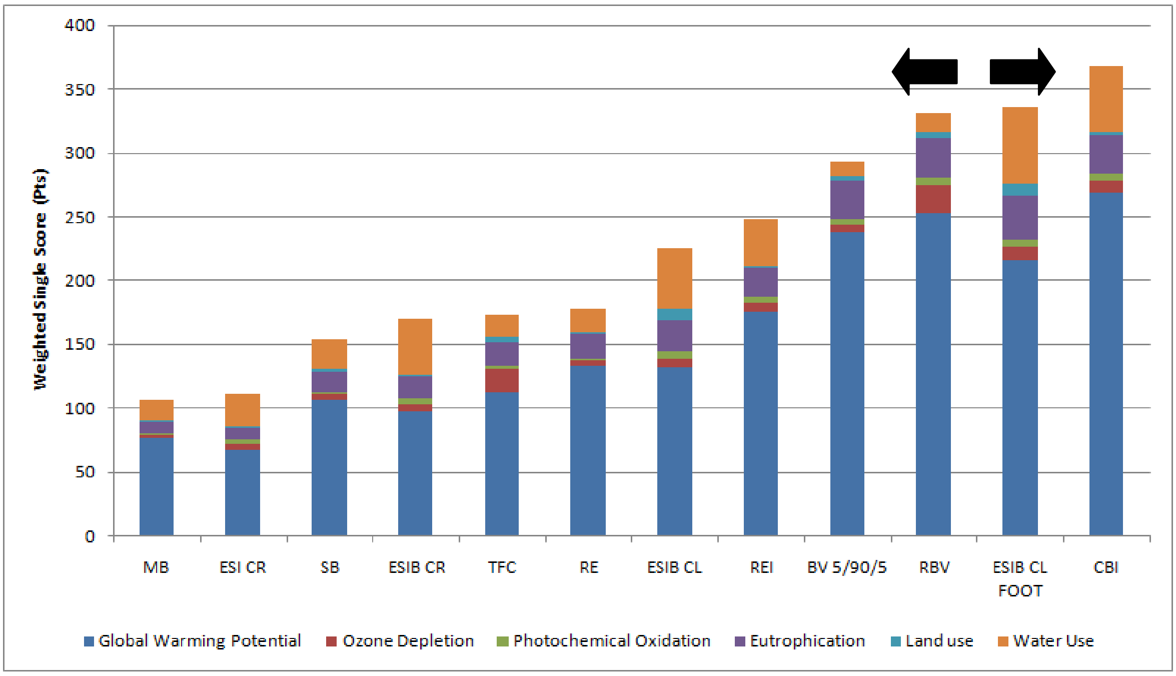

Figure 7.27 - Weighted Single Score, Sensitivity Study: Plus 20% Weighting For Non GWP Indicators

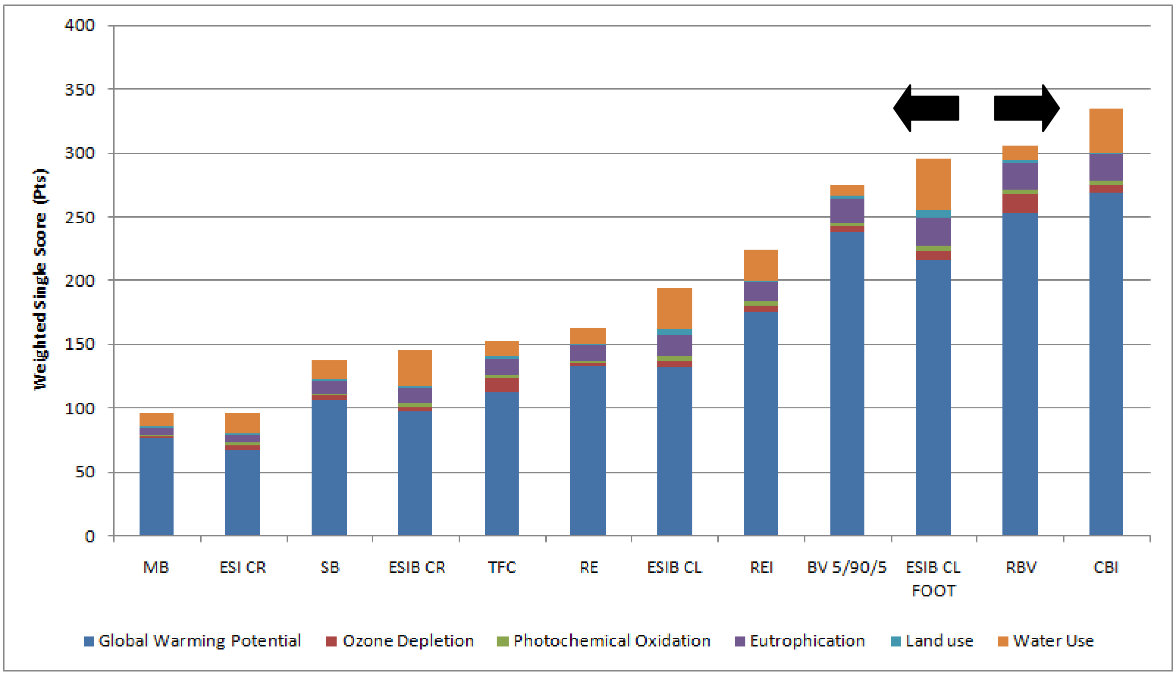

Figure 7.28 - Weighted Single Score, Sensitivity Study: Minus 20% for Non GWP Indicators

7.3.14 Discussion & Summary for External Wall

The LCA of the external walls indicates that the environmental impact of the Earthship wall varies greatly depending on the materials used and the EOL assumptions, with differing results for the various environmental indicators.

In terms of the overall weighted "eco" scores, the study found that:

- The effect of recycling the aluminium cans used in the bond beam is quite significant; when they are landfilled the aluminium is essentially "lost" and must be replaced with virgin aluminium, whereas when they are recycled the reclaimed aluminium avoids the need to produce virgin aluminium which is very energy intensive with significant environmental impacts.
- The effect of building an enormous reinforced concrete footing under the tyre wall was investigated and this had a huge impact upon the overall result. It should be noted that this is only necessary in areas of extreme earthquake danger and is not normal practice for Earthship construction.
- The effect of insulating (with 100mm of expanded polystyrene, with cement based render), rather than berming the tyre wall reduces the environmental impacts substantially, comparable to a Mudbrick wall.

Due to the high weighting for GWP, this indicator was the factor that determined the overall ranking although the sensitivity studies indicated that altering the relative weighting in relation to GWP did not greatly affect the results. Consequently walls incorporating materials that involve energy intensive manufacturing processes, such as brick and concrete, cause greater environmental impacts whereas materials such as strawbales, mudbricks, rammed earth, timber and in the case of Earthship, earth and old tyres, decrease environmental impacts.

In terms of the Earthships' performance against specific environmental indicators, Photochemical Oxidation, Water Use, Land Use, and Eco Toxicity were very high in comparison to other wall types and this was often due to the use of particular materials that could be substituted or avoided altogether for materials with less impact. For example insulation in the berm may not even be necessary for a temperate climate, and the cause of eco toxicity was jute which could be replaced by old carpet for example, or avoided altogether as is the case in standard Earthship construction.

Tyres have been modelled on the assumption that they are "borrowed" temporarily and will be land-filled eventually, perhaps in the very distant future. Hence only transport to the building site, transport to the landfill site, and electricity used to shred the tyres - so they are suitable for landfilling - has been modelled. This overlooks potential impacts that might arise from the use of tyres such as toxic substances emitted to air, soil or water throughout their lifecycle; however, due to lack of LCI data regarding this topic this issue has been addressed via a discussion of the literature (refer to Section 2.2.3.4).

In summary, the environmental impact of the external walls that have been assessed in this study varies considerably. If the assumption regarding the significance of global warming is correct, the results indicate that wall construction materials have a significant effect on environmental impacts with up to approximately triple the impacts incurred by some walls compared to the lowest impact walls.

While this part of the analysis has focused on the external walls in isolation, the next section investigates the environmental impact of the thermal envelope in which the results of the external wall analysis are aggregated with the results of roof, floor, internal walls, and in the case of the Earthship, the greenhouse.

7.4 Thermal Envelope

This section presents results and analysis of the Thermal Envelopes as defined in Table 7.2.

7.4.1 Global Warming Potential for Thermal Envelope

Characterisation results for the Thermal Envelopes' Global Warming Potential are given in Figure 7.29. The Thermal Envelope with the lowest GWP is the unbermed insulated Earthship (ESI lowEE) although if EOL credits (for recycling) are not counted the Mudbrick envelope is lowest. Each envelope has a significant proportion of impacts arising from roof construction and the floor which may account for approximately 50% in some cases.

The Earthship Base Case has the highest GWP although Brick Veneer, Concrete Block Insulated and Reverse Brick Veneer would be higher if the Earthship was constructed without a greenhouse, which represents approximately one third of the Earthship Base Case emissions. The "lowEE" Earthship, in which cement use is minimised and the aluminium cans are recycled at EOL, has slightly less than half the GWP of the Earthship Base Case with significant reductions of carbon emissions due to the internal walls and greenhouse construction assumptions.

The external walls of the unbermed, no greenhouse, Earthship (ESI) have less impact than the Earthship Base Case due to no buttresses, no wing walls and no berm. Also, aluminium cans in the bond beam and internal walls are assumed to be recycled, whereas in the Base Case they are land-filled.

The Glazed Wall category shows relatively high emissions for the Earthship scenarios due to extra construction materials being counted: for ESI lowEE a timber frame, insulated, steel clad wall (TFS), plus windows and frames, is included and for the other two Earthship scenarios, which include a greenhouse, the "Glazed Wall" is defined as a "can wall". All other thermal envelopes count only window frames and (double) glazing in the "Glazed Wall" category (refer LCI Chapter for a full discussion of this).

The greenhouse adds a significant amount of impact due to the cement use in the Base Case (Figure 7.30), whereas in the lowEE scenario it is the double glazing of the greenhouse which contributes most to the GWP impact.

The GWP of the Earthship roof versus the conventional gable roof is very similar; 4500kg and 4735kgCO_2eq respectively. Comparing the two floor types, the rammed earth floor has far less GWP than the concrete slab floor with 1500 and 4060kgCO_2eq respectively.

The Conventional Brick Veneer scenario (BV LW CONV) features the square floor plan (refer Figure 5.3) and light weight internal walls with the same amount of glazing as the other thermal envelopes which are all based on the passive solar floor plan typical of the Earthship. In this arrangement Brick Veneer is comparable to Strawbale and Rammed Earth Insulated; however, when the lightweight internal wall is replaced with thermal mass (fired clay brick), and the amount of external wall is increased to the standard passive solar layout, GWP for Brick Veneer (BV TM) increases to be similar to Concrete Block Insulated (CBI TM), and Reverse Brick Veneer (RBV TM).

The Strawbale (SB TM) envelope features fired clay brick internal walls which were specified because they were found to reduce heating and cooling loads; however, they contribute approximately 25% of the GWP, placing SB TM in the middle of the range. Strawbale has one of the lowest GWP for the external walls, yet to achieve a low overall score for the thermal envelope it would be necessary to employ low carbon emission internal walls and, for further reductions, a mud floor.

Recycling of concrete, or similar materials that can be recycled into aggregates such as brick and rammed earth lead to the majority of EOL credits shown by the black diamond (labelled "Total inc. EOL").

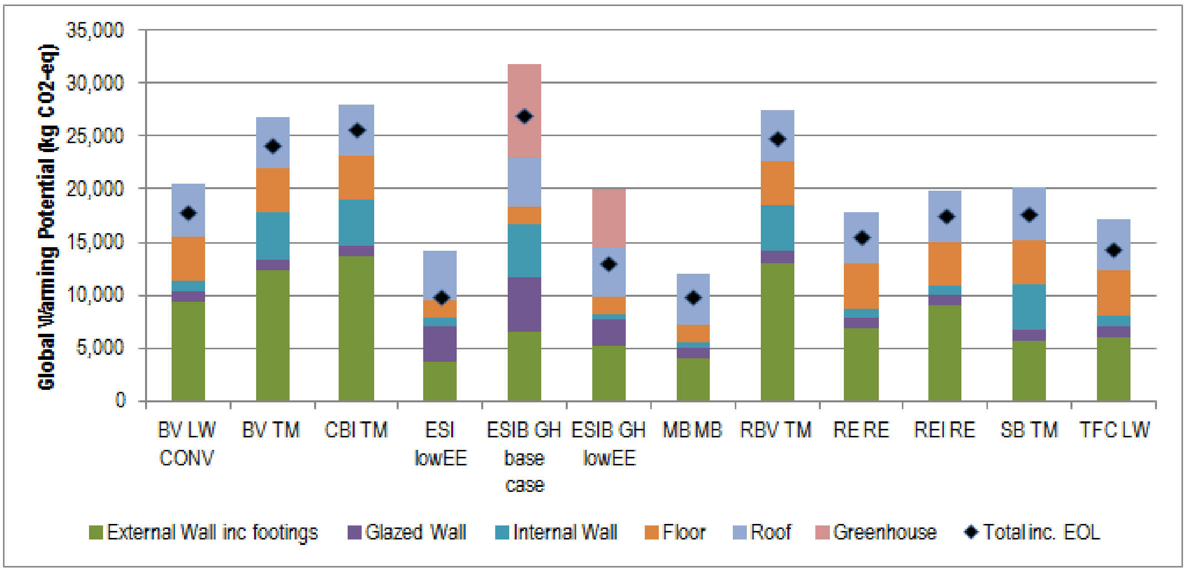

Figure 7.29 - Global Warming Potential, Thermal Envelope, Characterisation

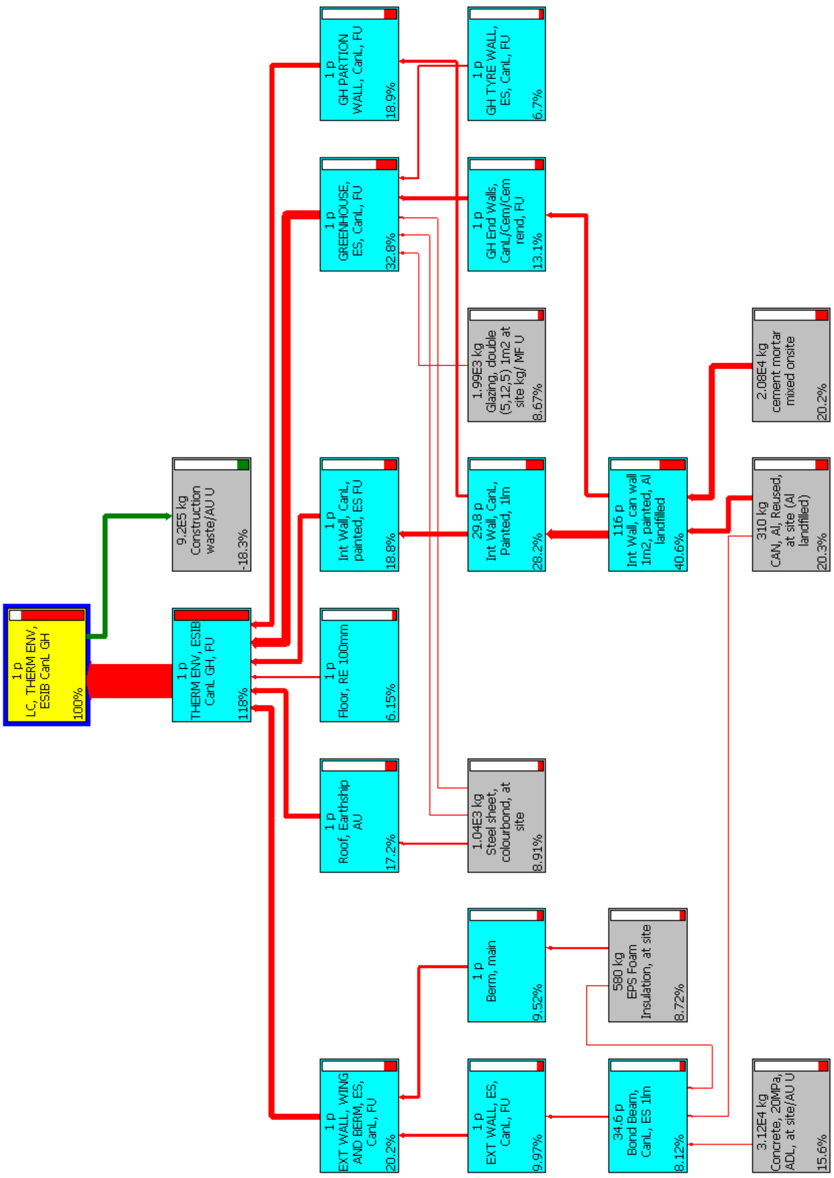

Figure 7.30 - Global warming potential, network diagram 5% cut off, Earthship Base Case

7.4.2 Ozone Depletion for Thermal Envelope

Characterisation results for the Thermal Envelopes' Ozone Depletion potential are given in Figure 7.31. The highest impacts are associated with: Reverse Brick Veneer and Timber Frame and the lowest with Mudbrick, Rammed Earth and the unbermed, insulated, "lowEE" Earthship.

Overall Ozone Depletion potential is generally differentiated by the external wall (and footing) as the emissions for the roof and floor are similar across all Thermal Envelopes.

The greenhouse is a significant contributor due mainly to zeolite powder which is used in the double glazed units (Figure 7.32). Zeolite powder is also responsible for the bulk of the emissions in the Glazed Wall category.

Emissions associated with the floor are generally similar although slightly less for the rammed earth floor specified in the Mudbrick and Earthship Thermal Envelopes.

Emissions associated with the roof are slightly greater than the floor.

In general, impacts arise from the transport processes underlying many of the processes.

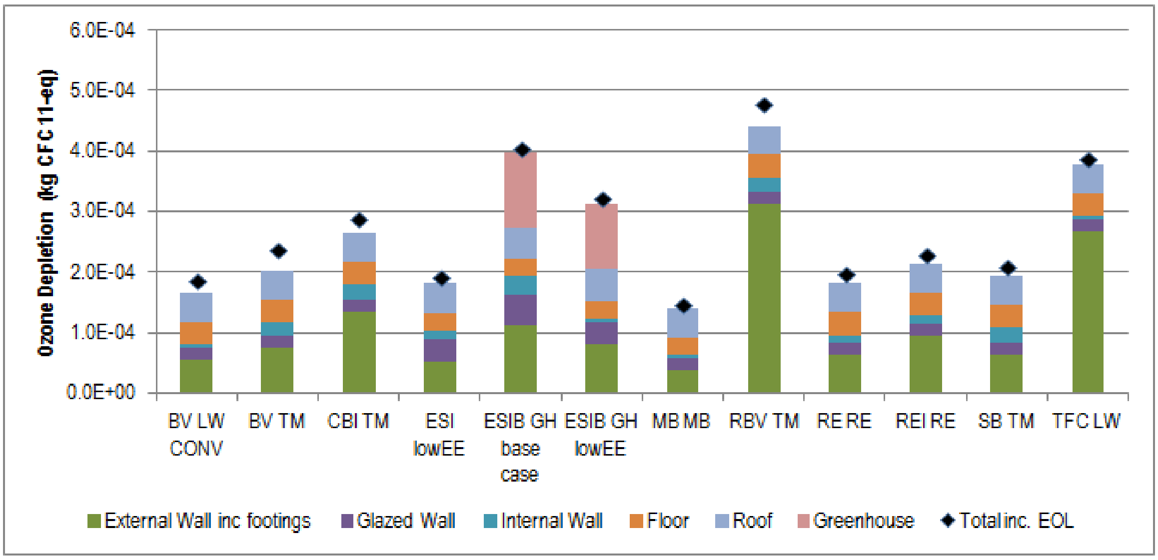

Figure 7.31 - Ozone Depletion, Thermal Envelope, Characterisation

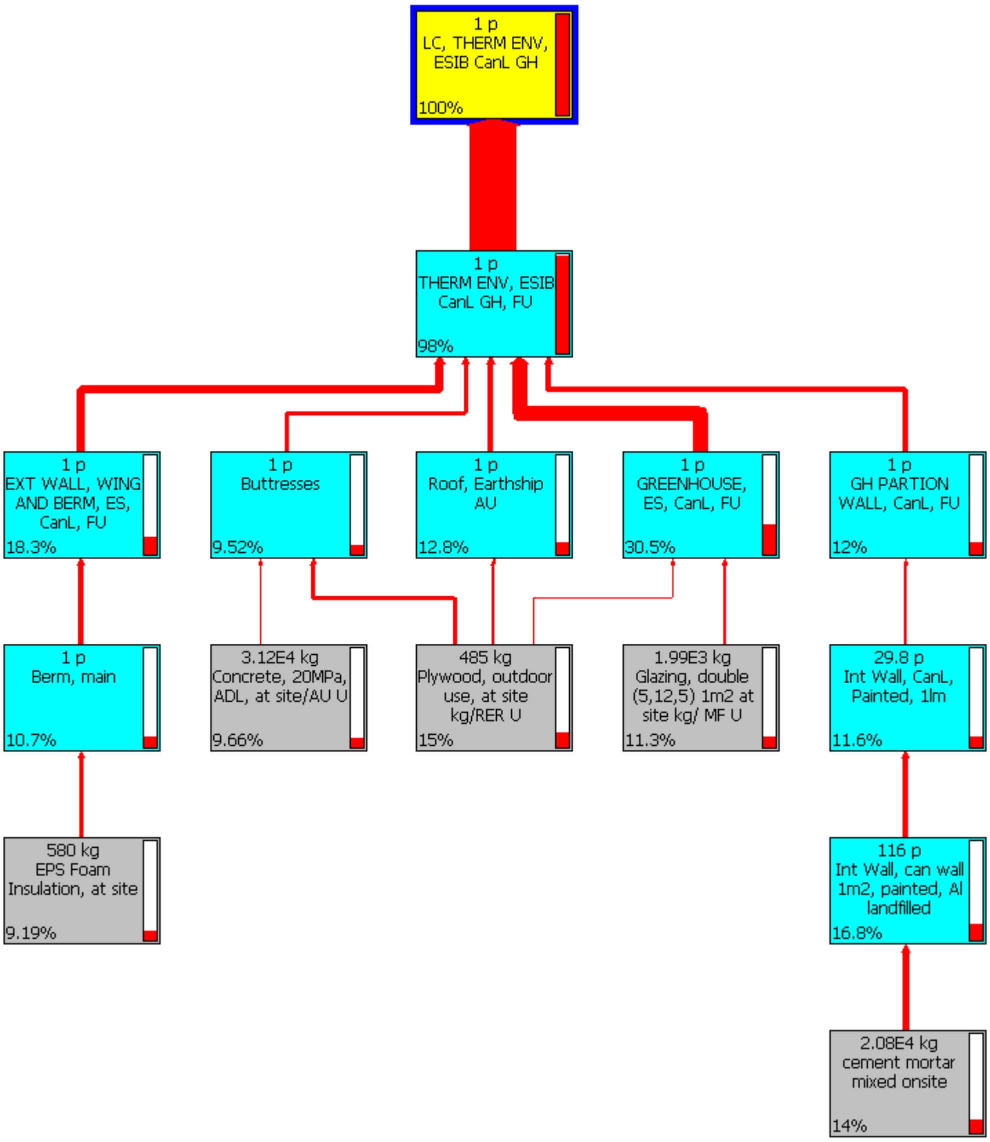

Figure 7.32 - Ozone Depletion, network diagram 8% cut off, Earthship Base Case

7.4.3 Photochemical Oxidation for Thermal Envelope

Characterisation results for the Thermal Envelopes' Photochemical Oxidation (smog) potential are given in Figure 7.33. Mudbrick, Rammed Earth and Strawbale have the lowest emissions, and the two Earthship scenarios with greenhouse are the highest due to high emissions from the external walls (due to EPS foam insulation in the berm – see External Walls section), the greenhouse construction, and the roof which shows higher emissions, due to increased use of steel and pine (Figure 7.34) compared to the standard gable roof.

Photochemical Oxidation potential is negligible for the floor construction and quite significant for the roof representing approximately 50% of emissions for many of the thermal envelopes. This is mainly due to the production of steel and structural pine which rely on large energy inputs and transport, both of which are known to generate smog causing chemicals. The greenhouse construction's emissions arise from the same sources as the roof construction.

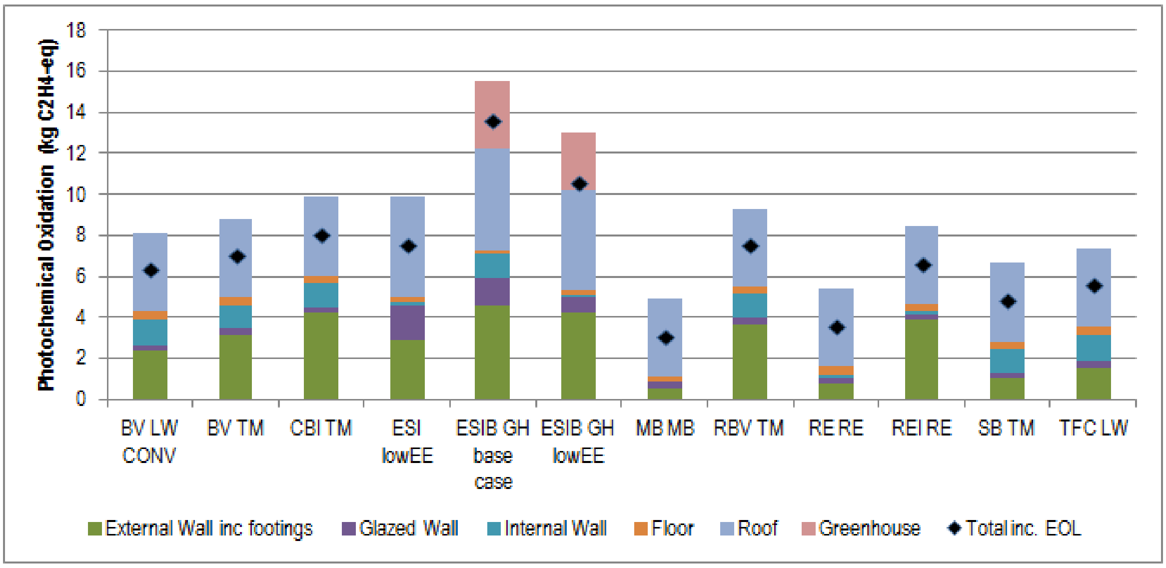

Figure 7.33 - Photochemical Oxidation, Thermal Envelope, Characterisation

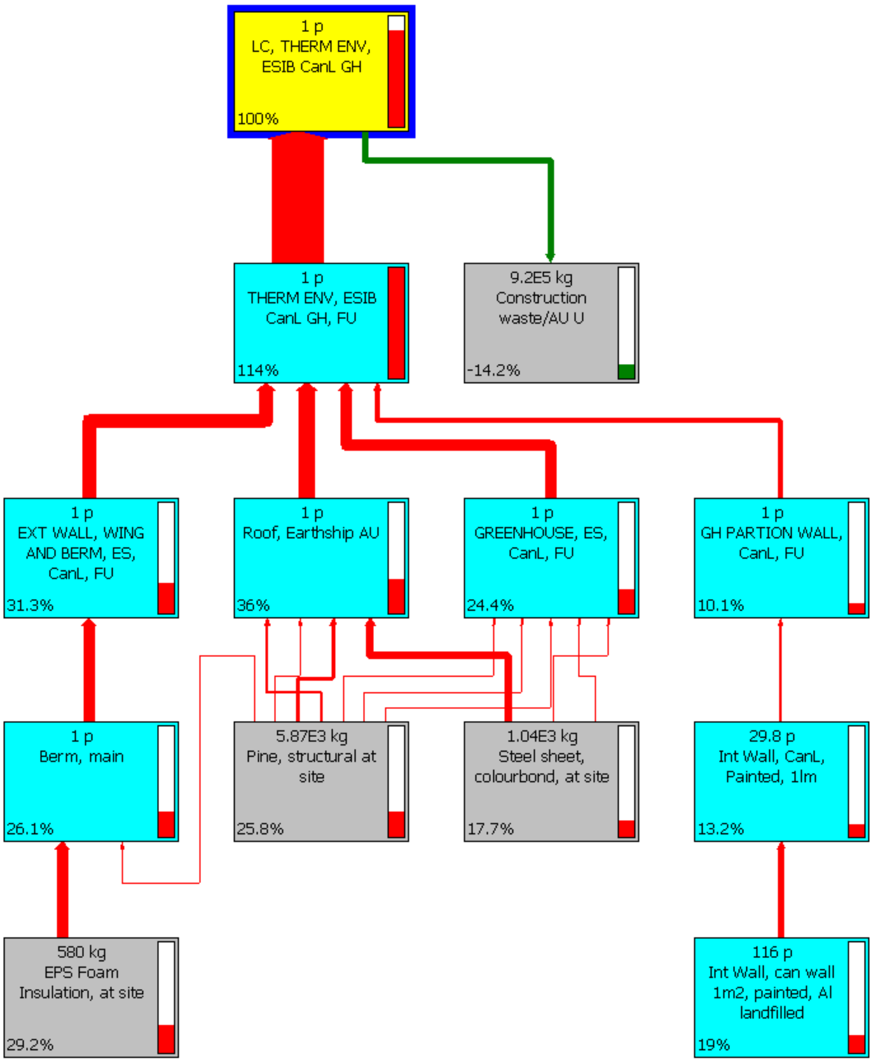

Figure 7.34 - Photochemical Oxidation, network diagram 8% cut off, Earthship Base Case

7.4.4 Eutrophication for Thermal Envelope

Characterisation results for the Thermal Envelopes' Eutrophication potential are given in Figure 7.35. The thermal envelope with the highest eutrophication potential is the Earthship Base Case due to jute geofabric in the berm (refer External Walls section) and use of cement throughout various construction elements such as the internal walls, glazed wall and greenhouse. The use of aluminium cans, assumed to be landfilled, also contributes (Figure 7.36). The effect of recycling the aluminium cans and reducing the cement use can be seen in the "lowEE" Earthship, leading to approximately 25% fewer emissions, and the effect of not constructing the berm (which contains the jute geofabric) can be observed in the ESI lowEE Earthship: which has the second lowest eutrophication potential.

Mudbrick has the least Eutrophication potential, its emissions arising mainly from roof construction where steel sheet (roof cladding), fibreglass batt insulation and plywood contribute most.

Brick Veneer with thermal mass (fired clay brick) internal walls (BV TM) is on a par with Concrete Block Insulated and Reverse Brick Veneer which are the highest emitters after the Earthship with greenhouse scenarios.

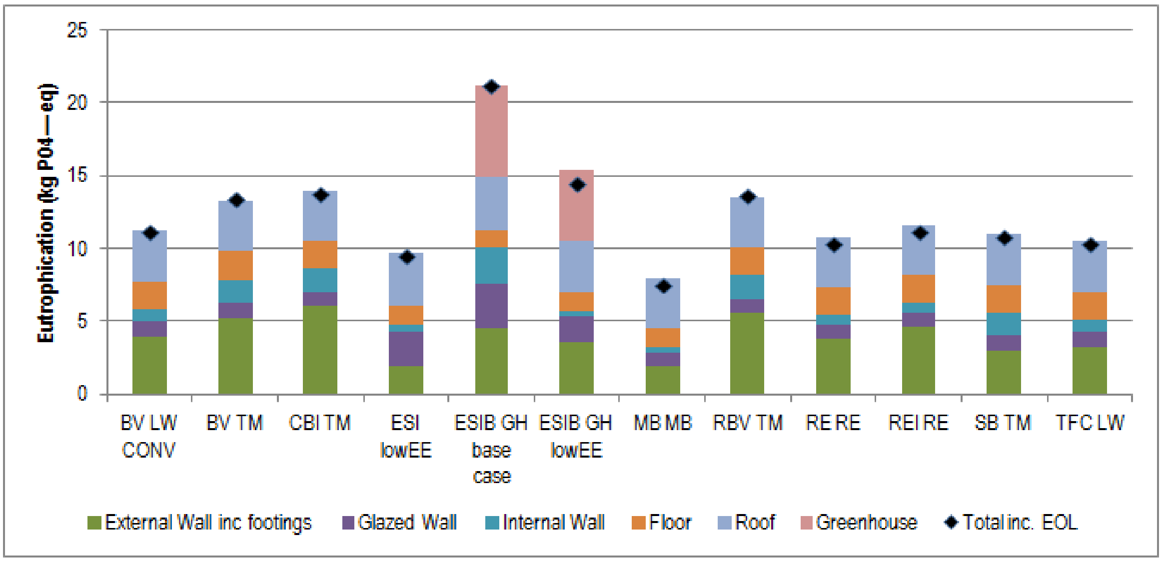

Figure 7.35 - Eutrophication, Thermal Envelope, Characterisation

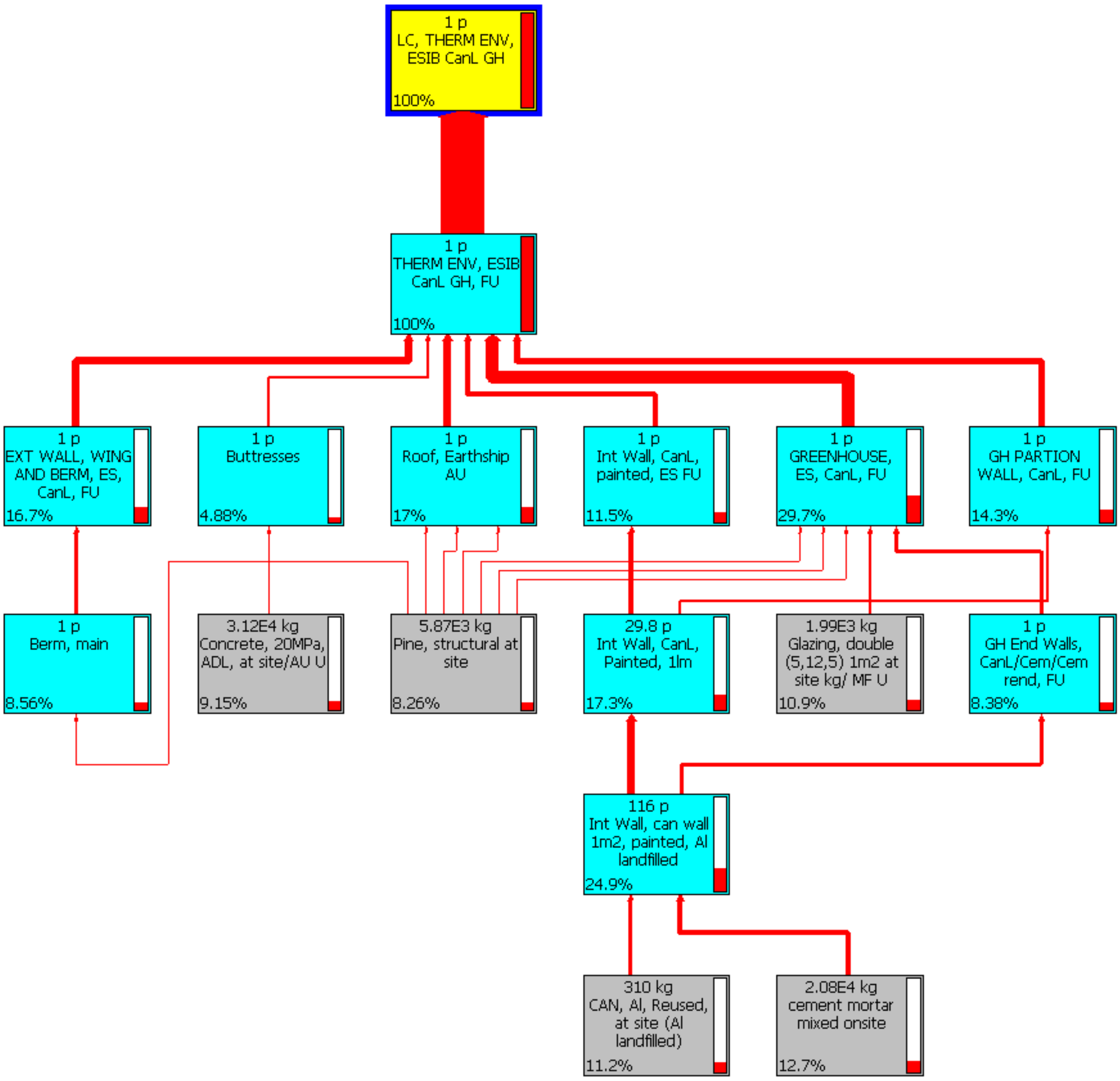

Figure 7.36 - Eutrophication, network diagram 8% cut off, Earthship Base Case

7.4.5 Land Use & Transformation for Thermal Envelope

Characterisation results for the Thermal Envelopes' Land Use & Transformation potential are given in Figure 7.37. The results for land use and transformation are driven by use of timber products such as plywood and structural pine, especially in the roof construction (Figure 7.38) which is responsible for the majority of emissions. The Earthship roof has greater impact due to increased use of ply and structural pine compared to the gable roof.

After roof construction, external wall (and footing) construction has the most influence and is the factor that determines the rankings of overall impact. Mudbrick has the lowest impact, and Rammed Earth, Rammed Earth Insulated, Strawbale and Concrete Block Insulated all have very similar land use results.

The Earthship glazed wall category has relatively high land use impact due to inclusion of a structural pine beam not assumed in the other envelopes.

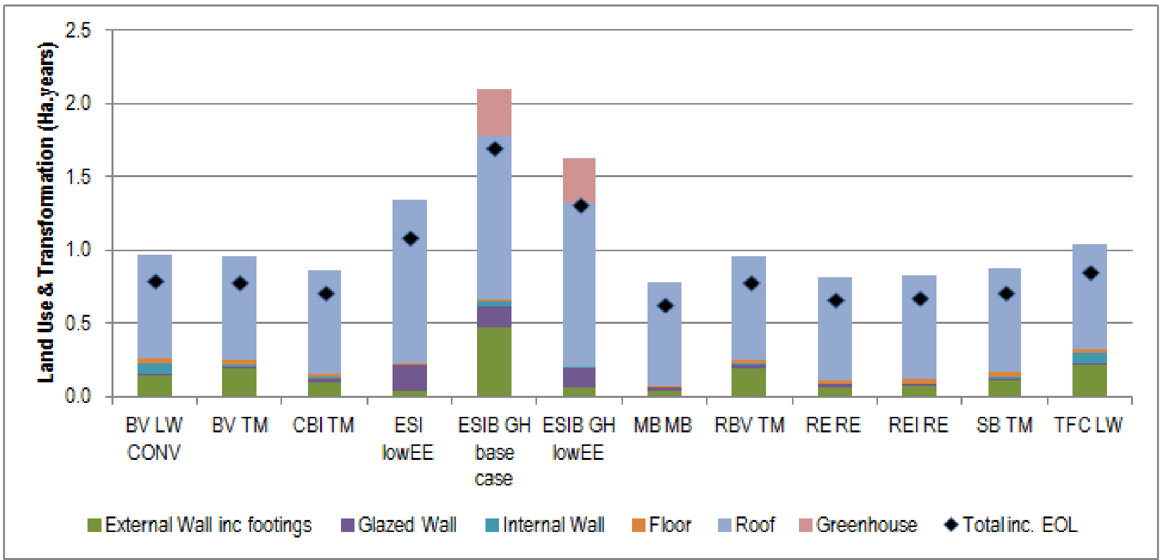

Figure 7.37 - Land Use & Transformation, Thermal Envelope, Characterisation

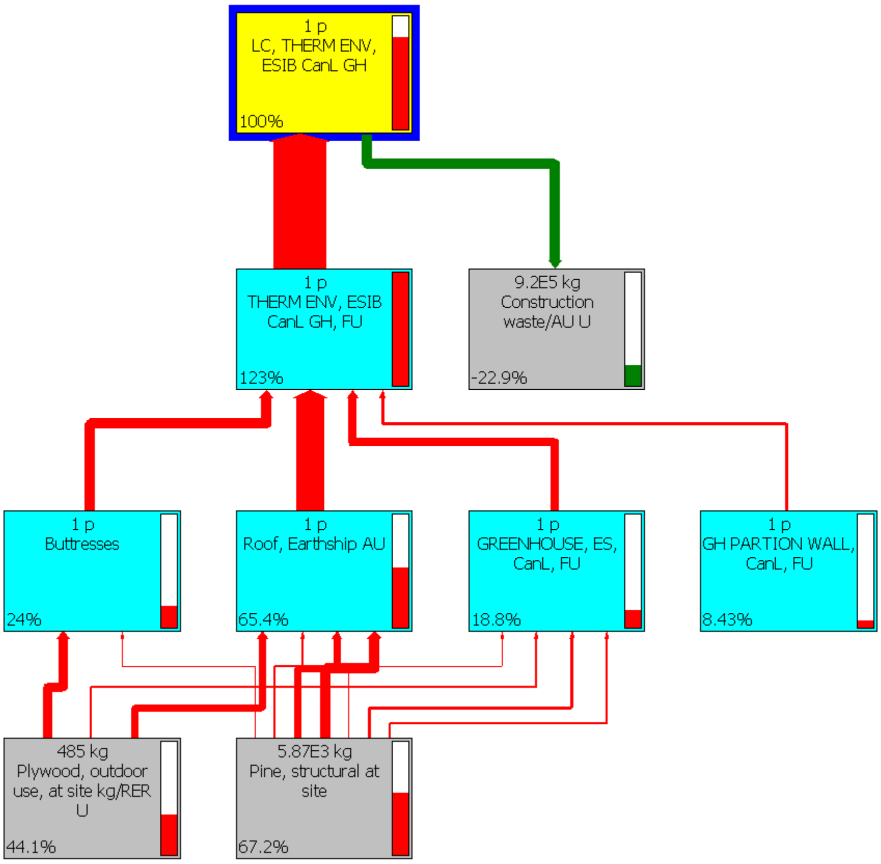

Figure 7.38 - Land Use & Transformation, network diagram 5% cut off, Earthship Base Case

7.4.6 Water Use & Depletion for Thermal Envelope

Characterisation results for the Thermal Envelopes' Water Use & Depletion potential are given in Figure 7.39. Brick Veneer (BV LW CONV) has the lowest water use before and after EOL credits are taken into account. The EOL credits are due to avoided water use arising from avoided aggregate production.

The Earthship greenhouse has the highest proportion of water use due mainly to cement used in the walls and polyurethane rigid foam insulation(Figure 7.40).

Both floor types; mud and concrete, use similar amounts of water as do the two types of roof construction.

The high water use in the Earthship external wall is associated with expanded polystyrene foam insulation and jute geofabric which are used in the berm (the berm is counted in the External Wall inc Footings category).

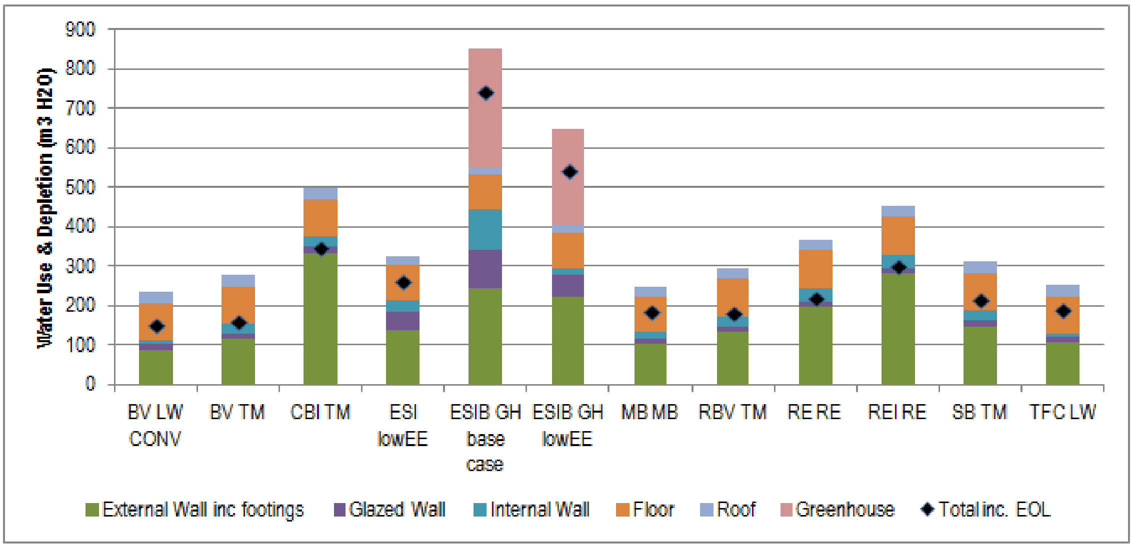

Figure 7.39 - Water Use & Depletion, Thermal Envelope, Characterisation

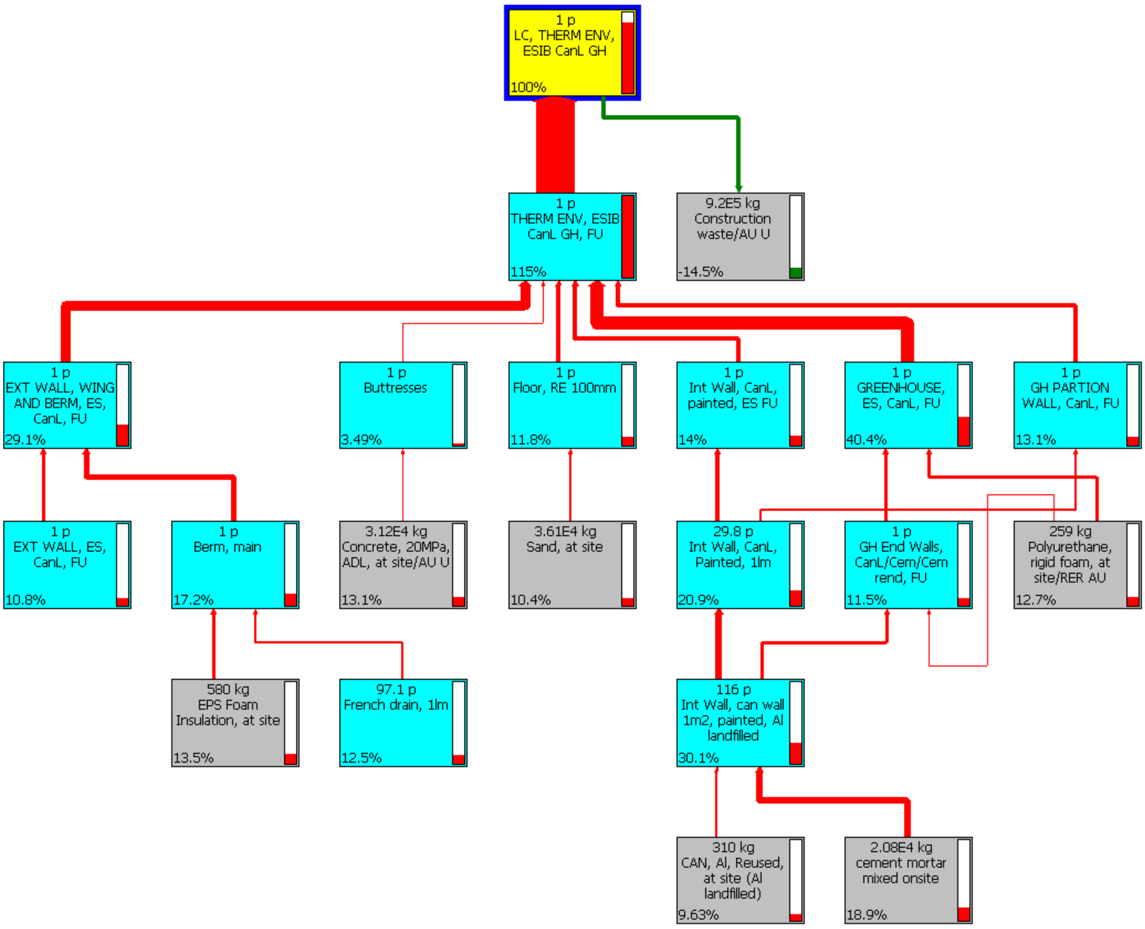

Figure 7.40 - Water use & depletion, network diagram 8% cut off, Earthship Base Case

7.4.7 Solid Waste for Thermal Envelope

Characterisation results for the Thermal Envelopes' Solid Waste potential are given in Figure 7.41. The manner in which the results are categorised is somewhat deceptive due to the way SimaPro™ handles the waste "flows": waste generated during the EOL stage (typically the bulk of the waste) aggregates waste from all construction elements whereas waste generated during the manufacturing stage is categorised as per the construction elements.

Therefore, to help clarify the source of the EOL waste flows, network diagrams for the floor and roof constructions are included:

- Figure 7.42 shows the quantity of EOL waste from the gable roof construction which includes 811kg of "inert waste" such as fibreglass insulation, 1.53 tonnes of timber, and 1.12 tonnes of "other" waste such as plasterboard (used for the ceiling). 122 kg of steel is recycled.
- Figure 7.43 shows the EOL waste sources for the "Australianised" Earthship roof. Approximately 3 tonnes of timber and 720kg of inert waste are assumed to be landfilled.
- Figure 7.44 shows the quantity of EOL waste from the 29 tonne concrete slab floor construction. Approximately 1.5 tonnes of waste is generated which correlates with the assumption that 5% of concrete is landfilled; the remainder is recycled into aggregates and is not counted in this waste flow.
- Figure 7.45 shows the waste sources for the rammed earth floor. 1.24 tonnes of "inert waste" is assumed to be landfilled.

The Concrete Block Insulated thermal envelope has the highest solid waste potential due to the large amount of cement used in the external wall for which waste is generated during the cement and concrete production processes. A large portion of the EOL waste category (brown colour column graph) is due to wall demolition, despite the assumption that large proportions of materials are recycled or reused, for example, 95% of concrete is assumed to be recycled yet for the CBI wall which embodies 58.6 tonnes of concrete in the wall plus 23.6 tonnes of concrete in the footing (total 82.2 tonnes) 5% of this, assumed as waste, equals 4.1 tonnes. The remainder is accounted for by the un-recycled or un-reused materials in the floor, roof, and glazing, such as timber, of which 20% is assumed to be reused, the rest landfilled.

Mudbrick has the least solid waste due to the assumption that the Mudbricks are able to disintegrate back into the ground, on site.

The Earthship without berm (ESI) has the second lowest solid waste impact whereas the Earthship Base Case has the second highest due in large part to the relatively large quantity of concrete that needs to be disposed of – comparable to Concrete Block Insulated.

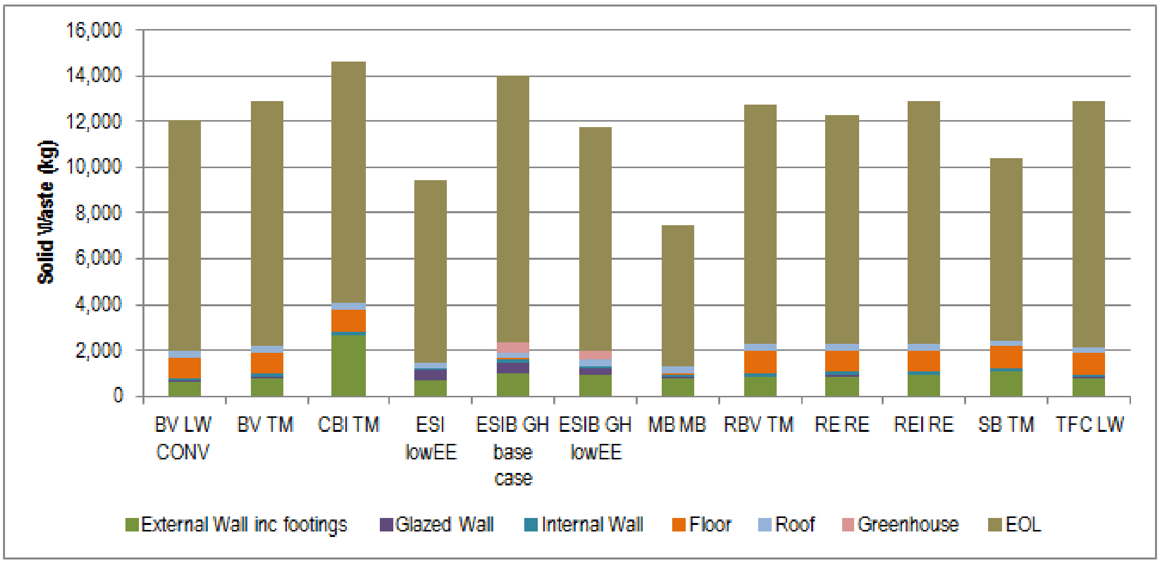

Figure 7.41 - Solid Waste, Thermal Envelope, Characterisation

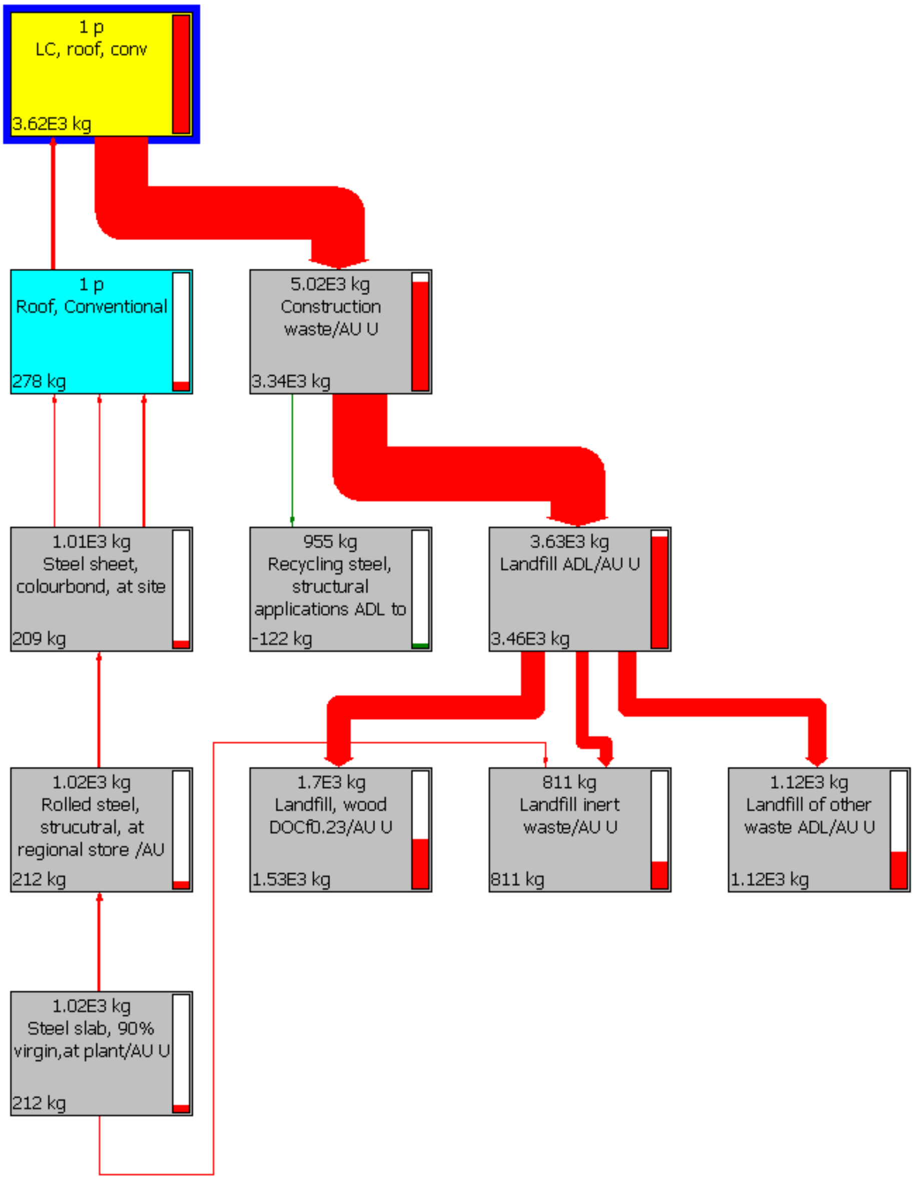

Figure 7.42 - Solid Waste, network diagram, 2% cut off, gable roof

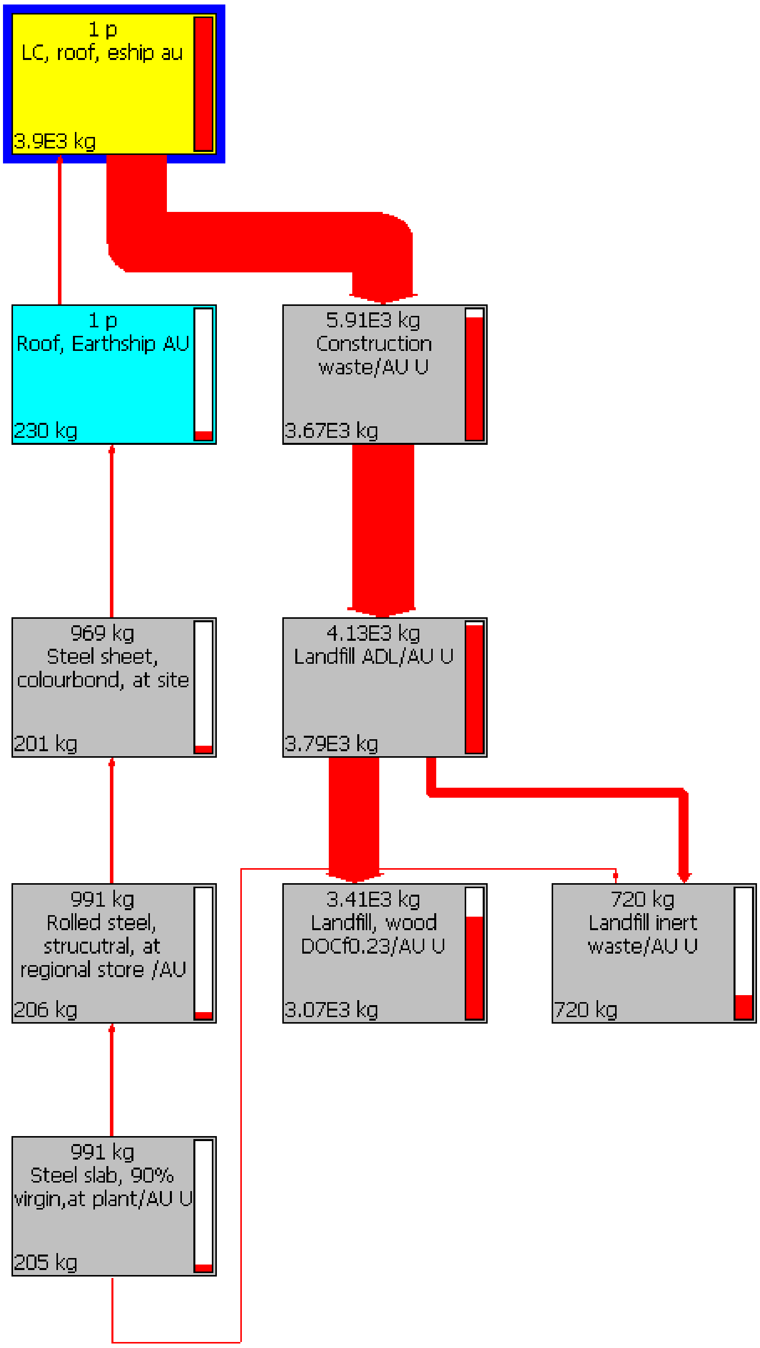

Figure 7.43 - Solid Waste, network diagram, 5% cut off, Earthship roof

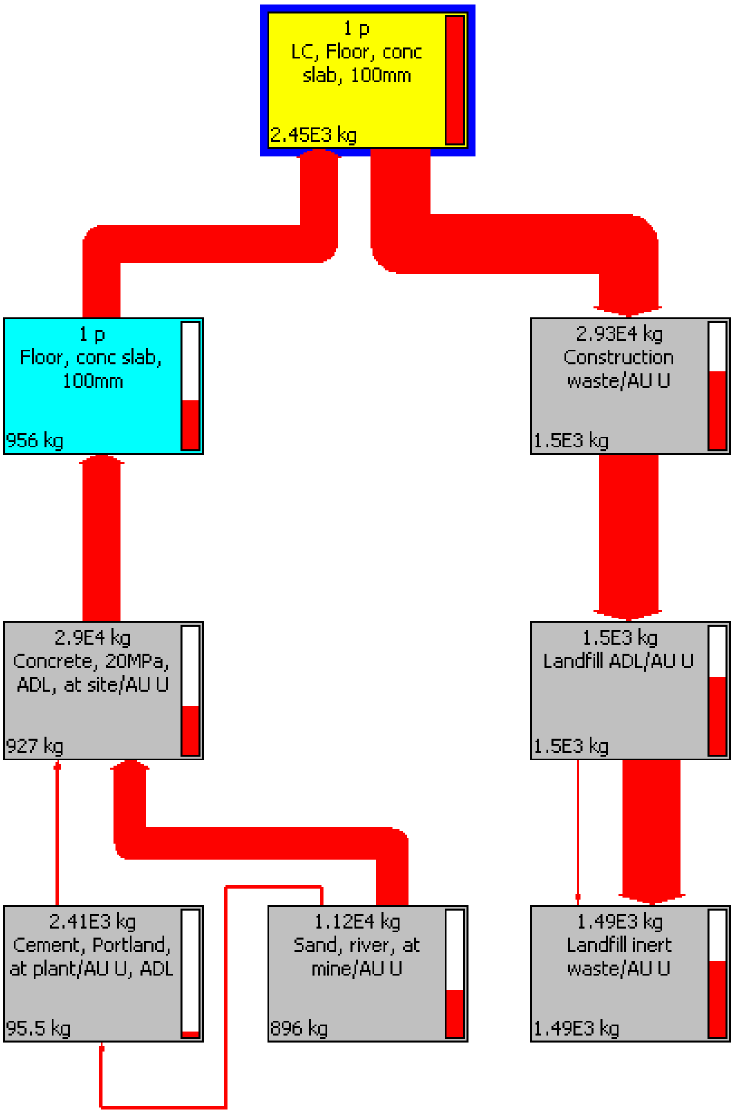

Figure 7.44 - Solid Waste, network diagram, 2% cut off, concrete floor slab

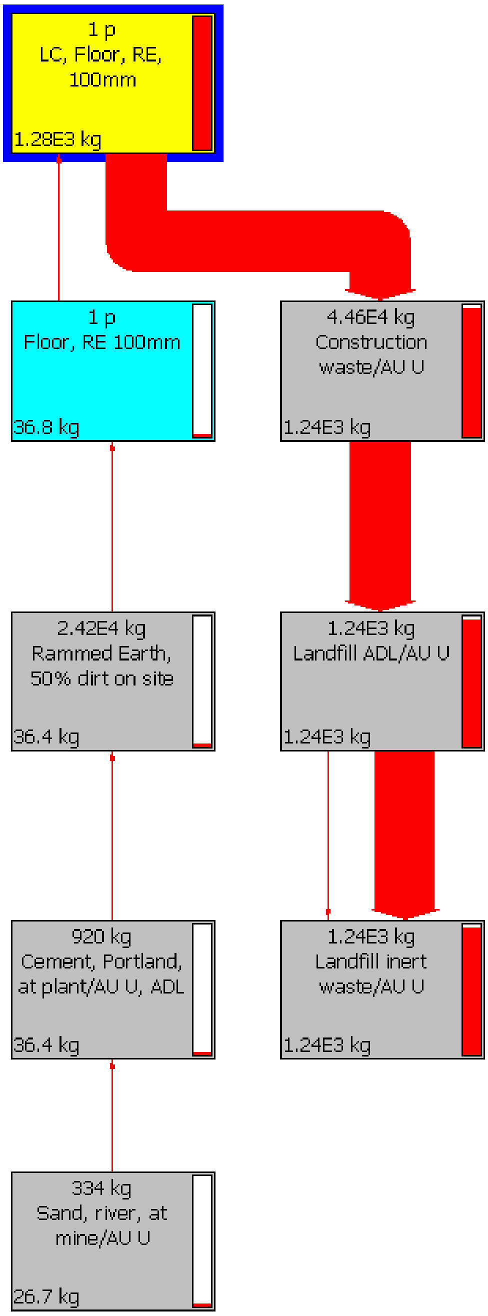

Figure 7.45 - Solid Waste, network diagram, 1% cut off, rammed earth floor

7.4.8 Embodied Energy for Thermal Envelope

Characterisation results for the Thermal Envelopes' Embodied Energy potential are given in Figure 7.46.

As is the case for the external wall analysis, the Embodied Energy characterisation of the various thermal envelopes is similar to the GWP characterisation. The Earthship Base Case has the highest embodied energy, due mainly to cement use, whereas the lowEE Earthship's embodied energy is approximately 29% less due to minimising cement use and recycling aluminium cans at EOL. The Earthship without berm and greenhouse (ESI lowEE) has the second to lowest embodied energy use, Mudbrick having the least.

In terms of the Earthship Base Case, the roof contains the most embodied energy (27%), followed by the greenhouse (24.1%) and external wall and berm (15.5%) (Figure 7.47).

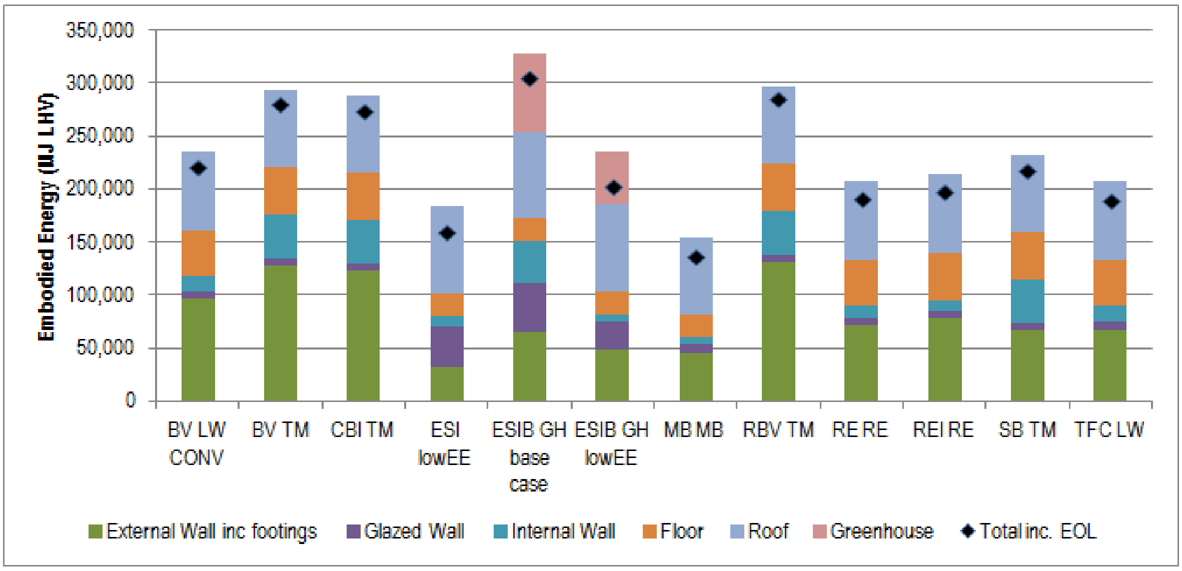

Figure 7.46 - Embodied Energy, Thermal Envelope, Characterisation

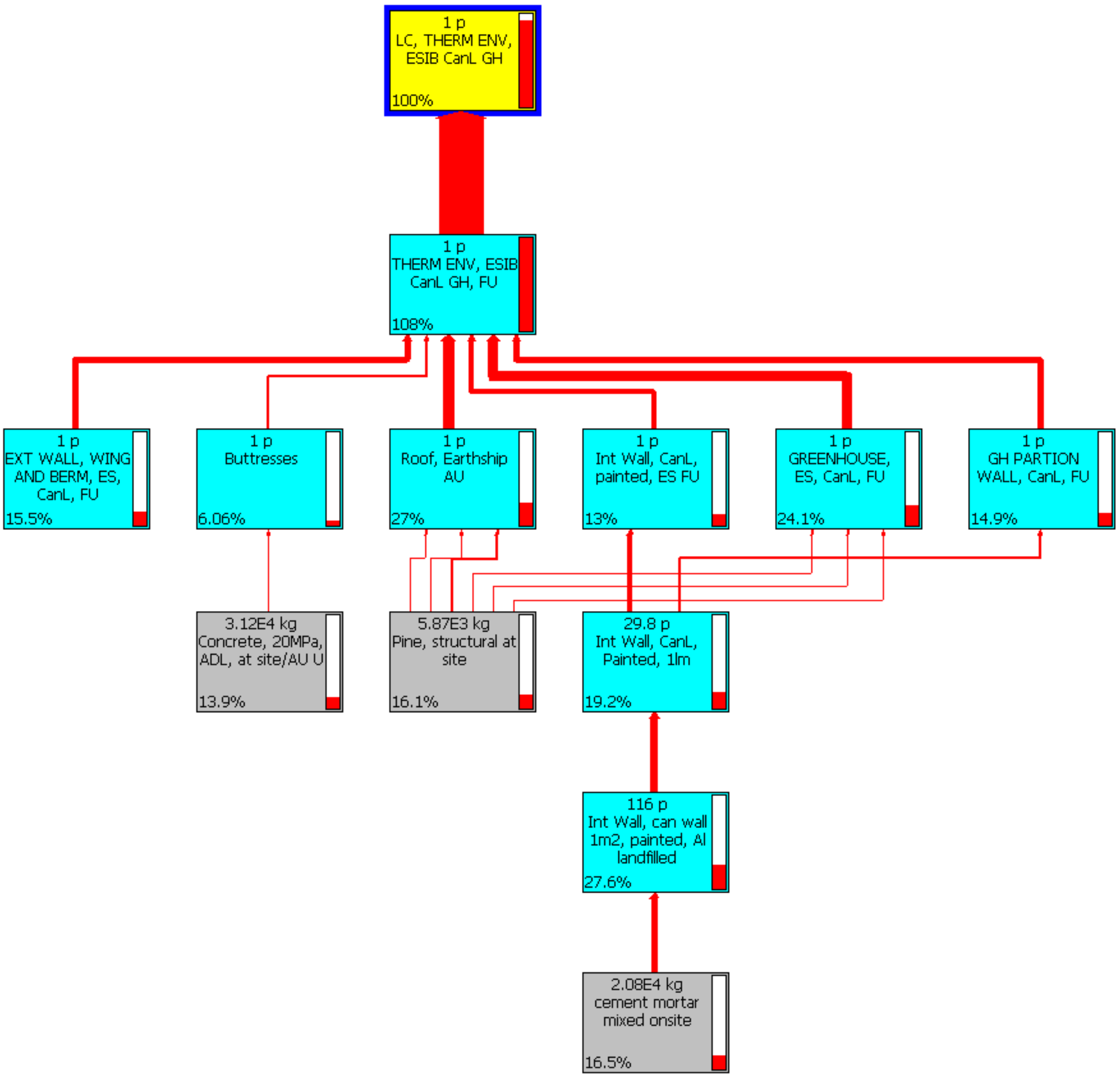

Figure 7.47 - Embodied Energy, network diagram 10% cut off, Earthship Base Case

7.4.9 Human Toxicity, Carcinogenic for Thermal Envelope

Characterisation results for the Thermal Envelopes' Carcinogenic Toxicity potential are given in Figure 7.48. The Thermal Mass (TM) Internal Wall, which is made from fired clay brick, causes a significant proportion of the carcinogenic human toxicity potential in the thermal envelopes where this internal wall type has been specified: BV TM, CBI TM, RBV TM and SB TM.

Toxicity associated with the roof construction is due mainly to "melamine formaldehyde resin" in the plywood which emits formaldehyde to the air (282g of formaldehyde per tonne of plywood AUSLCI/SIMAPRO™). This is evident in the network diagram of the Earthship Base Case which shows the majority of impacts arising from plywood, pine timber and production of aluminium - to replace landfilled aluminium cans (Figure 7.49).

Substances contributing more than 1% of non-carcinogenic toxicity potential to the Earthship Base Case Thermal Envelope (ESIB GH BASE CASE) inventory are listed and compared to national average emissions (where data is available) in Section 7.4.12.

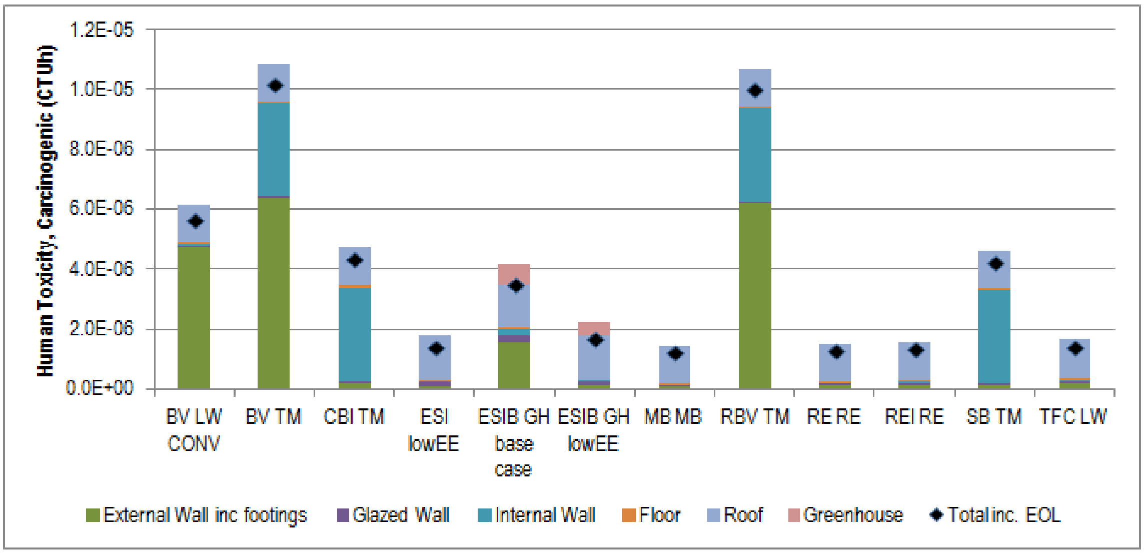

Figure 7.48 - Human Toxicity Carcinogenic, Thermal Envelope, Characterisation

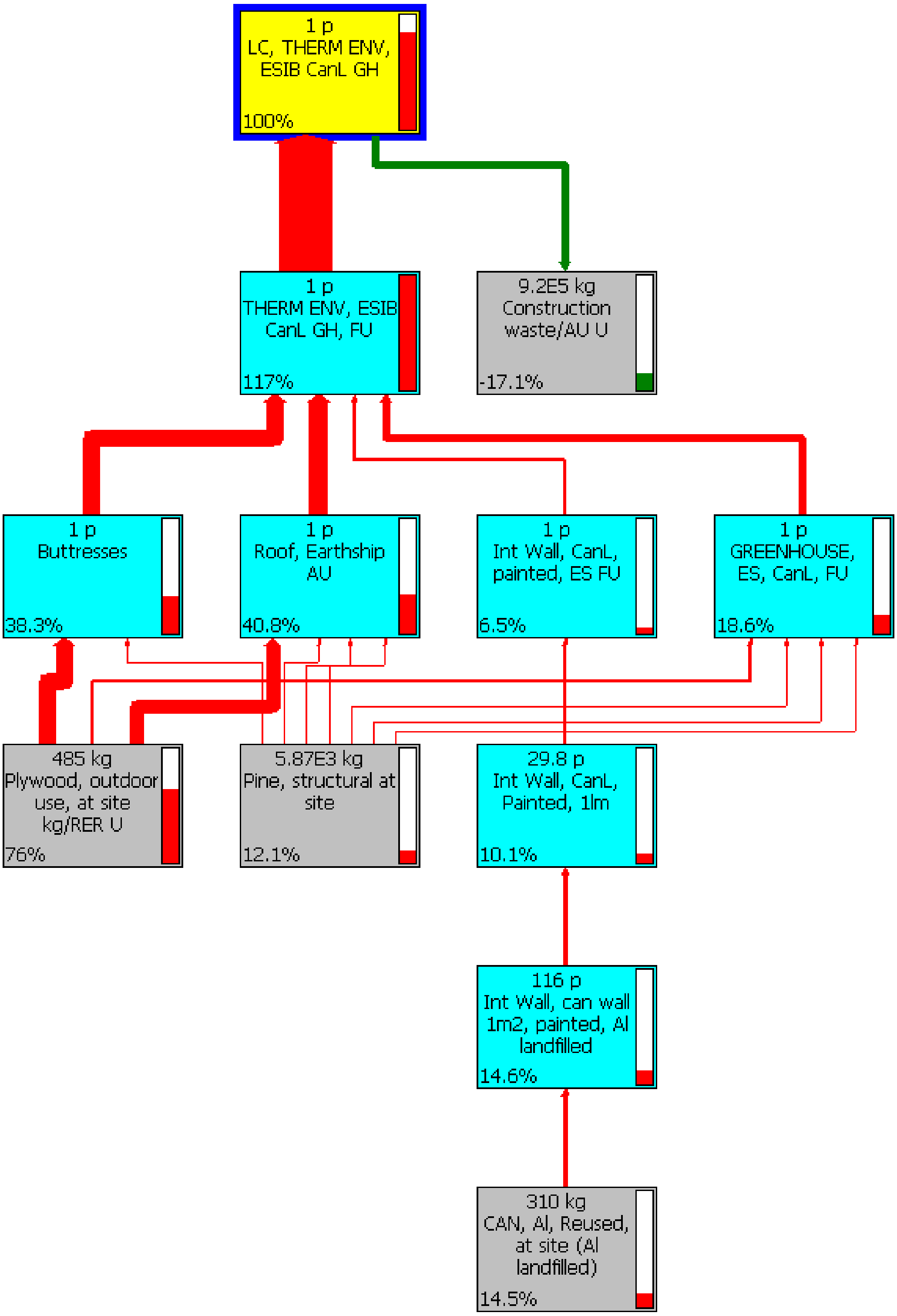

Figure 7.49 - Human Toxicity - Carcinogenic, network diagram, 5% cut off, Earthship Base Case

7.4.10 Human Toxicity, Non-Carcinogenic for Thermal Envelope

Characterisation results for the Thermal Envelopes' Non-Carcinogenic Toxicity potential are given in Figure 7.50

The materials causing the majority of non-carcinogenic human toxicity are:

- Zeolite powder which is used in the double glazed units, relevant to all thermal envelopes, and especially to the "greenhouse" category in which it represents most of the toxic impact;
- Jute geofabric (toxicity caused presumably by farming practices that involve chemicals) which is modelled in the "external wall inc footings" and "greenhouse" category;
- Aluminium (cans in "can walls") and cement.

In terms of the Earthship Base Case, the greenhouse has the largest proportion of emissions, followed by the roof, glazed wall, and external walls (including berm)(Figure 7.51).

Substances contributing more than 1% of Non-Carcinogenic Toxicity potential to the Earthship Base Case Thermal Envelope (ESIB GH BASE CASE) inventory are listed and compared to national average emissions (where data is available) in Section 7.4.12.

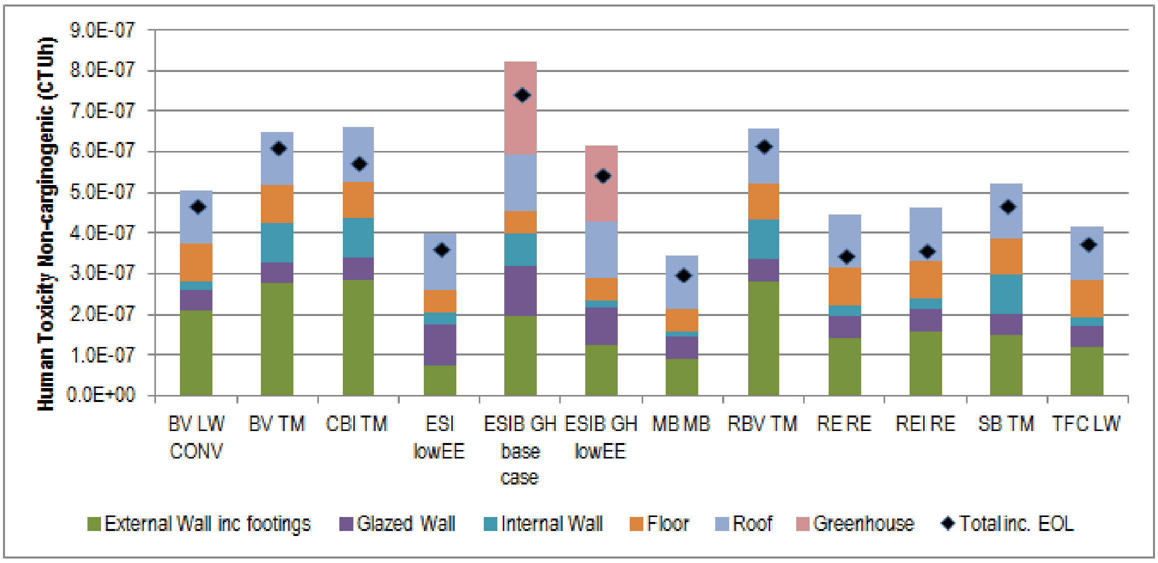

Figure 7.50 - Human Toxicity Non-carcinogenic, Thermal Envelope, Characterisation

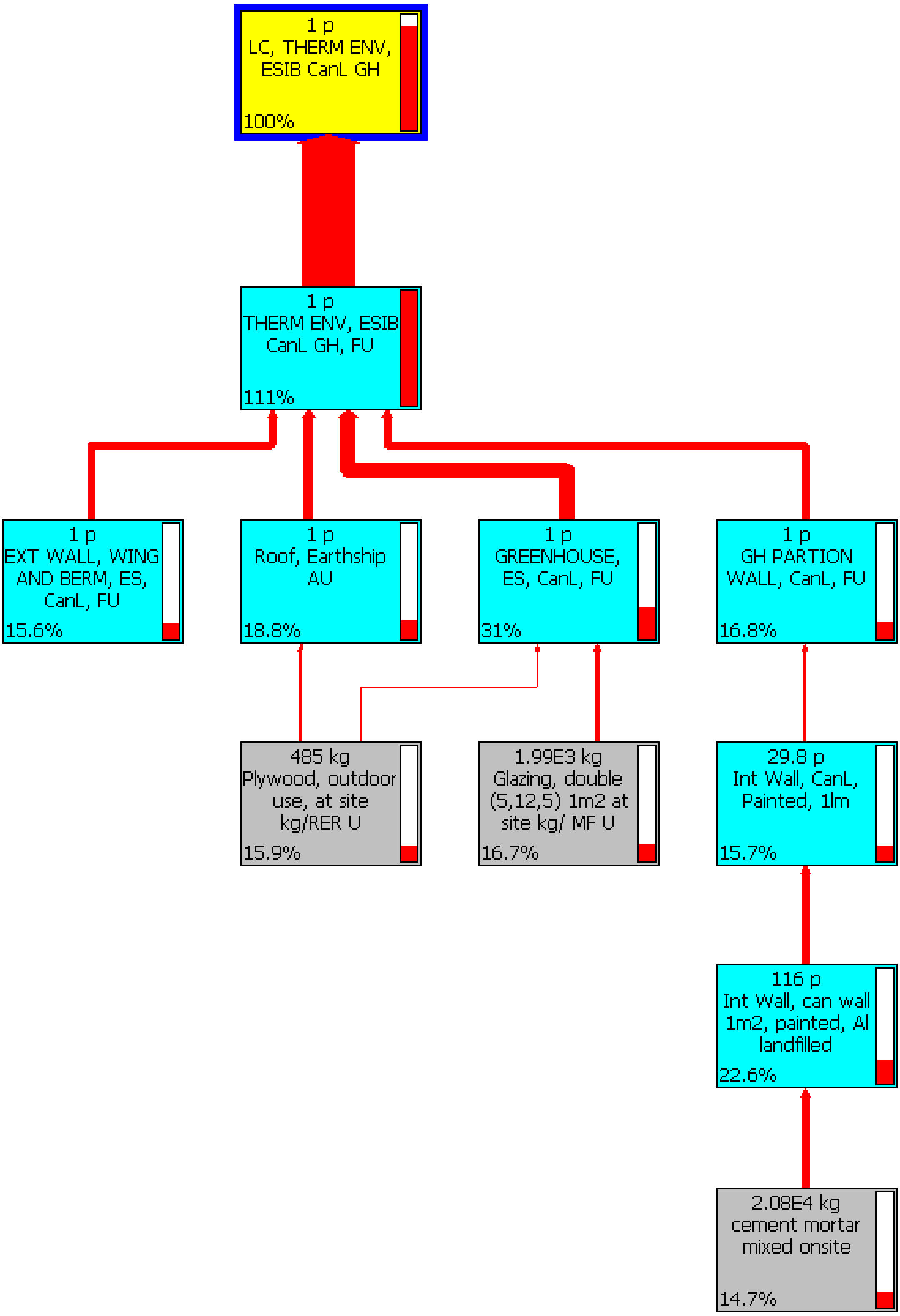

Figure 7.51 - Human Toxicity, Non-Carcinogenic, network diagram, 10% cut off, Earthship Base Case

7.4.11 Eco Toxicity for Thermal Envelope

Characterisation results for the Thermal Envelopes' Eco Toxicity potential are given in Figure 7.52

Substances contributing more than 1% of non-carcinogenic toxicity potential to the Earthship Base Case Thermal Envelope (ESIB GH BASE CASE) inventory are listed below. The main cause of eco toxicity is the growing of jute to make the geofabric, which is present in the "external wall inc footings" and "greenhouse elements" due to its use in the main berm and the small berm to the outside of the greenhouse wall. Jute production causes the release of chlorothalonil to soil, parathion to soil, phenol to water according to the EcoInvent LCI data (European) used to model this material.

Substances contributing more than 1% of Non-Carcinogenic Toxicity potential to the Earthship Base Case Thermal Envelope (ESIB GH BASE CASE) inventory are listed and compared to national average emissions (where data is available) in Section 7.4.12.

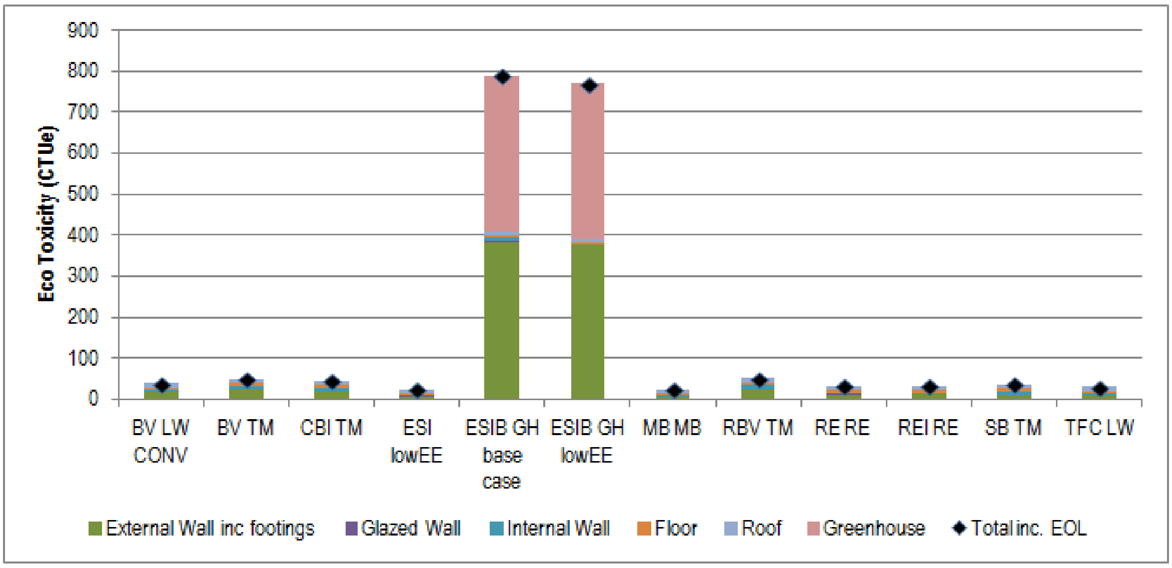

Figure 7.52 - Eco-Toxicity, Thermal Envelope, Characterisation

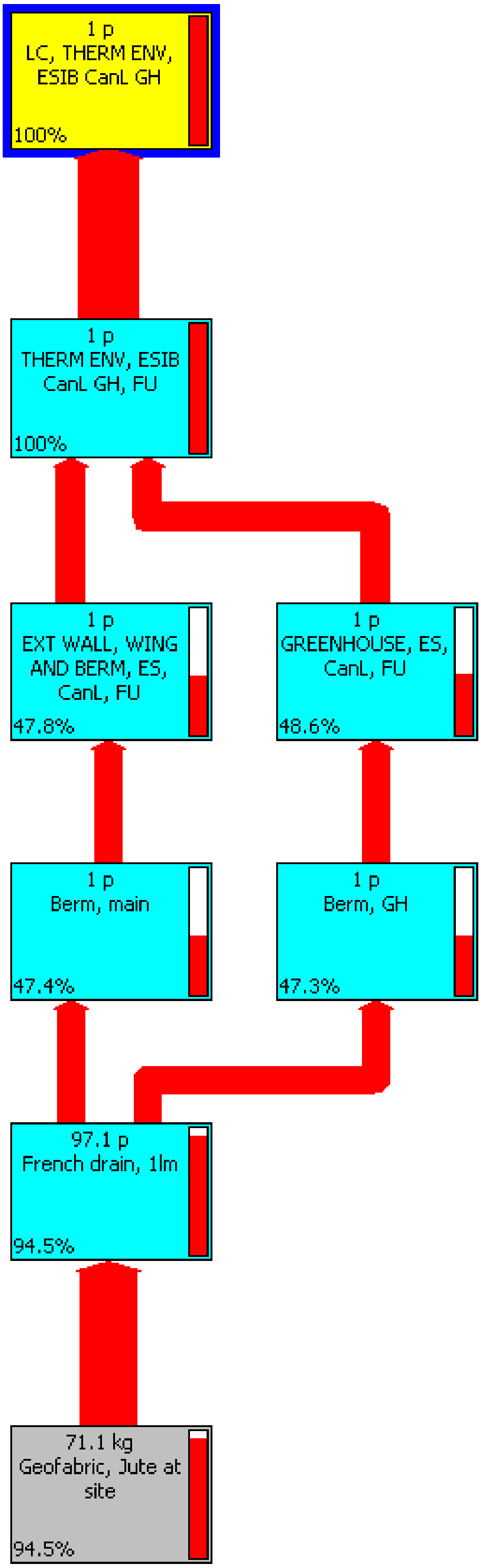

Figure 7.53 - Eco Toxicity, network diagram, 10% cut off, Earthship Base Case

7.4.12 Toxicity Analysis for Thermal Envelope

Table 7.5 lists the toxic substances contributing to more than one percent of impacts for each toxicity indicator for the Earthship Base Case compared with the Australian National Pollutant Inventory (NPI) (Commonwealth of Australia: Department of Sustainability, n.d.) annual emissions data (where data is available).

The "emission ratio" gives a number that represents the number of Earthship Base Case Thermal Envelopes that would produce the annual Australian average emissions of each substance based on data from 2011/12. The emission of toxic substances involved with the manufacture of the construction materials used in the Earthship Thermal Envelope are generally millions of times less than the annual emissions from general industry indicating that the scale of emissions from its lifecycle are relatively insignificant.

These results should also be considered in terms of the total number of houses constructed per annum which, based on figures produced by the Australian Bureau of Statistics for 2008-2014 (approximately 8000 homes constructed per month), is about 96,000 homes (Australian Bureau of Statistics, 2014).

Furthermore, the toxicity results are highly influenced by assumptions that are specific to a specific manufacturing process and may not "translate" to other circumstances. For example the high eco toxicity related to jute geofabric arises from the assumption that various synthetic chemicals are used in the production of jute, whereas it is possible that jute may also be grown organically without the use of such chemicals, or with different, less toxic chemicals.

Table 7.5 - Toxic substances from Earthship Base Case construction materials

Substance	Source	NPI 2011/12 ton p.a.	Earthship Base Case Emission	Unit	Emission Ratio
Aldrin	Cement manuf.	No data	91.3	mg	-
Benzene	Energy for steel manufacture, (roof)	610	101	g	6,039,604
Carbon disulfide	zeolite powder in double glazed units, also jute production	75	13.5	g	5,555,556
Chlorothalonil	jute geofabric (berm)	No data-	197	mg	-
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Sheet steel (roof)	No data-	15.1	mcg	-
Formaldehyde	Plywood (buttress formwork)	2100	181	g	11,602,210
Parathion	jute geofabric (berm)	-	8.88	g	
Phenol	jute geofabric (berm)	77	12.8	g	6,015,625
Styrene	energy source for EPS foam manufacture	200	26.2	g	7,633,588
Toluene	energy source for cement manufacture and EPS	1400	61.6	g	22,727,273
Xylene	energy source for cement manufacture and EPS	1000	43.7	g	22,883,295

7.4.13 Normalisation of Impacts for Thermal Envelope

Normalising the characterisation results against 50 years of per capita average values for each impact category, Solid Waste is indicated as having relatively more significance than the other impact categories (Figure 7.54). Every 0.02 on the y-axis represents one year of average Australian "emissions", therefore a range of 5.5 to 10.5 years' worth of waste generation is accounted for by the various thermal envelopes when they are demolished. This is not surprising given that the demolition of a house – the main contributor to the Solid Waste indicator – generates large volumes of waste, equivalent to many years of non-building domestic waste production.

Considering the average impact of all thermal envelopes in each impact category, Global Warming Potential and Eutrophication have similar levels of significance, more so than Water Use and Embodied Energy which have approximately half the significance of GWP. Ozone Depletion, Photochemical Oxidation and Land Use have relatively minor significance.

The ESI lowEE Earthship scenario shows the lowest GWP, accounting for approximately 4 months of Australian average annual per capita emissions, whereas the Base Case Earthship is the highest, accounting for approximately 11 months.

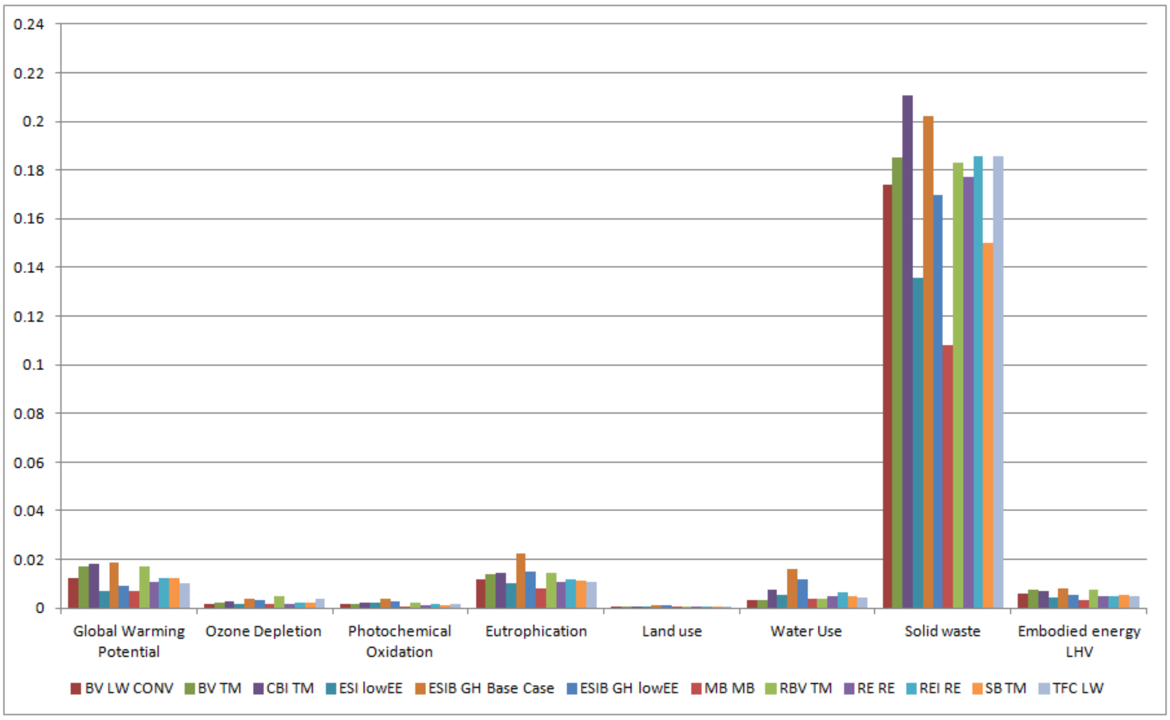

Figure 7.54 - Normalisation of Thermal Envelope Results

7.4.14 Weighted Single Score for Impacts, for Thermal Envelope

The weighted results for the Thermal Envelopes have been analysed using the same method as for the External Walls (refer to 7.3.13): results have been ranked using all indicators with the exception of the three toxicity indicators (Figure 7.55) and the ranking sensitivity has been tested via studies that:

1) Discount solid waste and embodied energy (Figure 7.56),

2) Add 20% to the weighting of the non-GWP indicators (Figure 7.57) and

3) Subtract 20% from the weighting of the non-GWP indicators (Figure 7.58).

Discounting solid waste and embodied energy improves the ranking of TFC and BV LW CONV by 2 places each, whereas SB TM and ESIB GH lowEE increase ranking by 3 and 1 place respectively. Ranking of all other Thermal Envelopes are unaffected. These ranking changes are shown by black arrows.

When the weighting of non-GWP indicators is increased by 20 percent, REI RE decreases ranking by one and ESIB lowEE increases by one ranking (compared to sensitivity study 1), yet when they are decreased by 20 percent, the ranking changes slightly for three thermal envelopes: ESIB GH lowEE decreases (improves) 2 places, and BV TM CONV and SB TM increase by one ranking (compared to sensitivity study 1).

Mudbrick has the lowest score and the Earthship Base Case has the highest in all sensitivity studies. The lowEE Earthship with Greenhouse is ranked 6th or if Solid Waste and Embodied Energy is discounted, 7th; if the non-GWP indicators are increased it is ranked 8th and if non-GWP indicators are decreased it is ranked 5th. ESI lowEE (without greenhouse or berm) is ranked 2nd in all studies.

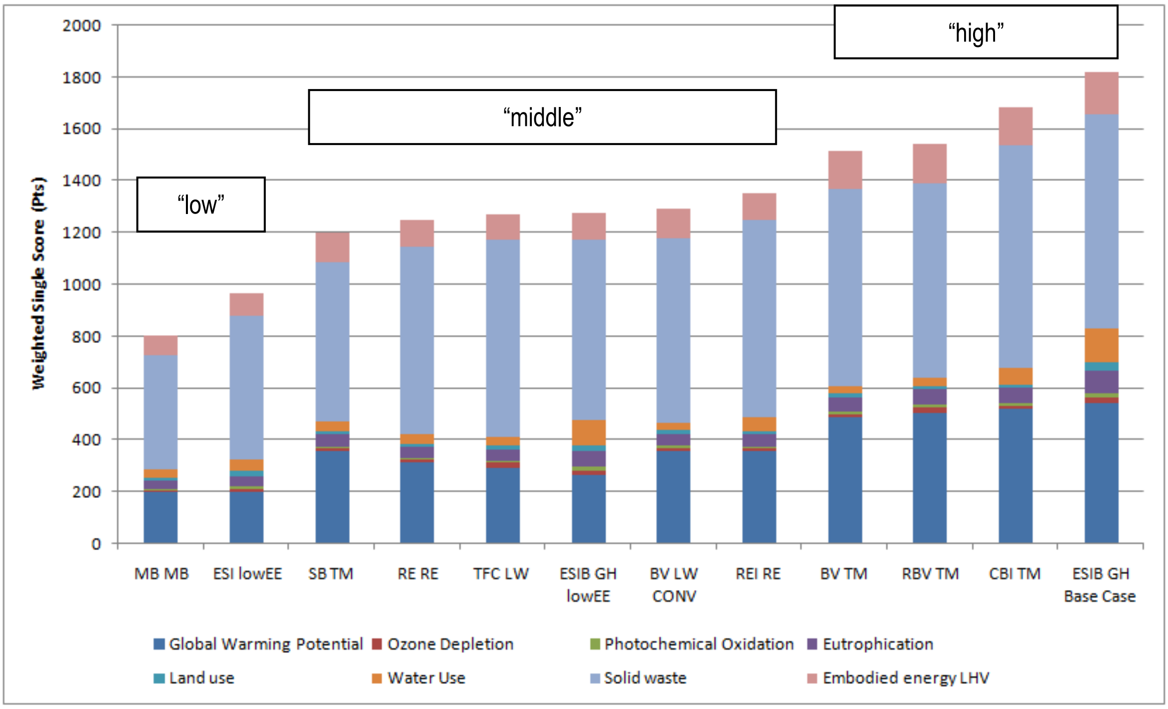

Figure 7.55 - Weighted Single Score, Thermal Envelopes, All Indicators

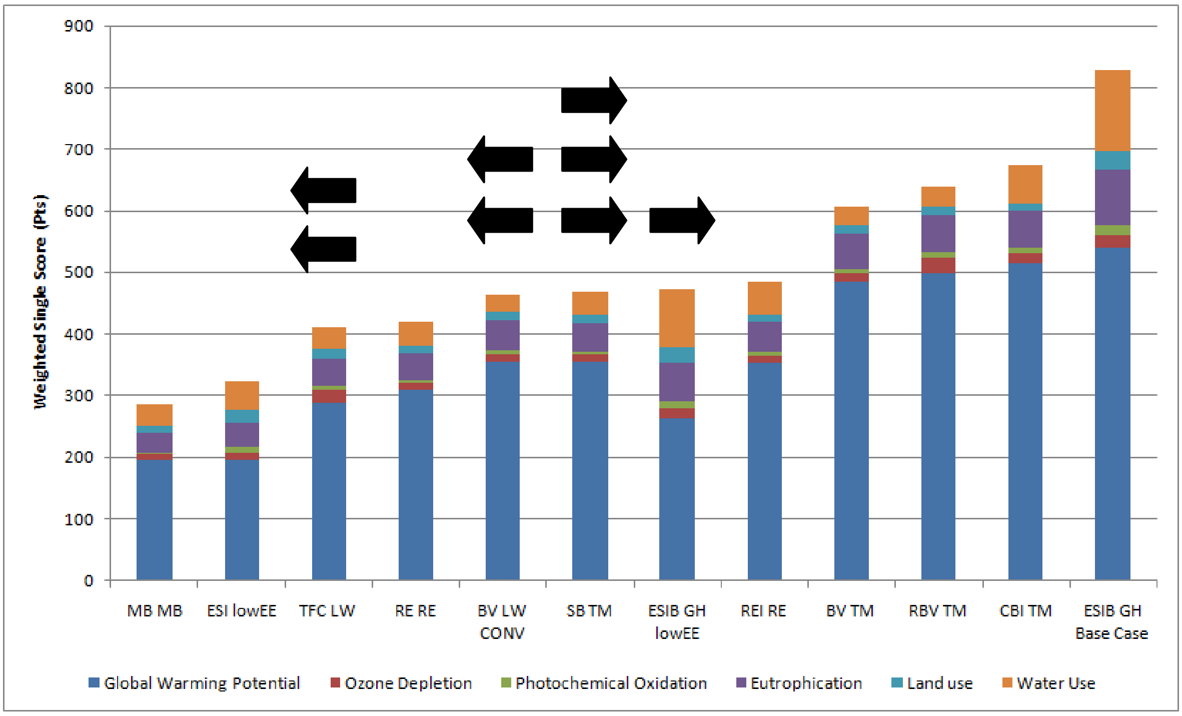

Figure 7.56 - Sensitivity Study 1: Weighted Single Score, Thermal Envelopes, Discounting Embodied Energy and Solid Waste

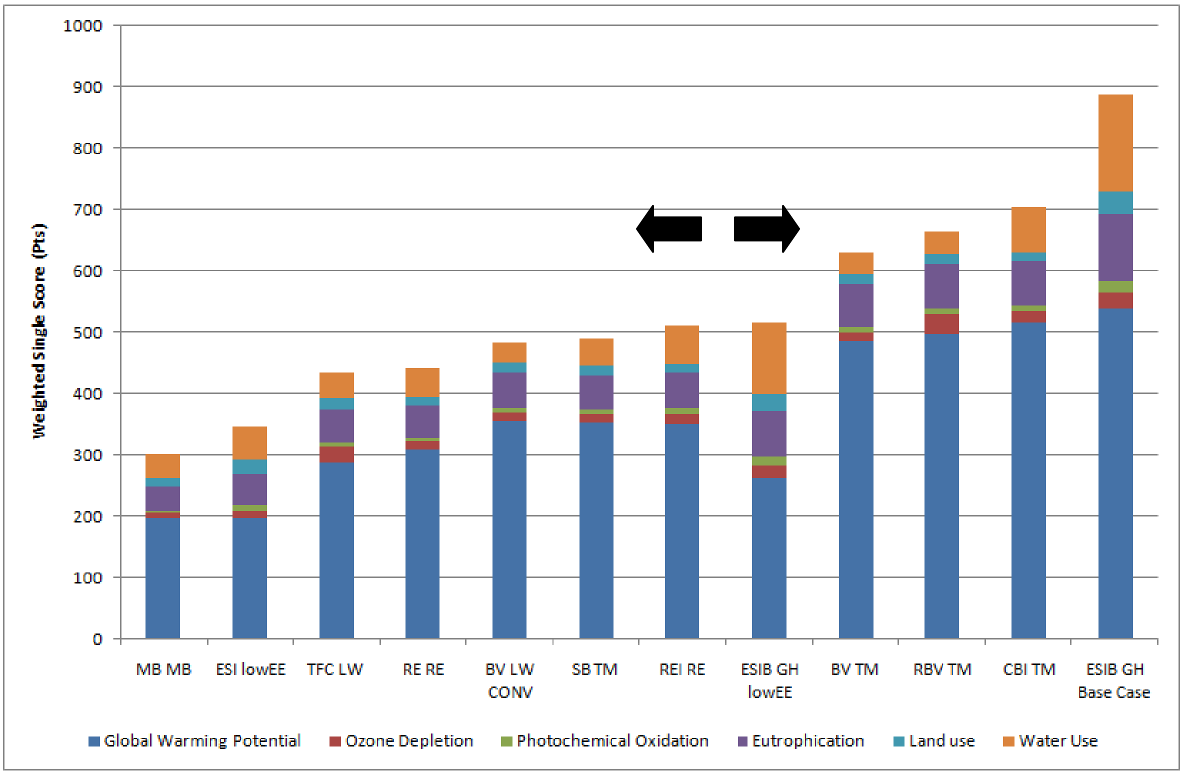

Figure 7.57 - Sensitivity Study 2: Plus 20% Weighting For Non GWP Indicators

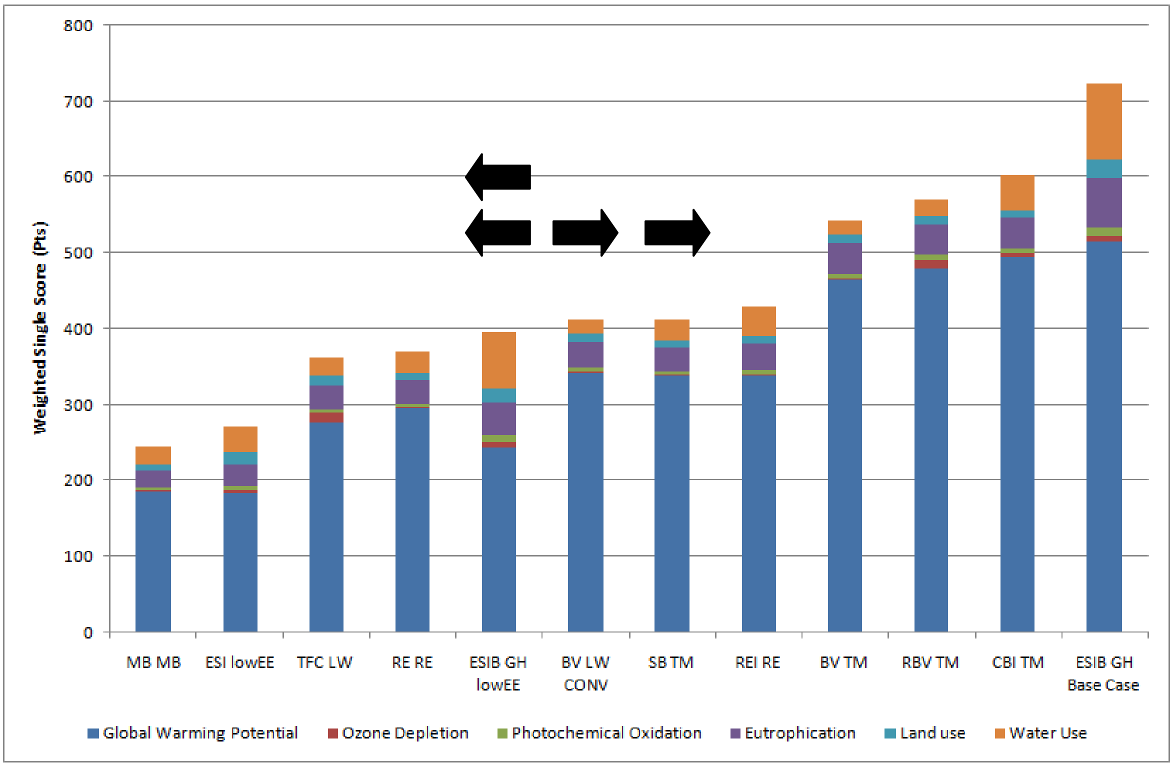

Figure 7.58 - Sensitivity Study 3: Minus 20% Weighting For Non GWP Indicators

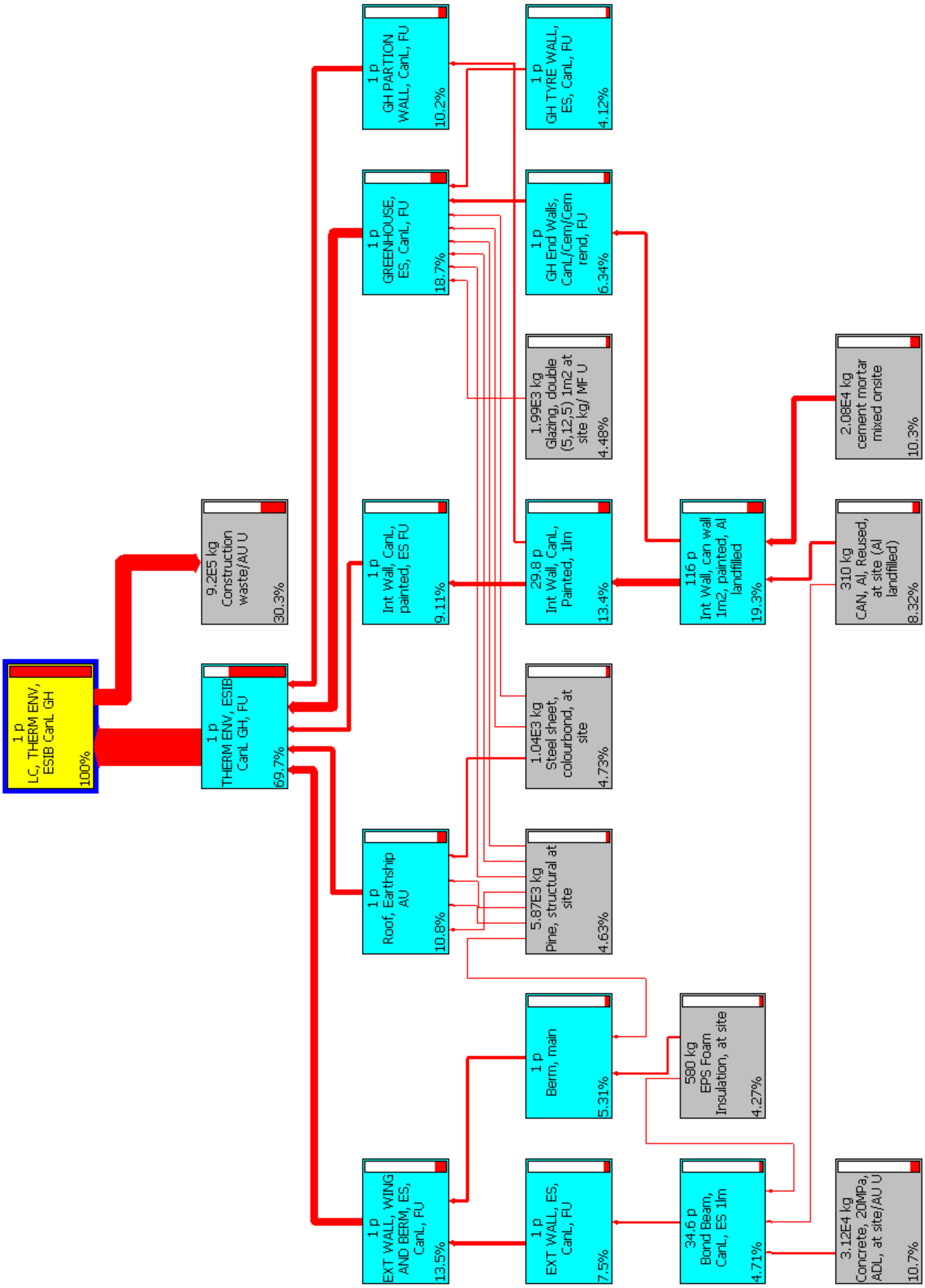

Figure 7.59 - Earthship Base Case, Weighted Single Score, 4% Cut Off

7.4.15 Discussion & Summary of Impacts for Thermal Envelope

The weighted single score indicates two thermal envelopes which stand out as having comparatively low impact: Mudbrick (MB MB) and the unbermed, insulated Earthship without greenhouse (ESI lowEE). A group of six thermal envelopes had fairly similar environmental impact in the middle range of the rankings: Timber Frame, Rammed Earth, Earthship, bermed with greenhouse (lowEE), conventional Brick Veneer (light weight walls with square floor plan), Strawbale and Rammed Earth Insulated. The remainder of thermal envelopes have approximately 30-70% more impact than those in the “middle range”: Brick Veneer (with brick internal walls), Reverse Brick Veneer, Concrete Block Insulated and Earthship Base Case.

The high environmental impact of the Earthship Base Case arises due to a combination of factors. The inclusion of a greenhouse, which is not counted in the other thermal envelopes with the one exception of the lowEE Earthship, contributes the greatest impact: approximately 27% of the impact of the entire thermal envelope, due to substantial quantities of double glazed units, timber, insulation and concrete render that comprise the greenhouse structure.

Similarly, another additional construction element of the Earthship Base Case is the berm. It causes impacts due mainly to the large quantity of insulation, and in terms of toxicity (although this is not factored into the weighted single score) the jute geofabric used in the drainage system of the berm leads to potential toxicity impacts due to the agricultural practices assumed in the production of jute.

The lowEE Earthship scenario however shows the potential to reduce the environmental impacts of the construction materials of the Earthship Base Case. The lowEE Earthship features a greenhouse and berm (ESIB GH lowEE) yet its impact is comparable to the “middle range” thermal envelopes mentioned above, none of which have a greenhouse or berm. This result was achieved by substituting the concrete buttresses with tyre buttresses, recycling the aluminium cans used in the bond beam, internal walls and glazed wall at the end of the building’s life, and replacing cement mortar throughout the building with adobe (mud and straw), using a thin layer of cement based render to protect the adobe wall in areas of the building that require water proofing – the greenhouse for example.

Furthermore, when the berm and greenhouse are removed from the thermal envelope of the Earthship and recycling of aluminium cans and cement mortar substitution by adobe is employed (ESI lowEE), the potential environmental impact of this variant of the Earthship drops to a similar “score” as the Mudbrick thermal envelope.

The rammed earth floor specified for the Earthship scenarios and Mudbrick scenarios reduces the GWP significantly in comparison to the reinforced concrete slab floor.

Roof design is not a significant differentiating factor due to similar quantities of steel, timber and insulation, in the “gable” and “Earthship” roof scenarios.

Analysis and comparison of the toxicity arising from the materials used in the Earthship Base Case is also relevant to the other scenarios where similar materials are used, for example steel for roofing, cement for footings and zeolite power for the double glazed units are applicable to all thermal envelopes. These results show that toxic emissions arising from the use of these construction materials represents a very small fraction of the total emitted in Australia on an annual basis. While it is desirable to reduce toxic emissions, the small fraction that the building materials represent is reassuring.

In summary, the analysis of the thermal envelope scenarios shows that external walls play a significant role in the final outcome. Some aspects of existing Earthship building systems, in particular the use of cement based mortar in “can walls”, lead to high environmental impacts, whereas replacing cement based mortar with adobe, and avoiding concrete buttresses by using tyre buttresses reduces the environmental impact significantly. It should be noted that these alternative methods have been employed by Earthship Biotecture on occasion but are not commonly used due to the speed with which Earthships are often built: compared to concrete, adobe takes much longer to dry, and pouring a concrete buttress is quicker and also takes up less floor space than a tyre buttress.

The importance of the thermal envelope's environmental impact will now be put into context with the other major elements of the house being factored into the "whole house" analysis. The energy system, water supply, and wastewater disposal systems will all be analysed individually in the following sections, culminating in the analysis of the whole house including the theoretical heating and cooling load, which was established in the Thermal Modelling study, and the impact of at-home food production which is common practice in the Earthship greenhouse.

7.5 Energy System

This section presents results and analysis of the Off-Grid Energy System and the Grid Connected Energy System. The two energy systems are compared on equal terms by analysing 5kWh electricity use per day over 50 years (total 91.25MWh) plus 2600MJ pa (gas) for cooking and 7470MJ pa (gas) for boosting the solar hot water service (SHWS). The Off-Grid system uses bottled LPG whereas "Grid" uses piped Natural Gas. This energy use is designed to fulfil all requirements except heating and cooling, which is modelled in the Whole House section of this Chapter (7.8), according to the thermal modelling study results (see LCI section for details regarding assumptions for energy use).

For each impact category the results are discussed in terms of the most influential processes and components, with an emphasis on the off-grid system, although the grid connected system is also discussed briefly.

7.5.1 Global Warming Potential for Energy System

The Global Warming Potential (GWP) of the South Australian energy supply ("Grid Energy South Australia") is approximately 2 times greater than the off-grid energy system ("Off Grid Energy System") when EOL credits are taken into account, even when allowing for replacement of batteries and solar panels. The impacts of the off-grid energy system arise mainly from the LPG used to boost the SHWS (solar hot water service), and secondly, from energy used in the manufacture of the renewable energy components, particularly the batteries and photovoltaic panels (labelled "Off-Grid *Electricity* System" in the legend of Figure 7.60), which represent approximately a third of the overall emissions of the off-grid system. Figure 7.60 compares the GWP of the two systems for 50 years.

Figure 7.61 shows the GWP impact of the major components of the off-grid electricity system (excluding gas backup), batteries being the major source of impact (75.3%), followed by photovoltaic panels (22.2%). Combustion of brown coal contributed the most emissions for the South Australian Grid Energy.

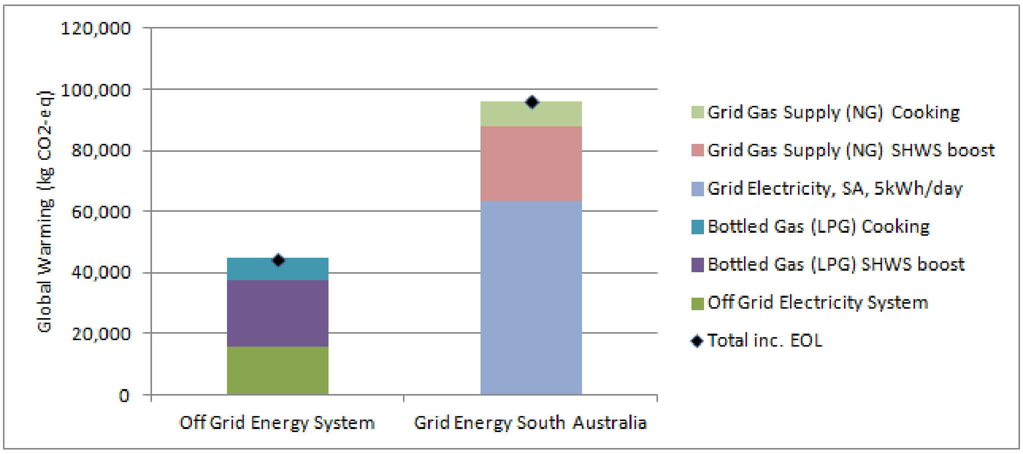

Figure 7.60 - Global Warming Potential, Energy Systems, Characterisation

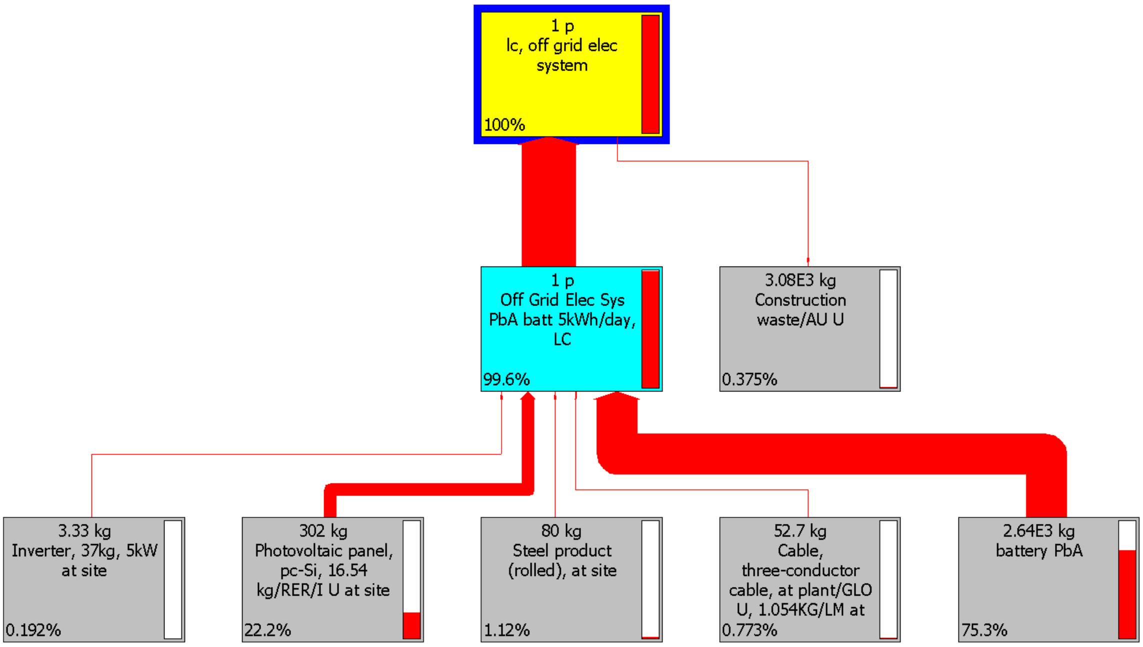

Figure 7.61 - Global Warming Potential, network diagram 0.19% cut off, off-grid electricity system (gas backup not included in analysis)

7.5.2 Ozone Depletion for Energy System

The Ozone Depletion potential of the off-grid energy system is approximately 6 times greater than the South Australian energy supply (Figure 7.62). Impacts arising from the off-grid energy system are due to manufacture of the renewable energy components; the photovoltaic panels accounting for approximately 20% more impacts than the batteries (Figure 7.63).

Recycling of the lead in the batteries ("construction waste") reduces the impact of the off-grid system slightly (indicated by the black diamond).

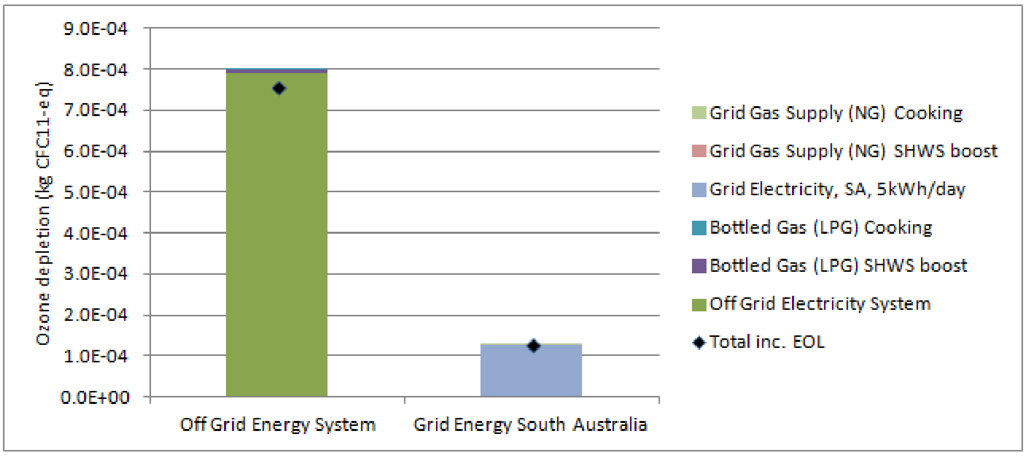

Figure 7.62 - Ozone Depletion, Energy Systems, Characterisation

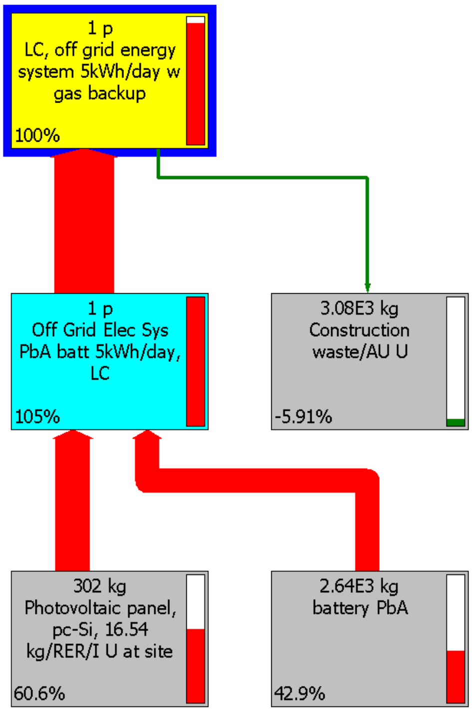

Figure 7.63 - Ozone Depletion, network diagram, 5% cut off, off-grid energy system

7.5.3 Photochemical Oxidation for Energy System

The Photochemical Oxidation potential of the South Australian energy supply is approximately 1.4 times greater than the off-grid energy system when EOL credits are taken into account (Figure 7.64). The off-grid system's impact is caused primarily by the manufacture of the batteries. The EOL credit is due to avoided lead production from recycling the batteries at EOL.

Electricity use contributes the most impacts for the South Australian Grid Energy.

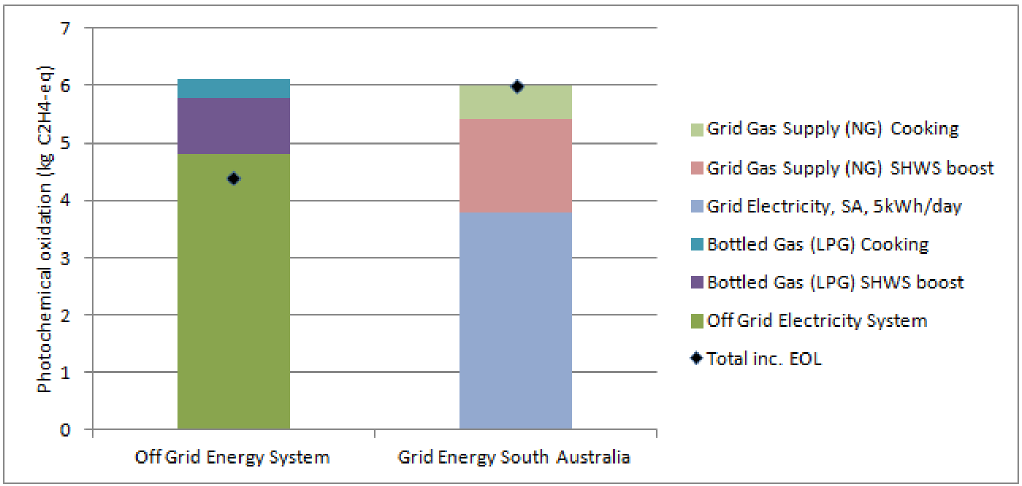

Figure 7.64 - Photochemical Oxidation, Energy Systems, Characterisation

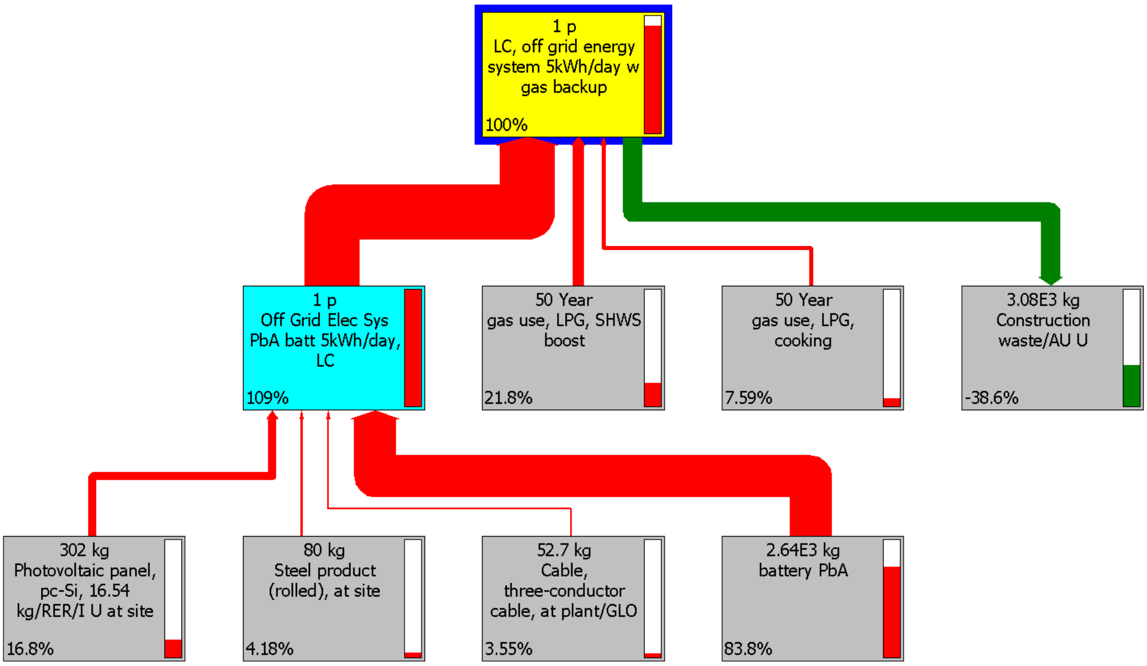

Figure 7.65 - Photochemical Oxidation, network diagram, 3% cut off, off-grid energy system

7.5.4 Eutrophication for Energy System

The Eutrophication potential of the off-grid energy system is approximately 2 times greater than the impact of the South Australian energy supply when EOL credits are taken into account (Figure 7.66). As illustrated in

Figure 7.67, the main causes of eutrophication potential for the off-grid energy system are:

- Battery manufacture, in which antimony is refined and sulphide tailings are disposed
- Production of silicon wafers in the photovoltaic panels (which has a similar level of impact as battery manufacture)
- LPG use for SHWS boosting

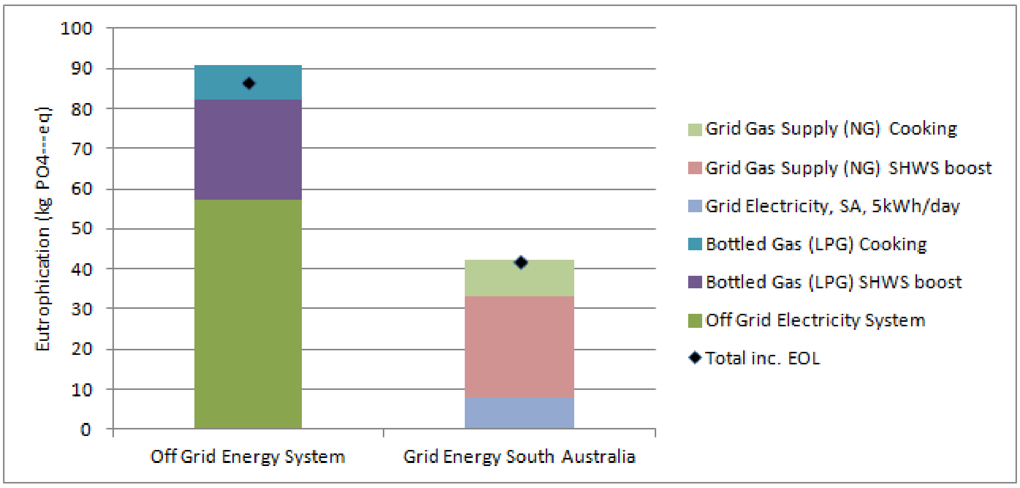

Figure 7.66 - Eutrophication, Energy Systems, Characterisation

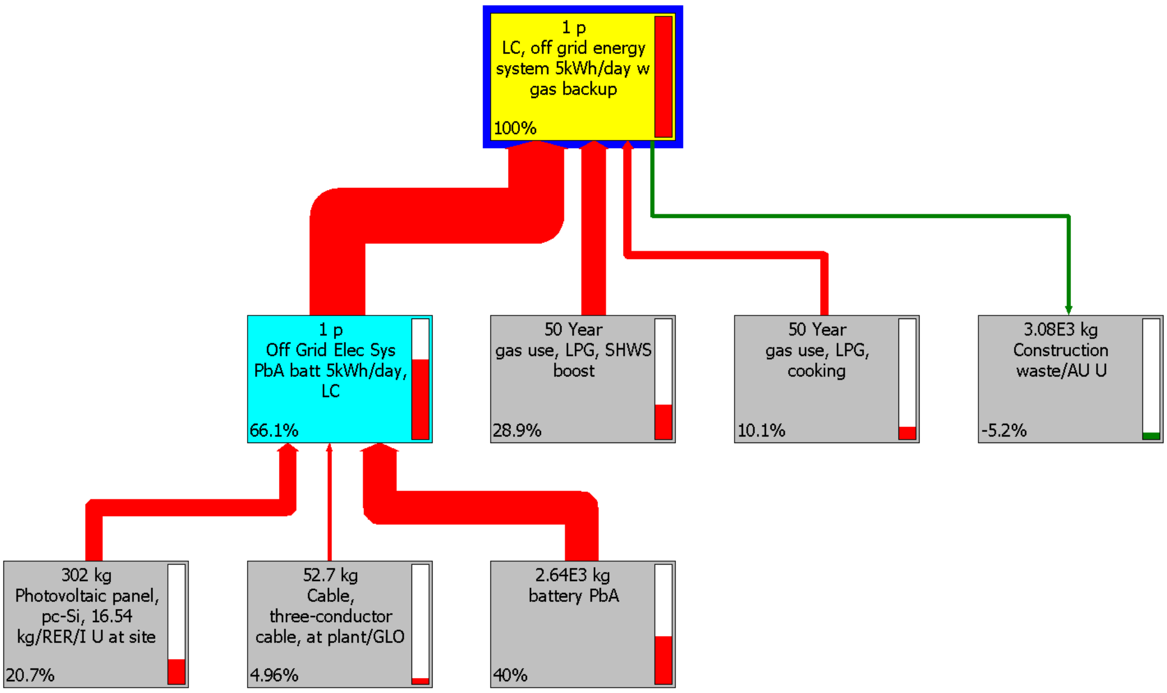

Figure 7.67 - Eutrophication, network diagram, 3% cut off, off-grid energy system

7.5.5 Land Use & Transformation for Energy System

The Land Use & Transformation potential of South Australian energy supply is approximately 25 times greater than the off-grid energy system when EOL credits are taken into account (Figure 7.68). The majority of impacts arising from the off-grid energy system are due to manufacture of batteries and to a lesser extent photovoltaic panels (Figure 7.69) both of which assume timber as a heating fuel source in their manufacturing processes (European EcoInvent data).

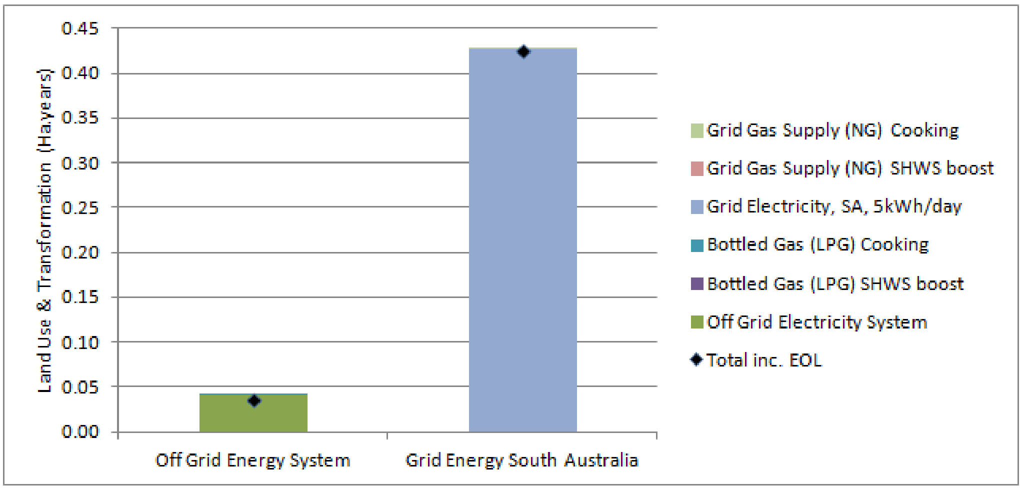

Figure 7.68 - Land Use & Transformation, Energy Systems, Characterisation

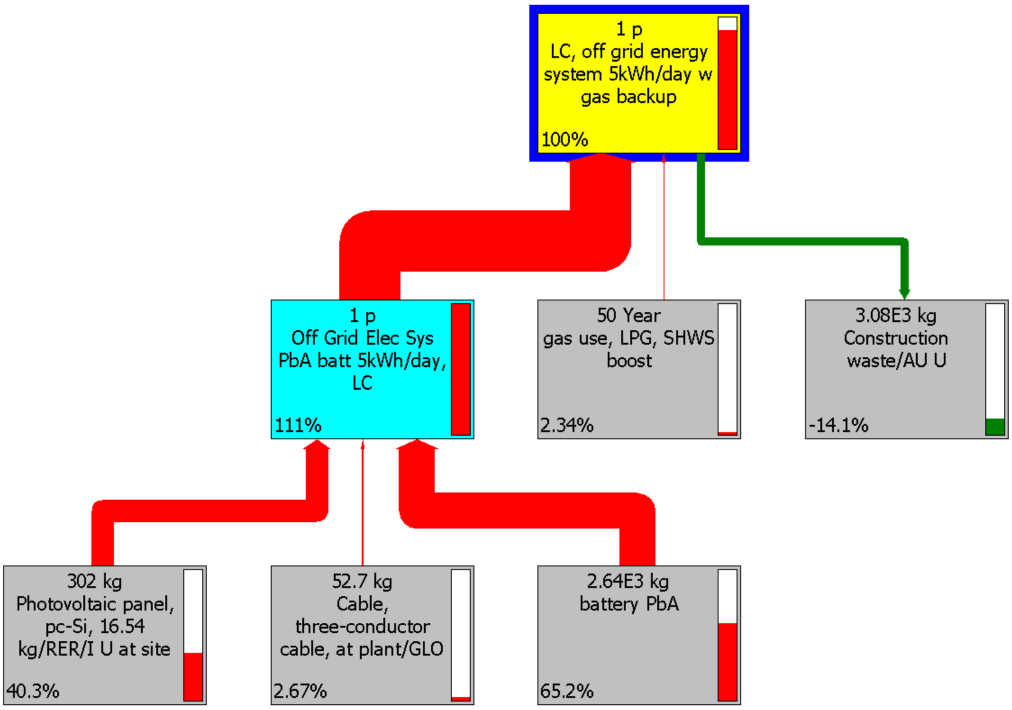

Figure 7.69 - Land Use & Transformation, network diagram, 2% cut off, off-grid energy system

7.5.6 Water Use & Depletion for Energy System

The Water Use & Depletion potential of the off-grid energy system is approximately 12 times greater than the South Australian energy supply (Figure 7.70). The significant water use of the off-grid energy system is due to the manufacture of photovoltaic panels which account for approximately 90% of the water use. Battery manufacture accounts for approximately 9% (Figure 7.71).

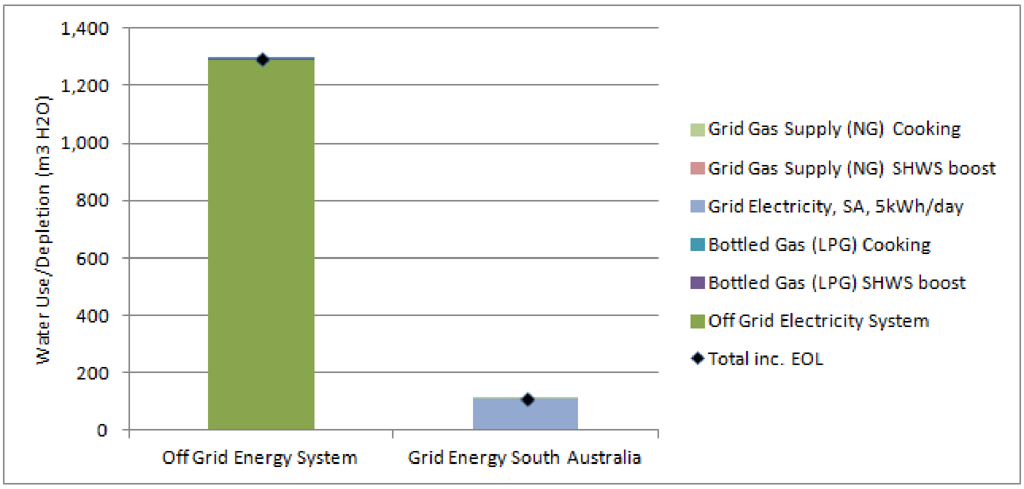

Figure 7.70 - Water Use & Depletion, Energy Systems, Characterisation

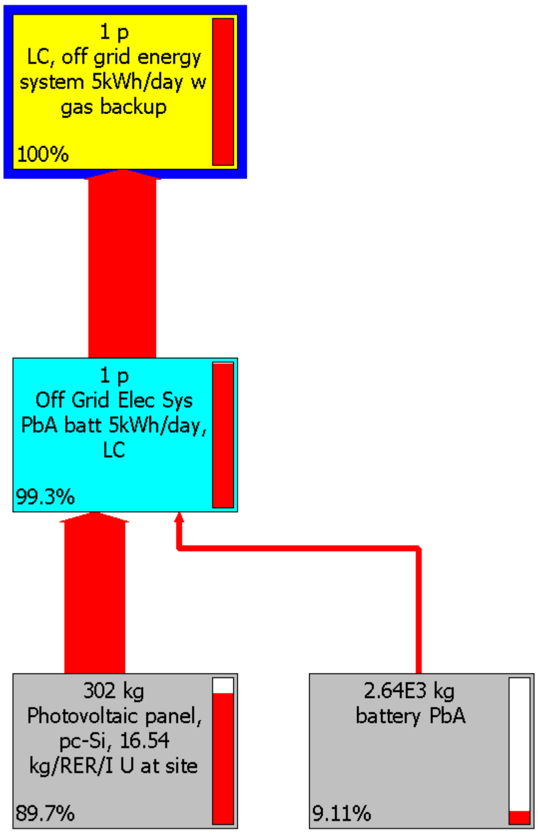

Figure 7.71 - Water Use & Depletion, network diagram, 2% cut off, off-grid energy system

7.5.7 Solid Waste for Energy System

The off-grid energy system has slightly more Solid Waste impact than the South Australian Grid Energy (Figure 7.72) – approximately 8% more waste is generated. This result does not include the potential solid waste reduction that would be achieved by recycling photovoltaic panels. As LCI data for recycling photovoltaic panels is not available in SimaPro™, it is assumed that PV panels are landfilled at EOL despite the fact that they are highly recyclable. Batteries, however, are recycled thereby preventing many hundreds of kilograms of waste. A small amount of waste is generated during steel manufacture; however, the majority is incurred during EOL disposal of PV panels (Figure 7.73). If PV panels were recycled this would reduce the waste at EOL to approximately 100kg (302kg of PV panels are included in the modelling which accounts for replacement panels every 25 years).

Waste from the South Australian Grid Energy is due to "ash waste" from the coal fired power station.

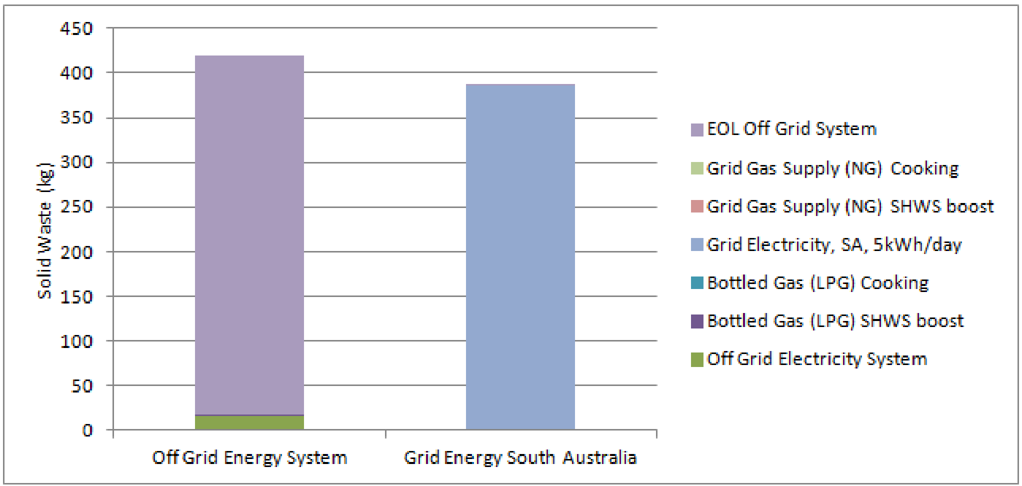

Figure 7.72 - Solid Waste, Energy Systems, Characterisation

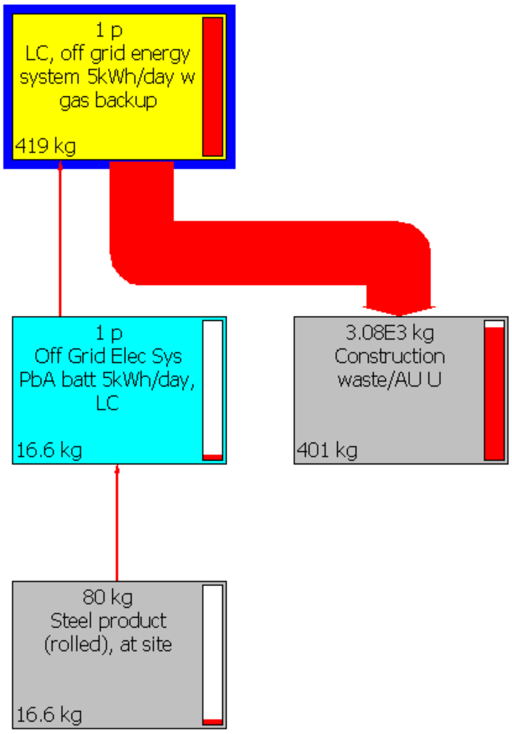

Figure 7.73 - Solid Waste, network diagram, 1% cut off, off-grid energy system

7.5.8 Embodied Energy for Energy System

The Embodied Energy potential of the South Australian energy supply is approximately 1.8 times greater than the off-grid energy system when EOL credits are taken into account (Figure 7.74). Liquid Petroleum Gas is the cause of the majority of embodied energy in the off-grid system, especially for SHWS boost (Figure 7.75), whereas electricity production is the major cause in the SA grid.

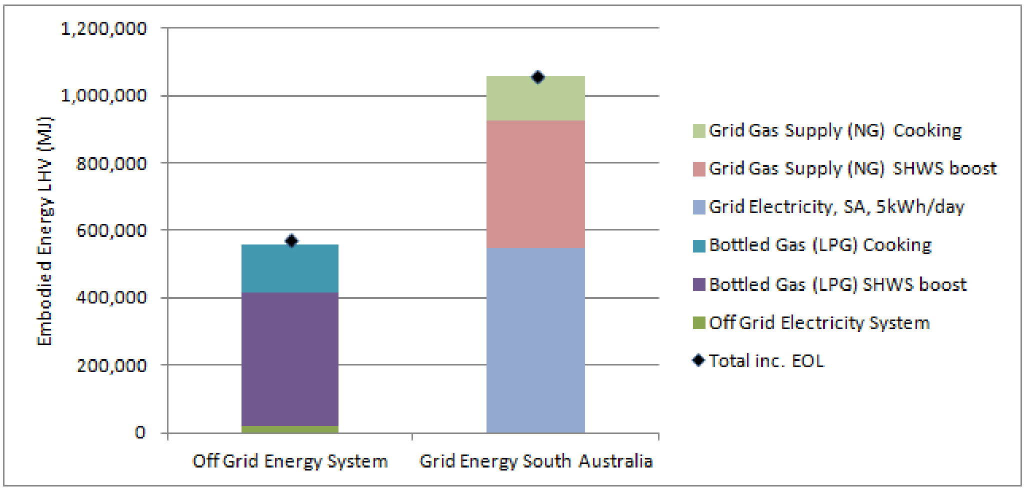

Figure 7.74 - Embodied Energy, Energy Systems, Characterisation

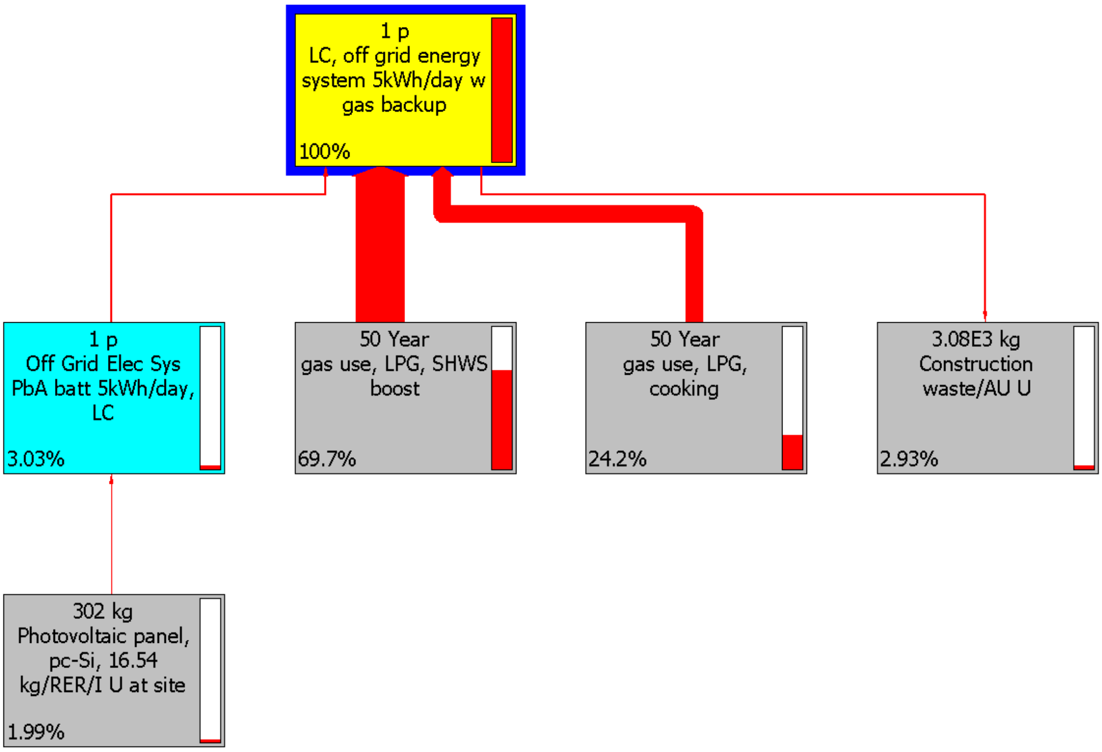

Figure 7.75 - Embodied Energy, network diagram, 1% cut off, off-grid energy system

7.5.9 Human Toxicity, Carcinogenic, for Energy System

The Carcinogenic Toxicity potential of the off-grid energy system is approximately 4 times greater than the South Australian energy supply when EOL credits are taken into account (Figure 7.76). The vast majority of this is due to the manufacture of lead which is contained in the batteries (Figure 7.77).

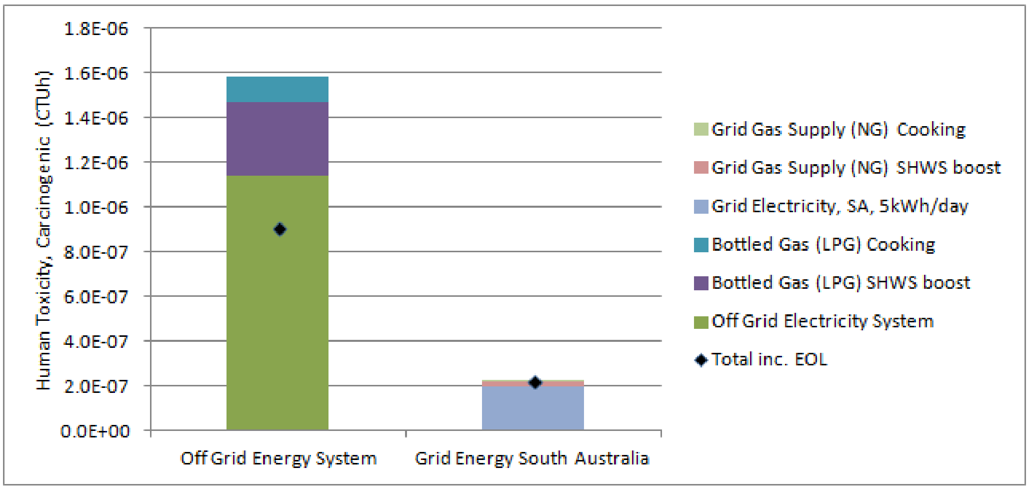

Figure 7.76 - Human Toxicity Carcinogenic, Energy Systems, Characterisation

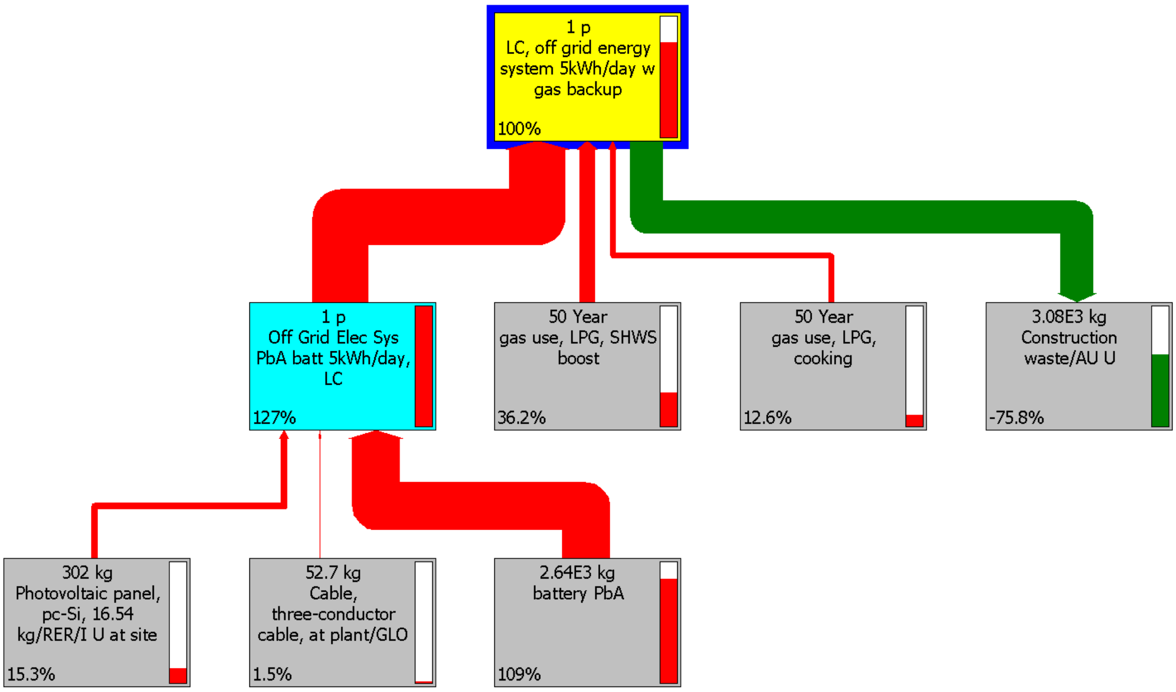

Figure 7.77 - Human Toxicity Carcinogenic, network diagram, 1% cut off, off-grid energy system

7.5.10 Human Toxicity, Non-Carcinogenic, for Energy System

The Non-Carcinogenic Toxicity potential of the off-grid energy system is approximately 52 times greater than the South Australian energy supply when EOL credits are taken into account (Figure 7.78).

The vast majority of this is due to the manufacture of lead which is contained in the batteries (Figure 7.79).

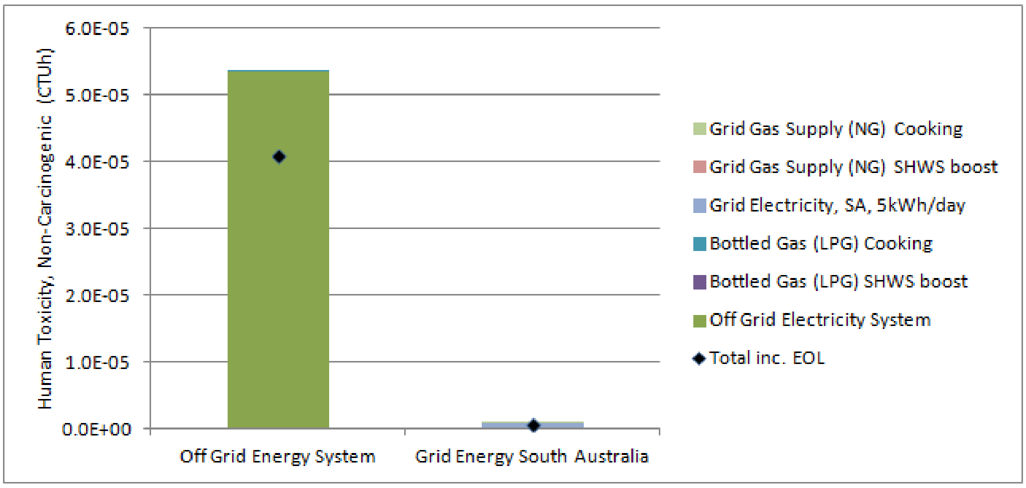

Figure 7.78 - Human Toxicity Non-carcinogenic, Energy Systems, Characterisation

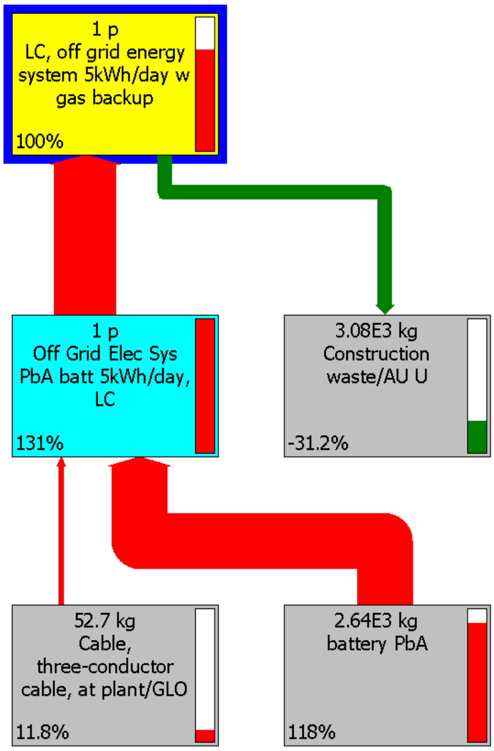

Figure 7.79 - Human Toxicity Non-carcinogenic, network diagram, 1% cut off, off-grid energy system

7.5.11 Eco Toxicity for Energy System

The Eco Toxicity potential of the off-grid energy system is approximately 7.5 times greater than the South Australian energy supply (Figure 7.80). A significant source of the toxicity is due to the manufacture of lead which is contained in the batteries and photovoltaic panel production (Figure 7.81).

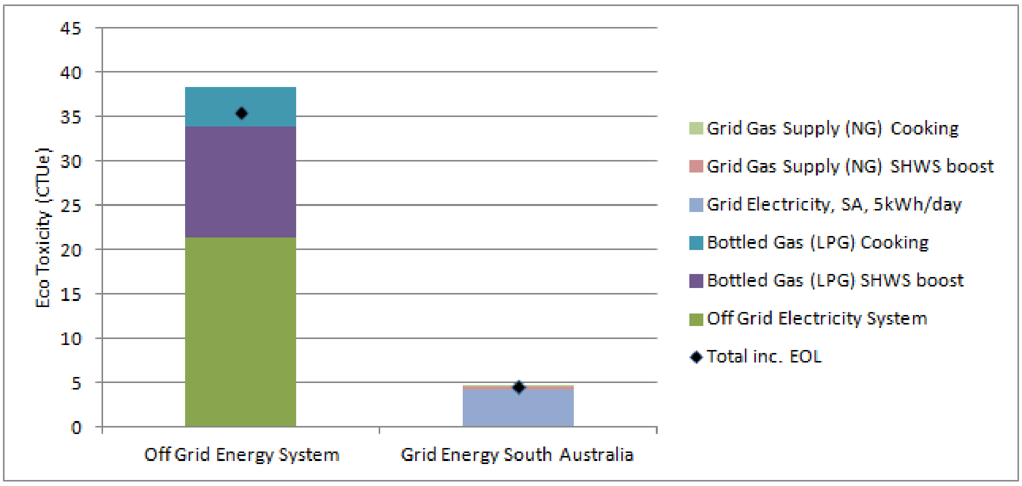

Figure 7.80 - Eco Toxicity, Energy Systems, Characterisation

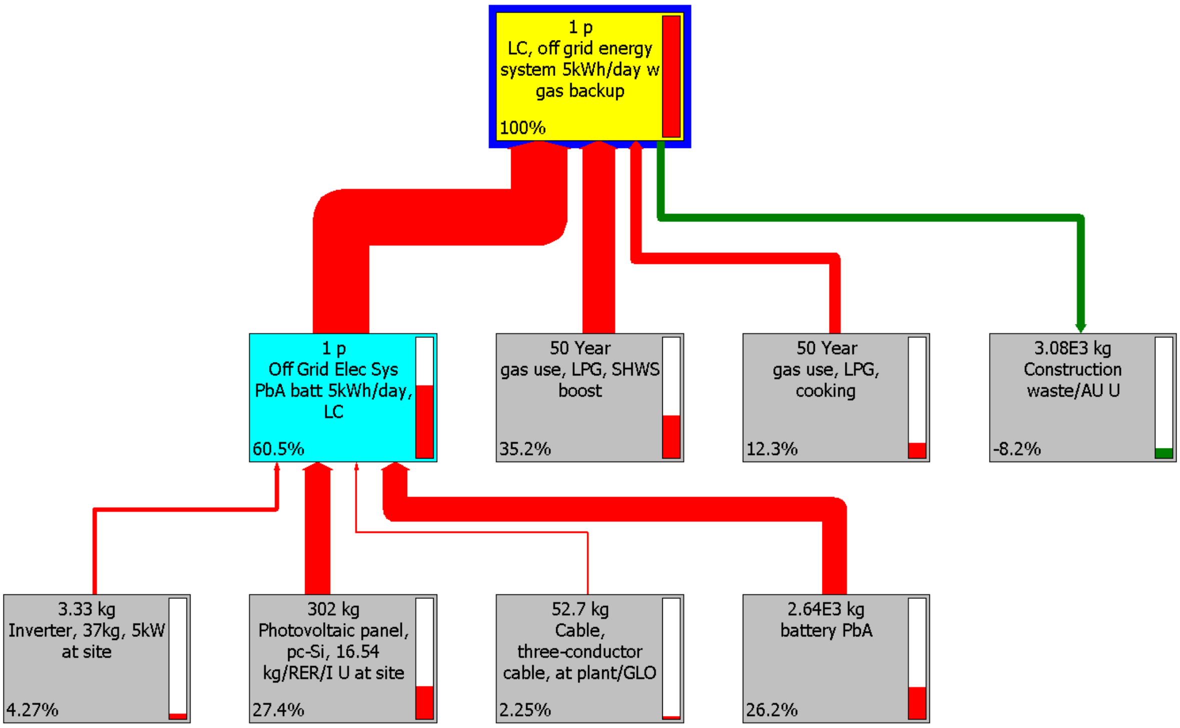

Figure 7.81 - Eco Toxicity, network diagram, 1% cut off, off-grid energy system

7.5.12 Toxicity Analysis for Energy System

Table 7.6 lists the toxic substances contributing to more than one percent of impacts for each toxicity indicator for the off-grid energy system compared with the Australian National Pollutant Inventory (Commonwealth of Australia: Department of Sustainability, n.d.) annual emissions data (where data is available).

The “emission ratio” gives a number that represents the number of off-grid energy systems that would produce the annual Australian average emissions of each substance based on data from 2011/12. The emission of toxic substances involved with the manufacture of the construction materials used in the off-grid energy system are generally millions of times less than the annual emissions per capita from general industry indicating that the scale of emissions from its lifecycle are relatively insignificant. An exception to this is benzene and carbon disulfide which are related to battery manufacture. This result arises from EcoInvent data as batteries are assumed to be manufactured in Germany, thus the comparison to Australian emissions may be the cause of the low emission ratio.

These results should also be considered in terms of the total number of houses constructed per annum which, based on figures produced by the Australian Bureau of Statistics for 2008-2014 (approximately 8000 homes constructed per month), is about 96,000 homes (Australian Bureau of Statistics, 2014).

Table 7.6 - Toxic substances from Off-Grid Energy System**

Substance	Source	NPI 2011/12 ton p.a.	Off-Grid Energy System Emission	Unit	Emission Ratio
Aldrin	Electricity production	No data	606	mcg	-
Benzene	Energy for battery manufacture	610	1.14	kg	535,088
Carbon disulfide	Antimony in batteries	75	0.872	kg	86,009
Chlorothalonil	Photovoltaic panels and battery manufacture	No data	163	mg	-
Cumene	LPG refining	31	11.38	g	2,724,077
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Lead in battery	No data	4.7	mcg	-
Formaldehyde	LPG refining	2100	41.1	g	51,094,891
Phenol	Steel production	77	32.8	g	2,347,561
Styrene	Silicon production for PV panels	200	619	mg	323,101,777
Toluene	LPG refining	1400	133.6	g	10,479,042
Xylene	LPG refining	1000	151.9	g	6,583,278

7.5.13 Normalisation of Impacts for Energy System

Normalising the characterisation results against 50 years of per capita average Australian values for each impact category, GWP and Eutrophication are indicated as having more significance than the other impact categories, with Land Use & Transformation and Photochemical Oxidation showing the least significance (Figure 7.82).

Every 0.02 on the y-axis represents one year of average Australian “emissions” and 1 represents the assumed 50 year lifecycle of the home. The results are significantly less than one, reflecting the fact that many other human activities, aside from house building and operation, contribute to an individual’s environmental impact.

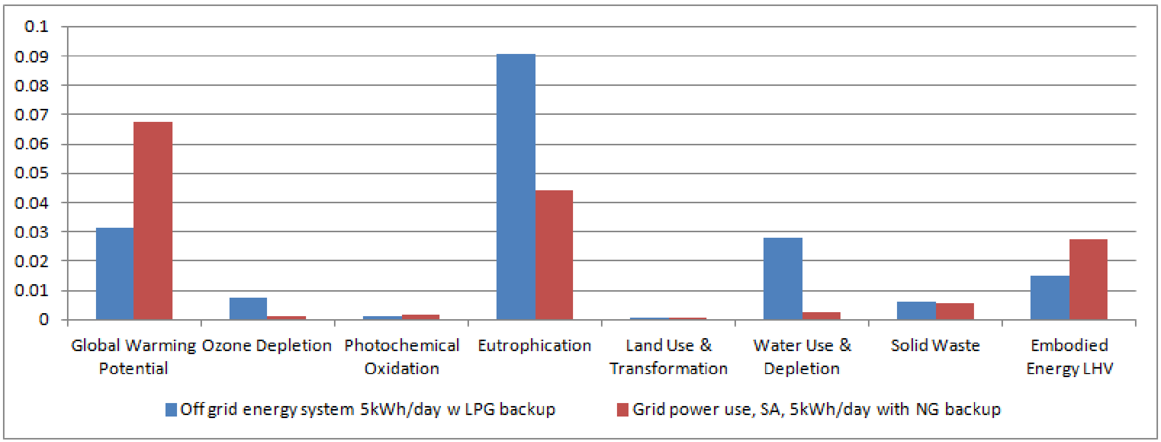

Figure 7.82 - Normalisation of Energy Systems Results

7.5.14 Weighted Single Score of Impacts for Energy System

When the weighting regime (as defined in Section 7.3.13) is applied to the normalised results, the South Australian energy supply has approximately 1.5 times greater overall impact than the off-grid energy system in terms of "eco points" (vertical axis) (Figure 7.83).

When solid waste and embodied energy are omitted (because they are not technically impact categories in their own right - refer 7.3.13), the comparison changes only slightly with 1.4 times greater impact for the South Australian energy supply Figure 7.84.

Global Warming Potential causes the majority of the weighted impact in both systems, followed by Eutrophication and in the case of the Off-Grid system, Water Use & Depletion.

The off-grid system components (batteries, photovoltaics in particular) are significant causes of the overall impact; however, the greatest impact is caused by liquid petroleum gas used for cooking and SHWS boosting (refer network diagram, Figure 7.87).

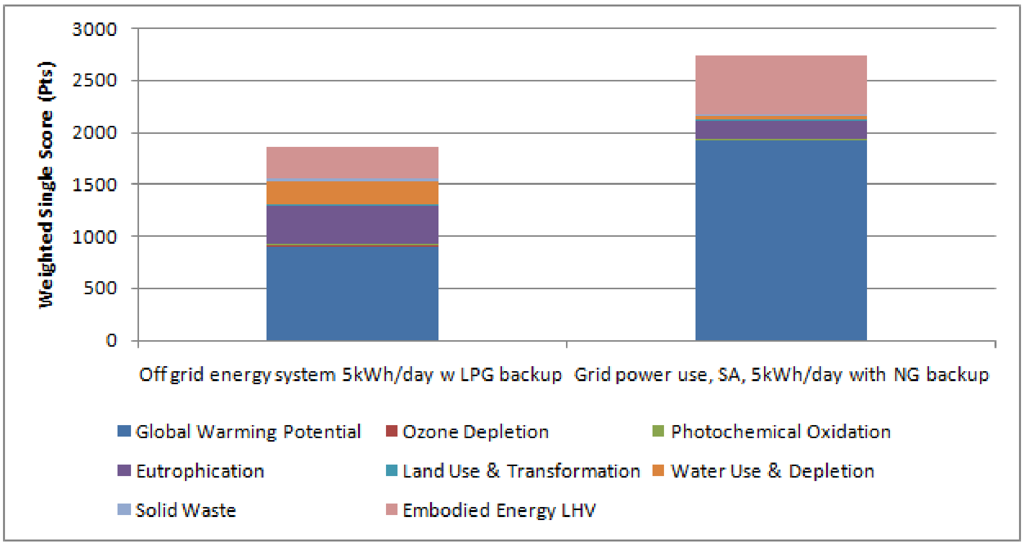

Figure 7.83 - Energy Systems, weighted single score, all indicators

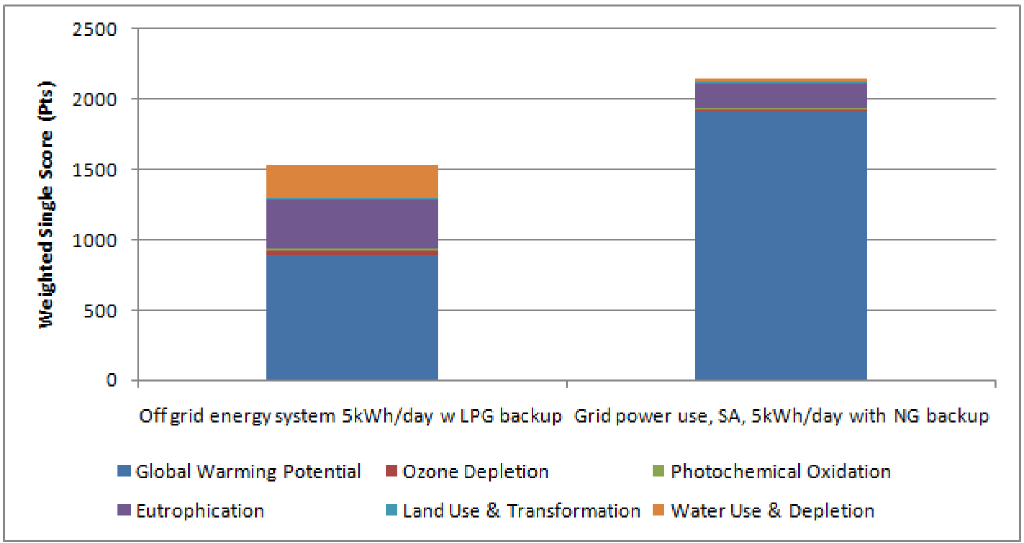

Figure 7.84 - Energy Systems, weighted single score, discounting Embodied Energy and Solid Waste

7.5.15 Backup Fuel

Given the high impacts associated with using LPG for cooking and SHWS boosting as a "backup" fuel for the off-grid system and the impacts associated with the battery bank, a study was conducted to investigate the effect of substituting gas with grid electricity. Table 7.7 lists assumptions for both of these scenarios and shows the resultant amount of energy assumed to be imported from the grid (for scenario 2). The study assumes that 2.285kWh/day of energy is used for appliances and 7.665kWh/day is used for cooking (electricity or gas) and SHWS boost (refer to Chapter 6 for discussion and calculations) which totals 9.95kWh/day.

Table 7.7 - Energy use and surplus/deficit for two PV/grid scenarios.

#	Description	Grid connect	Appliance Energy Use	Cook and SHW boost	Fuel for Cook and SHW boost	Total Energy Use	Energy from PV panels	Energy stored in Battery Bank	Energy from Grid
			kWh/ day	kWh/ day		kWh/ day	kWh/ day	kWh/ day	kWh/ day
1	Standard Earthship, with battery and 5kWh/day PV system - off-grid	no	2.285	7.665	gas	9.95	5	1.5	0
2	Earthship, with battery and 5kWh/day PV system - grid connected	yes	2.285	7.665	grid elec	9.95	5	1.5	3.45

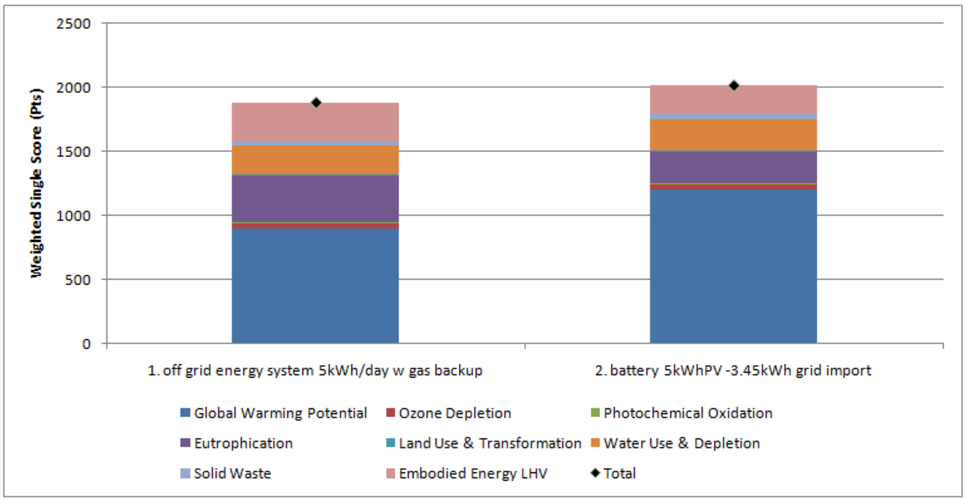

Figure 7.85 - Energy backup options, characterisation by impact category

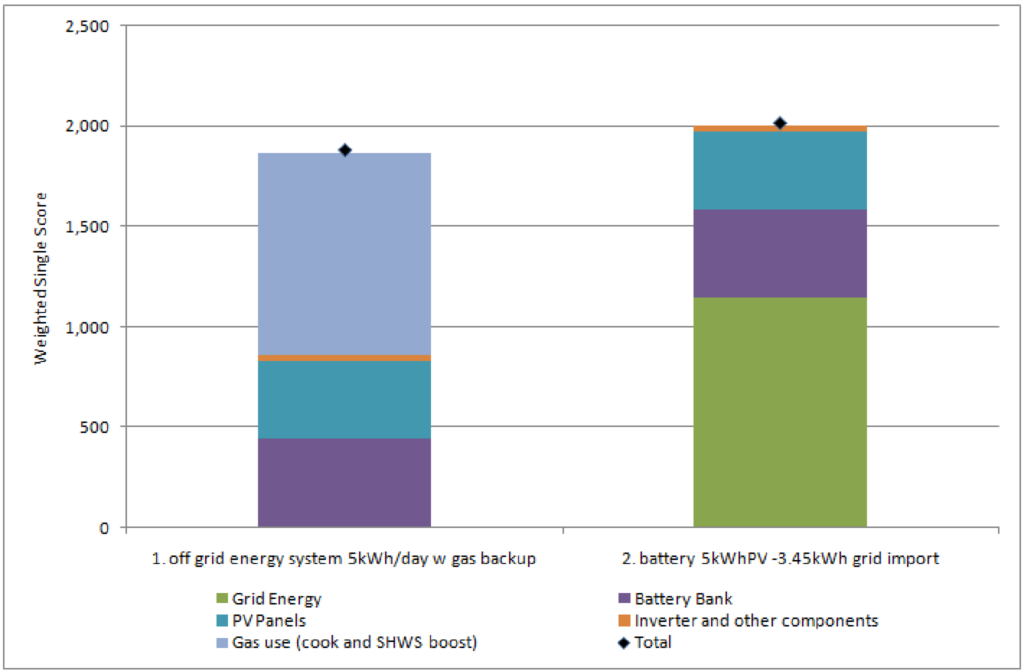

Figure 7.86 - Energy backup scenarios, characterisation by component

Although the assumptions are simplistic and do not delve into great detail regarding energy use patterns in the home (in particular, when energy is used: nighttime or daytime - when the sun is shining), they give an impression of how the fuel type used to supply energy to the home effects the environmental impact.

The Base Case - standard off-grid Earthship design – has impacts arising mainly from the use of gas as the fuel source for cooking and SHWS boosting. The scenario in which the gas use has been replaced by grid supplied electricity, shows a small rise in impact (7% more than base case), indicating that energy from gas is slightly more environmentally friendly than electricity in the South Australian context.

Network diagrams showing the single score for the Base Case and the South Australian grid energy are shown in Figure 7.87 and Figure 7.88 respectively. It can be seen that, in the SA grid, the majority of energy is derived from South Australian brown coal, with the remainder from local natural gas plants, imported brown coal energy from Victoria, and local wind energy.

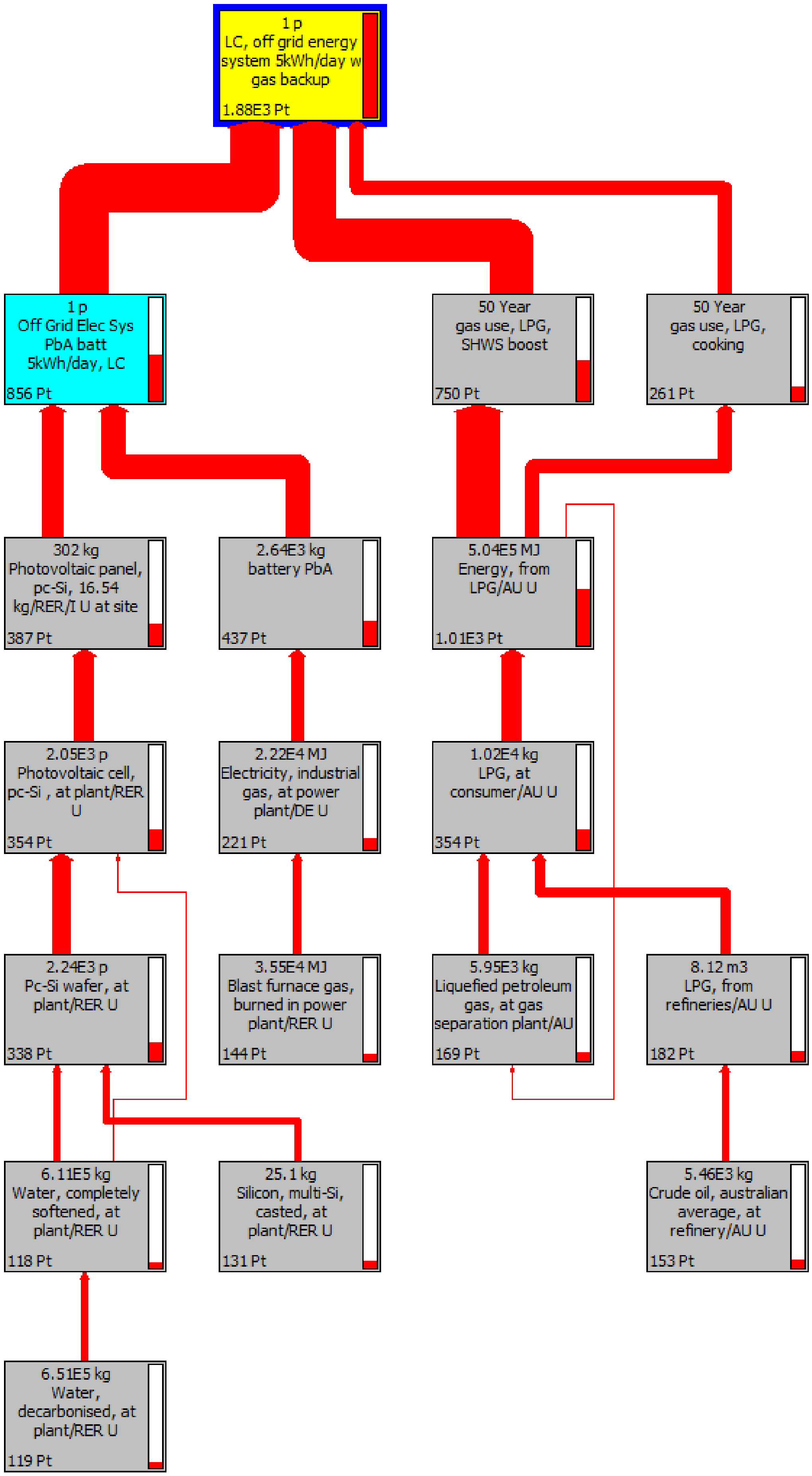

Figure 7.87 - Off grid energy system with gas backup (scenario 1), single score, 6% cut off

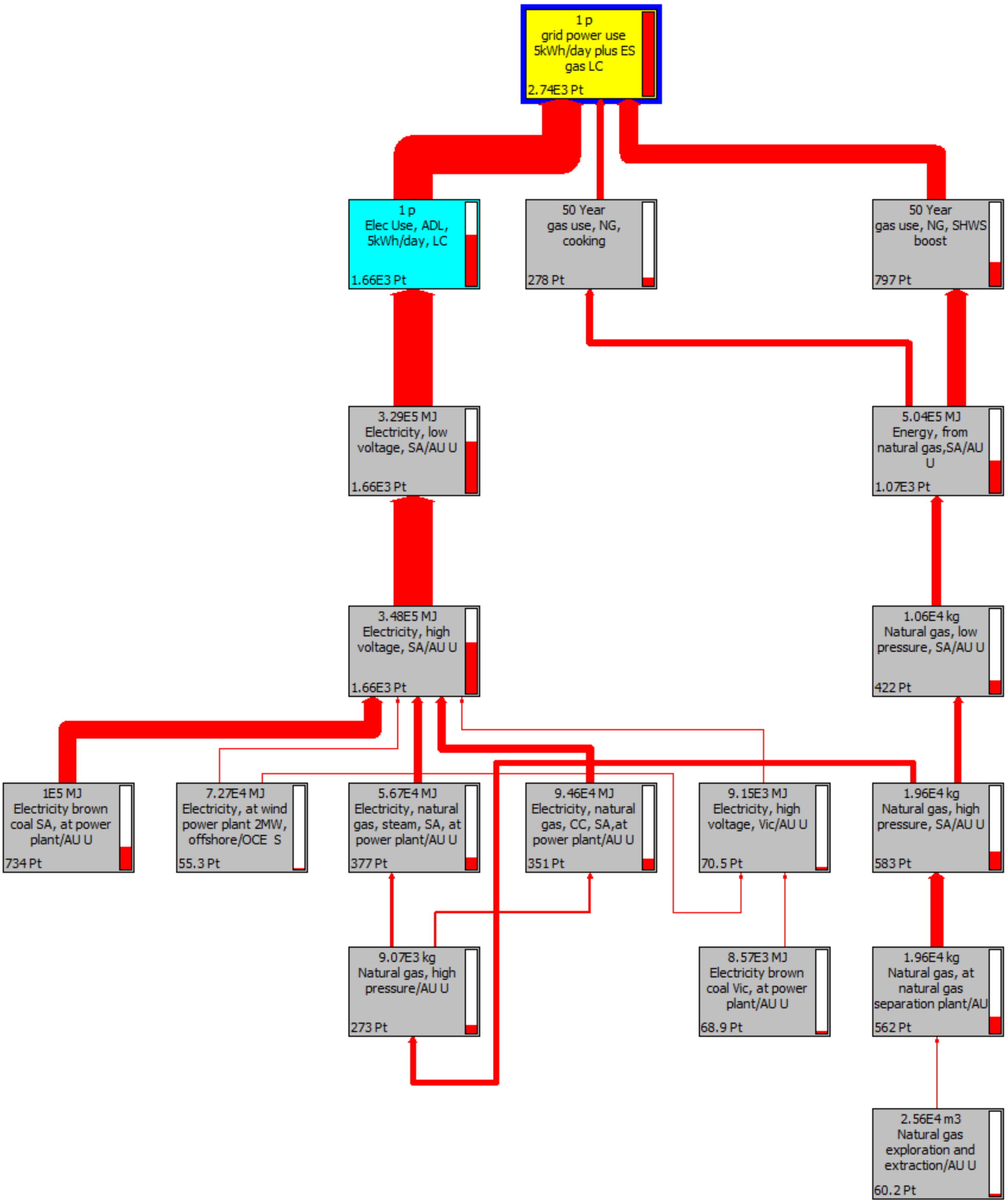

Figure 7.88 - SA grid energy, single score, 2% cut off

7.5.16 Discussion & Summary

The analysis has compared an off-grid energy system with battery backup, rated at 5kWh/day including 10070MJ of liquid petroleum gas for cooking and SHWS boost, with the same amount of South Australian grid electricity and the same amount of natural gas. The finding is that the grid energy has approximately 1.4 to 1.5 times more impact than the off-grid energy system. Modelling of the off-grid system did not incorporate recycling of the photovoltaic panels (due to lack of LCI data) whereas if this was possible it is likely the impacts would be even lower.

The liquid petroleum gas used to backup the off-grid energy system is a significant impact driver in many impact categories, indicating the potential to reduce overall impact by increasing the use of renewable energy technology; however, although renewable energy technology has less impact than the grid, it is not without environmental impacts. Therefore, the concept of minimising home energy requirements – a fundamental strategy in Earthship design – is desirable no matter what the energy source is.

Investigation of the fuel source to “backup” the Earthship’s renewable energy (e.g. to provide cooking fuel and SHWS boost) reveals that gas has a lower impact compared to grid electricity. This finding supports Reynolds’ assertion that Earthships should not be connected to the energy grid (Reynolds, 1990, p. 15); however, if a grid connection is available and is used to export energy rather than consume energy, the concept of a zero carbon home, or a less than zero carbon home, becomes possible due to the credits earned from exporting energy. This issue requires further research to establish whether or not the grid connection would lead to environmental benefits, as it is possible that the connection to the grid might override the need for energy saving behaviour change which was displayed by the Earthship occupants interviewed in the POE study (refer to Chapter 3).

On account of the considerable weight of the renewable energy system components, which are generally not manufactured in Australia (although some manufacturers of photovoltaic panels and inverters still exist), a sensitivity study investigated the effect of assuming different ocean freight transport distances for the renewable energy system. The main study assumed 25,000km journey from Europe by ocean freight, and the sensitivity study assumed 5,000km ocean freight from Asia. It was found that the reduced distance decreased global warming potential (GWP) by approximately 3 percent of the whole renewable energy system’s GWP.

7.6 Water Supply System

This section presents results and analysis of the Off-Grid Water Supply System and the Grid Connected Water Supply System. The system assumptions are based on waster use for a family of four in Adelaide. The Off-Grid System includes a shed for extra water catchment area, rainwater tanks, plumbing, a pump, and filters. This system is able to provide 73L per day for each occupant, which is the figure quoted for water use in an Earthship (Reynolds, 2005, p. 18). The Grid Connected System assumes that each occupant uses 390L per day which includes water for irrigating the garden (Australian Bureau of Statistics, 2011). Refer to Chapter 6 for details regarding these assumptions.

7.6.1 Global Warming Potential for Water Supply System

The Global Warming Potential of Adelaide's reticulated water supply ("Grid Water Supply, ADL") is approximately 2 times greater than the off-grid water system ("Off Grid Water Catch") when EOL credits are taken into account (Figure 7.89). While the off-grid system incurs most GWP emissions during the construction phase, the grid water supply has emissions throughout its lifecycle due to electricity used to treat and pump water to homes.

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks (Figure 7.90). EOL credits for the off-grid system are due to recycling of the rainwater tanks.

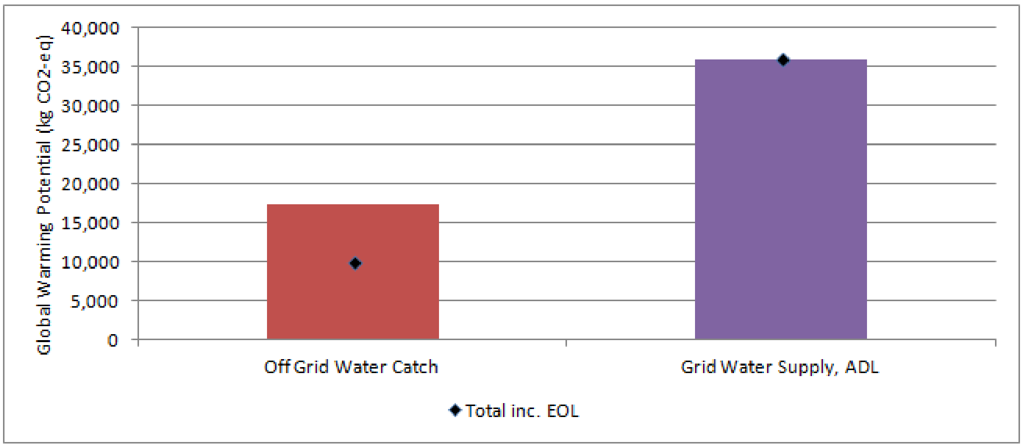

Figure 7.89 - Global Warming Potential, Water Systems, Characterisation

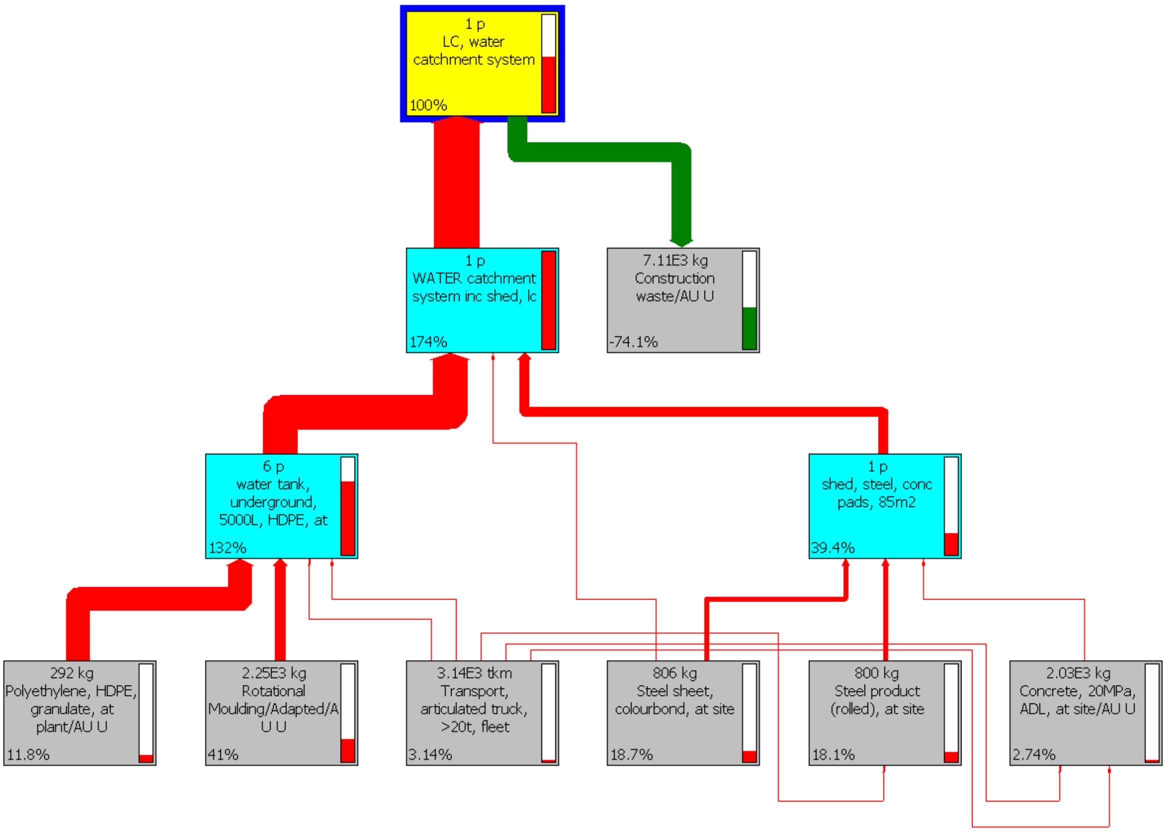

Figure 7.90 - Global Warming Potential, network diagram, 1% cut off, off-grid water catchment system

7.6.2 Ozone Depletion for Water Supply System

The Ozone Depletion potential of Adelaide's reticulated water supply is approximately 3 times greater than the off-grid water system when EOL credits are taken into account (Figure 7.91).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks (Figure 7.92). EOL processes contribute to the impact in both systems (rather than provide a credit); recycling of the HDPE tank is the main recycling activity in the off-grid system causing this EOL impact. This is due to transportation of the tank to the plastic recycler.

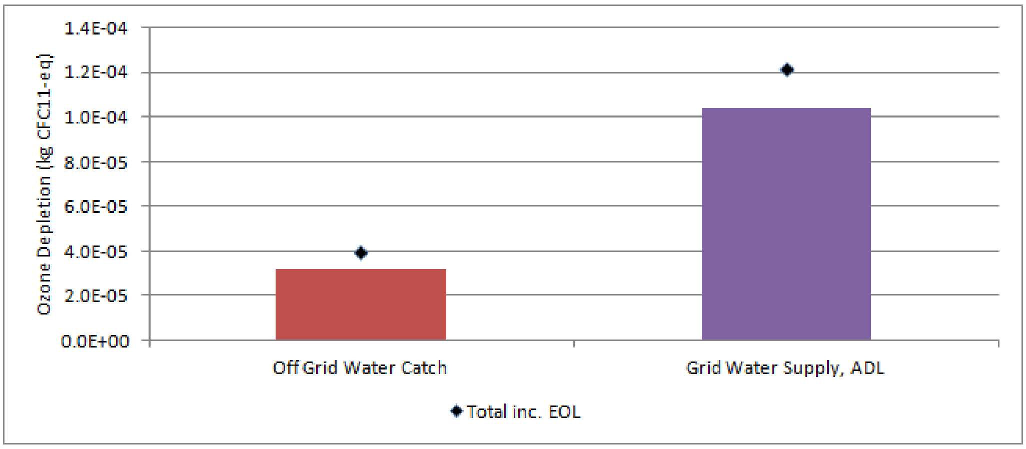

Figure 7.91 - Ozone Depletion, Water Systems, Characterisation

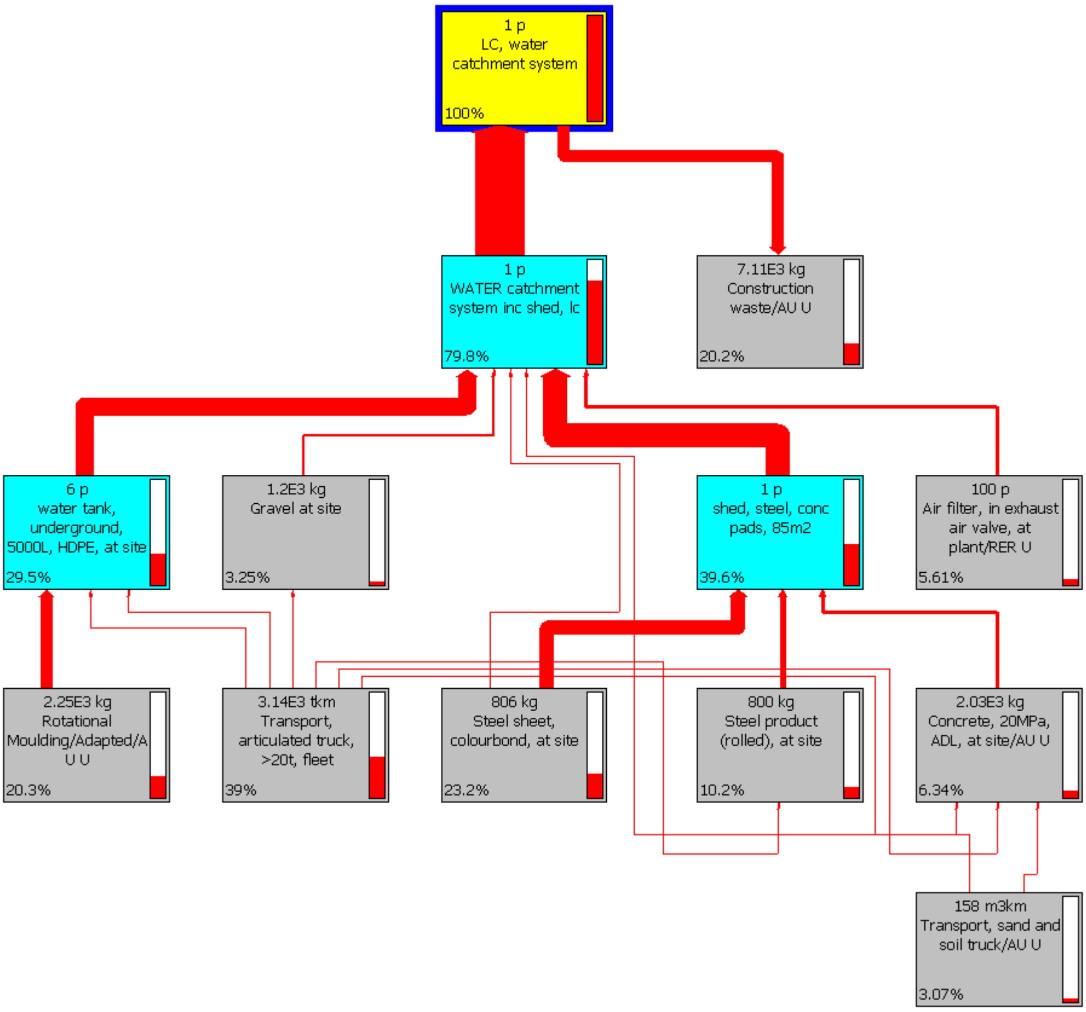

Figure 7.92 - Ozone Depletion, network diagram, 1% cut off, off-grid water catchment system

7.6.3 Photochemical Oxidation for Water Supply System

The Photochemical Oxidation potential of Adelaide's reticulated water supply is approximately 18% greater than the off-grid water system when EOL credits are taken into account (Figure 7.93).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks and the shed which provides extra roof catchment, adequate to provide a sufficient amount of water for 4 peoples' use. EOL credits for the Off-Grid system are due to recycling of the rainwater tanks and recycling of steel and concrete from the shed (Figure 7.94).

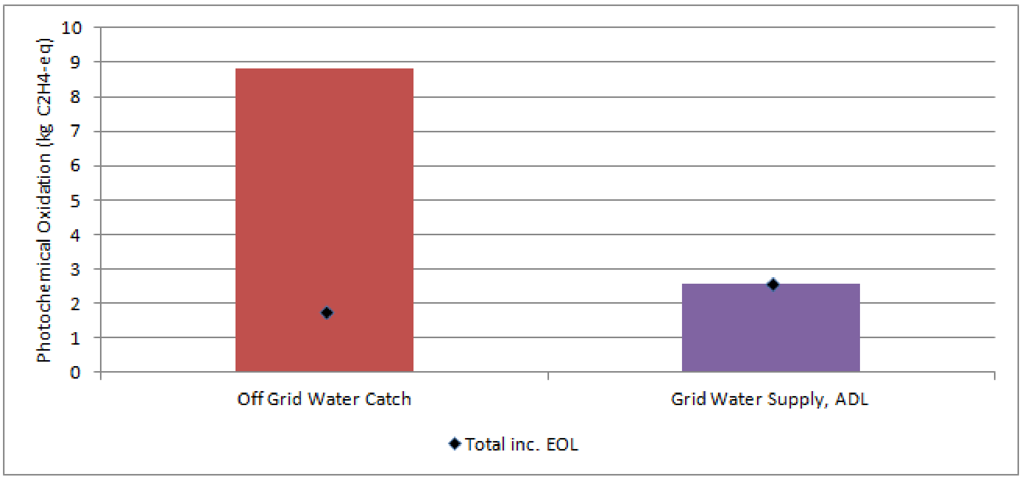

Figure 7.93 - Photochemical Oxidation, Water Systems, Characterisation

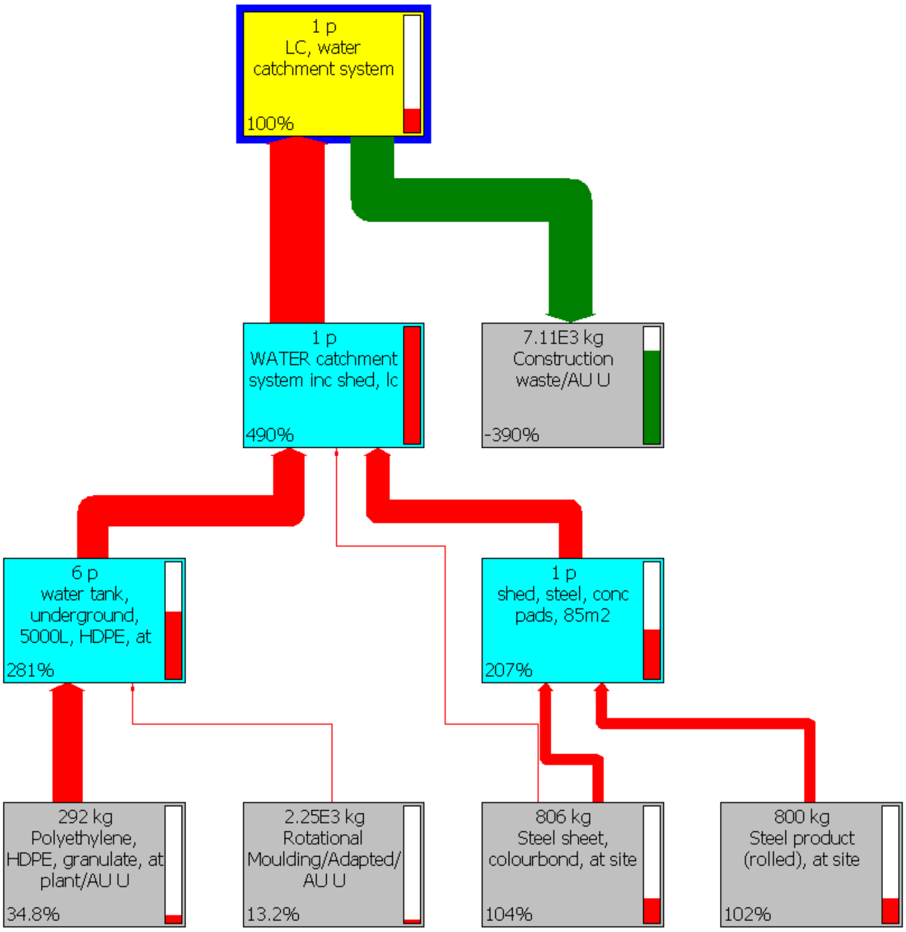

Figure 7.94 - Photochemical Oxidation, network diagram, 1% cut off, off-grid water catchment system

7.6.4 Eutrophication for Water Supply System

The Eutrophication potential of Adelaide's reticulated water supply is approximately 2 times greater than the off-grid water system when EOL credits are taken into account (Figure 7.95).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks and the shed (Figure 7.96).

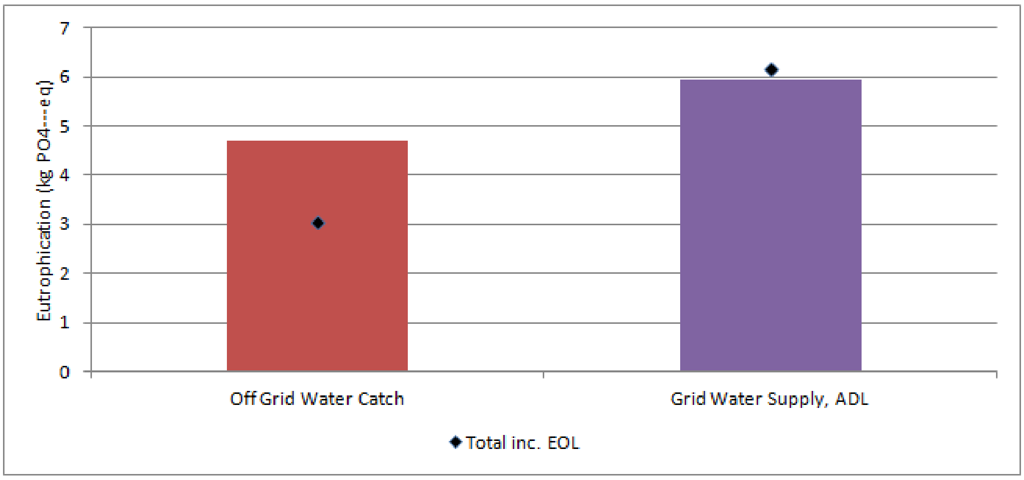

Figure 7.95 - Eutrophication, Water Systems, Characterisation

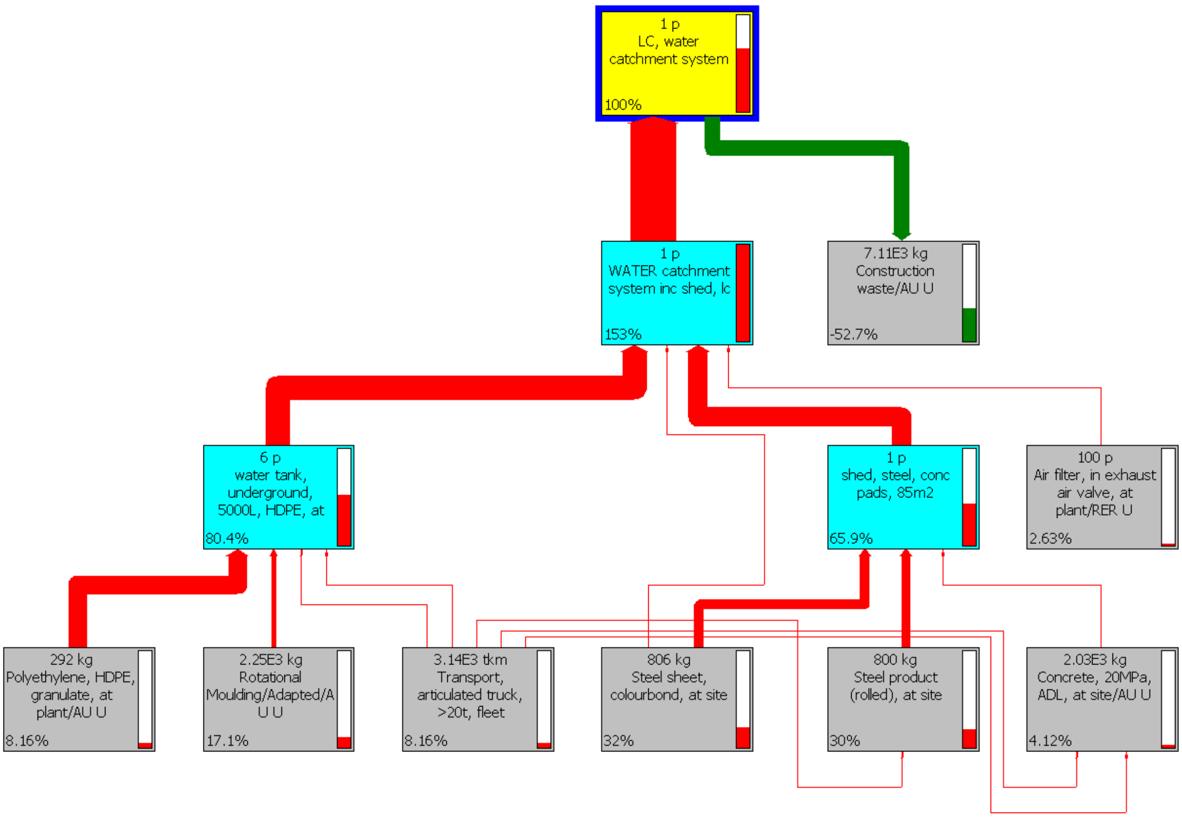

Figure 7.96 - Eutrophication, network diagram, 1% cut off, off-grid water catchment system

7.6.5 Land Use & Transformation for Water Supply System

The Land Use & Transformation potential of Adelaide's reticulated water supply is approximately 5 times greater than the off-grid water system when EOL credits are taken into account (Figure 7.97).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks (Figure 7.98). EOL impacts do not result in the usual credit due to the energy required to reclaim the recyclable materials being greater than the avoided energy; which is associated with land use/transformation.

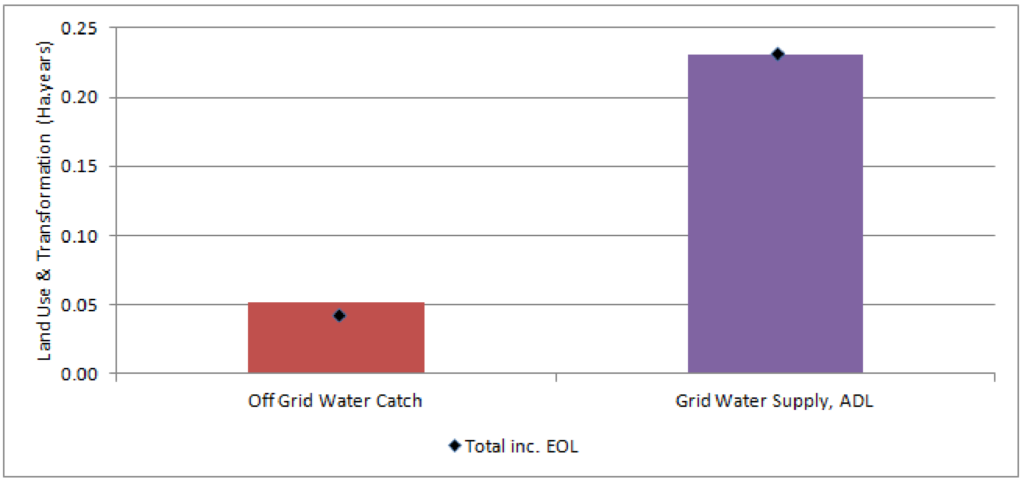

Figure 7.97 - Land Use & Transformation, Water Systems, Characterisation

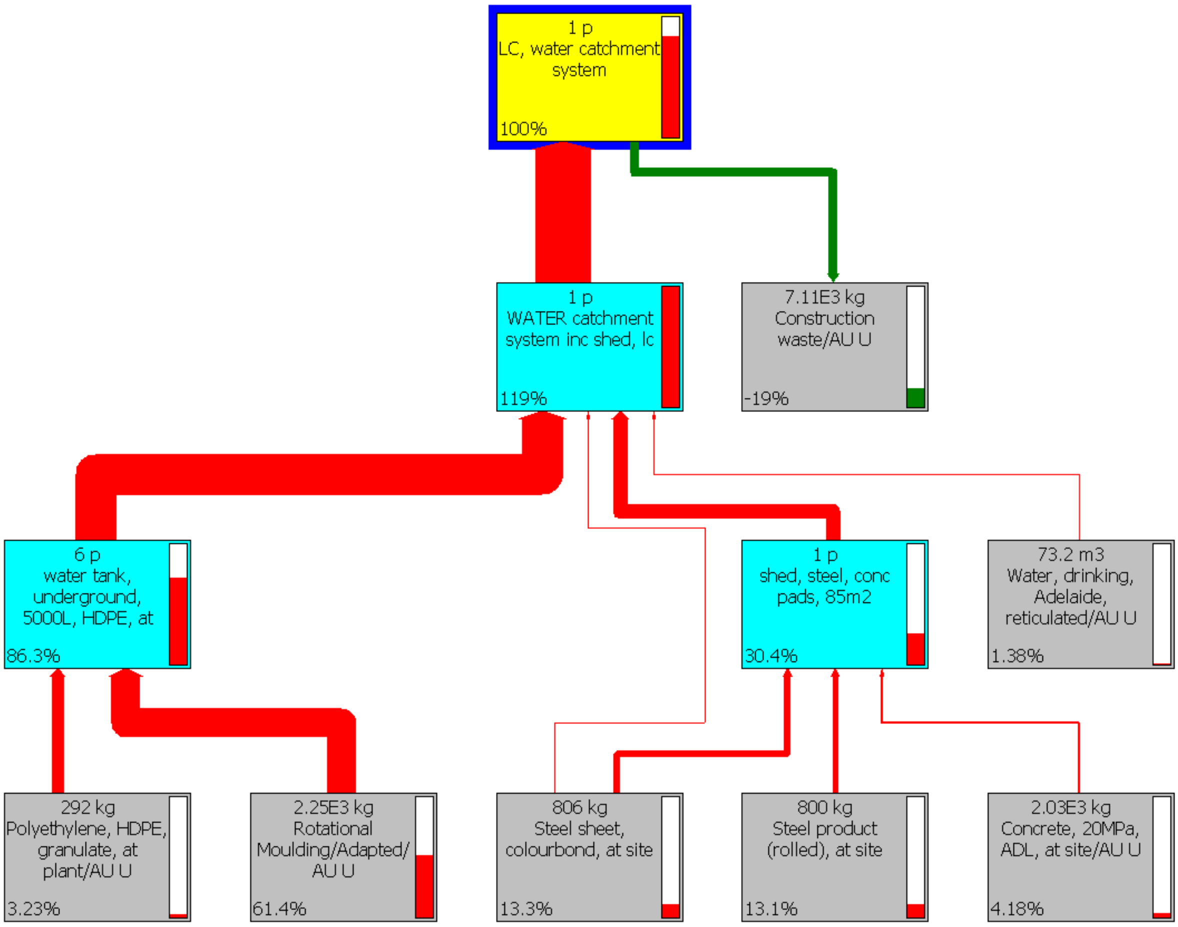

Figure 7.98 - Land Use & Transformation, network diagram, 1% cut off, off-grid water catchment system

7.6.6 Water Use & Depletion for Water Supply System

The Water Use & Depletion potential for Adelaide's reticulated water supply is approximately 80 times greater than for the off-grid water system when EOL credits are taken into account (Figure 7.99). This is due to water being provided "for free", once the initial infrastructure for the off-grid system has been installed, with little need for maintenance (that involves water use); whereas the grid supply is constantly drawing upon finite water resources.

Manufacturing and use stage impacts of the off-grid system are driven primarily by the rotational moulding process of the high density polyethylene (HDPE) rainwater tanks (Figure 7.100).

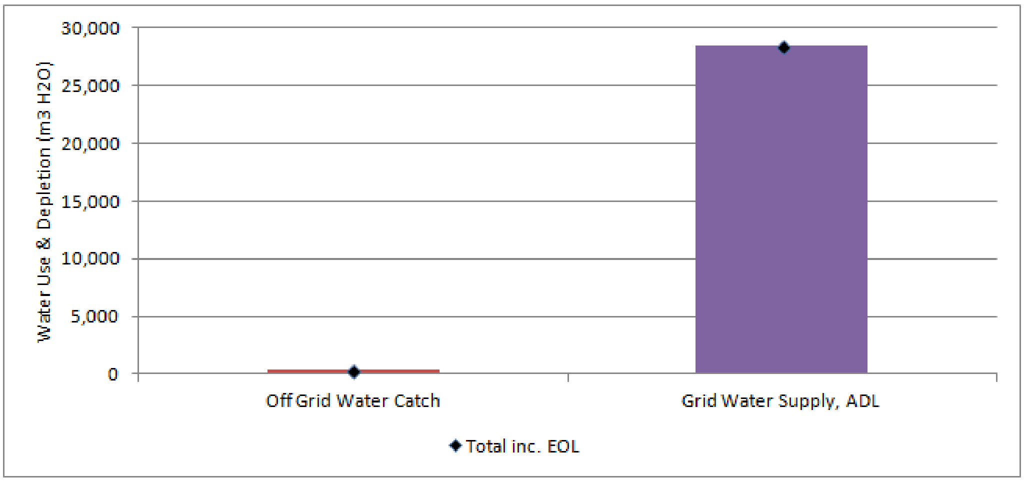

Figure 7.99 - Water Use & Depletion, Water Systems, Characterisation

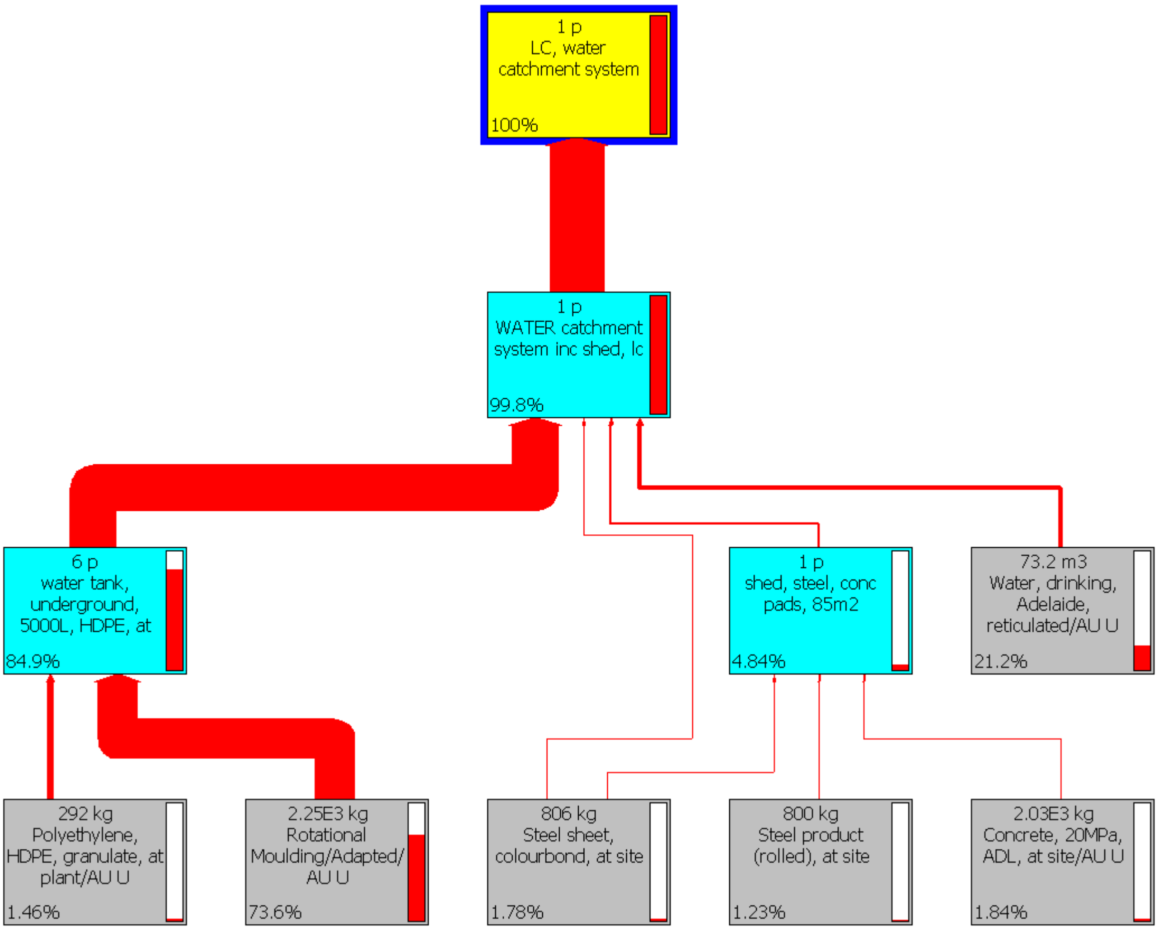

Figure 7.100 - Water Use & Depletion, network diagram, 1% cut off, off-grid water catchment system

7.6.7 Solid Waste for Water Supply System

The Solid Waste potential of the off-grid water system is approximately 4.5 times greater than Adelaide's reticulated water supply (Figure 7.101).

Manufacturing and use stage impacts of the off-grid system are driven primarily by steel production for the shed, whereas EOL impacts are driven by reprocessing HDPE, steel and landfill of non-recyclable components (Figure 7.102).

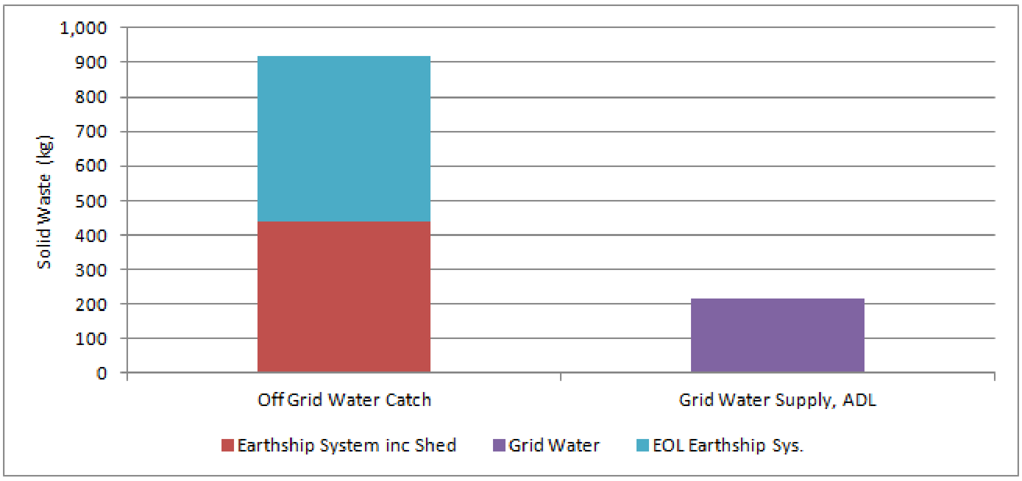

Figure 7.101 - Solid Waste, Water Systems, Characterisation

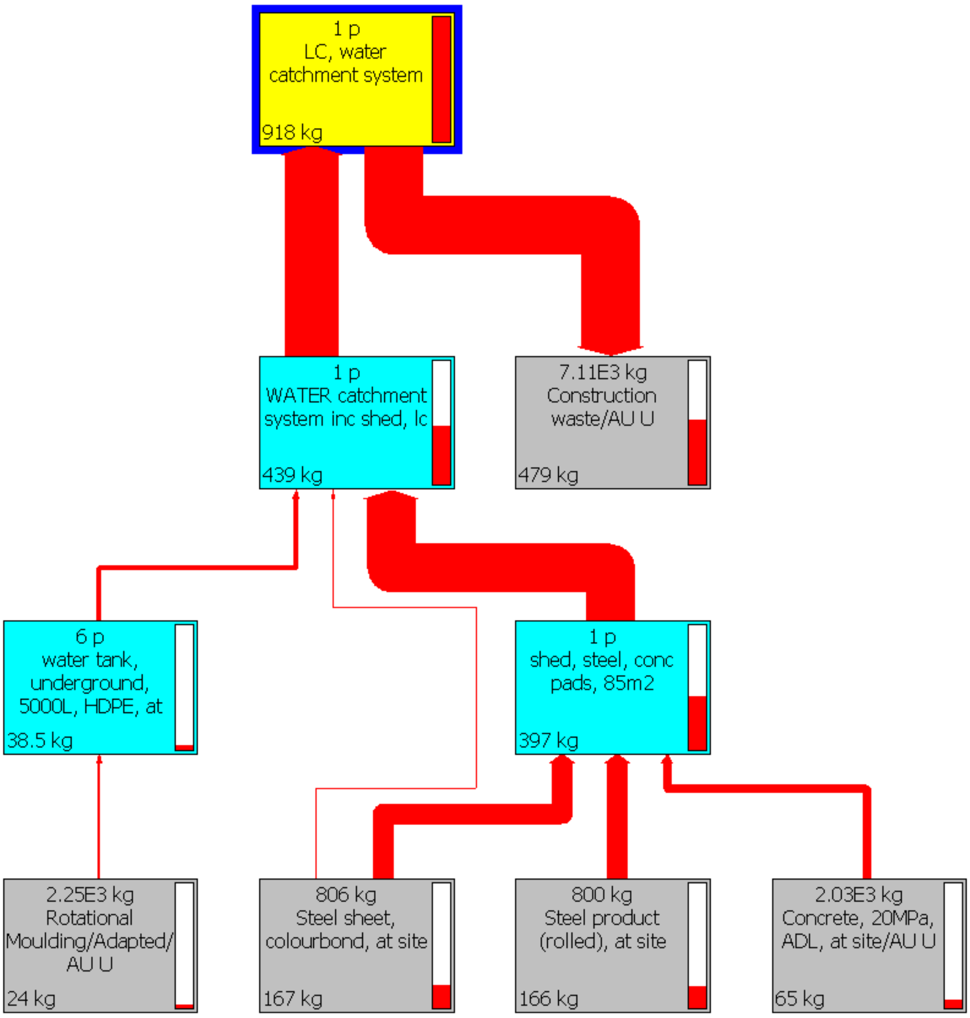

Figure 7.102 - Solid Waste, network diagram, 1% cut off, off-grid water catchment system

7.6.8 Embodied Energy for Water Supply System

The Embodied Energy of Adelaide's reticulated water supply is approximately 3 times greater than the off-grid water system when EOL credits are taken into account (Figure 7.103).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks (Figure 7.104). EOL impacts are significant due to the reclamation of HDPE which would otherwise need to be manufactured from virgin materials.

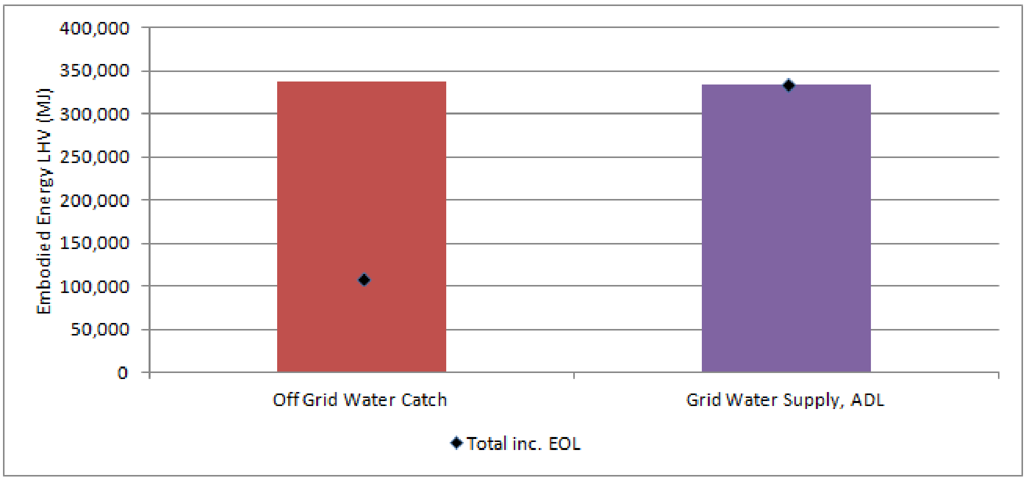

Figure 7.103 - Embodied Energy, Water Systems, Characterisation

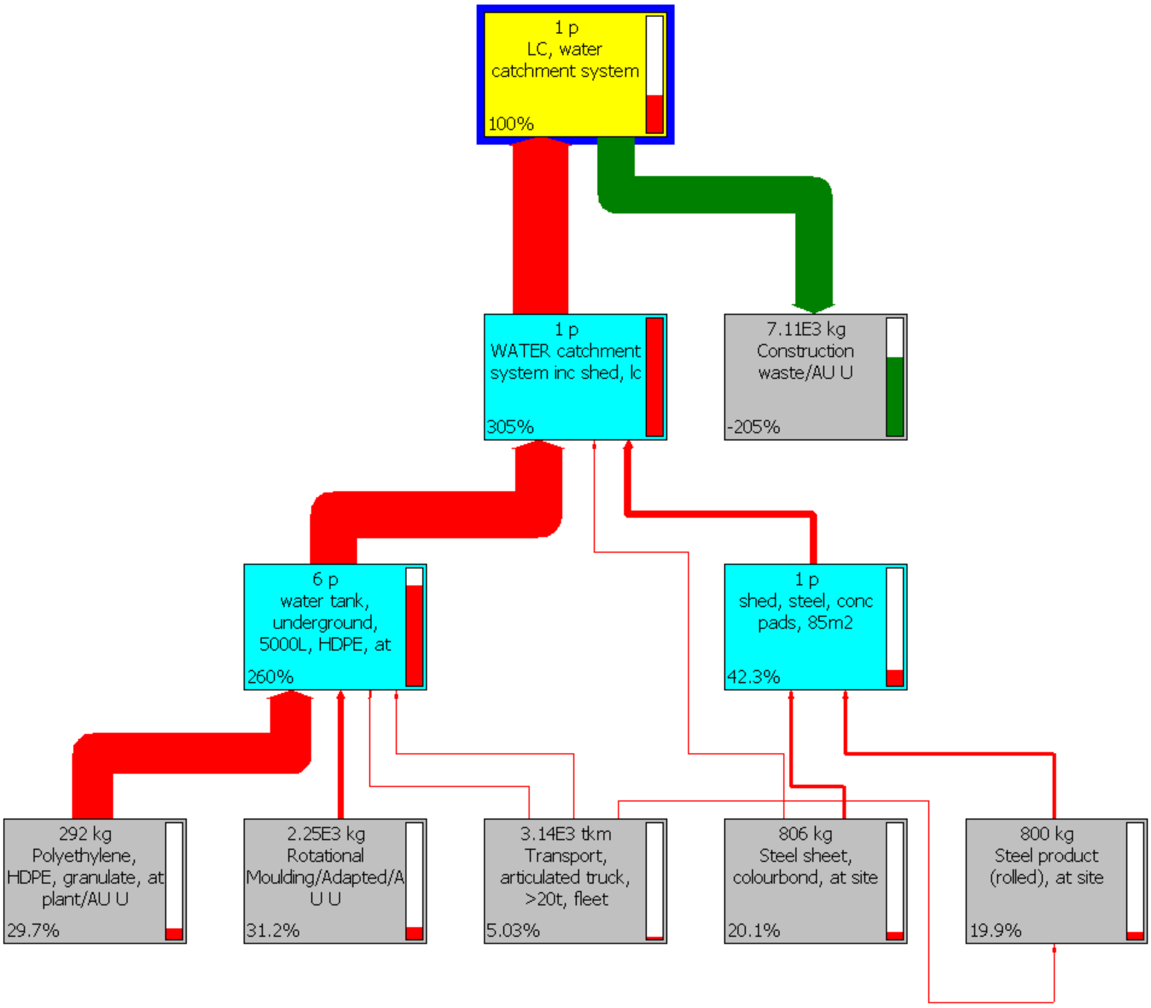

Figure 7.104 - Embodied Energy, network diagram, 1% cut off, off-grid water catchment system

7.6.9 Human Toxicity, Carcinogenic, for Water Supply System

The Carcinogenic Toxicity potential of the off-grid water system is approximately 10% greater than Adelaide's reticulated water supply when EOL credits are taken into account (Figure 7.105).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks (Figure 7.106). EOL impacts are significant due to the reclamation of HDPE which would otherwise need to be manufactured from virgin materials.

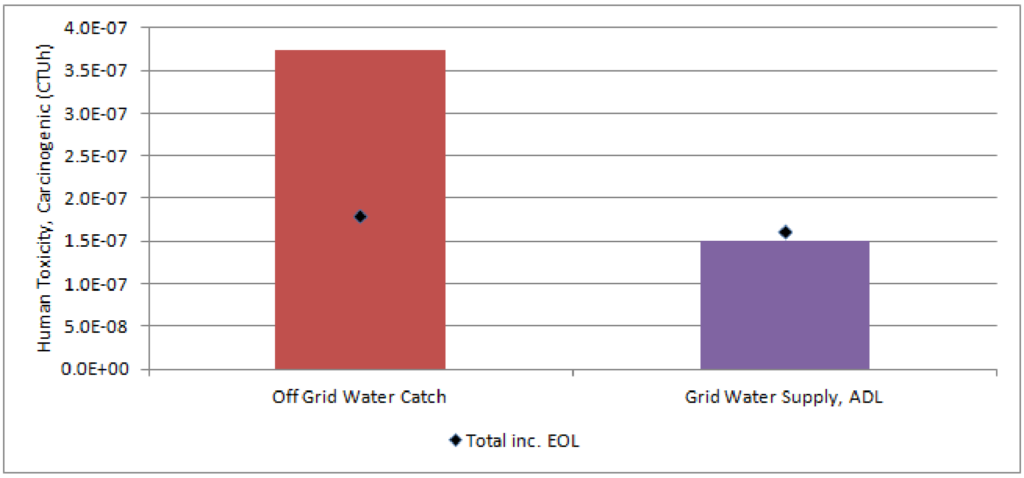

Figure 7.105 - Human Toxicity Carcinogenic, Water Systems, Characterisation

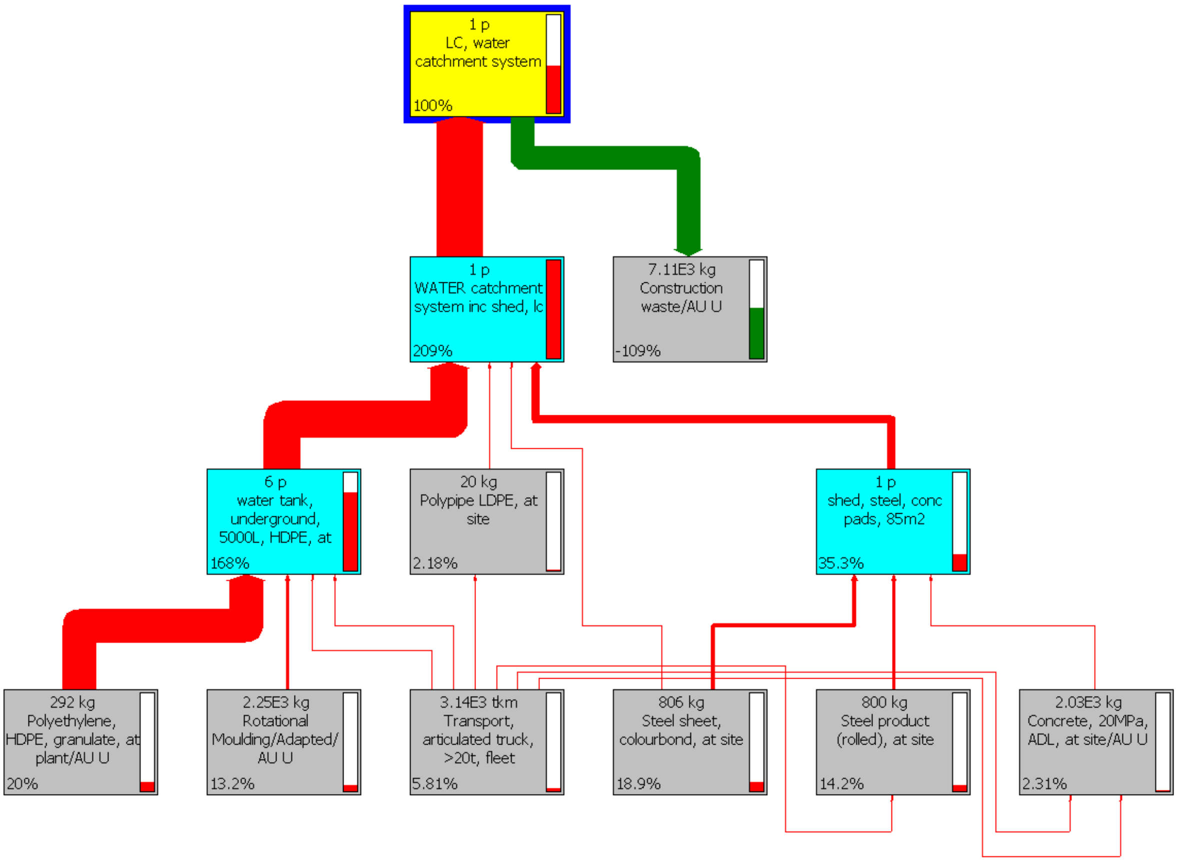

Figure 7.106 - Human Toxicity Carcinogenic, network diagram, 1% cut off, off-grid water catchment system

7.6.10 Human Toxicity, Non-Carcinogenic, for Water Supply System

The Non-Carcinogenic toxicity potential of Adelaide's reticulated water supply is approximately 3 times greater than the off-grid water system when EOL credits are taken into account (Figure 7.107).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of the high density polyethylene (HDPE) rainwater tanks (Figure 7.108). EOL impacts are due to the reclamation of HDPE which would otherwise need to be manufactured from virgin materials.

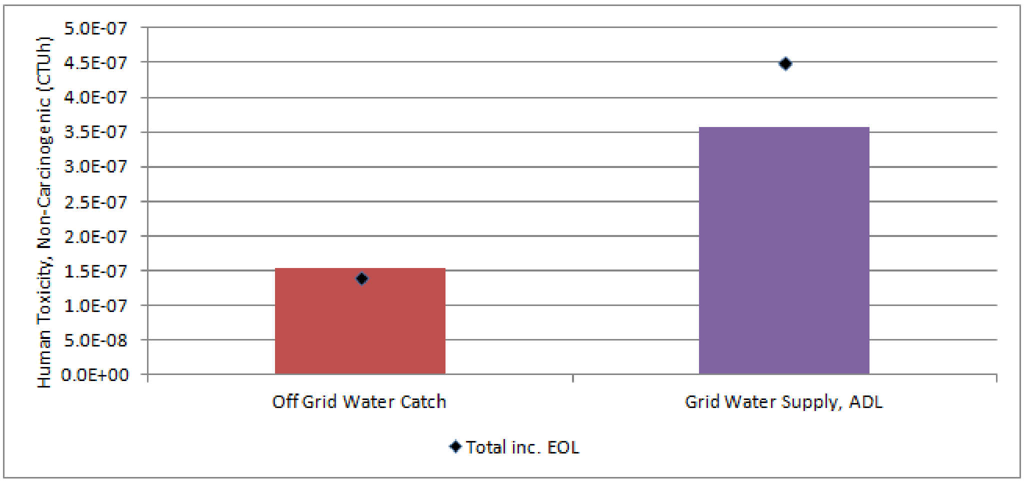

Figure 7.107 - Human Toxicity Non-carcinogenic, Water Systems, Characterisation

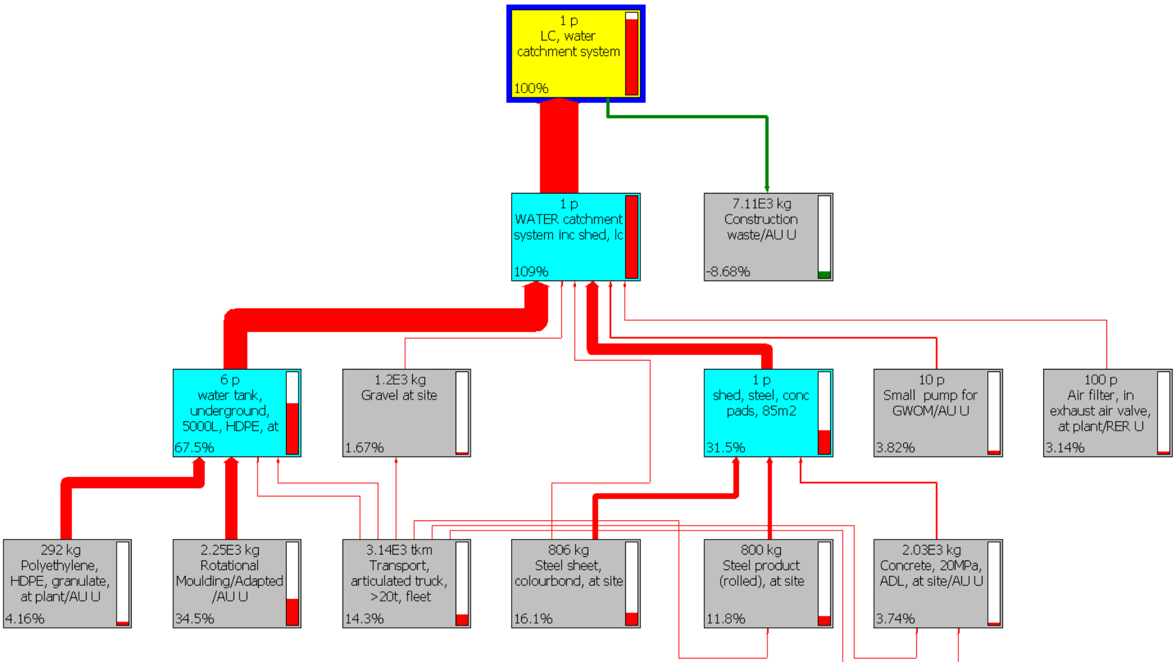

Figure 7.108 - Human Toxicity Non-carcinogenic, network diagram, 1% cut off, off-grid water catchment system

7.6.11 Eco Toxicity for Water Supply System

The Eco Toxicity potential of the off-grid water system is approximately 1.5 times greater than Adelaide's reticulated water supply (Figure 7.109).

Manufacturing and use stage impacts of the off-grid system are driven primarily by production of steel for the shed (extra roof catchment) and EOL impacts arise from avoided virgin materials such as steel, due to recycling (Figure 7.110).

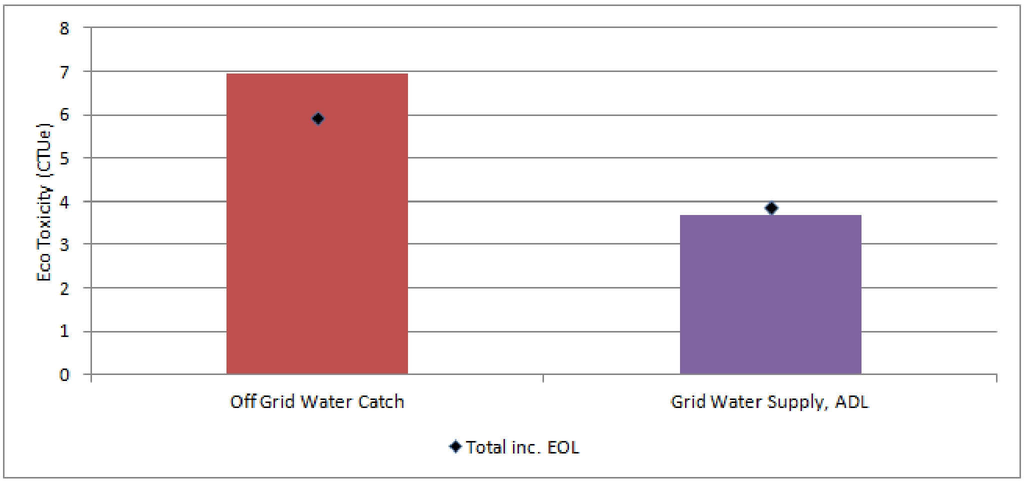

Figure 7.109 - Eco Toxicity, Water Systems, Characterisation

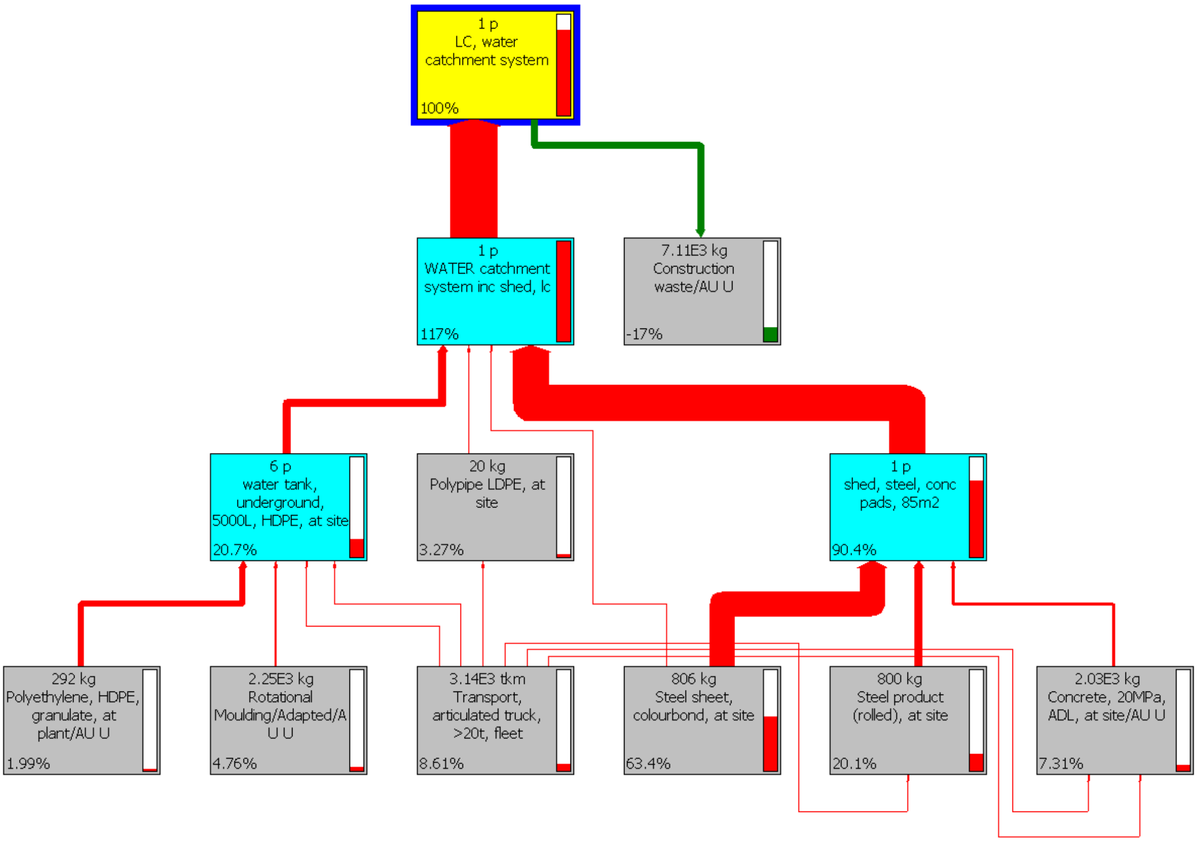

Figure 7.110 - Eco Toxicity, network diagram, 1% cut off, off-grid water catchment system

7.6.12 Normalisation for Water Supply System

A result of 1 on the vertical axis represents 50 years of impacts, hence the Water Use & Depletion result for the Grid Water Supply (0.66) indicates the quantity of water use modelled is 34% less than average water use, hence the result for Grid Water tends to underestimate average impacts. This is due to the normalisation factor referring to the national average rather than the South Australian average which is lower.

GWP is of minor significance for the Grid Water Supply, as is Solid Waste for the off-grid system. The significance of the other impact categories is negligible.

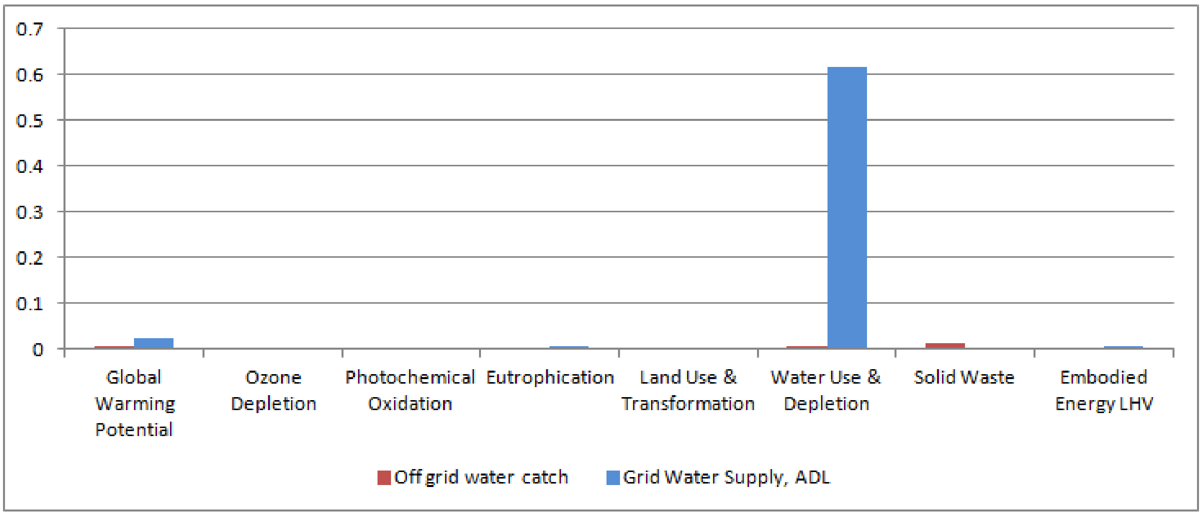

Figure 7.111 - Normalisation of Water Supply System Results

7.6.13 Weighted Single Score for Water Supply System

Adelaide's reticulated water supply has approximately 15 times greater environmental impact than the off-grid water system (Figure 7.112).

GWP represents approximately half the impacts of the off-grid system whereas Water Use & Depletion accounts for the vast majority of impacts for the Grid Water Supply.

The majority of impacts (76%) in the off-grid system arise from the manufacture of the high density polyethylene water tanks (6 tanks 5000L each). The shed, which is included for added roof catchment area, contributes approximately 21% of impacts (Figure 7.113).

Figure 7.114 shows the energy use in supplying reticulated water to Adelaide homes over a 50 yr time period. Approximately 177GJ of energy is required to supply 28.5ML of water.

Figure 7.115 is included to compare the Adelaide water supply (Figure 7.114) with the Melbourne water supply. The Melbourne water supply has approximately 15% less impact on the basis of the weighted single score, due to less energy use (less pumping of water).

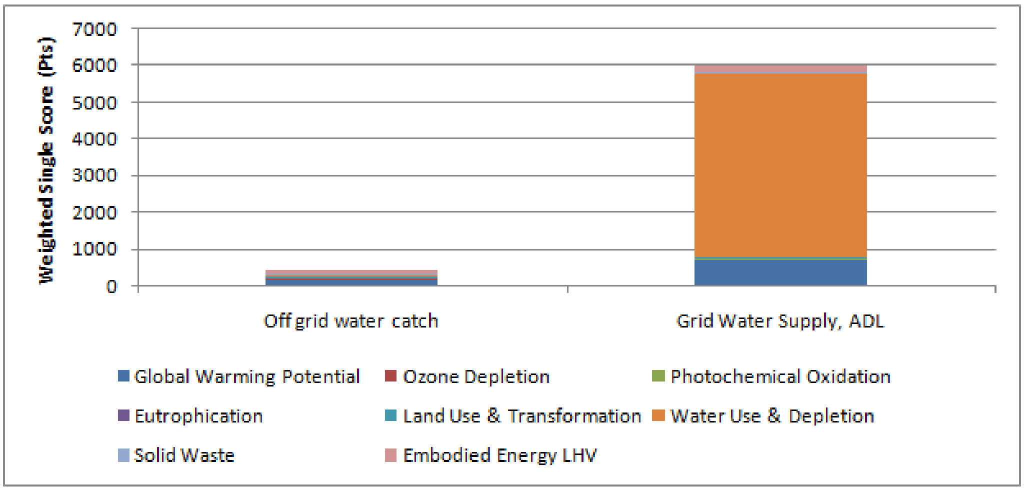

Figure 7.112 - Weighted Single Score, Water Supply Systems

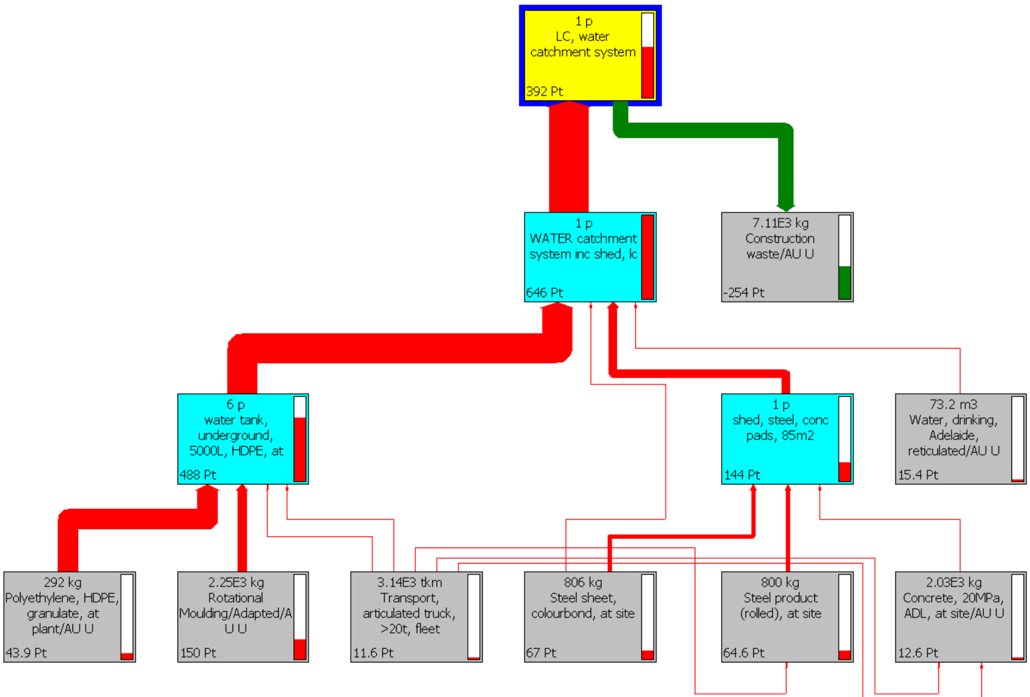

Figure 7.113 - Weighted Single Score Network Diagram, Off-Grid Water Catchment and Storage System, 50 yr Lifecycle

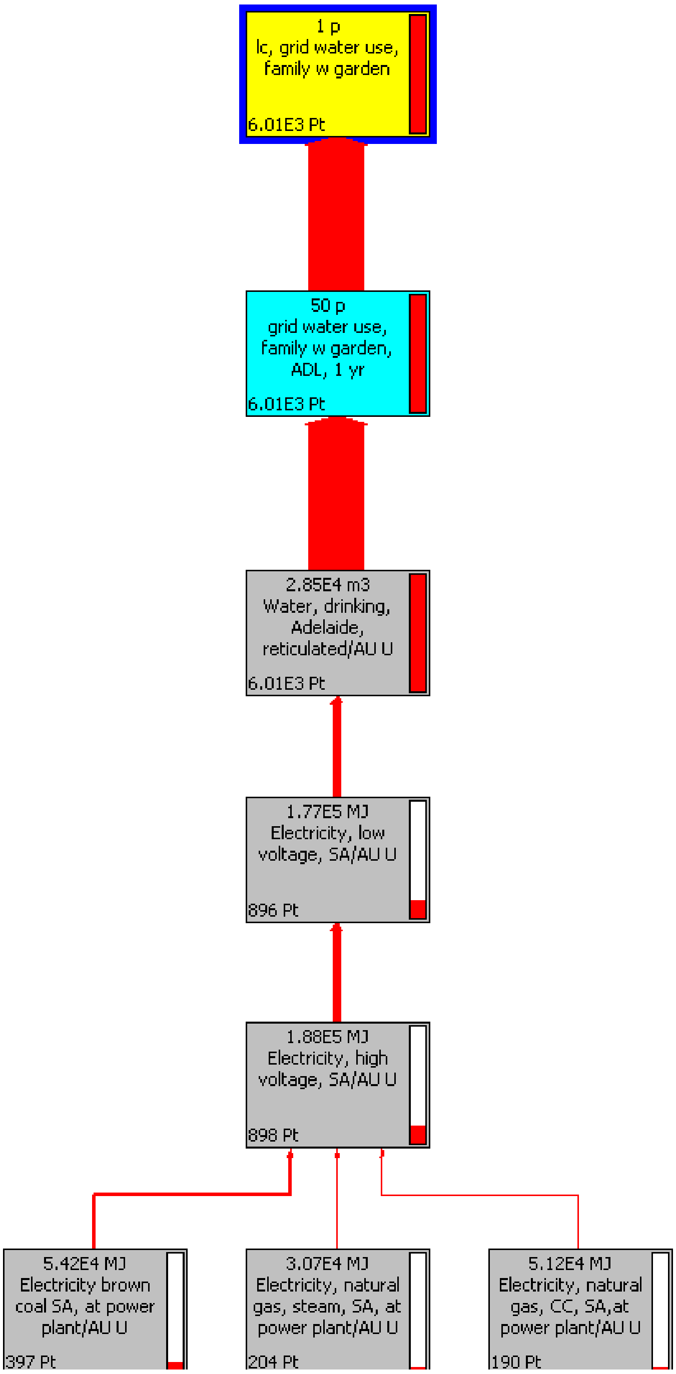

Figure 7.114 - Weighted Single Score Network Diagram, Grid Water Adelaide, 50 yr Lifecycle, cut off 1%

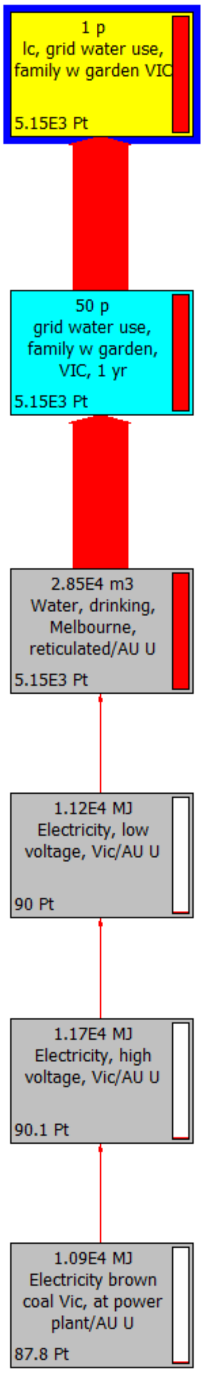

Figure 7.115 - Weighted Single Score Network Diagram, Grid Water Melbourne, 50 yr Lifecycle, cut off 1%

7.6.14 Discussion & Summary for Water Supply System

The analysis compares the Earthship's off-grid water catchment and storage system capable of supplying a family of four with 73L of water per day each (the quantity quoted by Reynolds for Earthship occupants) with the reticulated water supply in Adelaide for which it is assumed 390L per day, per person is used. The difference is due to the water efficient systems incorporated in the Earthship which provide the same "water service" (functionality) as a conventional home. The Earthship is approximately five times more water efficient.

It might then be expected that the reticulated water supply would have approximately 5 times more environmental impact, however this study shows the impact of the reticulated water supply to be about 15 times more than the off-grid system. The impacts from the reticulated system arise mainly due to the large quantities of water, which are drawn from sources such as the River Murray (LCI data does not include impacts from the recently constructed desalination plant which would be likely to increase impacts due to energy use of the desalination plant). A significant amount of energy required to supply water to homes which must be pumped over large distances produces greenhouse gas emissions and is another significant contributor to the environmental impact of the grid system. Furthermore the water must be treated, requiring more electricity and chemicals.

Thus the reticulated system has significant and consistent impacts throughout its lifecycle whereas the off-grid Earthship system (which is similar to the systems used by thousands of Australian homes) incurs impacts mainly during the construction stage with very few use stage impacts. These use stage impacts were limited to replacement of water filters and a pump which were modelled at a rate of 2 filters per year and 1 pump every 5 years – these had negligible impacts. The Earthship system benefits from "free" water from rainfall whereas the grid system must "pay" for its water supply which is modelled as depleting the natural systems e.g. the River Murray. While it could be argued that the roof catchment and storage system employed by the Earthship system (and thousands of Australian homes) prevents some water from reaching eco and techno systems (aquifers and reservoirs respectively) it certainly does not produce the significant GHG emissions arising from the need to pump large quantities of water from a centralised water source to distant homes, as in the reticulated water supply system.

Even if the comparison is based on an identical water supply rate, rather than Earthship's more efficient rate, the comparison still favours the Earthship which in this case incurs only a third of the impacts of the reticulated water supply.

It should be noted, however, that the efficiency of the Earthship is in large part due to its innovative wastewater system which is not accounted for here, but is discussed in detail in the following section where it is compared to a conventional sewer system.

In summary, this study demonstrates that the common practice (in Australia) of collecting and storing rainwater is environmentally responsible, and when coupled with the water efficient Earthship technology - flushing the toilet with biologically treated greywater, and irrigating gardens with wastewater – dramatic reductions in water use, energy use, and their associated environmental impacts are possible.

7.7 Wastewater System

This section presents results and analysis of the Off-Grid Wastewater System and the Sewer System. The system assumptions are based on waster use for a family of four in Adelaide.

The Off-Grid System includes materials and components for the typical Earthship system, that is, a greywater planter, septic tank and outdoor biological cell similar to a reed bed (Reynolds, 2005). The Adelaide Sewer System is assumed to be able to treat 150L per person per day. Refer to Chapter 6 for details regarding these assumptions.

Note that EOL impacts are not displayed or discussed as they were so small in comparison to the lifecycle impacts.

7.7.1 Global Warming Potential for Wastewater System

The Global Warming Potential (GWP) of the Adelaide Sewer System ("Sewer Use, ADL") is approximately 3.7 times greater than the off-grid wastewater system ("Earthship Wastewater System") (Figure 7.116). A large portion of the impact of the off-grid system is associated with manufacture of a 3000L high density polyethylene septic tank which is part of the blackwater system. Other significant impacts are associated with gravel, sand and rubber sheet (water proof membrane) used in the greywater and blackwater systems (Figure 7.117). GWP arising from use of the Adelaide Sewer System is driven by energy used for pumping and treating the wastewater.

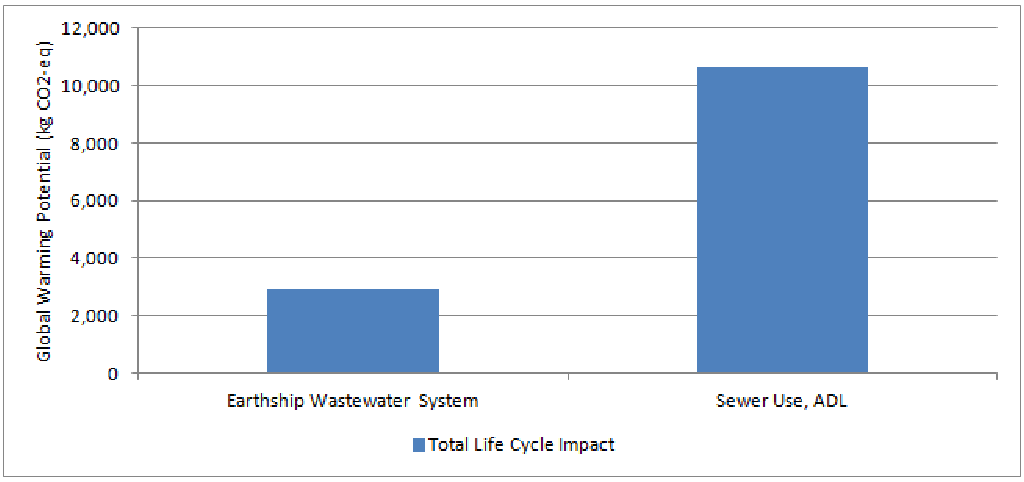

Figure 7.116 - Global Warming Potential, Wastewater Systems, Characterisation

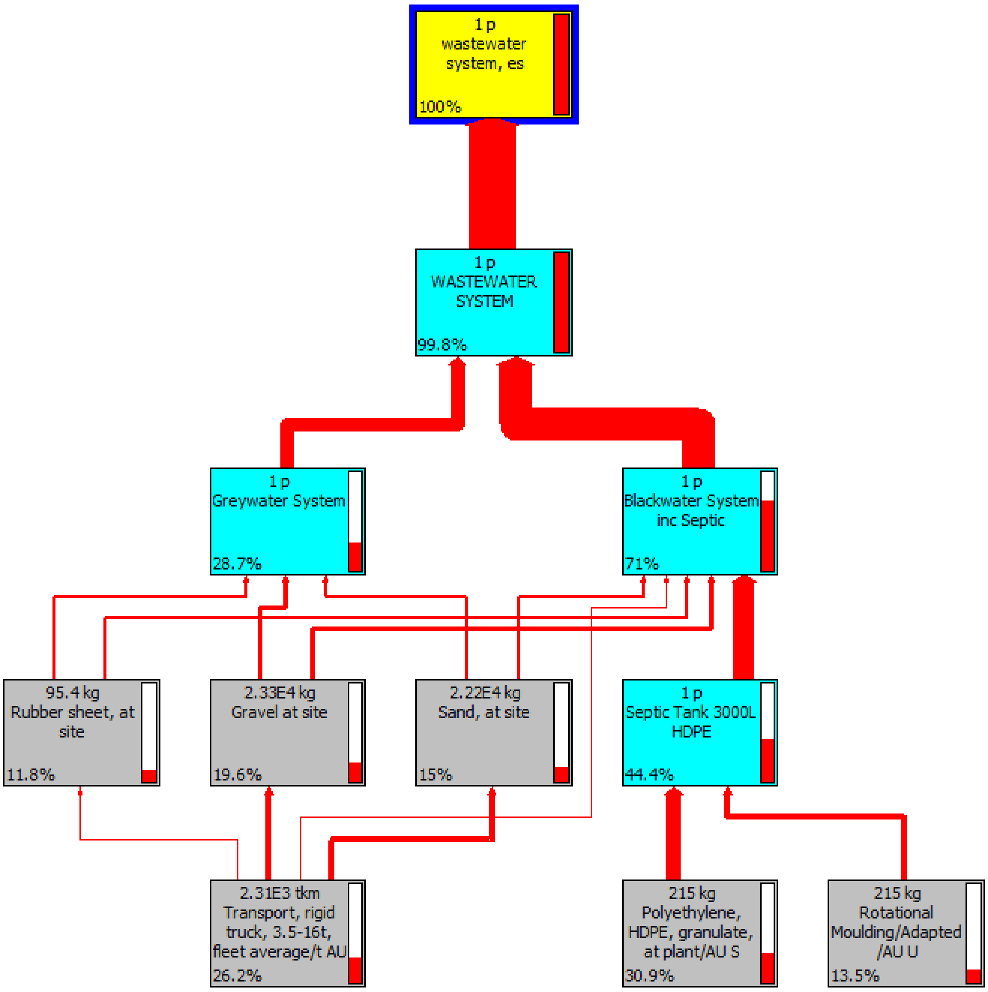

Figure 7.117 - Global Warming Potential, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.2 Ozone Depletion for Wastewater System

The Ozone Depletion potential of the Adelaide Sewer System is approximately 11 times greater than the off-grid wastewater system (Figure 7.118). Impacts from the off-grid system are caused by transport of gravel and sand and to a lesser extent the use of PVC pipe, used for plumbing (Figure 7.119), whereas impacts from the Adelaide Sewer System are driven by electricity derived from (natural) gas powered turbines.

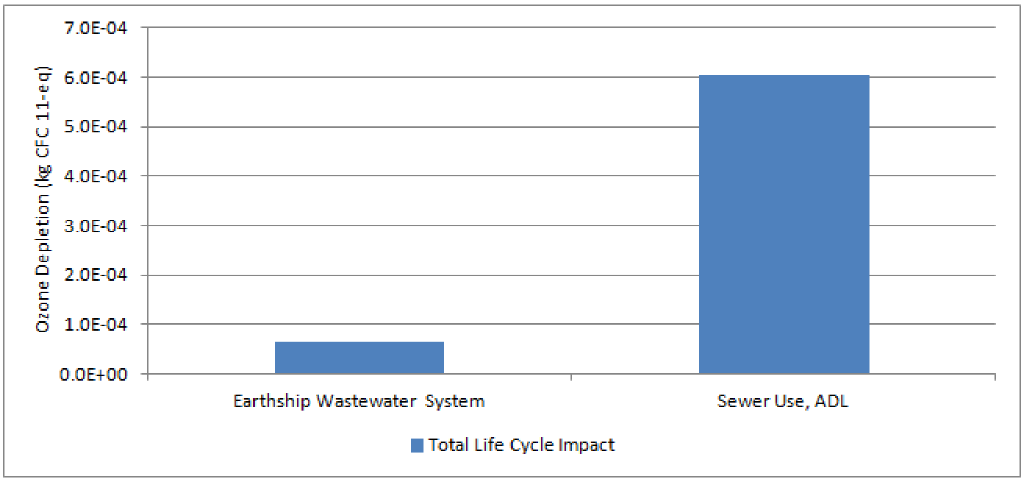

Figure 7.118 - Ozone Depletion, Wastewater Systems, Characterisation

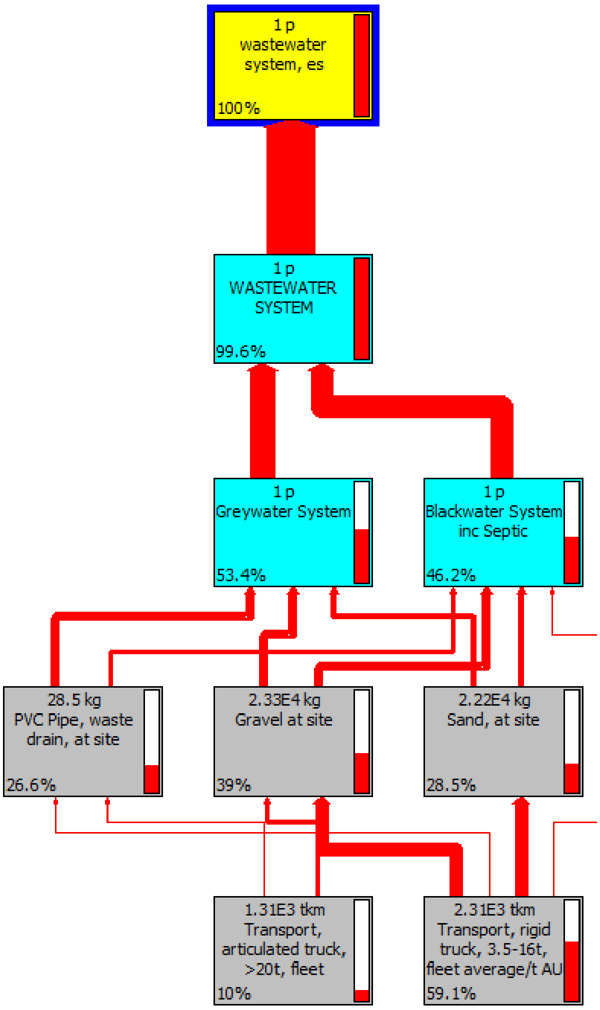

Figure 7.119 - Ozone Depletion, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.3 Photochemical Oxidation for Wastewater System

The Photochemical Oxidation potential of the Adelaide Sewer System is approximately 1.7 times greater than the off-grid wastewater system (Figure 7.120). Impacts from the off-grid system are caused mainly by the high density polyester resin used in the manufacture of the septic tank (Figure 7.121), whereas impacts from the Adelaide Sewer System are driven by energy use (coal and natural gas).

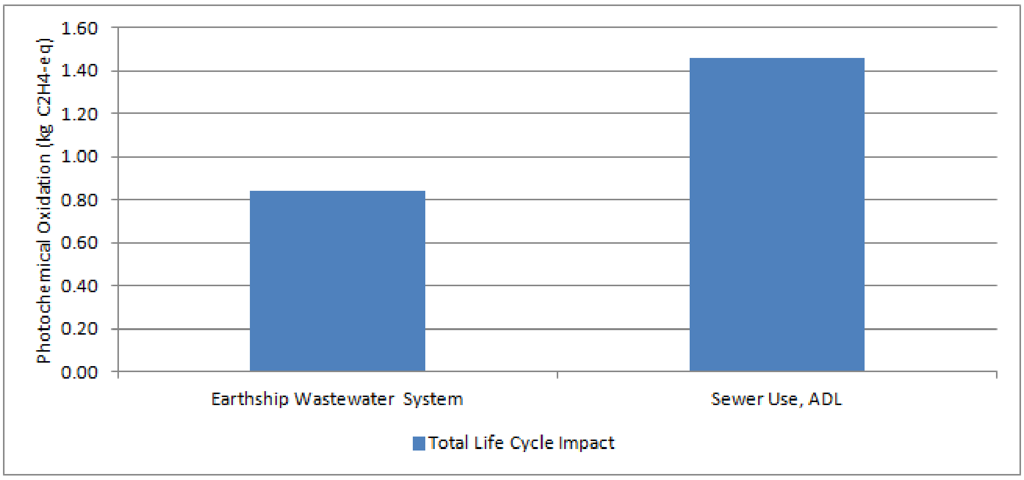

Figure 7.120 - Photochemical Oxidation, Wastewater Systems, Characterisation

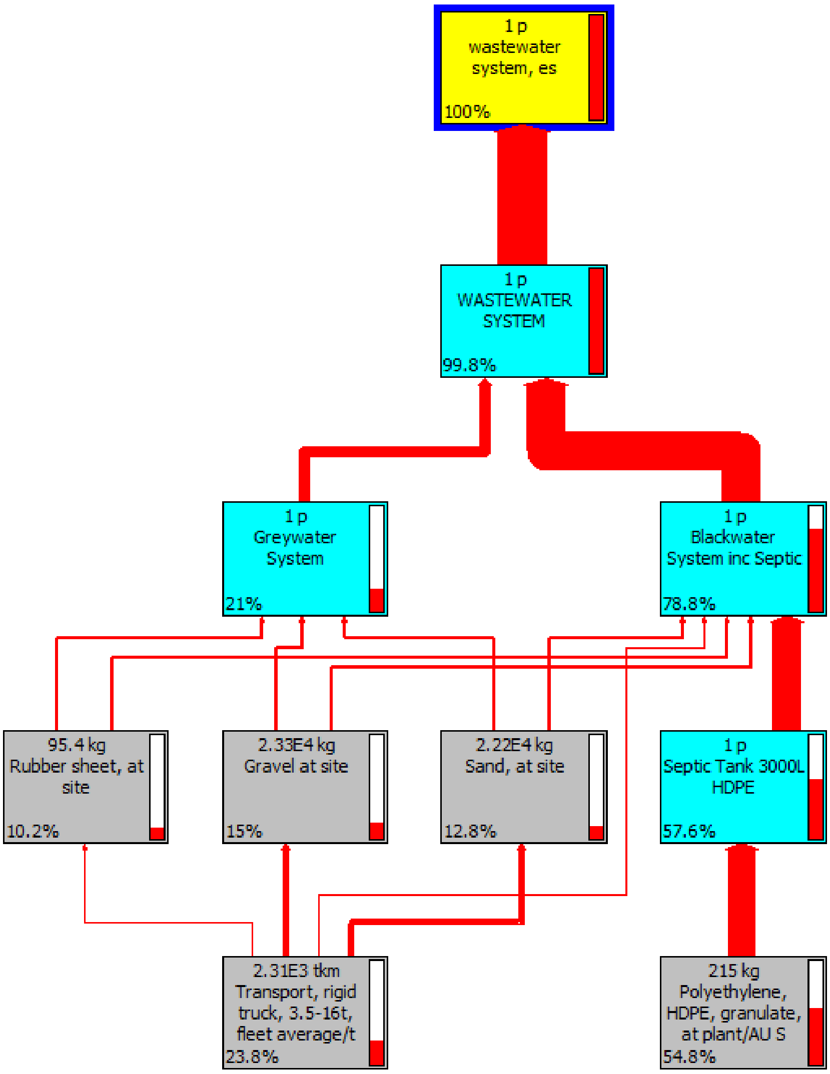

Figure 7.121 - Photochemical Oxidation, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.4 Eutrophication for Wastewater System

The Eutrophication potential of the Adelaide Sewer System is approximately 20 times greater than the off-grid wastewater system (Figure 7.122). Impacts from the off-grid system are driven by transportation of sand and gravel (used in the black and grey water botanical cells) to the building site (Figure 7.123), whereas impacts from the Adelaide Sewer System are driven by energy used for pumping and treating wastewater.

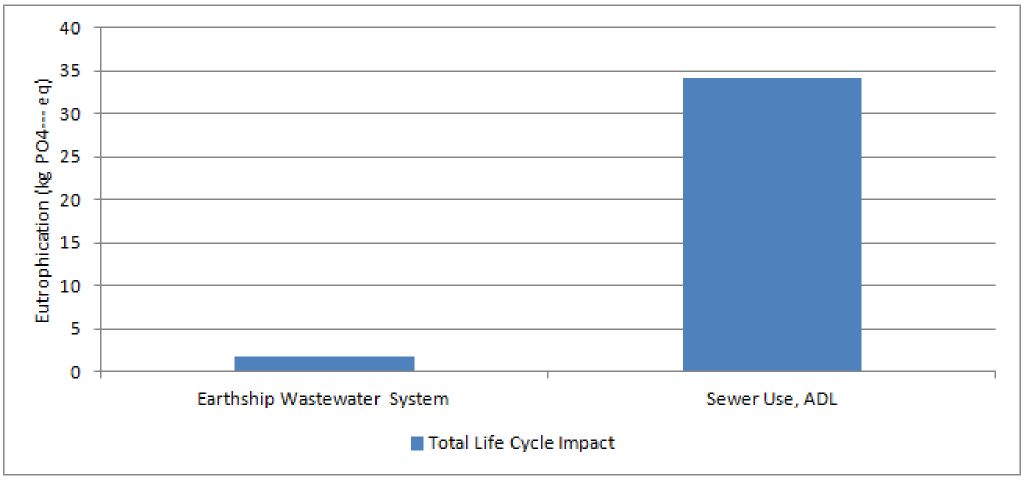

Figure 7.122 - Eutrophication, Wastewater Systems, Characterisation

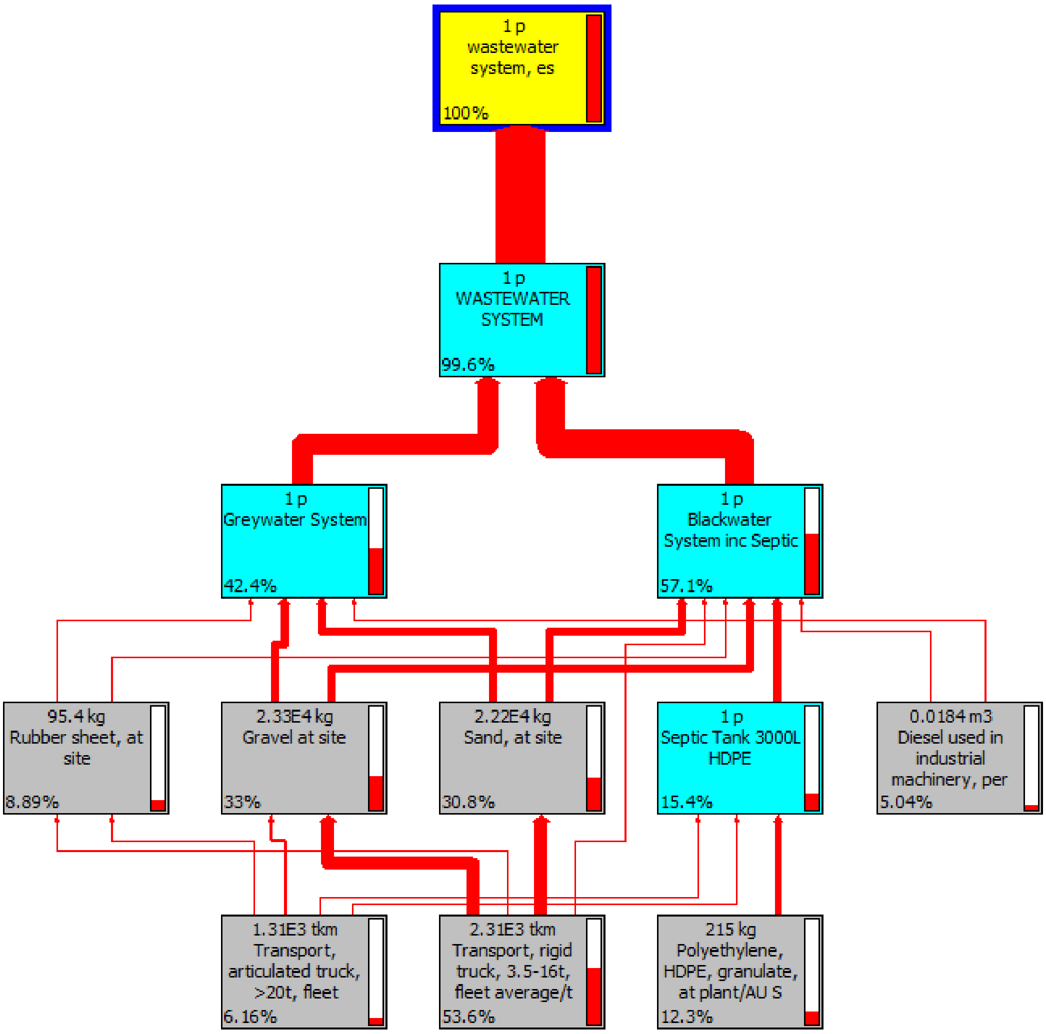

Figure 7.123 - Eutrophication, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.5 Land Use & Transformation for Wastewater System

The Land Use & Transformation potential of the off-grid wastewater system is approximately 18 times greater than the Adelaide Sewer System (Figure 7.124). Impacts from the off-grid system are driven by the requirement for 200m2 of land for disposal of waste water (Figure 7.125), whereas impacts from the Adelaide Sewer System are driven by energy used for pumping and treating wastewater – land used for the treatment plant for example.

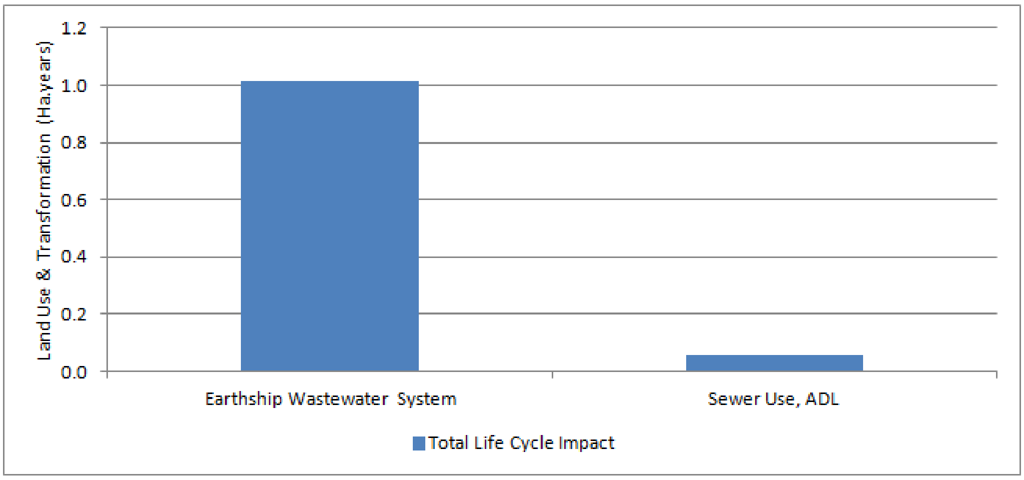

Figure 7.124 - Land Use & Transformation, Wastewater Systems, Characterisation

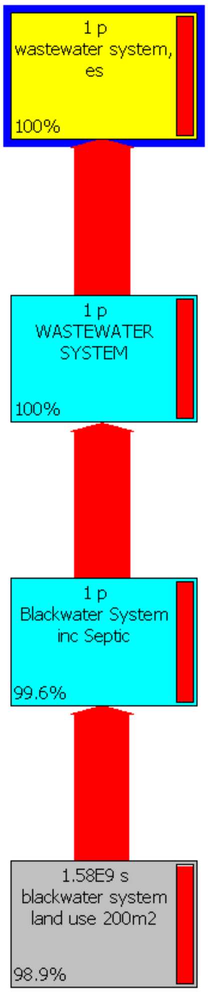

Figure 7.125 - Land Use & Transformation, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.6 Water Use & Depletion for Wastewater System

The Water Use & Depletion potential of the off-grid wastewater system is approximately 1.2 times greater than the Adelaide Sewer System (Figure 7.126). Impacts from the off-grid system are driven by water used in production of gravel followed by sand, septic tank, and rubber production (Figure 7.127), whereas water use arising from use of the Adelaide Sewer System are due to energy derived from natural gas, used for pumping and treating wastewater.

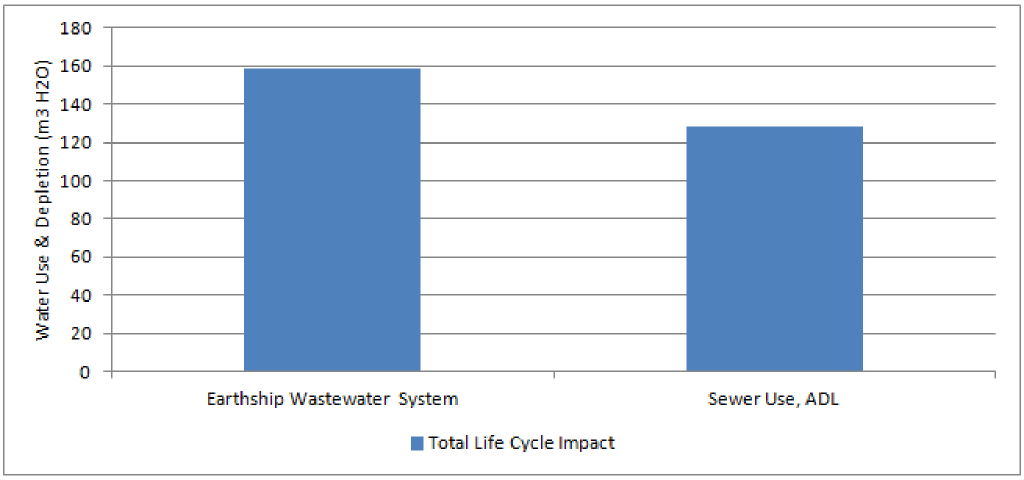

Figure 7.126 - Water Use & Depletion, Wastewater Systems, Characterisation

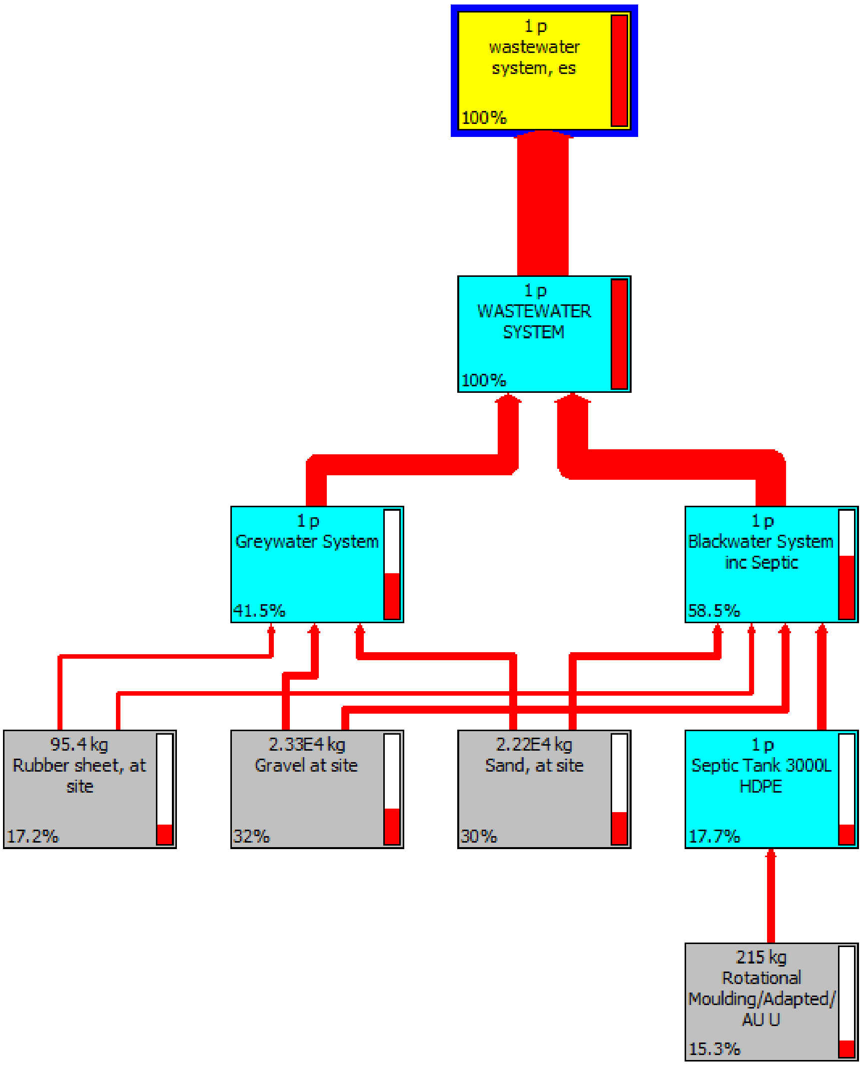

Figure 7.127 - Water Use & Depletion, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.7 Solid Waste for Wastewater System

The Solid Waste potential of the off-grid wastewater system is approximately 12.5 times greater than the Adelaide Sewer System (Figure 7.128). Impacts from the off-grid system are driven mainly by waste generated at EOL (346kg) from non-recyclable materials, and to a far lesser extent by waste generated during the manufacturing stage of the system (approximately 12kg) (Figure 7.129). Solid waste arising from use of the Adelaide Sewer System is due to energy derived from brown coal, used for pumping and treating wastewater.

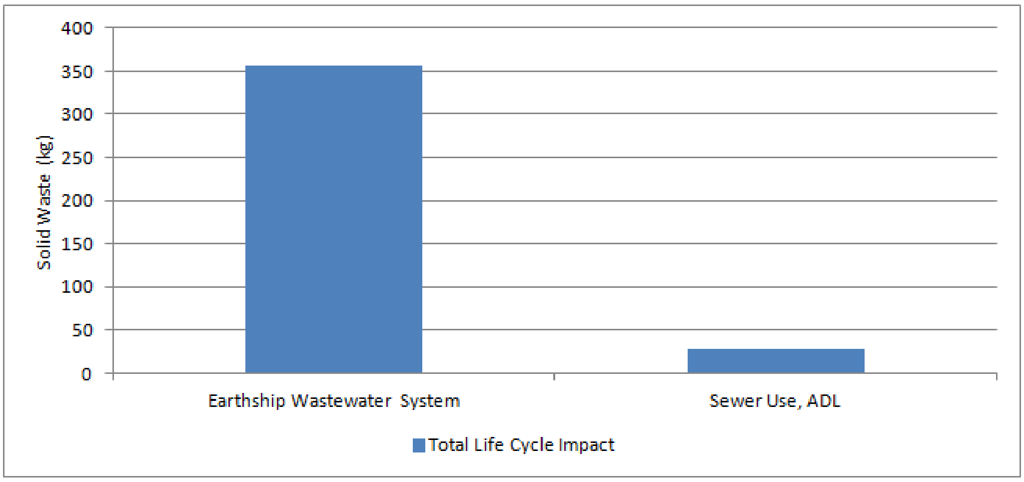

Figure 7.128 - Solid Waste, Wastewater Systems, Characterisation

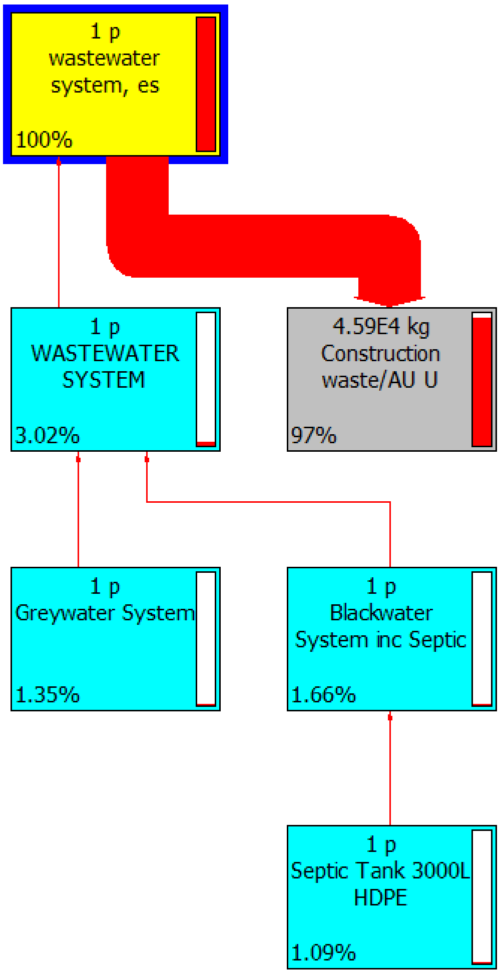

Figure 7.129 - Solid Waste, network diagram, 1% cut off, Off-Grid Wastewater Catchment System

7.7.8 Embodied Energy for Wastewater System

The Embodied Energy of the Adelaide Sewer System is approximately 2.4 times greater than the off-grid wastewater system (Figure 7.130). Impacts from the off-grid system are driven by energy used in the manufacture of the high density polyethylene resin used in the roto-moulded tank and less so, from gravel, sand and rubber production (Figure 7.131), whereas Embodied Energy arising from use of the Adelaide Sewer System is due to energy use from the South Australian grid.

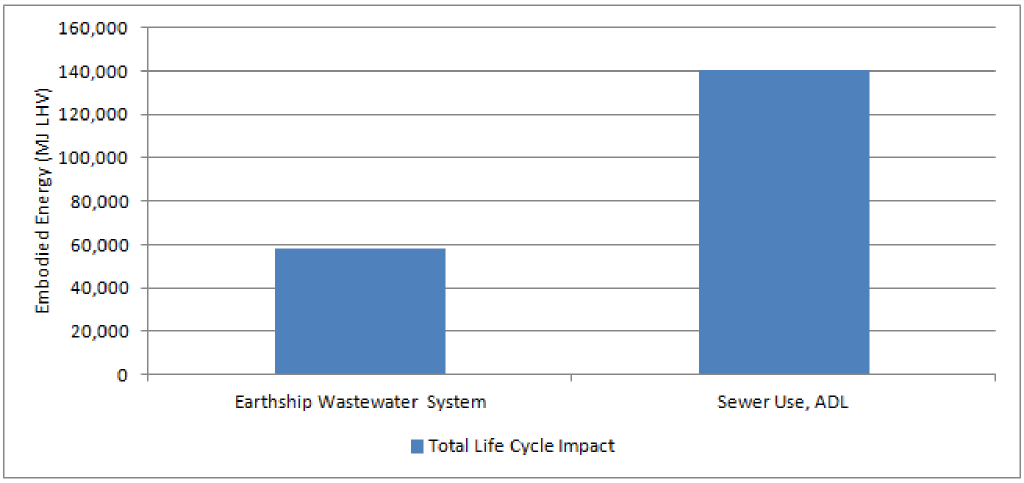

Figure 7.130 - Embodied Energy, Wastewater Systems, Characterisation

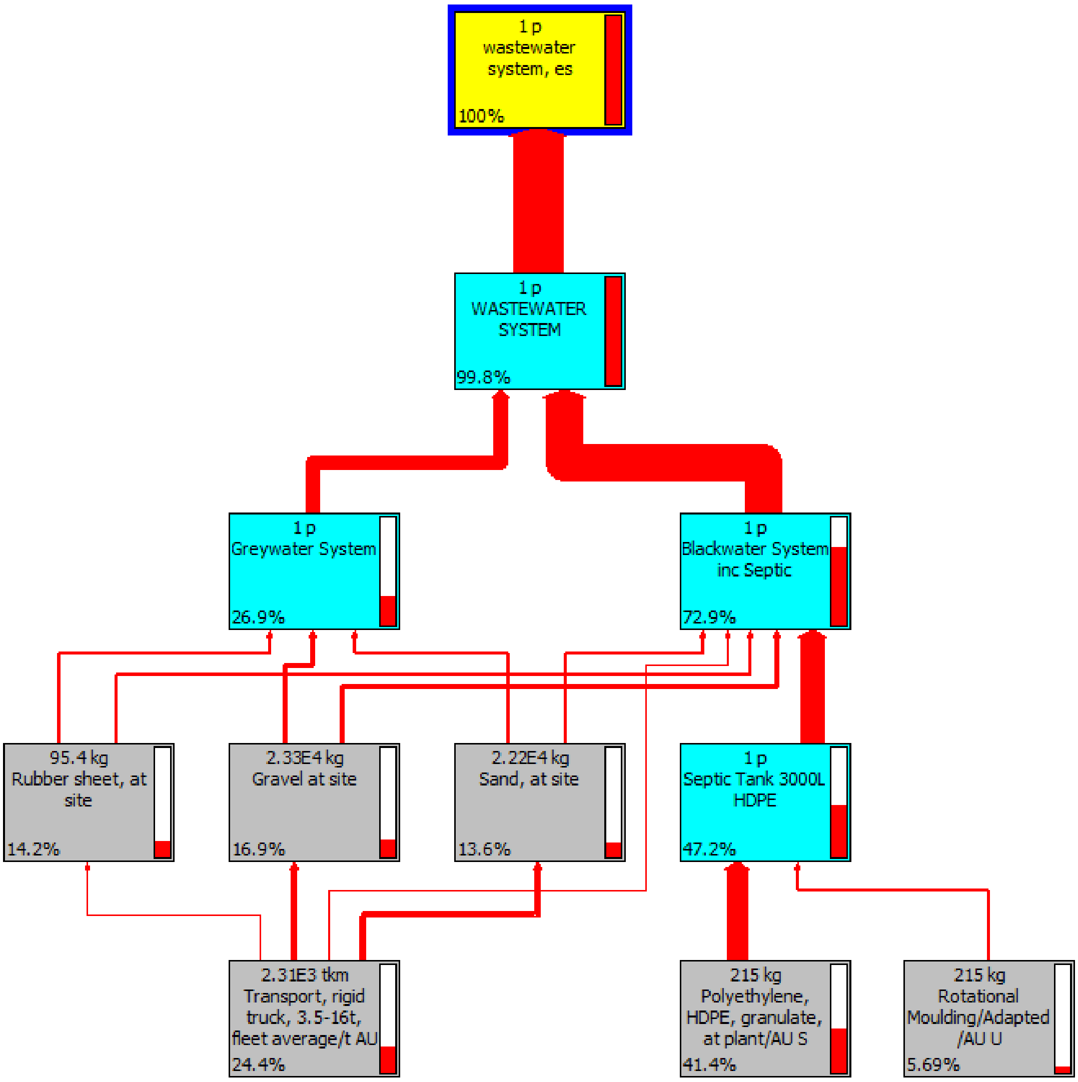

Figure 7.131 - Embodied Energy, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.9 Human Toxicity, Carcinogenic, for Wastewater System

The Carcinogenic Toxicity potential of the Adelaide Sewer System is approximately 4 times greater than the off-grid wastewater system (Figure 7.132). Impacts from the off-grid system are driven by the high density polyethylene resin used in manufacture of the septic tank (Figure 7.133), whereas carcinogenic emissions arising from use of the Adelaide Sewer System is due to energy derived from natural gas, from the South Australian grid.

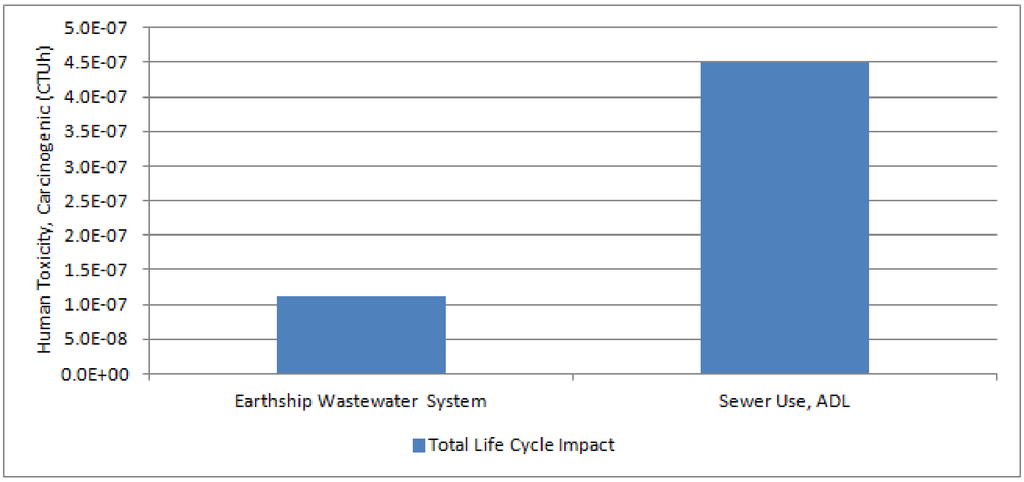

Figure 7.132 - Human Toxicity Carcinogenic, Wastewater Systems, Characterisation

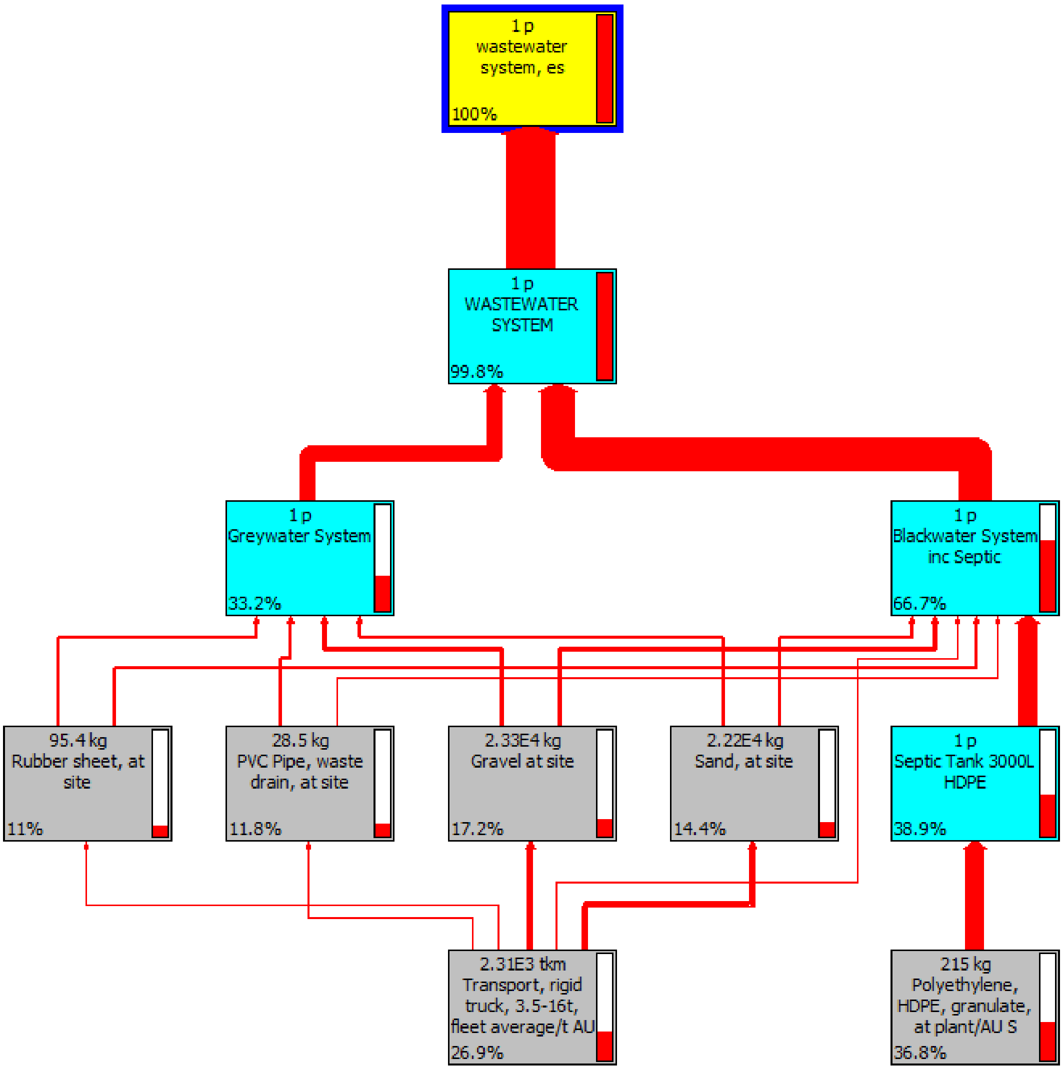

Figure 7.133 - Human Toxicity Carcinogenic, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.10 Human Toxicity, Non-Carcinogenic, for Wastewater System

The Non-Carcinogenic potential of the Adelaide Sewer System is approximately 8.5 times greater than the off-grid wastewater system (Figure 7.134). Impacts from the off-grid system are driven by the high density polyethylene resin used in manufacture of the septic tank (Figure 7.135), whereas carcinogenic emissions arising from use of the Adelaide Sewer System is due to energy derived from wind power and bagasse (sugar cane waste), from the South Australian grid.

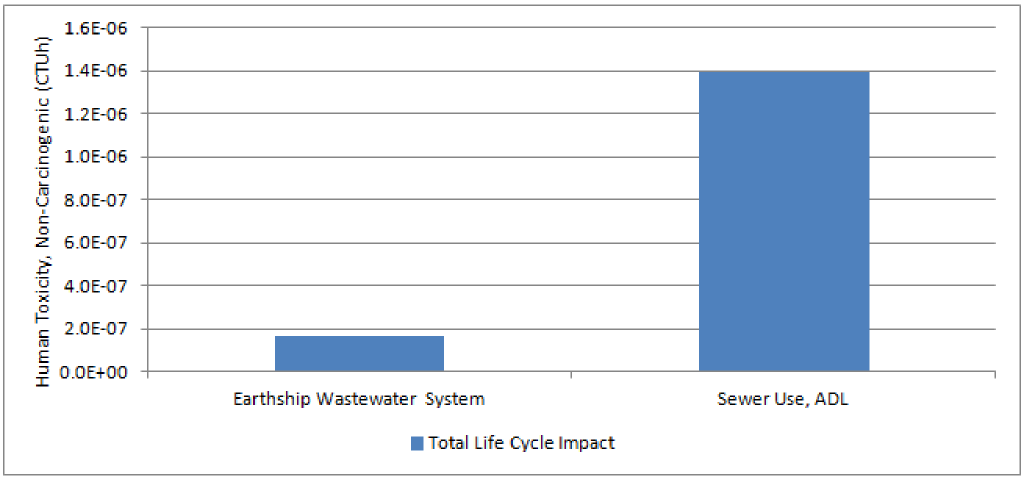

Figure 7.134 - Human Toxicity Non-carcinogenic, Wastewater Systems, Characterisation

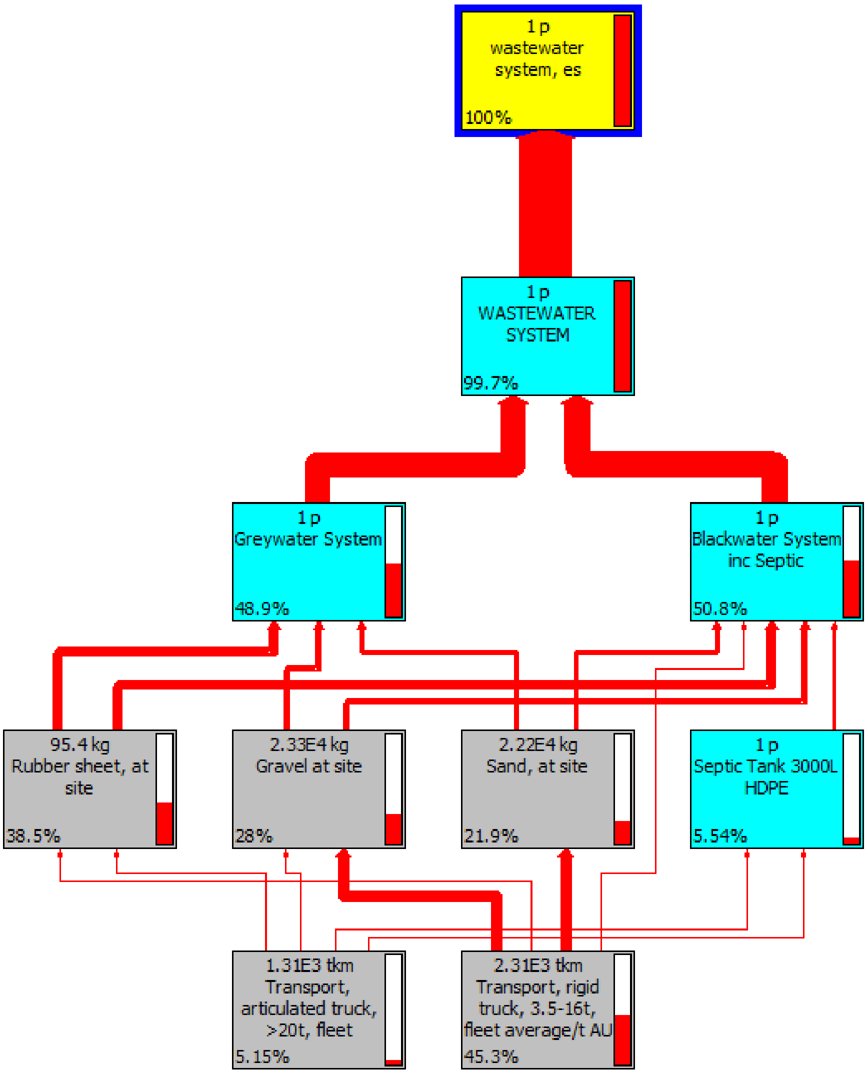

Figure 7.135 - Human Toxicity Non-carcinogenic, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.11 Eco Toxicity for Wastewater System

The Eco Toxicity potential of the Adelaide Sewer System is approximately 2.5 times greater than the off-grid wastewater system (Figure 7.136). Impacts from the off-grid system are driven by the rubber sheet used in manufacture of the biological filter systems (Figure 7.137), whereas eco toxic emissions arising from use of the Adelaide Sewer System are due to processes within the wastewater treatment plant.

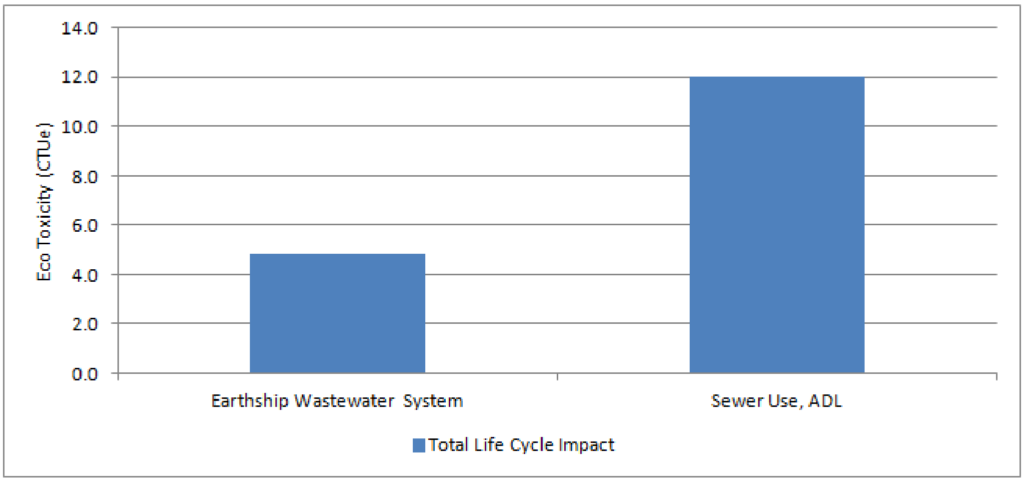

Figure 7.136 - Eco Toxicity, Wastewater Systems, Characterisation

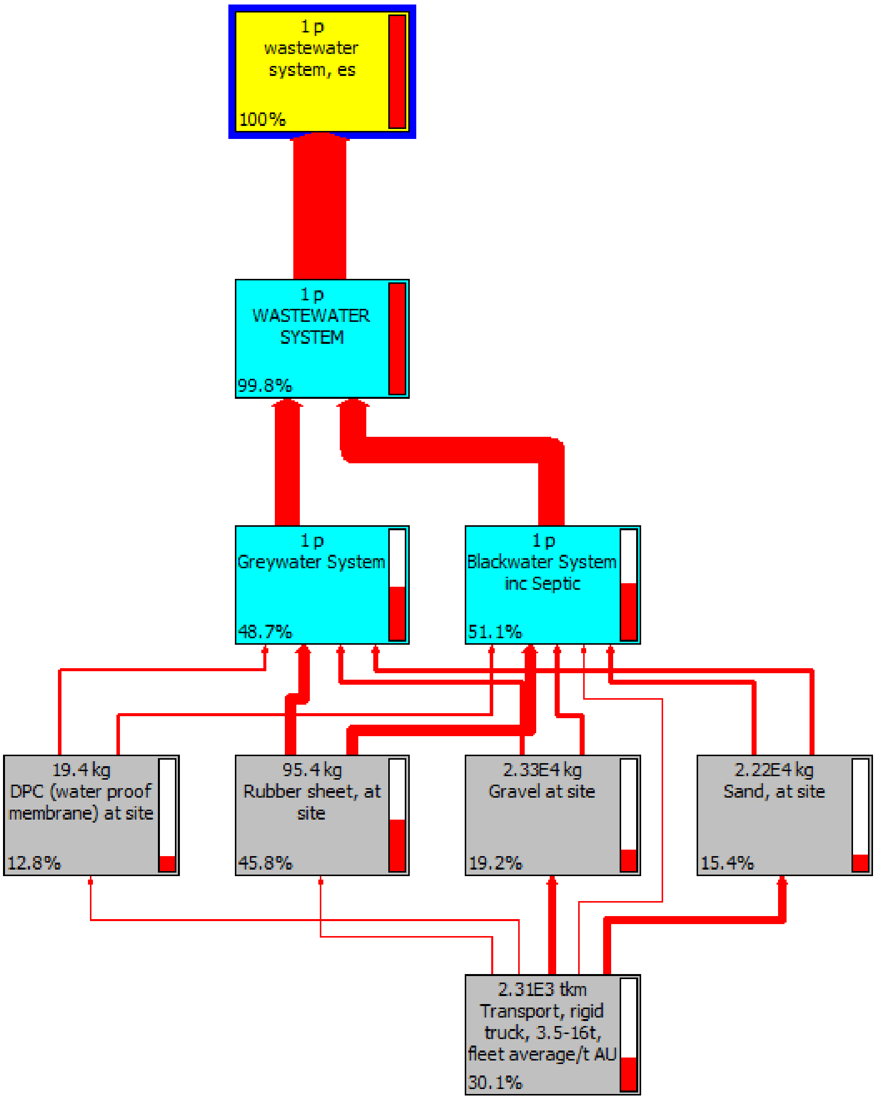

Figure 7.137 - Eco Toxicity, network diagram, 5% cut off, Off-Grid Wastewater Catchment System

7.7.12 Normalisation for Wastewater System

The most significant result is the Eutrophication potential of the sewer followed by the GWP of the sewer. This reflects the nutrient load that is emitted to water bodies through the use of the sewer system and the considerable energy demand needed to power the sewer infrastructure.

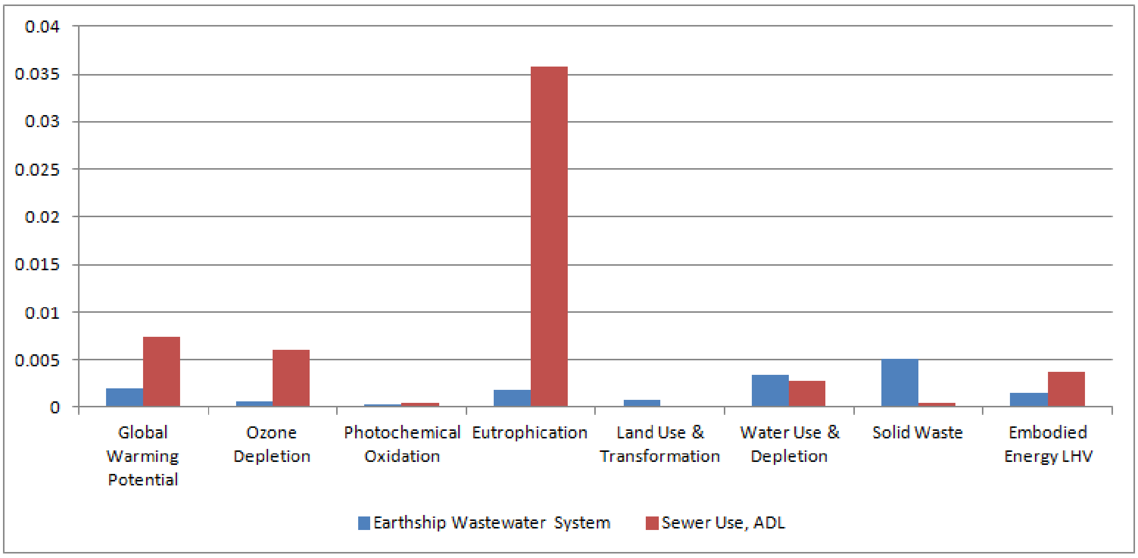

Figure 7.138 - Normalisation of Wastewater Systems Results

7.7.13 Weighted Single Score for Wastewater System

The weighted single score of the Adelaide Sewer system is approximately 2.9 times greater than the off-grid Earthship wastewater system. For both systems the most significant impact category is GWP. In the Sewer system, Eutrophication is also a significant contributor to impacts and in the off-grid system, Water Use, Land Use, Solid Waste and Embodied Energy all have similar significance (Figure 7.139).

In the off-grid system, the impacts are caused mainly by the high density polyethylene septic tank followed by gravel and sand production and delivery to site (Figure 7.140).

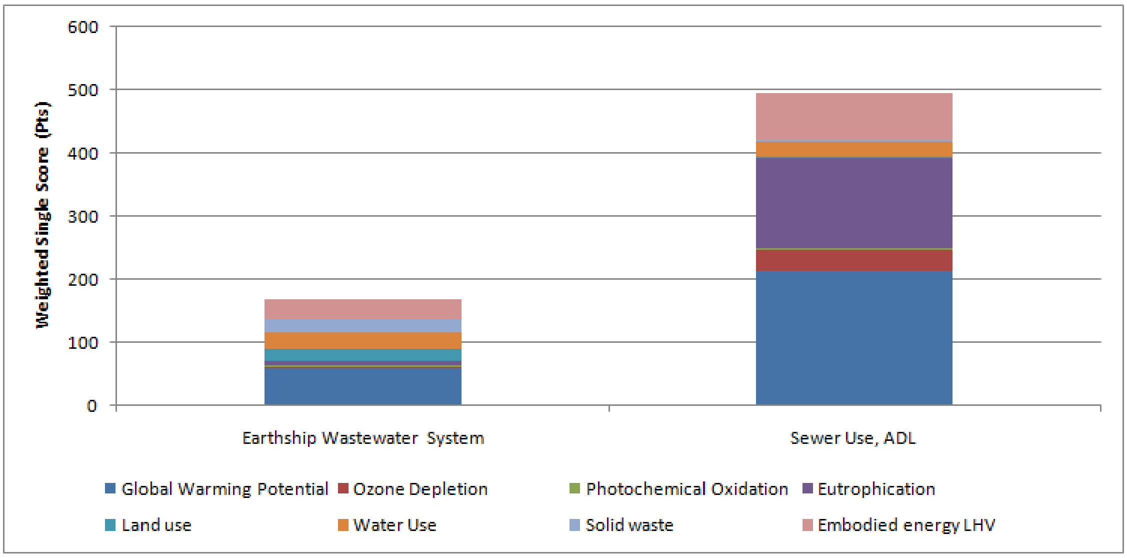

Figure 7.139 - Weighted Single Score, Wastewater Systems, All Indicators

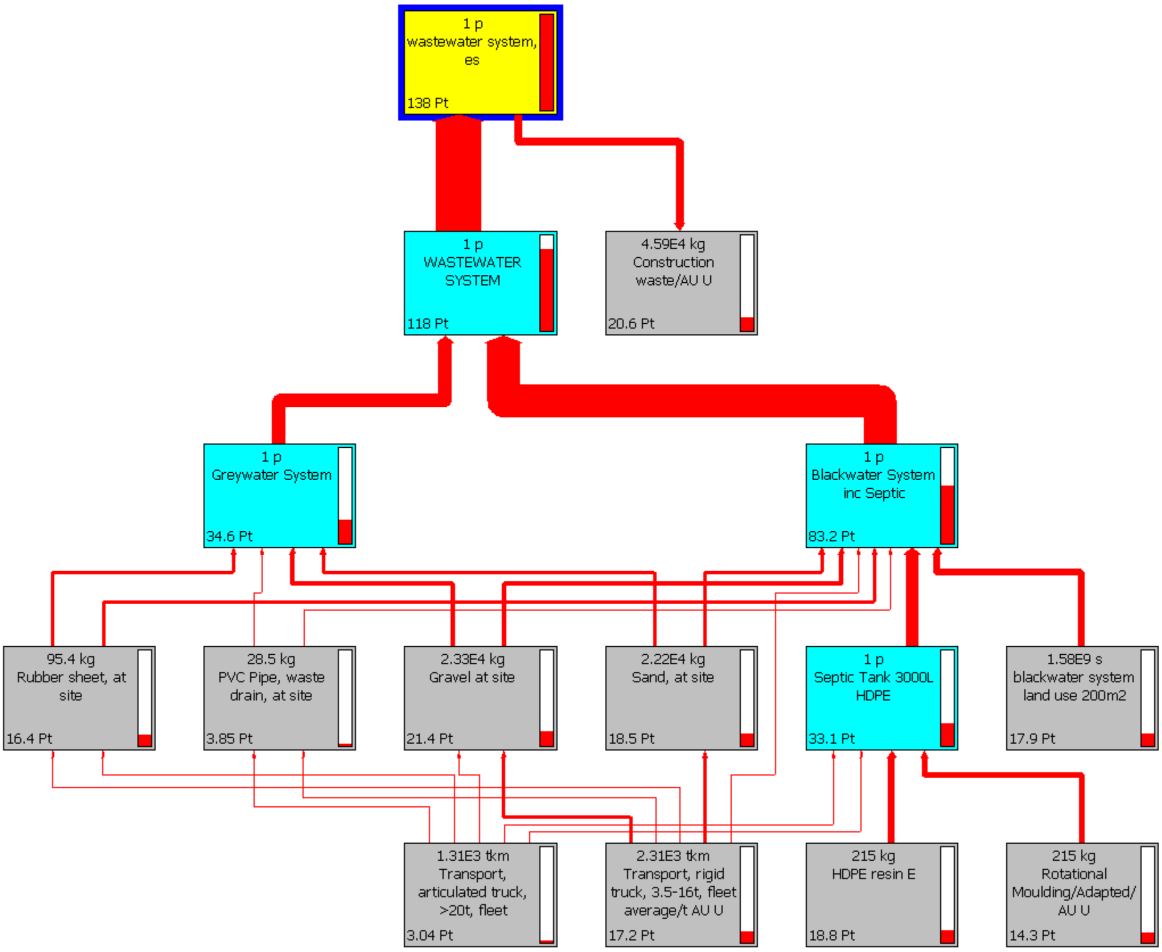

Figure 7.140 - Off-Grid Wastewater System, single score, 2% cut off

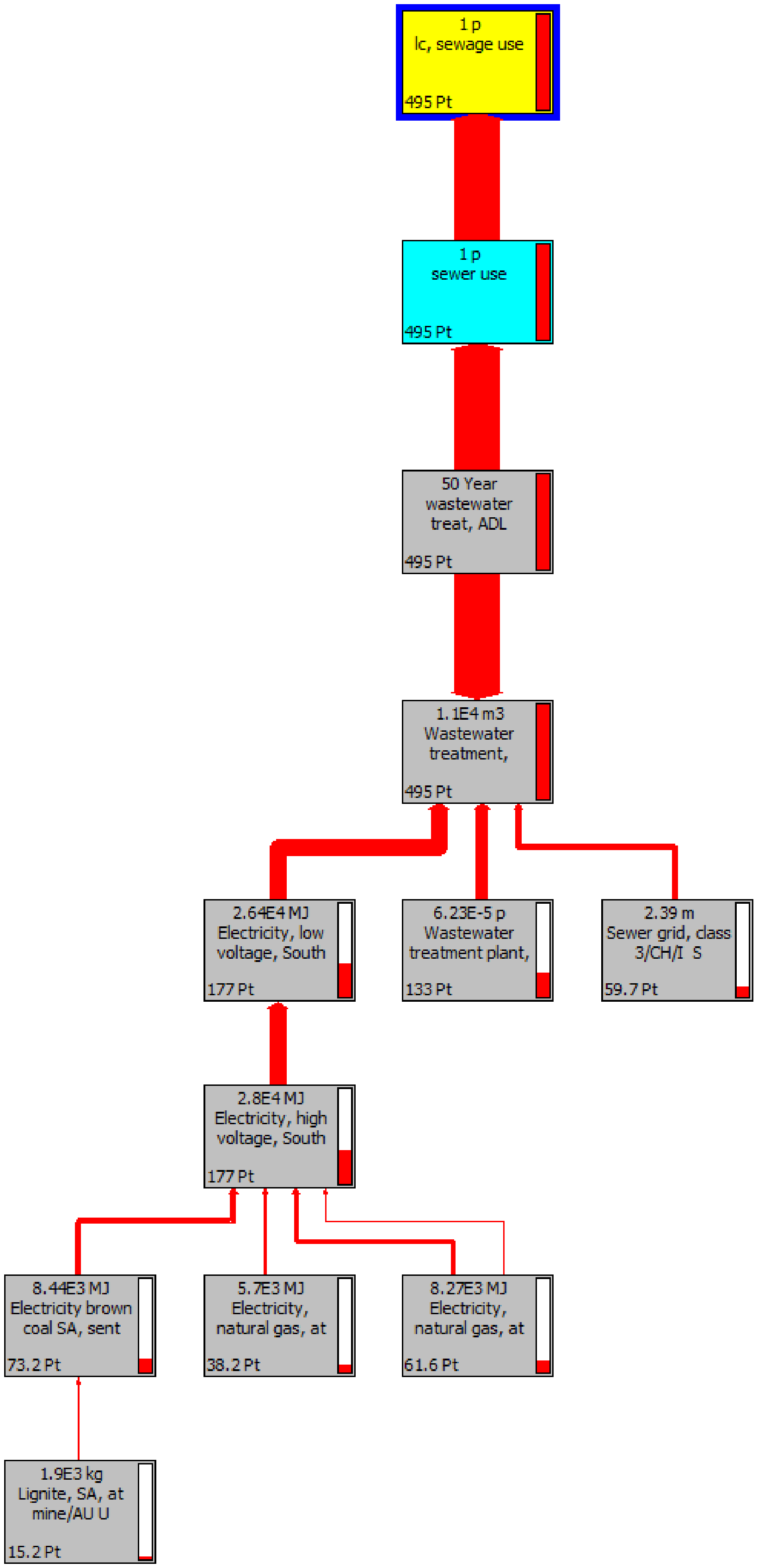

Figure 7.141 - Adelaide sewer use, single score 2% cut off

7.7.14 Discussion & Summary for Wastewater System

The off-grid Earthship wastewater system shows lower impacts in the majority of impact categories and this is especially so in the important (heavily weighted) Global Warming Potential category: the off-grid system has approximately one quarter of the GWP impacts arising from use of the sewer.

The Land Use & Transformation potential of the Earthship system is larger than the sewer system due to the assumption that 200m^2 of land area is needed for the Earthship system to function properly; however, this land is used for other productive purposes such as lawns, gardens and food production areas so this result is somewhat misleading.

Although water use and depletion potential is 1.2 times greater for the Earthship wastewater system this is offset by the minimal Water Use & Depletion potential of the Earthship water catchment and storage system which works in tandem with the Earthship wastewater system. The only other category which shows higher impact for the Earthship system is Solid Waste.

In summary, the majority of environmental impact categories indicate that the off-grid Earthship system is preferable to the use of Adelaide’s sewer network which relies on significant quantities of energy to operate.

7.8 Whole House

This section presents results and analysis of the “Whole House” which includes the Thermal Envelope, and the various Systems associated with the home for energy, water and wastewater treatment/disposal. In the case of the “off-grid” house scenarios –three Earthship variations and one Mudbrick – the utilities systems are provided by autonomous “off-grid” systems, whereas the other homes are assumed to be serviced by conventional “grid” infrastructure; which has been modelled using South Australian LCI data.

The results are presented for each impact category in terms of the impacts associated with various major elements of the house, each of which has its own category:

- “Thermal Envelope (matl & const)” refers to the materials and processes used in the construction of the thermal envelope – the internal and external walls, roof, floor and in the case of two Earthship scenarios, the greenhouse.
- “Heating and cooling (elec)” refers to the electricity used to heat and cool the home. The quantity of electricity modelled is based on the results of the Thermal Modelling Study: the average of the results from the initial study and the final study were used (see LCI section for full details).
- “Other household elec” refers to the use of non-heating and cooling energy use such as appliances and lighting. In the case of the off-grid houses electricity is supplied by the off-grid electrical system (photovoltaics and battery bank) whereas for the majority of houses electricity is supplied by the South Australian electricity grid (which contains significant amounts of renewable energy such as wind energy). Maintenance and replacement of components is included in the modelling of the off-grid electrical system.
- “Gas for hot water boost” refers to the use of gas for boosting the solar hot water service (SHWS).
- “Gas for cooking” refers to the use of gas for cooking. The modelling assumes liquid petroleum gas in the case of the off-grid homes and natural gas in the case of the gird connected homes.
- “Water and wastewater” refers to construction and maintenance of the off-grid water catchment and storage system and the associated off-grid wastewater treatment system, or in the case of

the grid connected homes, it refers to the use of reticulated water supply and sewer infrastructure.

- "Food production" applies only to the off-grid house scenarios. It refers to the production of food which is assumed to be irrigated by wastewater and grown in the greenhouse, or outdoors, where a greenhouse is not included in the thermal envelope.
- "Waste" refers to the waste generated during all life cycle stages, for example, waste generated during manufacture of raw materials, and materials sent to landfill at the end of life of the house.
- "Miscellaneous" refers to elements not allocated to the major groups outlined above: the materials used to manufacture the solar hot water service, materials used to manufacture the air conditioner, maintenance of paint finishes to the thermal envelope, and land occupancy – the land used as the site for the house and the wastewater system.
- "Total inc. EOL" indicates the total value, taking into account any "credits" (negative values), for example credits may be counted in the "waste" category due to reclaimed materials that avoid being landfilled and thereby avoid the production of virgin materials.

This section aggregates the results from the previous studies that analysed the various elements in isolation, hence to avoid repetition, the discussion of the Whole House has been limited to findings specific to the Whole House analysis, and the reader is expected to refer to the previous sections for additional information.

7.8.1 Global Warming Potential for Whole House

Characterisation results for Global Warming Potential (GWP) of the Whole House scenarios are given in Figure 7.142. The highest impact is caused by the conventional brick veneer home which uses 20kWh/day of electricity (BV LW Conv. 20) followed by the same brick veneer design but with far less energy assumed to be used for heating and cooling. The lowest impact is caused by the homes assumed to be off-grid: three Earthships and Mudbrick. The bermed and insulated Earthship with greenhouse and minimal use of cement (ESIB GH lowEE) has the lowest impact of all.

With the exception of the conventional homes (labelled "conv.") all other homes were assumed to use 5kWh of electricity per day for appliances and lighting ("other household elec"), hence the substantially lower result in this category for the off-grid homes is due to the renewable electricity system having lower GWP than the grid supplied electricity.

Another important factor contributing to the lower GWP of the off-grid homes is their "water and wastewater" systems, which have minimal maintenance throughout their lifecycle; the majority of their emissions generated during the manufacturing stage. In contrast the reticulated water supply and sewer system involves comparatively large quantities of electricity throughout their use stage (assumed to be 50 years) leading to approximately double the GWP compared to the off-grid water systems.

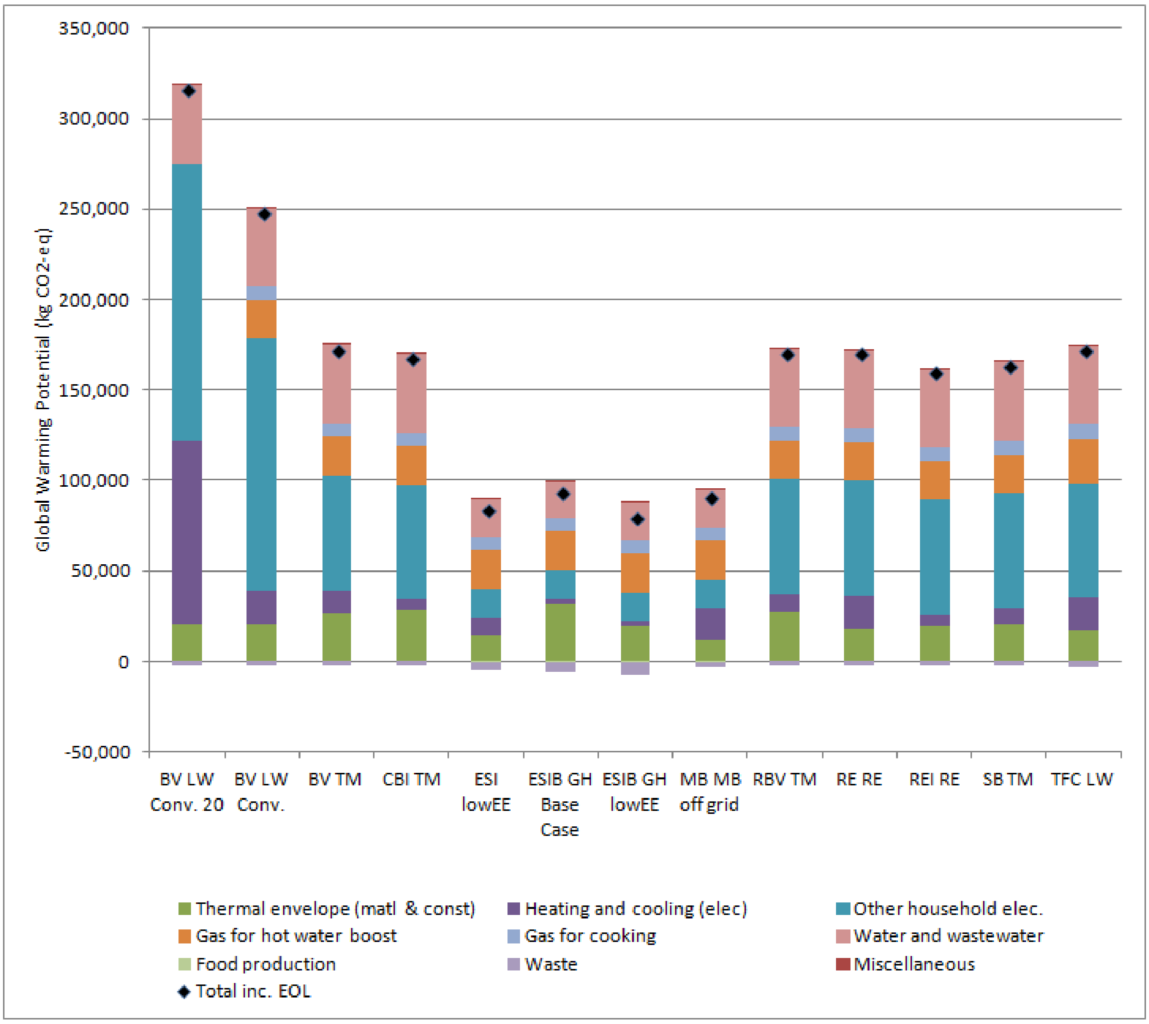

Figure 7.142 - Global Warming Potential, Whole House, Characterisation

7.8.2 Ozone Depletion for Whole House

Characterisation results for Ozone Depletion potential of the Whole House scenarios are given in Figure 7.143. The highest impact is caused by the conventional brick veneer home with 20kWh/day electricity use (no gas use assumed in this home).

While the off-grid scenarios have comparatively low emissions associated with the water and wastewater systems, emissions of the off-grid energy systems are comparatively high, hence the defining factor tends be the emissions arising from construction of the thermal envelope.

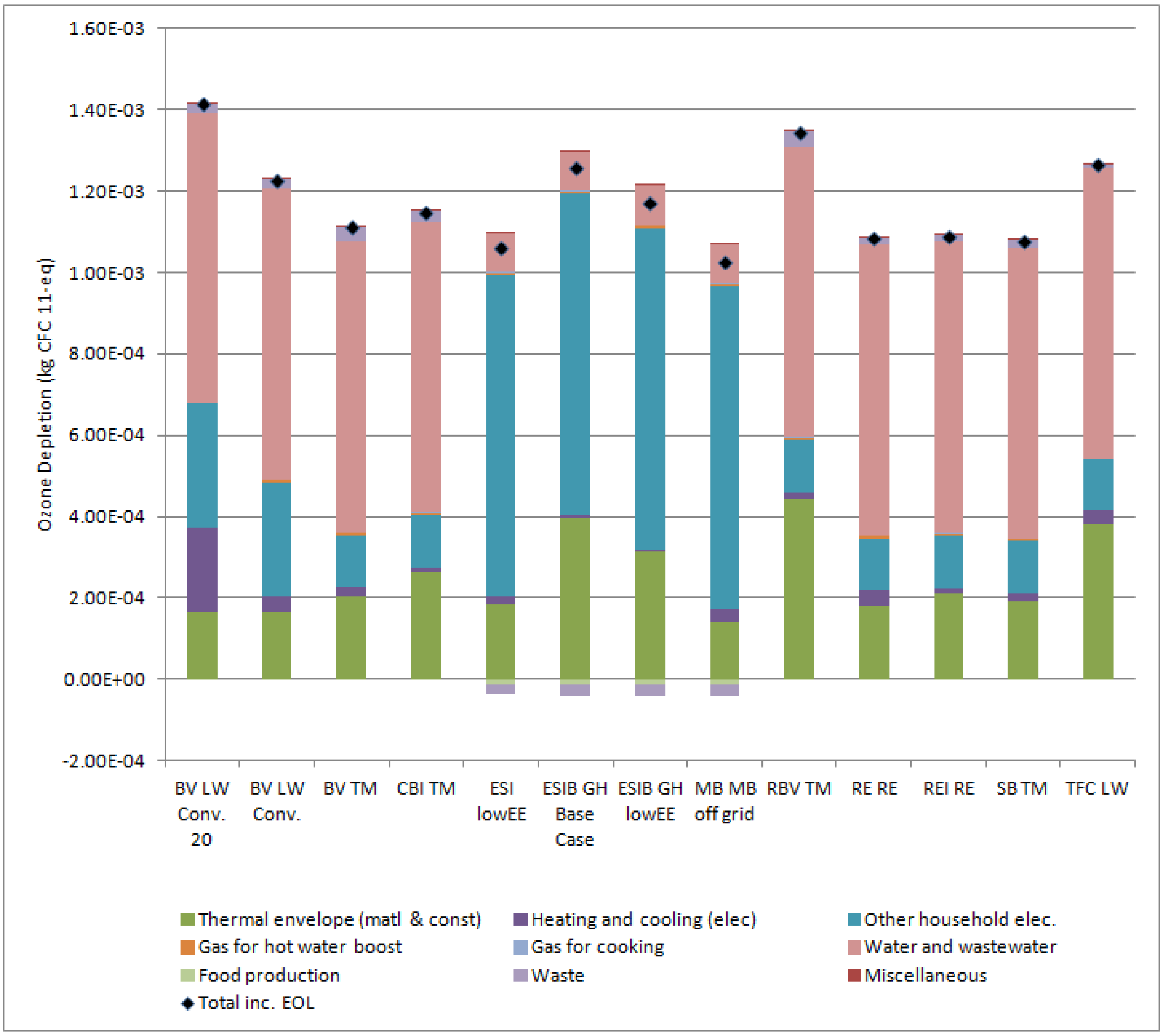

Figure 7.143 - Ozone Depletion, Whole House, Characterisation

7.8.3 Photochemical Oxidation for Whole House

Characterisation results for Photochemical Oxidation potential of the Whole House scenarios are given in Figure 7.144. The Earthship scenarios have the highest emissions due mainly to the comparatively high emissions of the water and wastewater systems and construction of the thermal envelope. The conventional brick veneer scenarios also have relatively high emissions due to additional energy use for running appliances and lighting. Rammed Earth (with and without insulation) and Strawbale scenarios have the lowest emissions due to comparatively low emissions from construction of the thermal envelope.

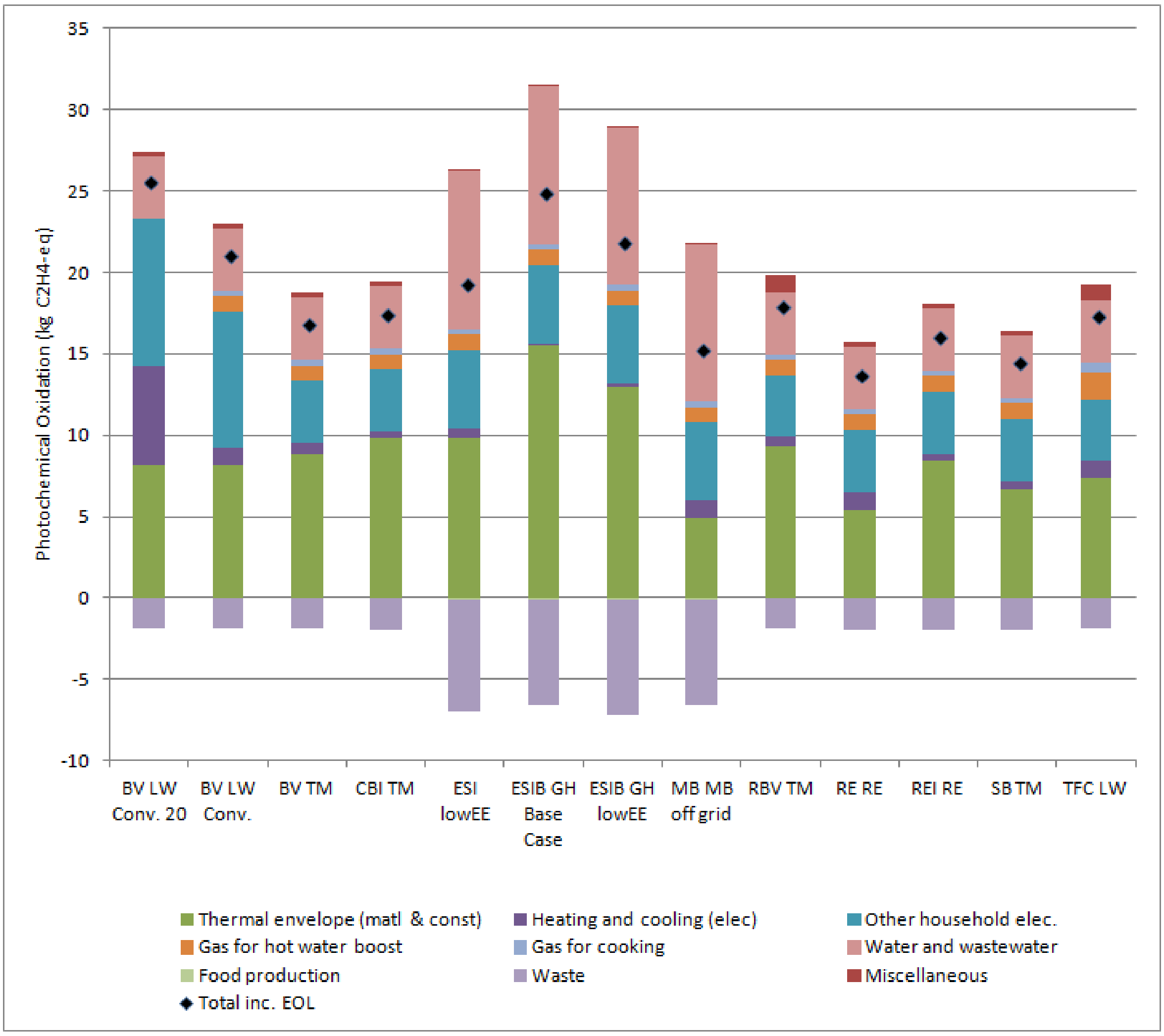

Figure 7.144 - Photochemical Oxidation, Whole House, Characterisation

7.8.4 Eutrophication for Whole House

Characterisation results for Eutrophication potential of the Whole House scenarios are given in Figure 7.145. The off-grid scenarios (Earthships and Mudbrick) have the highest impact potential due to the off-grid electricity system which by far outweighs the reduction in impact due to the water and wastewater systems.

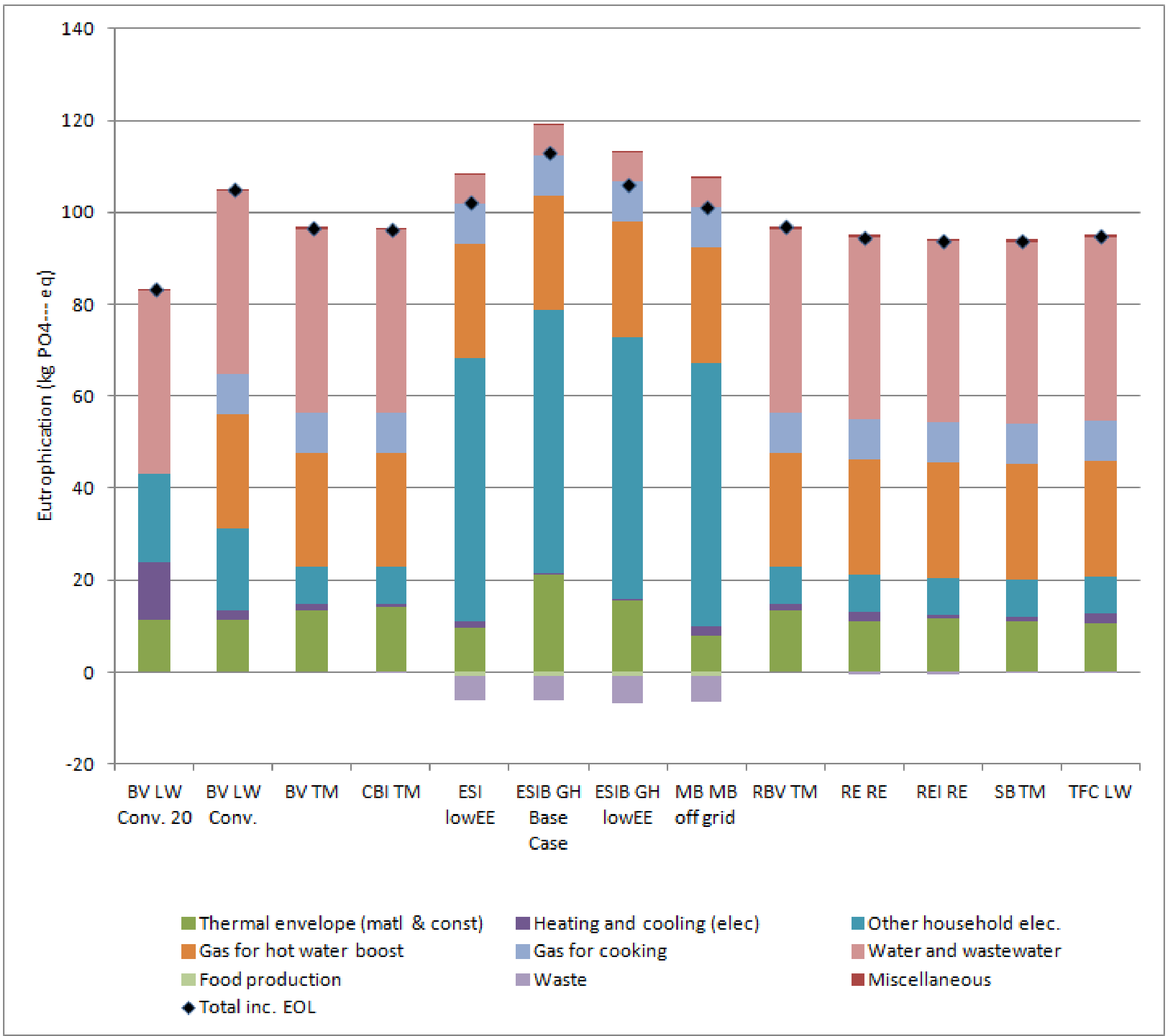

Figure 7.145 - Eutrophication, Whole House, Characterisation

7.8.5 Land Use & Transformation for Whole House

Characterisation results for Land Use & Transformation potential of the Whole House scenarios are given in Figure 7.146. The Miscellaneous category is, in this case, representative mainly of the land occupied by the home and the wastewater system, hence its significance for the off-grid homes which assume 200m2 of land for wastewater irrigation. The land occupied by the earth berm is also a significant contributor to the Miscellaneous category for the two bermed Earthship scenarios. Construction of the water and wastewater system and the thermal envelope are significant factors for the Earthship scenarios.

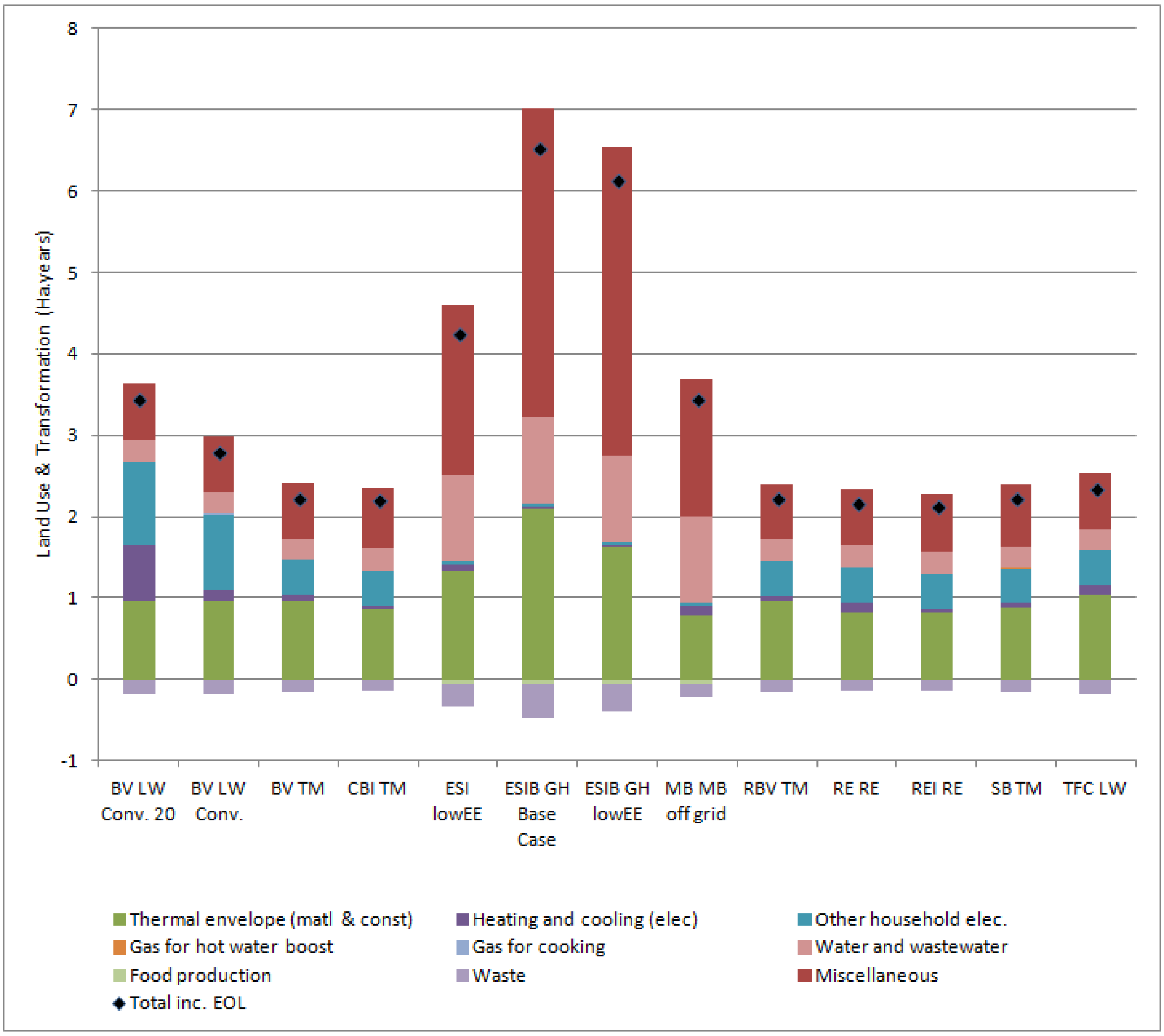

Figure 7.146 - Land Use & Transformation, Whole House, Characterisation

7.8.6 Water Use & Depletion for Whole House

Characterisation results for water use and depletion potential of the Whole House scenarios are given in Figure 7.147. Although the Earthship base case uses more water in its construction than the other thermal envelopes, this is offset by the ultra water efficient water and wastewater systems. Although the off-grid electrical systems require more water during their manufacturing stage, this is offset by the off-grid water and wastewater systems.

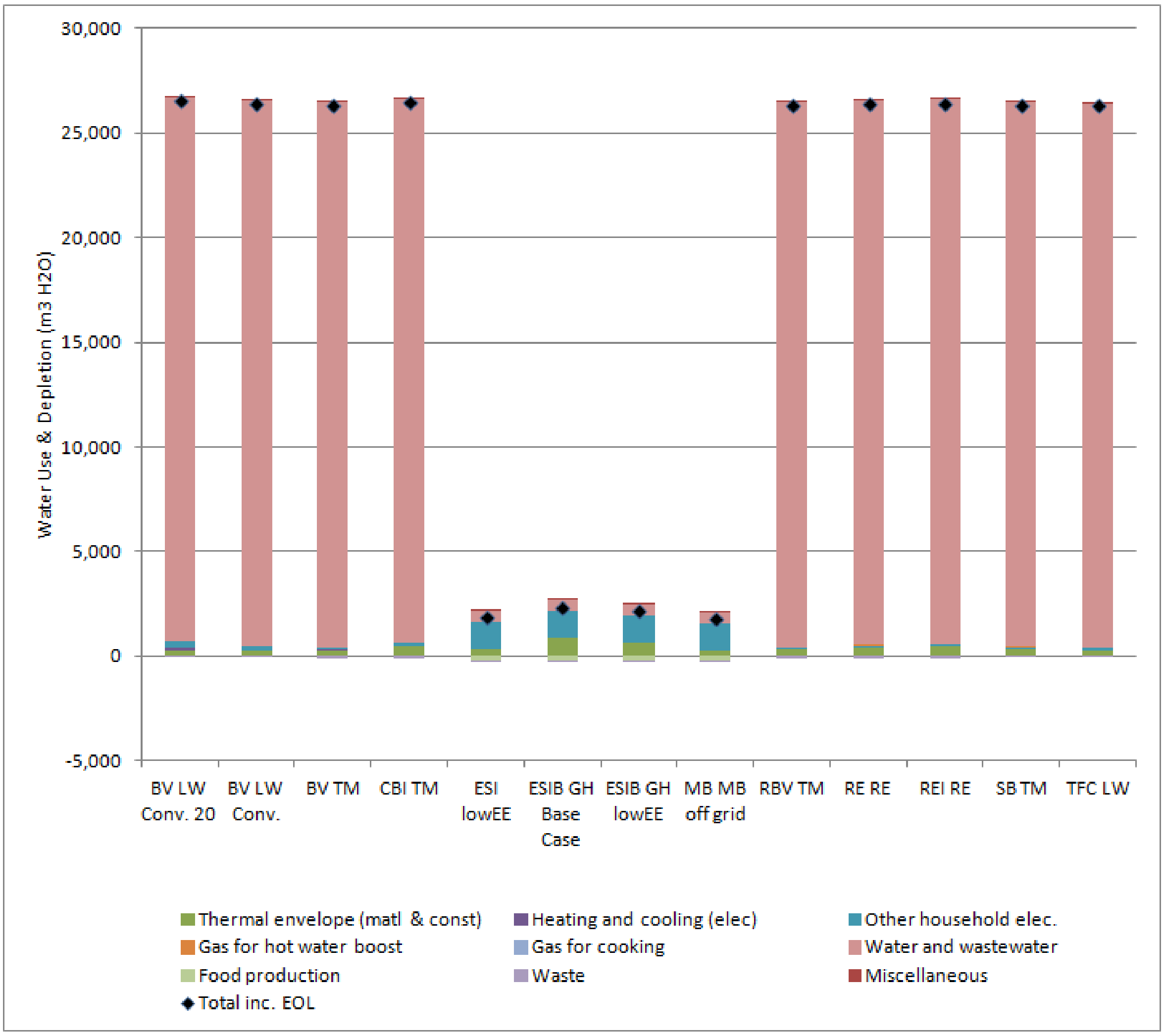

Figure 7.147 - Water Use & Depletion, Whole House, Characterisation

7.8.7 Solid Waste for Whole House

Characterisation results for Solid Waste potential of the Whole House scenarios are given in Figure 7.148. In this figure, the "Waste" category indicates the EOL landfill quantity for all categories, whereas other categories indicate waste generated during construction and use lifecycle stages for each category.

Mudbrick has the lowest impacts due to the assumption that Mudbrick does not need to be landfilled, and Concrete Block and the Earthship base case have the highest impact due to large volumes of concrete that must be landfilled (although note that only 5% is assumed to be landfilled, the rest is recycled into aggregates).

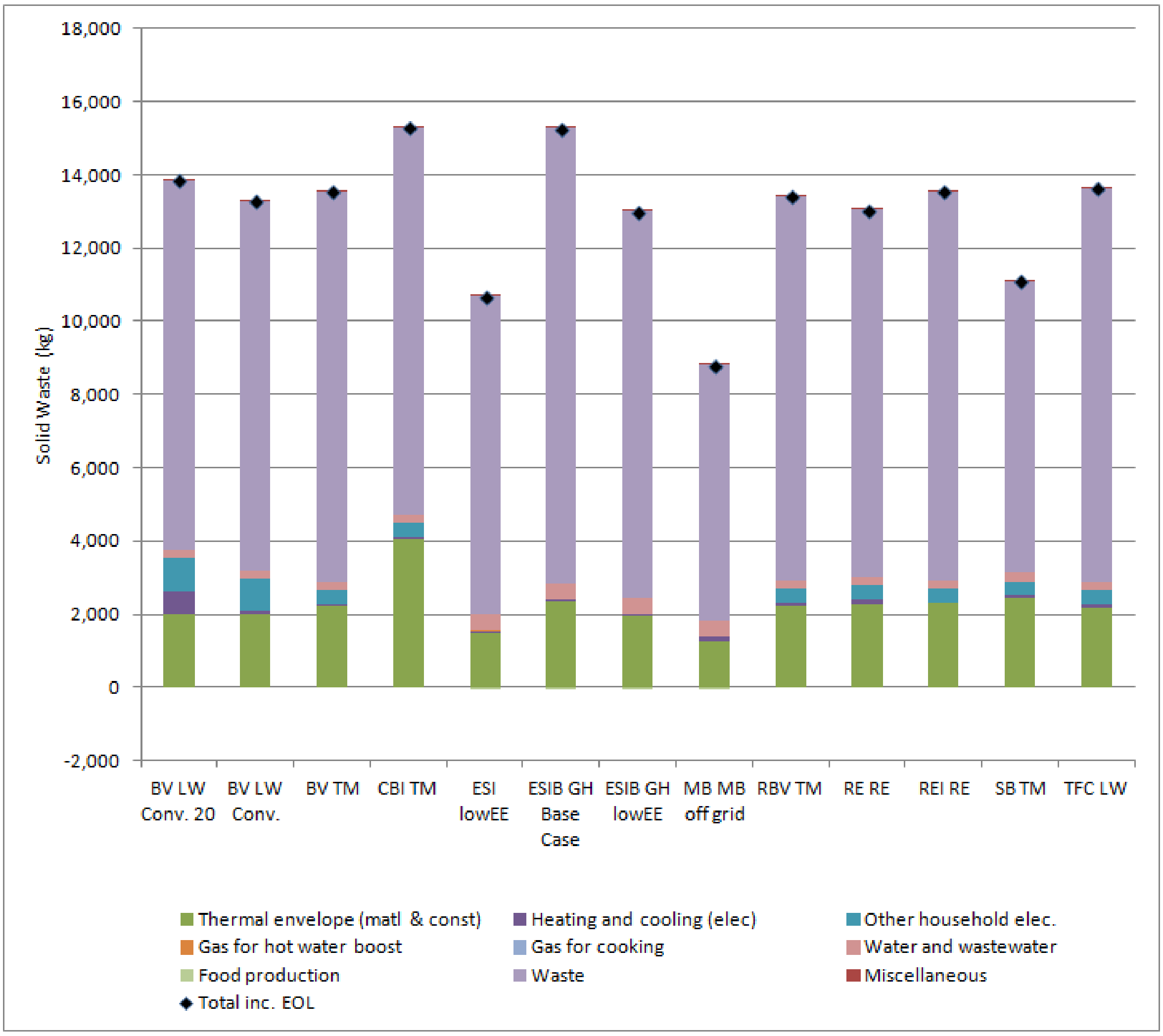

Figure 7.148 - Solid Waste, Whole House, Characterisation

7.8.8 Embodied Energy for Whole House

Characterisation results for Embodied Energy potential of the Whole House scenarios are given in Figure 7.149. The off-grid scenarios show reduced embodied energy due to the comparatively low embodied energy of the off-grid electricity system compared to the grid supplied electricity. The lowEE Earthship with greenhouse and berm has the lowest embodied energy and the passive solar Brick Veneer with thermal mass internal walls (BV TM) has the highest when comparing on an equal basis for electricity and gas use, whereas the conventional brick veneer scenarios (BV LW Conv / Conv 20) show higher embodied energy due to the assumption that they use more electricity than the other grid connected scenarios.

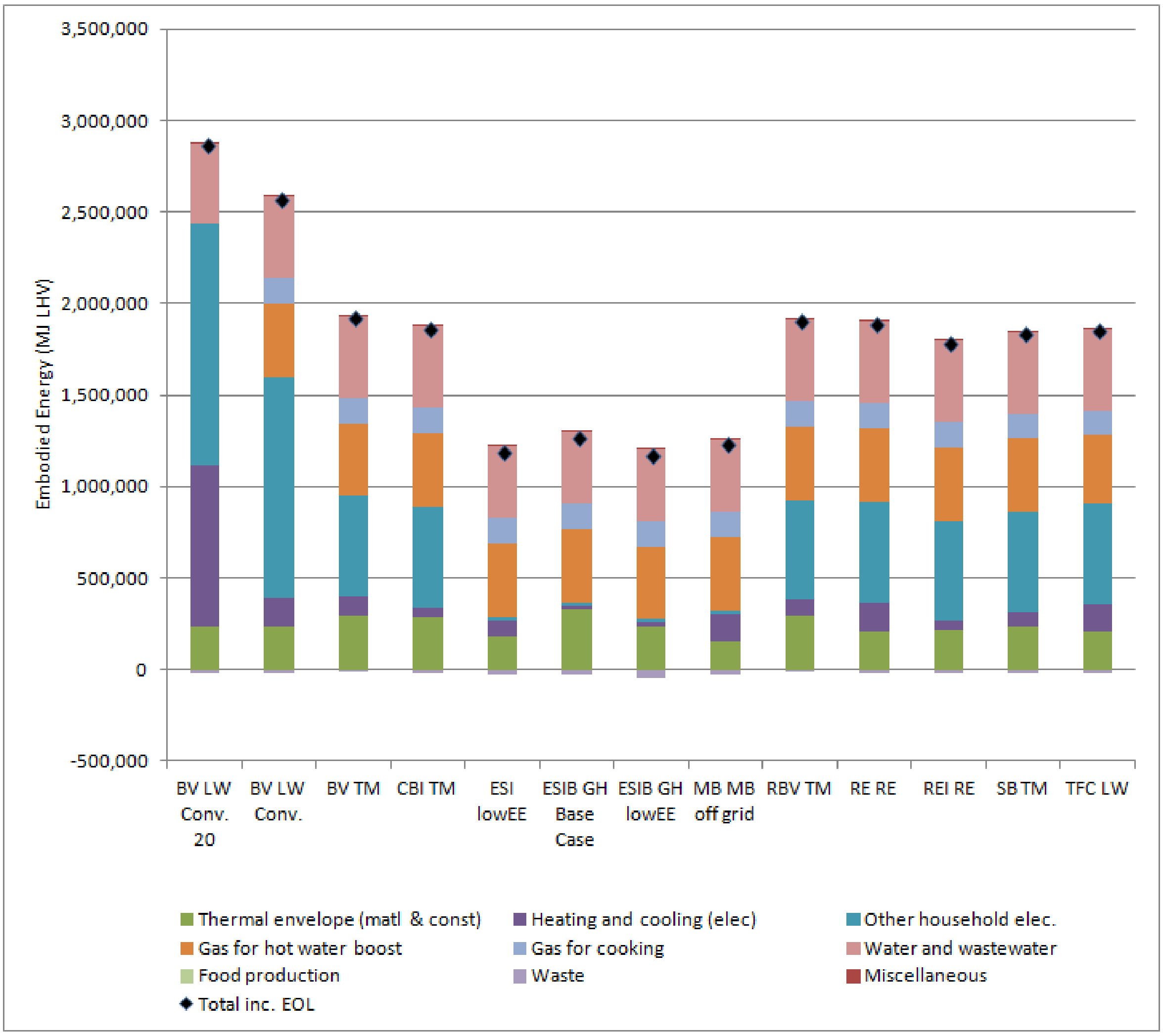

Figure 7.149 - Embodied Energy, Whole House, Characterisation

7.8.9 Human Toxicity, Carcinogenic, for Whole House

Characterisation results for Carcinogenic Human Toxicity potential of the Whole House scenarios are given in Figure 7.150. The highest impacts arise from construction of the thermal envelope especially in constructions that employ bricks (BV and RBV), whereas the lowest impacts arise from the off-grid whole house scenarios which benefit from avoided impacts arising from home food production, and also the rammed earth (RE RE and REI RE), and lightweight timber frame construction (TFC LW) also have very comparatively low impacts.

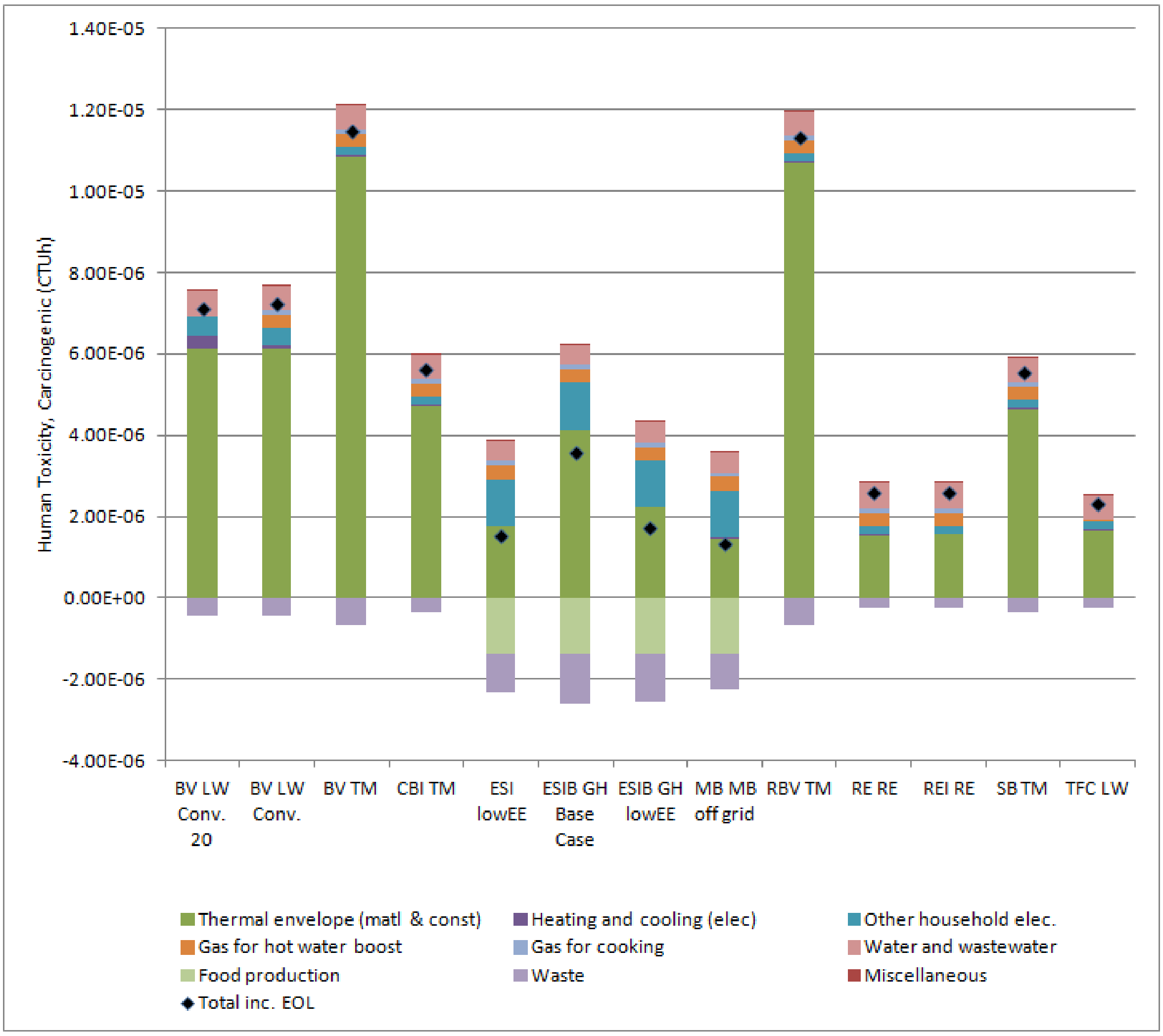

Figure 7.150 - Human Toxicity Carcinogenic, Whole House, Characterisation

7.8.10 Human Toxicity, Non-Carcinogenic, for Whole House

Characterisation results for Non-Carcinogenic Human Toxicity potential of the Whole House scenarios are given in Figure 7.151. The off-grid scenarios have the highest impact potential due to the batteries in the off-grid electricity system. Recycling of the lead in the batteries “waste” and avoided chemical use in agriculture due to home food production (“Food production”) reduces the total impact significantly.

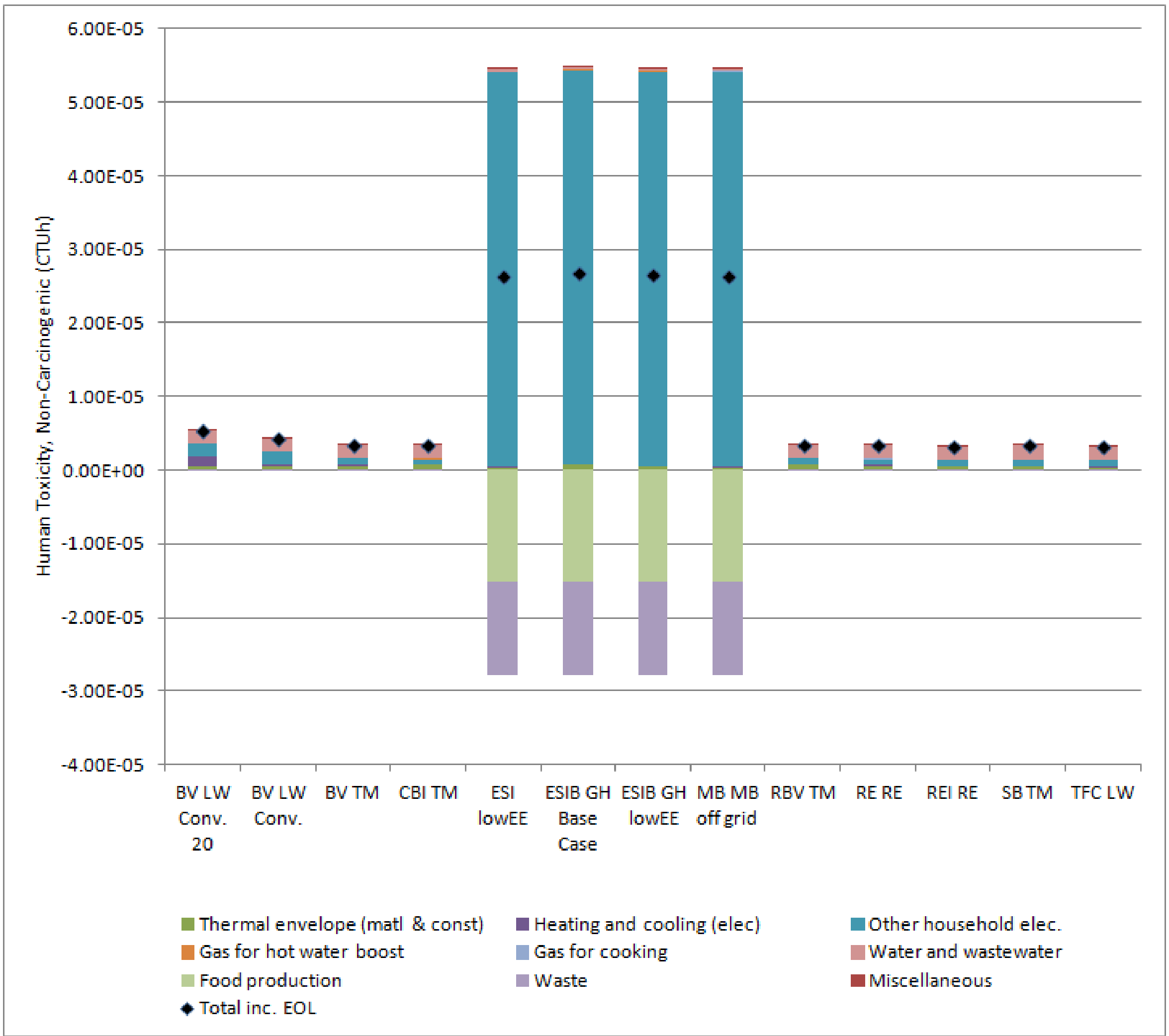

Figure 7.151 - Human Toxicity Non-carcinogenic, Whole House, Characterisation

7.8.11 Eco Toxicity for Whole House

Characterisation results for Eco Toxicity potential of the Whole House scenarios are given in Figure 7.152. Home food production, which is assumed in the off-grid homes, offsets the toxic emissions arising from all the other categories by a huge margin.

Construction of the thermal envelope has the highest impacts for all scenarios, however in the case of the off-grid homes, the toxic emissions arising from thermal envelope construction and other categories are offset significantly by home organic food production which avoids the use of chemicals in the agricultural industry.

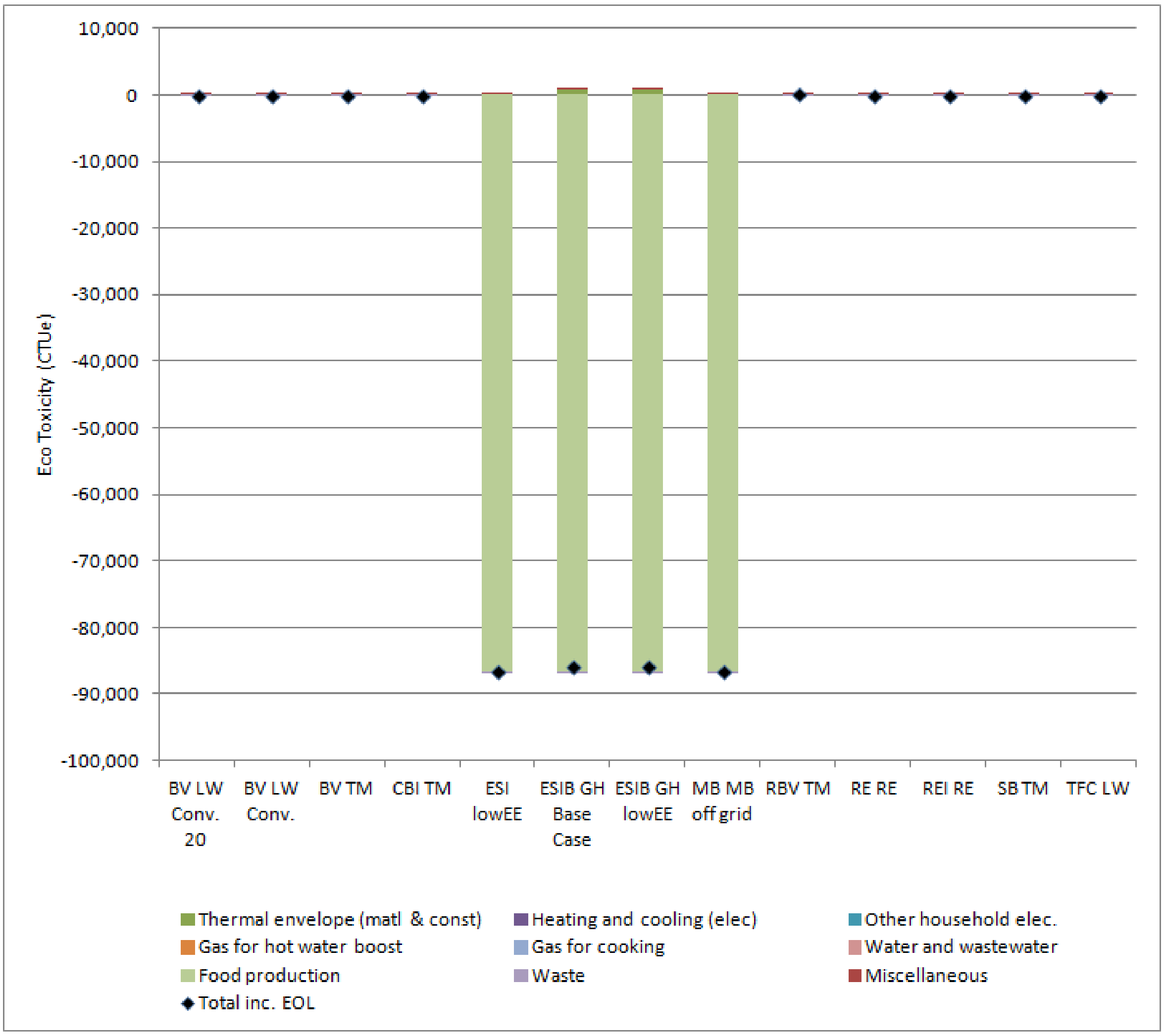

Figure 7.152 - Eco-Toxicity, Whole House, Characterisation

7.8.12 Toxicity Analysis for Whole House

Table 7.8 lists the toxic substances contributing to more than one percent of impacts for all the scenarios. For brevity only data for the Earthship Base Case and the Brick Veneer Conventional home is given, and is compared with Australian National Pollutant Inventory annual emissions data (where data is available) (Commonwealth of Australia: Department of Sustainability, n.d.). Quantity of each substance is listed as well as the USEtox CTUh units which are defined as:

“The characterization factor for human toxicity impacts (human toxicity potential) is expressed in comparative toxic units (CTUh), providing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue.

Unit: [CTUh] = [disease cases per kg emitted]”(USEtox, 2013)

The Earthship has approximately 10 times more emissions of carbon disulfide to air than the conventional brick veneer home, and approximately 6.5 times more benzene. This is due to the use of batteries for energy storage as opposed to grid energy supply which emits fewer of these emissions.

Similar quantities of dioxin are released by both house types, whereas the conventional brick veneer home releases almost double the amount of formaldehyde due to emissions from brick manufacture.

It should be noted that the toxicity of materials used in house construction may be an issue at any stage throughout the lifecycle of the material. The toxic impacts identified in this study are primarily the result of the manufacturing stage of the materials and to a lesser extent the end-of-life stage (typically landfill). While toxicity may also be a hazard during the “use” stage, for example, through the process of off-gassing, this is not what is being measured in this study. Therefore it is unlikely that these results would suffice as even a rough guide to the indoor air quality of each particular building, with many other factors aside from material selection effecting this important aspect of building design; for example ventilation rate plays a key role in controlling build-up of toxic emissions (which also emanate from the human inhabitants, for example the carbon dioxide we exhale).

Table 7.8 - Comparison of quantities of toxic substances from Whole House

Substance	Compart-ment	NPI 2011/12 ton p.a.	Earthship Base Case Emission	CTUh	Source	BV LW Conv Emission	CTUh	Source
Benzene	Air	610 ton	1280g	1.88E-07	battery	197g	6.04E-08	Energy use
Carbon disulfide	Air	75 ton	891g	4.16E-05	battery	89.5g	4.18E-06	Energy use
Dioxin, 2,3,7,8 Tetrachlorodibenz o-p-	Air	No data-	21mcg	6.06E-07	Thermal envelope construction	20.3mcg	5.89E-07	Wastewater treatment
Formaldehyde	Air	2100 ton	236g	3.80E-06	Roof and buttress construction	466g	6.51E-06	Bricks

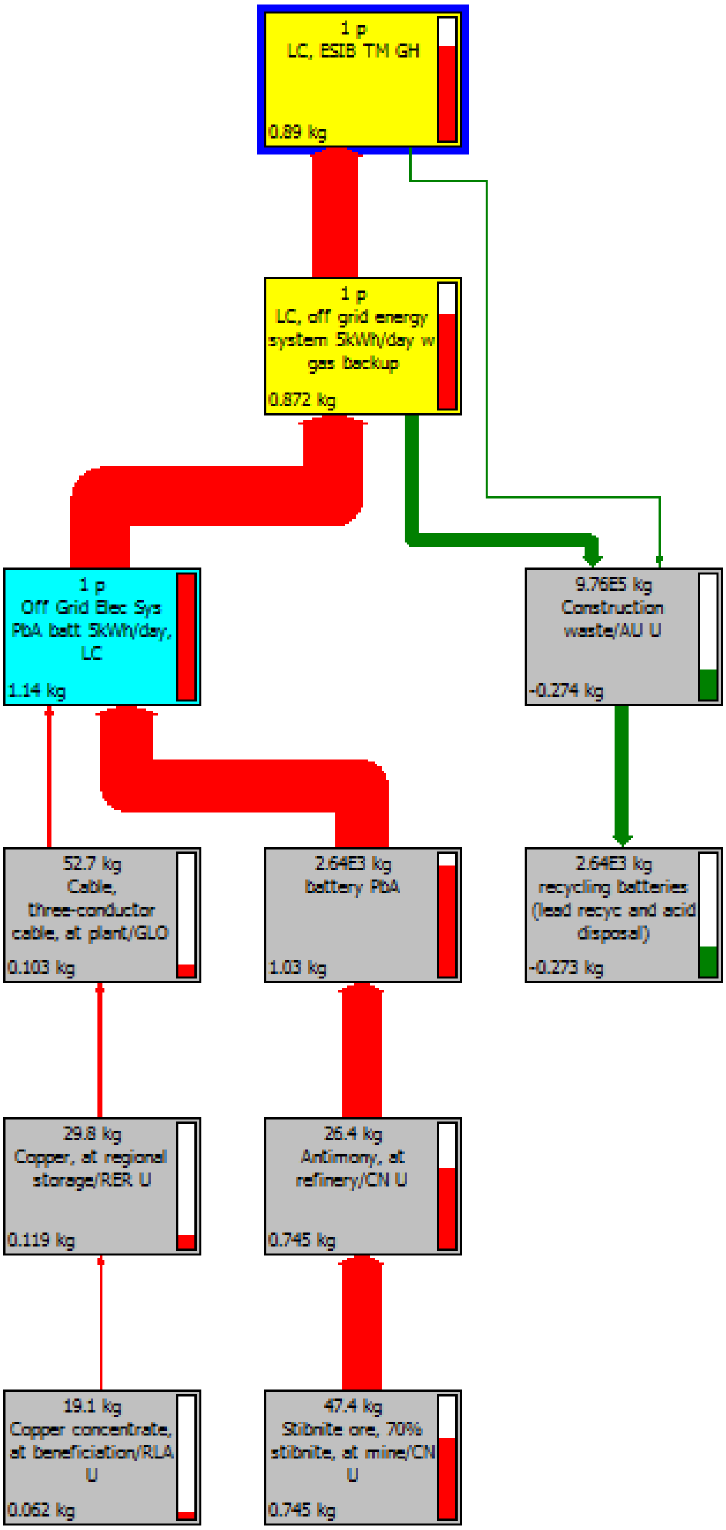

Figure 7.153 - Carbon Disulfide network diagram 5% cut off Earthship Base Case

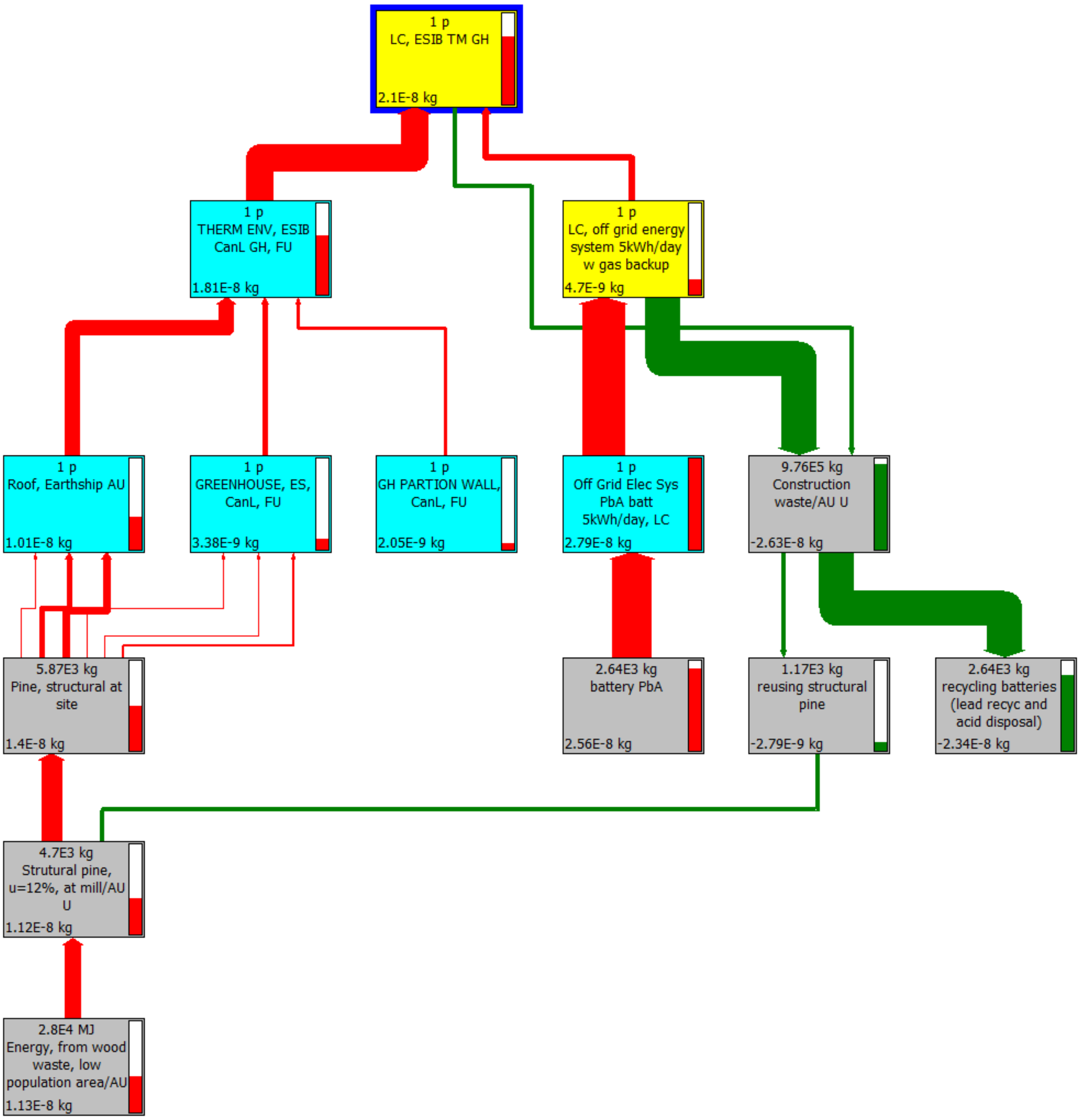

Figure 7.154 - Dioxin network diagram 7% cut off, Earthship Base Case

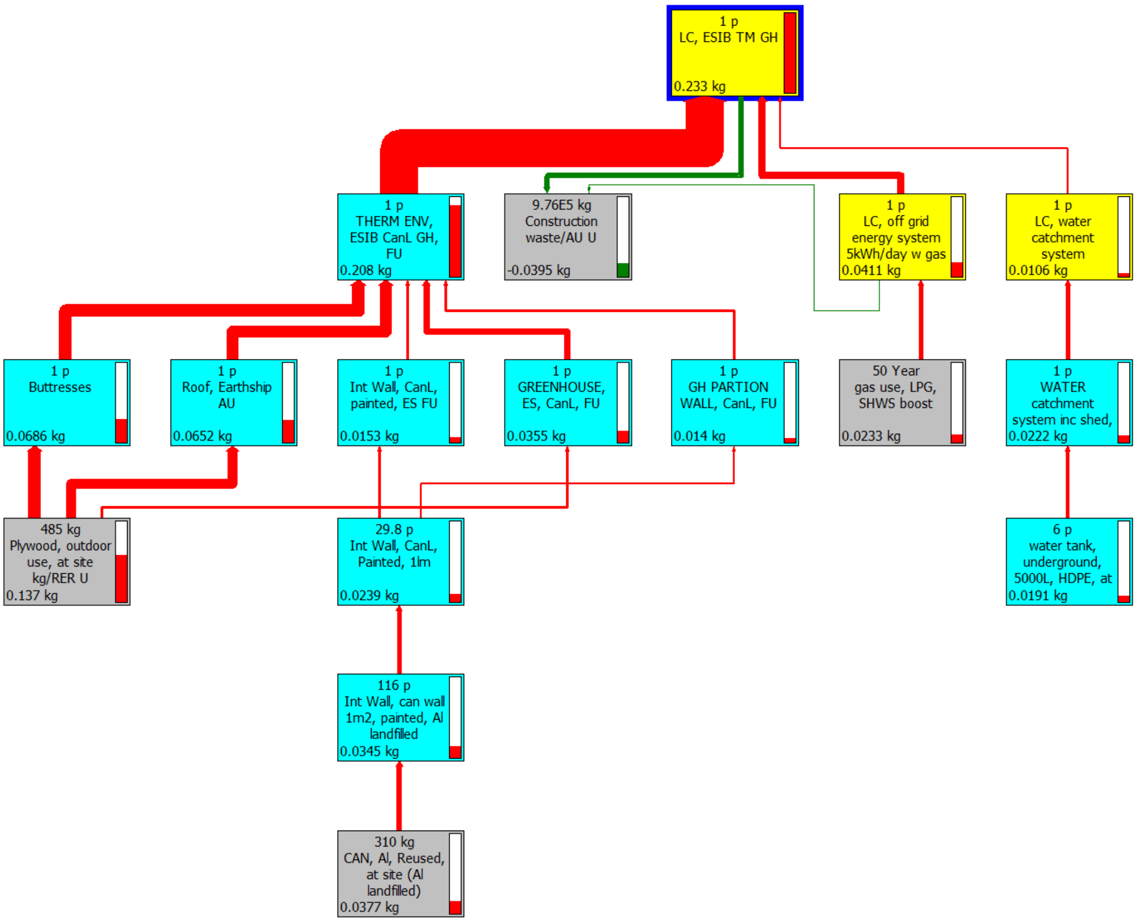

Figure 7.155 - Formaldehyde network diagram 5% cut off, Earthship Base Case

7.8.13 Normalisation for Whole House

The normalised results (50yrs per capita AUS) for all house types, shown in Figure 7.156, indicate that the houses considered contribute most significantly to the average Australian's water depletion impacts although this is not so for the off-grid homes (which catch and store rain water).

The next most significant impact is Solid Waste, followed by Eutrophication, Global Warming Potential (less so for off-grid homes), and Embodied Energy (less so for off-grid homes). There is relatively minor contribution to the average Australian's impacts on Ozone Depletion, Photochemical Oxidation, and Land Use/Transformation.

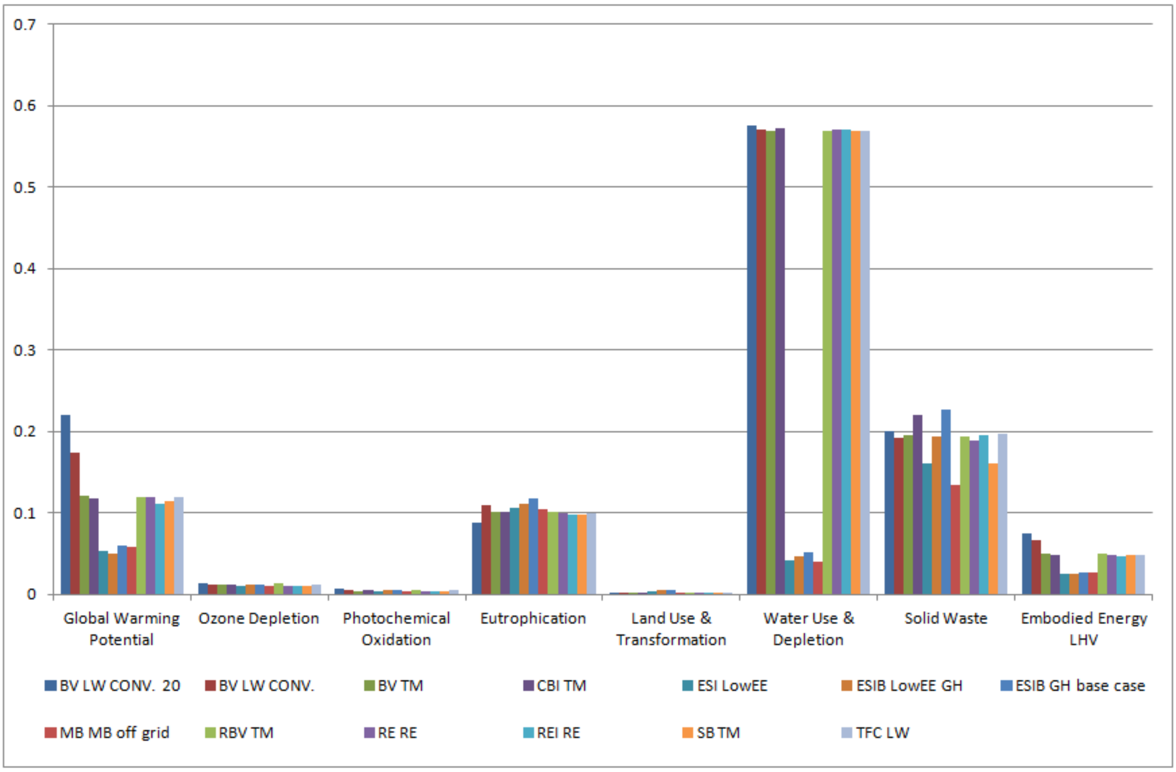

Figure 7.156 - Normalisation of Whole House Results

7.8.14 Weighted Single Score for Whole House

Weighted results for the Whole House analysis are presented via two methods: 1) in terms of impact categories (Figure 7.157) and 2) in terms of construction materials used to build the thermal envelope, electricity use for heating and cooling, other electricity use (e.g. appliances), gas use for SHWS boosting, gas use for cooking, water and wastewater system, food production, EOL waste, and miscellaneous issues: land occupation, SHWS components, air conditioner system components, and maintenance of paint finishes (Figure 7.158). Results are in "eco points" (vertical axis) which are calculated on the weightings established and discussed in Chapter 5.

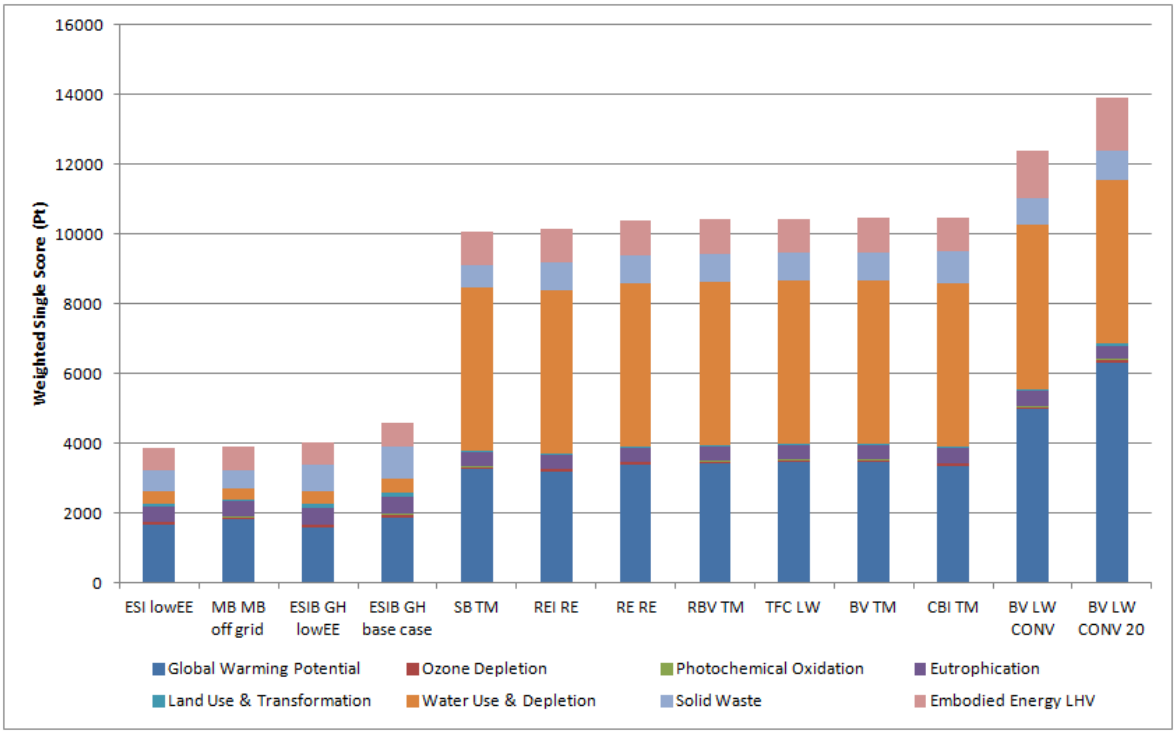

Figure 7.157 - Weighted Single Score, Whole House, All Indicators

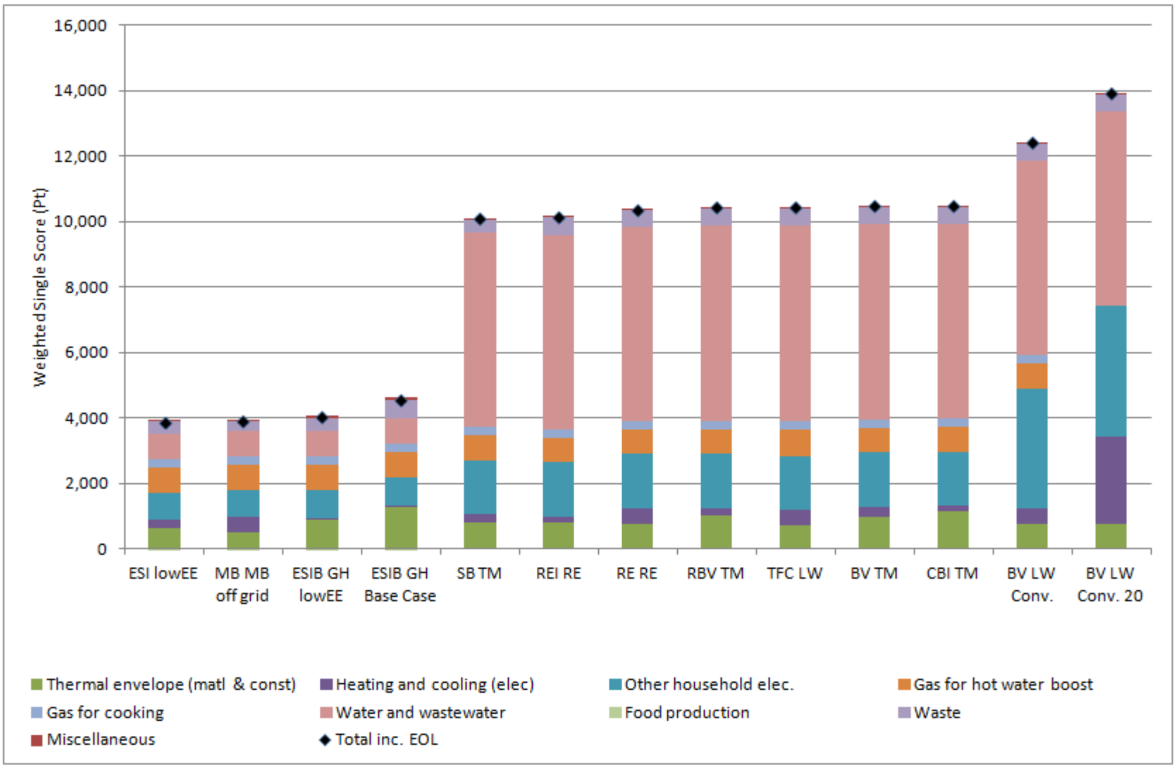

Figure 7.158 - Weighted Single Score, Whole House, All Indicators, Categorised by Construction/Systems Element

A sensitivity study, identical to the one conducted in the External Wall and Thermal Envelope analysis, is included to test the effect of altering the relative influence of Global Warming Potential (GWP) in comparison to all the other impact categories (toxicity categories excluded). Figure 7.159 presents the results when non-GWP categories are increased by 20% and Figure 7.160 shows the result when they are decreased by 20%.

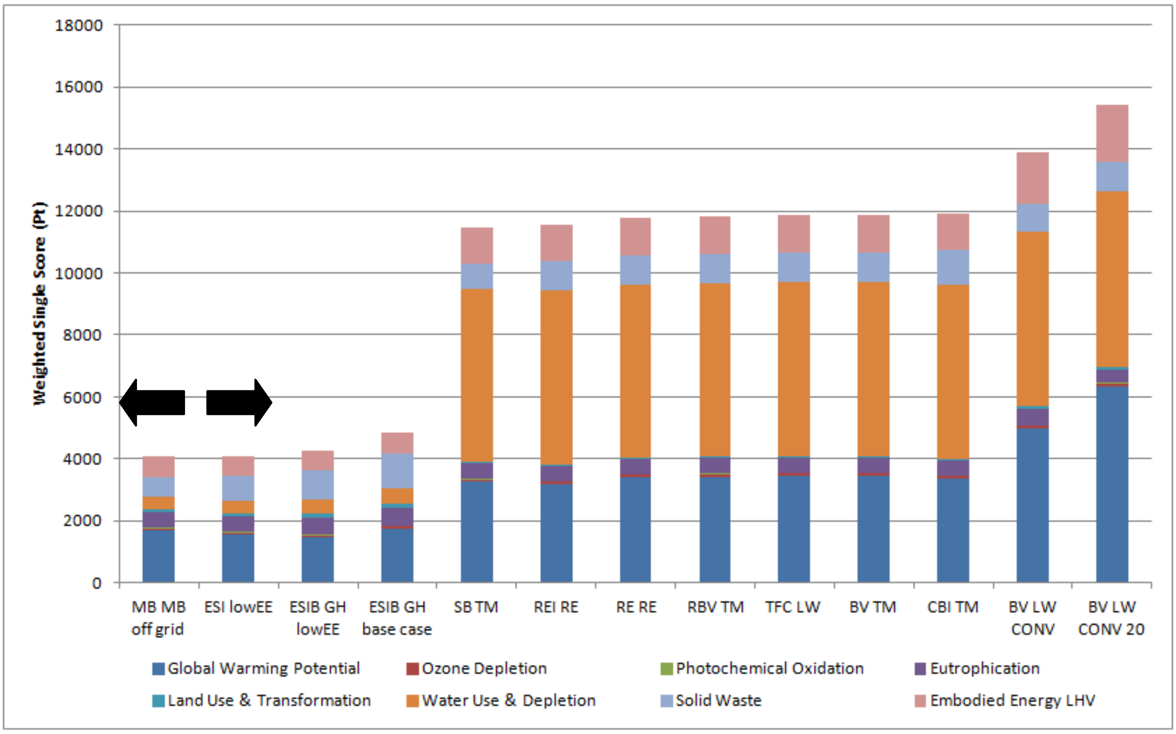

Figure 7.159 - Weighted Single Score With 20% Extra Weighting For Non-GWP Indicators

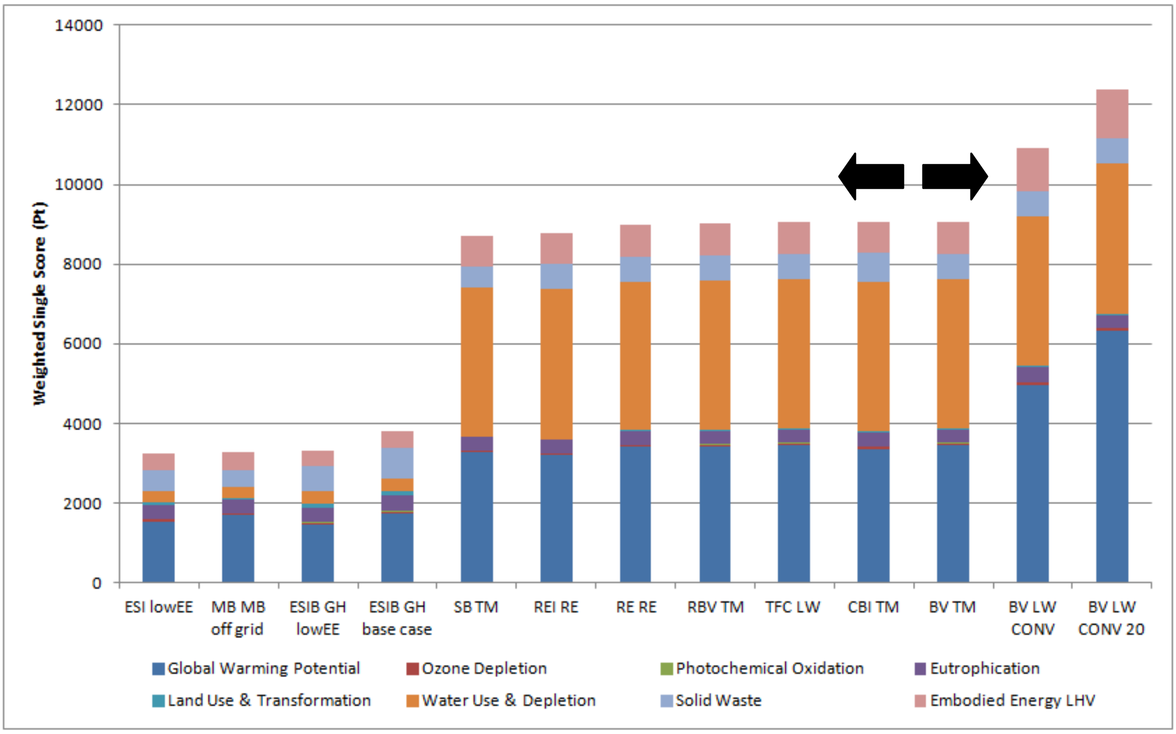

Figure 7.160 - Weighted Single Score With 20% Less Weighting For Non-GWP Indicators

Figure 7.161 includes an additional scenario: the Mudbrick house with grid connected systems compared to the Mudbrick house with off-grid systems. This highlights the differences between the “off-grid" and "grid" systems and it is important to note that these results have implications for all housing types, not just Mudbrick. The comparison shows a significant difference for the categories: "other household elec.", "gas for hot water boost", "gas for cooking" and "water and wastewater" (indicated by the red line). To highlight this reduction in environmental impacts due to off-grid homes Figure 7.162 displays the results of modelling all thermal envelopes with off-grid (indicated by red line), the only exceptions being the two Brick Veneer scenarios which are modelled with grid connected systems for comparison. It is important to note that this is a very simplistic comparison which models the same renewable energy system for all homes (5kWh/day capacity - indicated by the blue bands labelled "other household elec" in Figure 7.162), whereas many of these homes would require a larger renewable energy system due to their heating and cooling requirements (purple bands in Figure 7.162). Larger renewable energy systems required to power additional heating and cooling appliances would certainly increase the environmental impacts, but even if the renewable energy system's capacity was four times larger (i.e. 20kWh, "BV LW Conv 20 Grid" models a grid connected home using 20kWh/day, a typical household average in South Australia), the total environmental impact would still be approximately 25-30% less than if an electricity grid connection was assumed for the home.

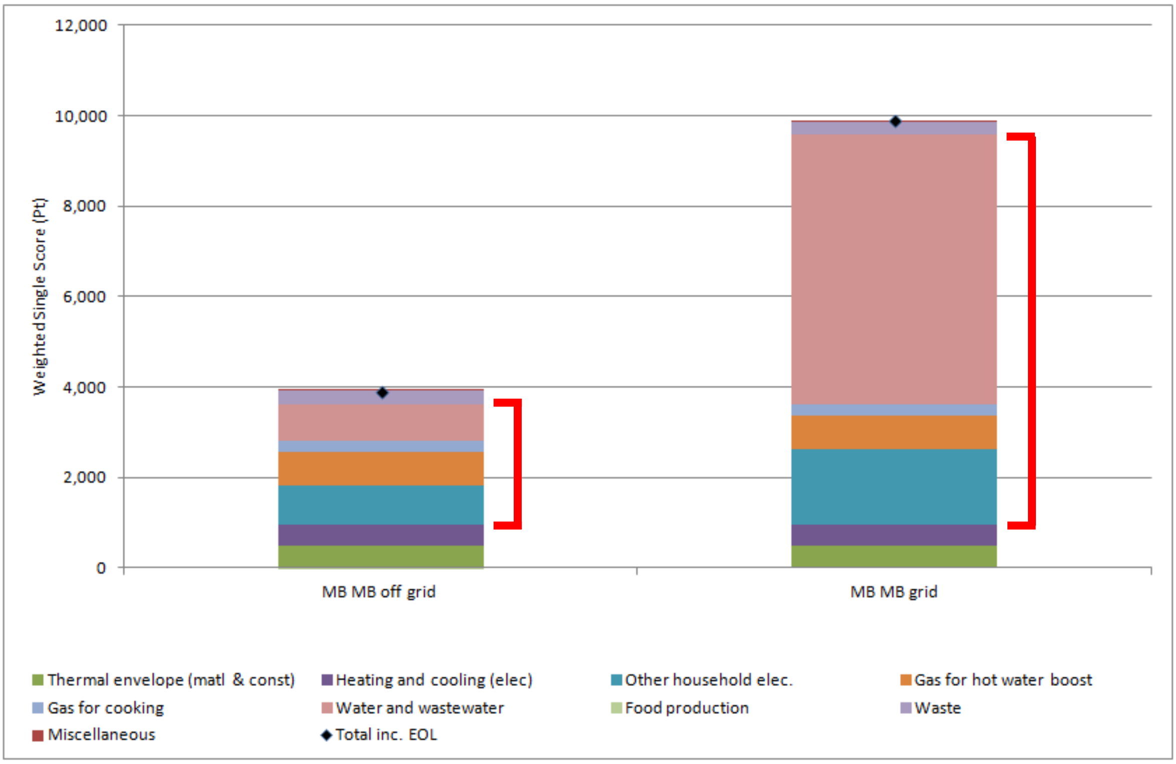

Figure 7.161 - Off-Grid versus Grid connected, Mudbrick Home

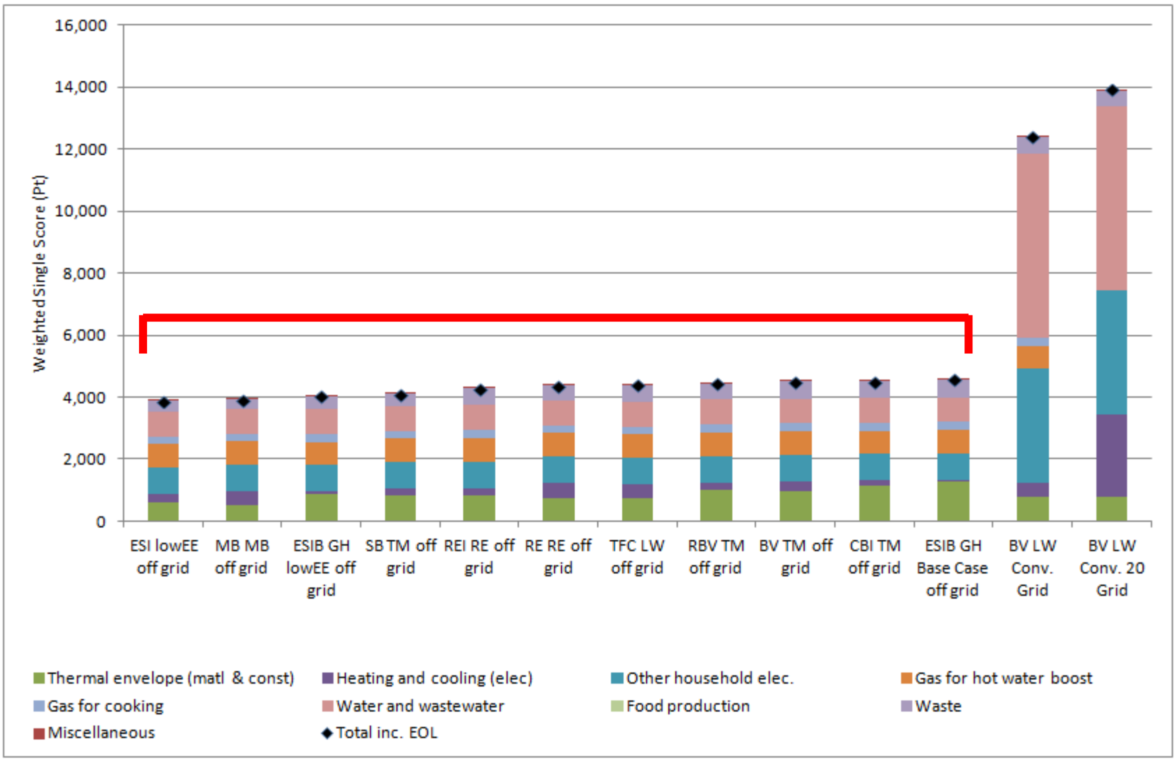

Figure 7.162 - Weighted Single Score, Off-Grid, Whole House, All Indicators, Categorised by Construction/Systems Element

Weighted single score network diagrams are shown for the Earthship Base Case (Figure 7.163) and for the Conventional Brick Veneer home (Figure 7.164) to illustrate the elements that contribute most to the overall environmental impact: the off-grid energy system in the case of the Earthship and water use and energy use in the case of the conventional home.

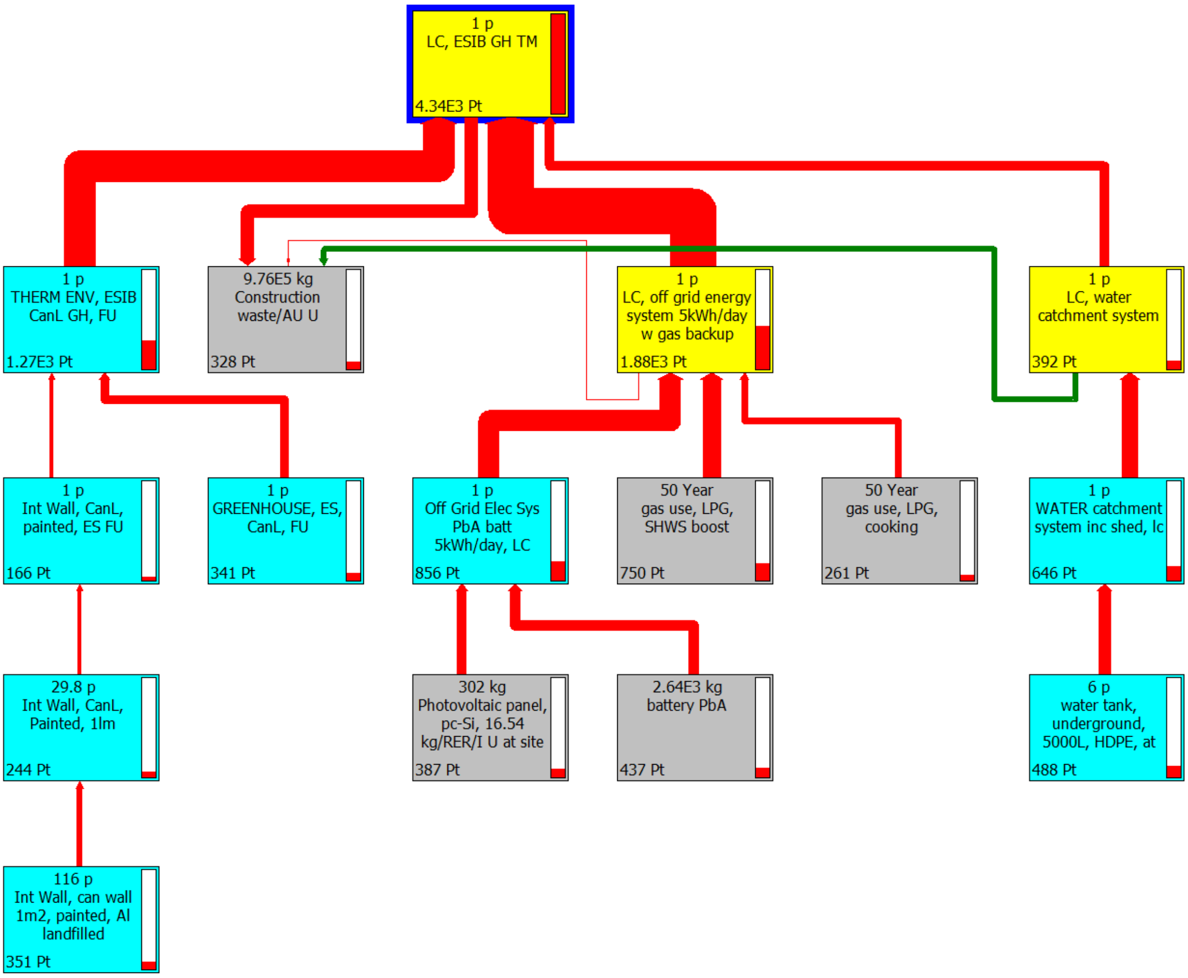

Figure 7.163 - Earthship Base Case, Weighted Single Score, 6% Cut Off

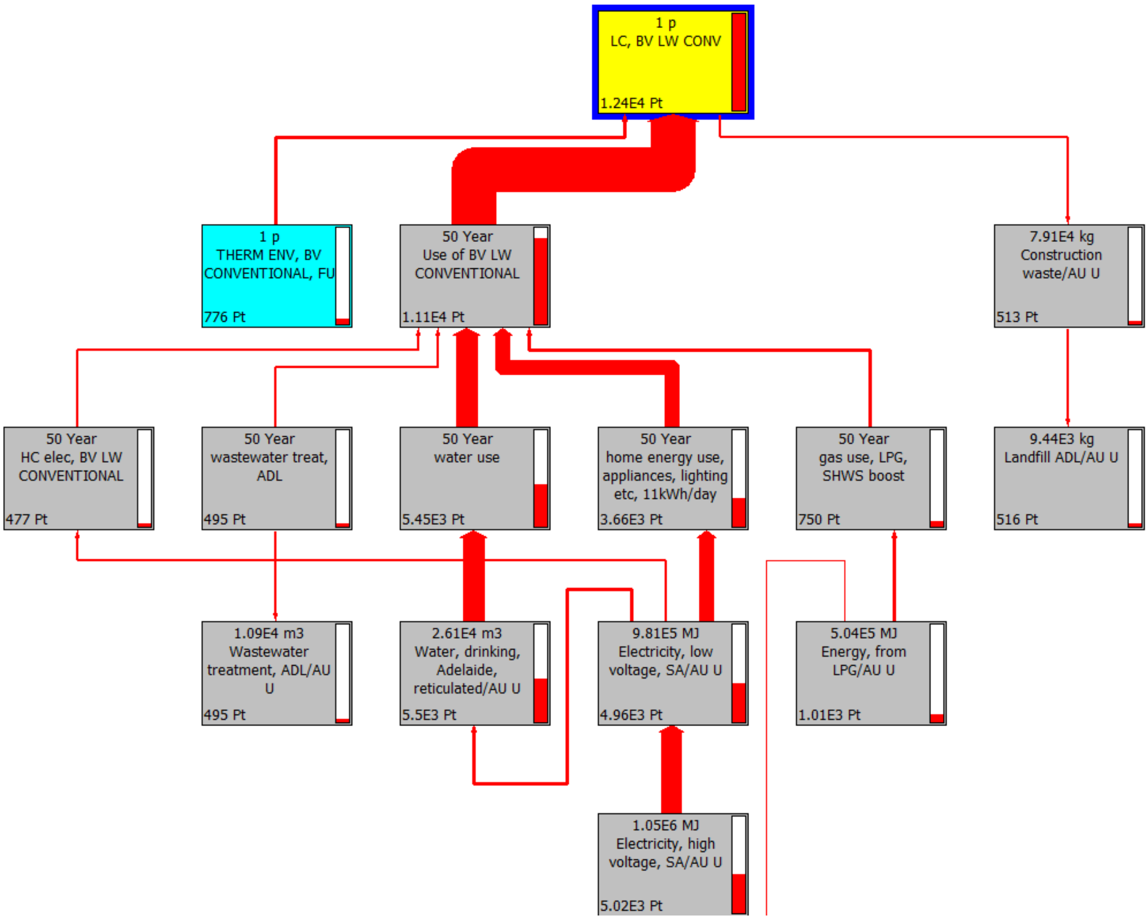

Figure 7.164 - Conventional Brick Veneer Light Weight Internal walls, Weighted Single Score, 3% Cut Off

Figure 7.165 indicates the lifecycle impacts when only heating and cooling impacts are counted, plus the lifecycle impacts of construction of the thermal envelope. This draws attention to the inter-related issues of construction materials and thermal performance.

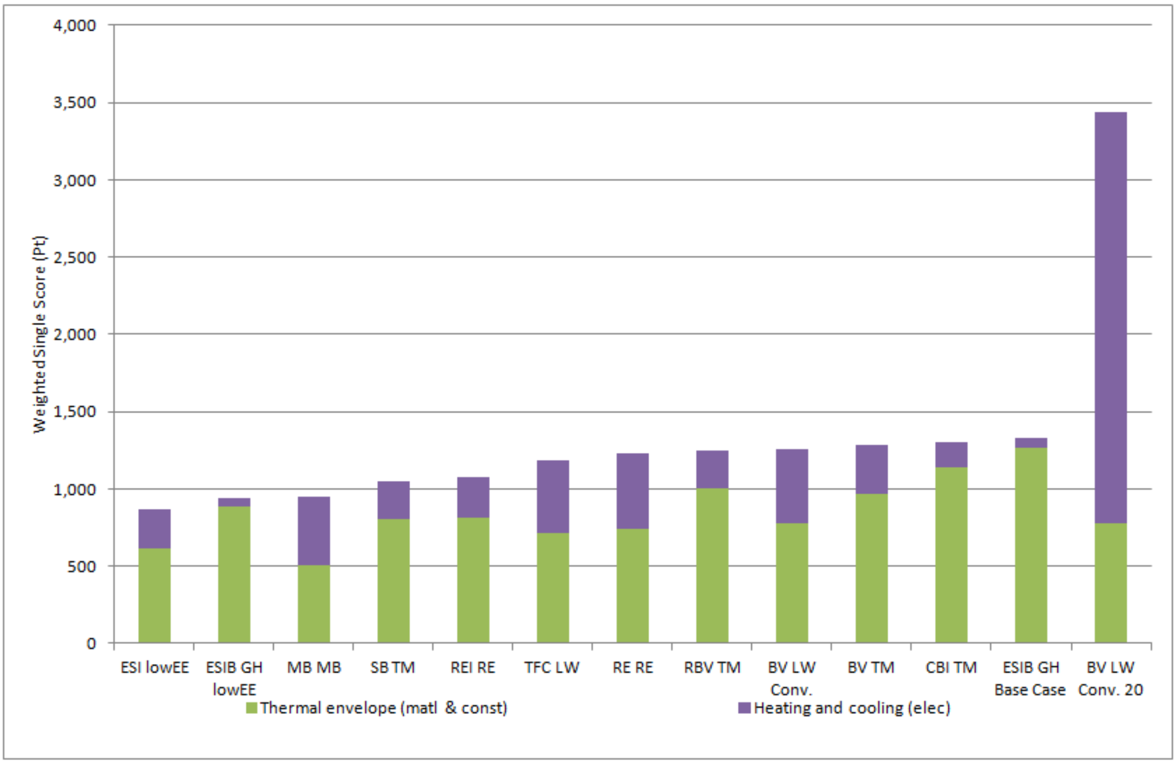

Figure 7.165 - Impacts due to Thermal Envelope construction (and EOL) and Heating and Cooling over 50 years

7.8.15 Discussion & Summary for Whole House

When considering only the impacts of construction, demolition/recycling and the heating and cooling energy (Figure 7.165) the results show that the Base Case Earthship has the highest impacts for construction and the lowest impacts for heating and cooling. This is due to extra materials used to build the greenhouse and berm (which are not modelled in the other scenarios, with the exception of the "lowEE" Earthship which includes a greenhouse and berm) and the concomitant reductions to heating and cooling requirements; however, when the construction materials of the Earthship are altered and if aluminium cans are assumed to be recycled at the end of the building's life (ESIB GH lowEE), the overall impact of the Earthship is less than the non-Earthship buildings. Furthermore, if the Earthship is constructed without the berm and without the greenhouse and with minimal concrete and aluminium can recycling (ESI lowEE), although the heating and cooling energy increases somewhat (similar to Strawbale and Rammed Earth Insulated), the reduction in impacts from construction of the building results in the lowest of all the construction types evaluated by this study. It is interesting to compare the rammed earth envelopes (REI RE and RE RE) and note that adding an insulation layer to the exterior of the external wall only slightly increases the construction/EOL stage impacts but significantly reduces the use stage impacts. The Conventional (non-passive) Brick Veneer construction with average energy use for heating and cooling (BV LW Conv. 20) has the highest overall impact due to far greater need for heating and cooling than the passive solar homes it is compared to, although when the simulation results from the Thermal Performance study are used (rather than average energy use data) to model the energy use (BV LW Conv.) the overall impact is similar to many of the other envelopes.

These results highlight the difficulty of designing a home that has low environmental impacts throughout all life cycle stages, as additional construction materials, aimed at reducing use stage impacts, increase the construction and EOL stage impacts. Another issue relates to the timing of impacts: designs that have a higher proportion of construction stage impacts than use stage impacts have a more immediate effect upon the environment incurring impacts upon construction, whereas designs which have relatively low construction stage impacts and high use stage impacts delay a larger proportion of the environmental impacts until the use stage which is protracted over many years.

Adding the impacts of water use, sewage treatment, cooking fuel, and other operational energy the benefits of off-grid systems can be seen (refer Figure 7.157 and Figure 7.158). The lowest impacts are achieved by the unbermed, insulated Earthship with no greenhouse with minimal use of cement and aluminium recycling (ESI lowEE). This is followed closely by the off-grid Mudbrick (MB MB off-grid) home, then the "low EE" bermed, insulated Earthship with greenhouse (ESIB GH lowEE), and the base case Earthship (ESIB GH base case) which is identical to the previous but has typical cement usage for Earthship construction and aluminium cans are assumed to be landfilled at EOL. These homes are all assumed to be self-sufficient, using off-grid systems, and it is this factor in particular that causes the comparatively low environmental impact of the off-grid homes, as highlighted by the direct comparison of the Mudbrick Home with and without off-grid systems (Figure 7.161) and the study that modelled many other thermal envelopes with off-grid systems (Figure 7.162).

The remainder of homes are assumed to be connected to energy, water and sewer infrastructure. They all show significantly more environmental impact than the off-grid homes; more than double, and in the case of the conventionally designed (i.e. non-passive solar) homes which are constructed from brick veneer with light weight internal walls (BV LW CONV and BV CONV 20) and assume more operational energy use than the other homes, the environmental impact is approximately 3 times greater than the off-grid homes.

In comparison the passive solar, grid connected homes all have very similar environmental impact profiles, the most significant being Water Use & Depletion and GWP. The characterisation results for GWP, Water Use & Depletion and Embodied Energy indicate relatively low impacts for the off-grid homes, whereas the opposite applies to Photochemical Oxidation (smog), Eutrophication (excess nutrients in waterways), Land Use, and Non-Carcinogenic Human Toxicity which all have greater impact when compared to the grid connected homes; however, these latter categories are not indicated as being significant by the normalisation exercise and in many cases the quantitative differences in impact, although lower for the grid connected houses, is not significant.

In the case of toxicity indicators the quantities of toxic substances associated with the *lifecycles* of the homes are a small fraction of the overall Australian *annual* emissions. Although there is significant uncertainty about the quality of the toxicity data the results indicate that toxicity is not a significant issue; however, it should not be discounted and the high (non-carcinogenic) toxic emissions associated with battery manufacture should be investigated further.

To avoid controversy about weightings, and focus instead upon GWP which is often used as the sole measure of environmental impact, the characterisation results of GWP tell a similar story: the off-grid homes have approximately a third of the impact compared to a conventional home, and approximately a half of the impact of a grid connected passive solar home. The comparative difference is due mainly to efficiencies in the off-grid systems. Using approximate figures, the off-grid energy system produces half the GHG emissions compared to grid energy, or, discounting the gas use, the renewable electricity system produces a quarter of the lifecycle GHG emissions compared to South Australian grid electricity. The off-grid water catchment and storage system produces a third of the emissions compared to the grid, and the off-grid wastewater system, a quarter of the emissions compared to the grid.

In summary this LCA study indicates that the environmental impacts of the off-grid Earthship are substantially less than grid connected homes of comparable size and functionality. The relatively low impact of the Earthship arises from the off-grid systems (energy, water and wastewater treatment) rather than the methods and materials used to construct the external wall and thermal envelope. However, it is important to note that it is the construction methods and design of the home that dictate comfort levels and the concomitant heating and cooling energy use and consequently, the home's ability to operate in an off-grid fashion. When heating and cooling energy use approaches zero it becomes feasible for occupants to tolerate brief periods of slightly uncomfortable temperatures and live quite comfortably without heating and cooling appliances. As heating and cooling energy is generally a significant component of domestic energy use, a home that stays comfortable passively has greater potential to provide for itself via an off-grid energy system compared to a home that needs a lot of energy for heating and cooling. The latter would require far more photovoltaic panels and batteries than a passive, energy efficient home such as the Earthship and this is unlikely to be practical or economical, and it is unlikely to be ecological due to the environmental impacts associated with photovoltaic panels and batteries. Similarly, water use, and the associated wastewater, must also be minimised, as these critical functions of the home were found to represent a significant proportion of the home's environmental impacts. An Earthship, which uses water four times (compared to a conventional home which typically uses it once), minimises its demand for water and its generation of waste water demonstrating that extremely high levels of water efficiency can be achieved without overly complex or technological systems that require large quantities of energy or chemicals throughout their operation. Thus, for off-grid homes to be environmentally sustainable, energy and water use, and the associated systems, must be minimised.

8 Conclusions

8.1 Summary

Earthships are autonomous off-grid homes that produce renewable energy, collect water, treat wastewater and grow food indoors all year round. They are highly energy and water efficient and typically do not require heating and cooling to maintain comfortable indoor temperatures, even in extreme climates. Although they use small amounts of fossil fuel (gas) for cooking and boosting the solar hot water system they are essentially self sufficient.

While the concept of autonomous homes is not new, the design of the Earthship is unconventional due to the way that it combines many "sustainable" design principles and innovative construction methods. Perhaps the most unconventional feature is the (re)use of waste products, in particular old car tyres, which are used to form a durable external wall that is earth-sheltered (bermed) on all but the equator facing side of the home (e.g. north side in the southern hemisphere). Another important and unconventional feature is the greenhouse which serves multiple functions: it serves as a corridor, a place to grow food and to treat wastewater, and is a passive solar space heater (in the winter) and a "convection engine" that passively draws cool air through earth tubes (in the summer). The Earthship's creator, American architect Michael Reynolds, claims that they are the most environmentally sustainable homes in the world, and that they have the capacity to reconnect their occupants with nature and realign their intentions towards the conservation of the planet. It is these claims that prompted this research.

As stated in Chapter 1, the aim of this research was to understand: a) the environmental impacts of the Earthship lifecycle, b) the amenity it provides to its occupants in terms of thermal comfort, electricity supply, water supply, and sewage treatment and c) the occupant's motivation for seeking this lifestyle.

The overall hypothesis for this research was that the Earthship is able to provide a highly acceptable level of amenity ("modern conveniences" and thermal comfort) with much lower environmental impact than other conventional (and alternative) houses.

In order to achieve the research aims a Life Cycle Assessment (LCA) study was used to compare the environmental impacts of the Earthship lifecycle, including construction, use (operation) and end-of-life (recycling and demolition), to that of other construction methods and utilities systems:

a) the off-grid systems of the Earthship which enable it to function autonomously were compared to conventional grid connected infrastructure,
b) the unusual Earthship wall constructions were compared to conventional (e.g. typical standard construction practice such as brick veneer, timber frame) and alternative (e.g. strawbale, rammed earth) wall construction methods, and
c) the unusual Earthship design features (the greenhouse and earth berm) were evaluated in the context of the Earthship and in the context of various "conventional" and "alternative" wall construction methods.

To support the LCA study two other major studies were conducted: a Post Occupancy Evaluation (POE - refer to Chapter 3) and Thermal Performance studies (refer to Chapter 4). The aim and rationale of the POE study was to:

1. gain a better understanding of the thermal performance of the Earthship in various climates including its climate of origin, Taos, New Mexico, USA. Provision of thermal comfort is critical to the amenity provided by a house and this aspect was critical to the LCA as many studies have documented the substantial environmental impacts arising from the energy used to heat and cool homes.
2. evaluate the level of amenity provided by the Earthship's off-grid systems and what was involved with maintaining these systems throughout the use phase of the home. This was of interest because it helped to establish whether or not the Earthship provided a commensurable level of amenity compared with conventional grid connected houses.
3. investigate the lifestyle the Earthship provided its occupants, trying to understand why they chose to live "off-grid" in a house made from "waste".

The aim and rationale of the Thermal Performance study was to:

4. investigate the thermal performance of the Earthship and other housing types in the Adelaide climate, especially in relation to their wall constructions, to enable a direct comparison. Performance of the Earthship in other climates was also investigated to evaluate the claim that it can provide thermal comfort with minimal heating or cooling in many climates.

While of interest in their own right, the POE and Thermal Performance studies provided information essential to addressing the overall aim. Furthermore, because LCA is best conducted as a comparative exercise it was important to establish "functional equivalency", to demonstrate that the amenity provided by the Earthship was commensurable with grid connected homes of various constructions, and the POE and Thermal Performance studies helped to investigate this issue.

A summary of these studies is now given, followed by discussion, implications, recommendations and concluding remarks.

8.1.1 Post Occupancy Evaluation Overview and Results

This study involved measurement of the indoor comfort conditions of Earthship homes in Taos, New Mexico, which were monitored, producing the most extensive set of data ever collected for these types of homes and this data was analysed and cross referenced using international standards. Modelling exercises were conducted in the Taos climate, using the measured data to calibrate the simulation model, and then this model was used to simulate the performance of the Earthship in a variety of climates. The effect of Earthship design strategies, such as earth sheltering and incorporation of a greenhouse, were also modelled and quantified in the context of the Earthship, and in the context of their application to other types of wall constructions.

Interviews were conducted with four Earthship occupants, and this was followed up with a daily survey of the indoor comfort conditions of their homes during one week in winter, spring and summer. Another survey was conducted worldwide, with 16 valid responses, which included questions relating to location, climate, design, thermal comfort, maintenance, performance of off-grid systems, lifestyle and behaviour, motivation and basic demographic information of the occupants.

The key findings of this study were that the Earthships' off-grid systems provided a high degree of amenity provided they were used as intended and provided the minimal and manageable maintenance tasks were undertaken when necessary. Despite the wide range of locations and climates, respondents indicated a high degree of thermal comfort with minimal energy use and with minimal effort required to operate the natural ventilation systems. The occupants were very amenable to making changes to their behaviour to enable them to live within the limits of their off-grid homes. The most common motivation for living in an Earthship was to be more self sufficient, followed by a desire to reduce their "eco-footprint" and lastly, to reduce utility bills.

The implications of this study are that the Earthship is likely to be acceptable to people accustomed to high levels of modern conveniences and therefore it has potential to proliferate especially if aimed towards people who are interested in being more self-sufficient, reducing their environmental impacts and reducing their utility bills.

8.1.2 Thermal Performance Overview and Results

This study involved computer simulation models using EnergyPlus and DesignBuilder software and statistical analysis to compare simulated results with actual results measured during the POE study. New methods for predicting ground temperatures in Earthships were developed and incorporated into a model which was calibrated using data from the POE study, resulting in a model that was able to predict the indoor air temperature of the Earthship in the Taos climate with an acceptable degree of accuracy. The calibrated model was used to predict the likely energy use for heating and cooling of Earthships to satisfy standard thermal comfort conditions in the Adelaide climate, and also in a variety of other climates, indicating how current Earthship design might be expected to perform and how the design might be adapted to suit various climates.

Limitations of data, and of the simulation software employed, meant that the thermal simulation results could not be interpreted as absolute, but rather they indicated the relative performance of the buildings modelled. The limitations included uncertainty regarding properties of the soil used for earth sheltering, and the fundamental mechanics of the modelling software, which is essentially one dimensional rather than three dimensional, and for these reasons it was not possible to accurately simulate the effect of the Earthship's passive cooling, earth tube system. Nevertheless, it was possible to simulate the performance of an Earthship in Taos with acceptable accuracy giving confidence that the model, albeit with some limitations, would provide a reasonable estimate in other climates.

The results of the Thermal Performance Studies revealed that Earthship occupants generally experience high levels of thermal comfort, although in overcast, cold climates small quantities of backup heating were indicated. In many of the Global Model Earthship designs evaluated in Taos the monitored data confirmed that heating and cooling was not necessary (even in the extreme climate) and this finding was backed up by survey responses from the occupants.

In the Adelaide climate the thermal performance of the Global Model Earthship (earth sheltered design with a greenhouse) was superior to other dwelling types, although wall constructions with similar properties such as concrete block and precast concrete slab walls were also predicted to provide very comfortable indoor conditions. The addition of a greenhouse (integrated with appropriate quantities of thermal mass) substantially reduced the heating/cooling load for all wall construction types indicating a potent retrofitting solution where the addition of an equator facing greenhouse is possible.

An investigation of the thermal performance of variations of the tyre wall in which the berm was replaced by an exterior insulation layer indicated very good thermal performance, comparable to strawbale walls, leading to the conclusion that un-bermed, insulated, tyre walls may prove to be a viable option in the suburbs on small blocks of land where an extensive earth berm is not practical.

This study indicates that the thermal envelope of the Global Model Earthship provides thermal comfort without air conditioning in a range of climates and that it can be successfully reinterpreted and adapted in a variety of ways to accommodate limitations imposed by the site or to accommodate preferences for different materials and construction methods.

8.1.3 Life Cycle Assessment Overview and Results

Using the Global Model Earthship as the basis of the study (i.e. the "functional unit") architectural drawings supplied by Earthship Biotecture were used to calculate quantities of materials and energy use in construction processes. Using the basic dimensions of this Global Model Earthship other thermal envelope constructions were analysed in terms of their materials and processes, thereby providing data to support assumptions regarding the construction lifecycle stage and to a lesser degree the end-of-life stage. Findings from the POE and Thermal Performance studies were used to inform assumptions regarding heating and cooling energy, and also maintenance requirements, especially of the Earthship systems (energy, water and wastewater). A review of the literature and primary research were the basis of assumptions regarding the end-of-life stage. SimaPro LCA software was used to model the environmental impacts arising from the assumptions derived from the various studies providing the basis for an assessment of the Earthship's environmental sustainability compared to other housing types.

The Life Cycle Assessment study produced some unexpected results. It was found that the various external wall construction materials had a wide range of impacts, and as expected the Earthship, which uses large amounts of earth and reuses materials which are also highly recyclable at their end-of-life, performed very well, comparable to a mudbrick wall which also uses large amounts of earth and very little else. However, when construction and EOL stages of the whole thermal envelope were considered and the additional construction elements of the Earthship were included (such as the earth berm, reinforced concrete buttresses, internal "can walls" made with concrete and aluminium beverage cans, and most notably the greenhouse which incorporates large quantities of double glazing) the environmental impact of the Earthship's thermal envelope was the highest of all the thermal envelope types that were evaluated. This was somewhat unexpected; however, for a "fairer" comparison to the other thermal envelopes, when the greenhouse and berm were not included, and by reducing the quantity of concrete by modifying the "can walls" to use adobe mortar (with a thin layer of cement based render for weather proofing) instead of cement based mortar, and by using short "stub" tyre walls instead of concrete buttresses, the environmental impact of the Earthship thermal envelope (construction and EOL stages) was halved with the result that it was the second lowest of all the constructions evaluated. Hence with some minor material changes - not a radical redesign - the construction and EOL impacts of the Earthship were significantly reduced without affecting thermal performance and hence the use (occupancy) stage impacts.

The results of the thermal performance analysis and the LCA highlights the need for careful selection of materials that will minimise heating and cooling requirements during the use (occupancy) stage of the building and minimise environmental impacts during construction and end-of-life stages. Herein lies the design challenge; of balancing "embodied energy" of construction materials with operational energy use, the latter being driven largely by the decisions made regarding the arrangement (design) and selection of the construction materials. Furthermore, the challenge becomes far greater as the need for heating and cooling diminishes because this increases the relative impact of choices regarding material selection and design which become more influential as drivers of environmental impact.

While this is somewhat self evident, another important finding was that the systems used to provide energy, water and wastewater were the main determinants of the lifecycle environmental impacts, far more so than construction materials, although materials and design still played a critical role in determining heating and cooling energy requirements. The weighted single score analysis showed that the off-grid systems had less environmental impacts than the grid systems. The off-grid water supply system provided the greatest benefit as the Adelaide reticulated water supply caused 15 times greater environmental impact than the off-grid system. The Adelaide Sewer System had 2.9 times greater impact than the off-grid wastewater system, and the South Australian grid energy had 1.5 times greater impact than the off-grid energy system. The significant benefit arising from the off-grid water supply and to a lesser extent the off-grid wastewater system, was due to energy use associated with the provision of potable water and "disposal" of wastewater both of which require significant quantities of energy to pump water and waste over long distances.

It should be noted that some of the toxicity indicators (which were not factored into the weighted single score) indicated worse results for the off-grid systems; however, when the quantities of toxic substances were evaluated against national levels they were insignificant. Limited data regarding toxicity in the Life Cycle Inventory (LCI) database prevented any firm conclusions being drawn about this important impact category and hence more research is needed in this area.

The assumed lifespan of the buildings in this LCA study was 50 years, a common assumption in other LCA studies of buildings. Many studies noted that this assumption is arbitrary and is influenced by social and economic factors more so than issues such as the durability of construction materials. Hence, further research is needed to investigate the effect of the lifespan variable; however, as shown in other similar studies (Carre, 2011; Fay, Treloar & Iyer-Raniga, 2000) longer lifespans tend to diminish the environmental impacts of the construction and recycling stages relative to the use stage because of the ongoing energy and water required to operate the home throughout the longer lifespan compared to relatively small "once off" inputs of materials and energy required to construct the home and to undertake maintenance of the home. The implications of this are that design efforts should focus on minimising use stage impacts if it is expected that the home will have a very long lifespan and conversely, homes that are expected to have short lifespans should use construction materials with low embodied energy and construction processes that maximise reuse and recycling potential.

An important finding, related to the off-grid systems, was that Earthship occupants were very satisfied with the amenities that the off-grid systems provide, despite the fact that they require maintenance and behaviour change, for example occupants need to observe weather patterns so that resource intensive activities can be scheduled for appropriate times of the day/season to avoid depleting their stores of electricity and water. The limits that the Earthship's off-grid systems impose ensure that overall resource use is not excessive, yet they provide adequate, and at times abundant, provisions for the occupants allowing them to live comfortably with many modern conveniences with minimal reliance particularly on fossil energy - which they tend to use only for cooking and boosting the solar hot water systems.

The implications of this study are that off-grid electricity, water and wastewater systems and the concomitant energy and water efficiency measures that are required to minimise the load of the off-grid systems, are the most potent means for reducing environmental impacts over the lifecycle of a home. While construction materials play a significant role in determining the use stage impacts due to the significant role they play in determining the heating and cooling energy demand, their influence on the construction stage and the EOL stage impacts are relatively low. Hence designers should prioritise design criteria to aim for homes that require little or no heating and cooling and that they be self sufficient in energy, water and wastewater treatment using minimal, small scale, off-grid systems as per the Global Model Earthship archetype. The materials used to achieve this end result are of less concern but are still important.

8.2 Discussion & Recommendations

This research indicates that the Earthship principles offer a potent solution for reducing environmental impacts over the lifecycle of homes in the Adelaide climate and technosphere (infrastructure), and initial investigations of other climates indicate that the LCA findings can be extrapolated to other locations, especially where similar technological infrastructure systems exist (i.e. "developed" countries).

If new homes followed Earthship principles and existing homes were retrofitted where possible to achieve similar levels of efficiency (in energy, water and wastewater) and self sufficiency, a significant reduction in the environmental impact of residential housing could be realised. Although this study did not specifically investigate the broader impact on infrastructure it is hypothesised here that increasing numbers of self sufficient homes would lead to decreasing demand on infrastructure which might eventually only be needed to supply the demands of industry. The implication of this is that instead of continuously expanding infrastructure, it could be scaled back, decommissioned and, where needed for industry, replaced with new technology with less environmental impact.

In terms of specific design strategies for implementing the Earthship principles in the context of the Adelaide climate, some recommendations arising from this study are outlined below.

The first recommendation is indicated by the thermal modelling study in Adelaide which indicated that the indoor temperature in the Earthship would occasionally become slightly uncomfortable (too cool) in the winter. This suggests that backup heating would be advisable although the relatively low theoretical heating load suggests that the duration and severity of the discomfort would be minimal and easily addressed by, for example, by wearing extra clothing.

Secondly, extra photovoltaic panels and batteries may be necessary due to Adelaide's overcast winter conditions.

The "thermal wrap" - a layer of 100mm thick expanded polystyrene insulation positioned vertically in the berm approximately 1200mm from the tyre wall - should be considered carefully. Although it improves performance in the winter, elevating indoor temperature due to the insulative effect, it has a negative effect in the summer, increasing the cooling load. With a warming climate the thermal wrap may eventually prove to be detrimental, but for now the annual net result is that it is beneficial.

When thinking long term about climate change, additional earth tubes should also be considered to offset the additional cooling load caused by hotter summers. Furthermore the possibility of using mechanical ventilation (e.g. an electric exhaust fan) in conjunction with the earth tubes to enable nighttime purging should be evaluated. It should be noted however, that this study did not investigate the specific effect of the earth tubes (although four Earthships with earth tubes were monitored) and therefore further research on the design and performance of earth tubes is needed before making any conclusions or recommendations regarding their applicability in the Adelaide climate.

Shading of the greenhouse in summer is recommended due to the substantially hotter summer conditions in the Adelaide climate compared to Taos; however, the shading should be achieved via a controllable, variable element such as blinds, awning or even deciduous vines so that the ideal amount of solar gain can be achieved, otherwise the greenhouse may not heat up sufficiently to provide the convective effect required for the earth tubes to operate.

The possibility of automating the Earthship's natural ventilation systems via an intelligent network of temperature and humidity sensors should be considered as this has potential to improve thermal comfort by automatically opening and closing earth tubes, skylights, windows et cetera at optimal times. Otherwise, if natural ventilation is managed manually by the occupants, an optimal result is less likely, unless the occupant is diligent and is physically able to interact with the system. For example if they are not at home or they are asleep they will not be able to open and close vents and windows at the correct time. Furthermore, they also need to know when the optimal time to make such adjustments is, and without a reasonably sophisticated system to sound an alarm and issue instructions regarding which window or vent needs to be opened, it is left to the occupant's best guess as to what needs to be done at any given time. While these skills can be learned, not everyone will have the time, diligence and motivation to vigilantly attend to these tasks leading to sub-optimal indoor temperature and potentially dissatisfaction with the home's performance. This may ultimately lead to the installation of energy consuming heating, ventilation and air conditioning systems. While automation may optimise the performance of the Earthship, the typical unautomated Earthship has demonstrated that it performs well without constant interventions by the occupants to the natural ventilation systems, all of which only need to be adjusted seasonally or daily, but not constantly. Perhaps a more appropriate focus for "automation" would be to automatically collect and display data via a "dashboard" that shows energy use and water use in conjunction with weather forecasts so that the occupants could plan their activities according to the limitations of the off-grid systems and future predictions of rain and sun. As the environmental impacts arising from the manufacture, operation and disposal of automation and data collection equipment have not been assessed by this study, further research is needed to ascertain the benefits of these systems.

In a suburban context Earthships present some challenges due to their requirement to face the equator (e.g. north in the southern hemisphere) for passive solar design and due to the large earth berm and greenhouse - important design elements that contribute to the Earthship's excellent thermal performance. These requirements take up considerable space which may not be available on small suburban blocks; however, this may be addressed by innovative landscape design of the berm, perhaps including additional retaining walls (made with tyres) to reduce the size of the berm while still maintaining its important thermal performance characteristics. Another option would be to use insulation on the outside of the tyre wall, or use strawbale for the external walls - two wall construction options that performed well, especially when coupled with a greenhouse and thermal mass internal walls. Furthermore, the Earthship's off-grid systems, especially the wastewater system, may be somewhat redundant due to laws requiring connection to existing infrastructure; however, a simple approach would be to make these connections but not use them, or only use them very occasionally. Where new suburban developments are being planned the Earthship concept can be implemented as shown by the Aardehuis Earthship inspired suburban development in the Netherlands which is currently under construction (Vereniging Aardehuis Oost Nederland, 2011).

A final recommendation, made tentatively, is aimed at reducing the lifecycle impacts of the Earthship even further. If the Earthship was connected to the electricity grid, yet still retained its battery bank and solar panels, it could help become part of a distributed energy system and earn carbon credits resulting in a "zero carbon" home. A significant downside to grid connection is that it removes the powerful incentive for the occupants to be frugal with their electricity use with the likely end result that they are no longer self-sufficient in electricity, drawing down more electricity than they export; however, this problem might be overcome with technology that prevents supply from the grid, only allowing a one way flow of electricity to the grid. Or, in an emergency, it could allow a relatively brief "charge" from the grid with financial disincentives to ensure that positive behaviour change is encouraged. Taking this idea a step further, a "virtual" system that simulates a limited electricity supply in conventional grid connected homes would be an interesting social experiment aimed at teaching people to be more energy efficient while providing the security of extra energy if it was desperately needed. The same could be done with the water supply.

8.3 Concluding Remarks

The possibility of running out of water and not having energy seems to be a powerful motivator for Earthship occupants to adopt a more frugal, yet satisfying lifestyle, to the extent that this ultimate "threat" of the Earthship rarely occurs, but rather it provides gentle "encouragement" to the occupants to live within the limits that the Earthship and the prevailing weather conditions dictate. In contrast, grid connected homes create the illusion that there is a seemingly inexhaustible supply of energy and water, limited only by the occupant's ability to pay for it, which in the "developed world" is made simple through the provision of financial credit.

It seems to be the case that the apparent abundance provided by the grid has lulled people of the "developed world" into the erroneous belief that there is an inexhaustible supply of energy and water and that their use of resources has little or no consequence to the overall health and vitality of the Earth and its ecosystems, whereas many scientists are warning that we are living beyond the capacity of the planet, such that we would need two and a half planets to sustain our current rate of resource use and pollution. Thus it is incumbent upon everyone to reduce their own "eco footprint". The Earthship is an effective means for achieving this goal as it teaches those who choose it for a home, that they must change their ways and live by some hard and fast rules, or suffer immediate consequences, whereas conventional homes tend to delay the consequences until the end of the quarter - when the bills arrive - or delay consequences for future generations, when the wasteful practices of the previous custodians of the planet will have to be dealt with, possibly in the context of fuel scarcity and an unpredictable and extreme climate.

Like a parent who must nurture and discipline a child so that they may grow up to become an independent adult, the Earthship nurtures the occupant, providing comfort, protection, nourishment and joy, while teaching self reliance, diligence and the consequences of "bad" behaviour. The Earthship can be thought of as a tool that teaches us to be aware of our surroundings and our influence over them so that we may understand the bigger picture: our interconnectedness to the planet and our responsibility towards its health and vitality. In the words of one Earthship occupant surveyed in this study: "It is quite simply the best and most comfortable place I have ever lived. It requires awareness and thought - but life should."

This thesis has not delved into the issue of population density and the associated trend for people to live in large cities rather than car reliant suburbs and rural areas, it has not investigated economic issues, and nor has it investigated social issues related to living in isolated off-grid communities; however, there is evidence that Earthships can be deployed successfully practically anywhere and at any scale. Reynolds' numerous projects which range from communities housing hundreds of people in North America, to community buildings in Africa built by locals, and his master plans for Earthship villages and cities, demonstrate that Earthship principles can be scaled and adapted to suit a wide variety of social and economic contexts from high to low population density and from developed to developing worlds. And increasingly, other architects are embracing Earthship principles as evidenced by the Aardehuis Earthship inspired suburban development in the Netherlands.

Another issue that has not been investigated by this study is the effect that widespread uptake of the Earthship concept would have on infrastructure demand. The Earthship's self sufficient qualities would dramatically reduce load on already strained infrastructure which must be continually upgraded and maintained, yet large scale deployment of Earthship technology may bring about dramatic social, economic and environmental advantages due to significant diversions of resources currently required to maintain and expand water, energy and wastewater infrastructure.

While there is much more research to be done regarding the Earthship, this thesis demonstrates that it lives up to many of its claims; providing thermal comfort and modern conveniences with only a fraction of the environmental impacts that a comparable "conventional" building creates.

Looking into the future it seems highly likely that there will be significantly more people on the planet, and declining availability of natural resources. Experts also warn of more extreme weather and natural disasters. There is a serious threat to global food supplies and the opportunity to harvest fresh water, both of which will challenge our ability to maintain our current life-styles. Therefore, we need to develop new ways of living that do not damage the ecosystems that we rely on for our survival. With regard to our dwellings, it is imperative that we urgently retrofit existing homes so that they are far more energy and water efficient. If this can be achieved then it may be possible for them to be converted to off-grid homes, providing even more environmental benefits, and potentially social and economical benefits too - fewer bills to pay, more time to play. New homes and developments should be firmly founded on the Earthship principles of living self-sufficiently in passively heated and cooled homes built substantially with natural/recycled materials. If these new homes are not built with bermed, car tyre walls along passive solar design principles they must somehow achieve extremely low energy use for heating and cooling, or risk becoming a totally unsustainable home, with a short future on a crowded, warming planet that has been exhausted of fossil fuels.

The homes of the future may not be called Earthships, but it is likely they will be utilising many principles of design in common with Earthships.

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Appendices

CONTENTS OF APPENDICES

Appendix A - Ethics Application & Approval

A1 - Ethics Application Form

THE UNIVERSITY OF ADELAIDE HUMAN RESEARCH ETHICS COMMITTEE

LIST OF HEADINGS APPLYING TO ALL APPLICATIONS

Guidance information for completion of this form is notated in (*italics)* under each heading. Please complete all headings.

1. TITLE

   Earthship Perceptions and Performance

2. INVESTIGATORS & QUALIFICATIONS
   (Provide brief details of the researchers' previous experience with the specific research techniques that will be used in this study. If this study involves direct contact with participants, give details of the research student's experience and/or training in conducting research of this kind.)

   Assoc Prof Terence Williamson has conducted numerous studies of this kind.

   Assoc Prof Veronica Soebarto has conducted numerous studies of this kind.

   Mr Martin Freney (research student) is a lecturer in industrial design at UniSA (currently on leave) and was the project leader for a federally funded teaching and learning project which involved qualitative and quantitative data collection methods. He is attending the Ethics and Integrity in Research with Humans workshop on 14-15 November 2011.

3. PURPOSE OF THE STUDY
   - Aims (*What research hypothesis is being investigated? What benefits does the study aim to produce?)*

   This study aims to develop new knowledge that may be useful in mitigating and adapting to climate change in terms of residential house design and the associated lifestyle that the house confers to the occupants. It is part of the research student's proposed PhD studies (upgrading from Masters to PhD in November 2011).

   Anecdotal evidence suggests that the "Earthship" housing concept offers many ecological, social and economic benefits. It claims to be comfortable, energy efficient, to reuse and recycle "waste" materials in its construction, to be affordable to build and operate, and to provide a self-sufficient lifestyle with a minimum of hassle. However, these claims need to be examined scientifically and evaluated for their relevance within an Australian context.

   In particular this study aims to investigate the claim that Earthships' indoor air temperatures remain comfortable without active heating or cooling systems and that there is adequate daylighting. Other claims that will be investigated include; negligible utility bills (electricity, water, gas), and the ability to grow a substantial amount of food using the indoor greywater treatment system. The study will also explore the level of behaviour change, and motivations for them, that are necessitated by the off-grid autonomous systems that form the basis of the Earthship concept.

The results of the study will enable calibration of software to the unusual construction methods employed in Earthship architecture which uses end-of-life car tyres to create earth-sheltered (bermed) exterior walls. This will improve the accuracy of simulations conducted by designers, engineers and scientists (and the research student) when estimating energy use, comfort levels, and greenhouse gas emissions of homes constructed in this manner. A better understanding of the occupants' motivations for adopting this technology, and the associated lifestyle (behaviour change), will aid in the development of strategies for adapting Australian housing and the Australian lifestyle in the face of challenges such as climate change and resource depletion.

- Rationale *(Explain your research methodology and its appropriateness to achieving the study aims. Provide evidence that the sample size is adequate to establish a valid research result.)*

The research will employ a variety of methods for achieving the study aims. Case studies involving monitoring of indoor temperature, humidity and daylight levels (natural lighting) will be conducted to determine the comfort conditions of various Earthships. This data will be cross referenced with questionnaires of the occupants which will be aimed at revealing their perceptions of the comfort conditions and their involvement in the operation of their home. A broader study involving more research participants will also be conducted via another questionnaire to determine the general perceptions of Earthship dwellers to issues relating to the Earthship lifestyle.

The case studies will focus on approximately six Earthships in the Taos region where three Earthship communities are located plus numerous other single Earthships. Currently there are no Earthships in Australia and very few in other parts of the world. Taos is the epicentre of Earthship activity offering many opportunities to study this form of architecture. Furthermore, due to the wide range of extreme weather conditions experienced in Taos, New Mexico, USA where Earthships originated (a high altitude desert) similarities with Australian weather conditions will occur and can be used to study how the design would perform in Australian conditions. This will give designers and engineers greater confidence in simulation results, enabling more accurate calculations of carbon emissions and energy use by Earthships built in Australia.

Study 1: Case Studies – *Earthship Comfort Levels*

To understand the Earthship's comfort conditions, six Earthship homes will be studied in detail.

Each Earthship will be fitted with data logging devices to record indoor comfort conditions (temperature, relative humidity, lighting level) and outdoor weather conditions (temperature and relative humidity). Weather records kept by the local airport will be obtained to augment the outdoor weather data providing further information such as wind speed/direction, solar radiation, etc.

A questionnaire titled *Earthship Daily Comfort* will be used to record the occupants' perceptions of comfort and their activities which relate to how they interact with the home to influence comfort conditions e.g. opening and closing windows, lighting fires, using vents etc. These records will be kept on a daily basis. This data will help explain the data logging results and will also be useful in configuring parameters in the subsequent thermal modelling study which is part of the research student's PhD study.

For the thermal modelling study to be possible architectural design parameters (e.g. floor plan, ceiling height, roof insulation) will be needed. This information will be gathered during interviews of the occupants that are planned as part of the *Earthship General Questionnaire*. Thus it will be necessary for participants of the Case Studies to also participate in the General Questionnaire.

The data collection period will be from December 2012 to July 2012 capturing the coldest and warmest times of the year.

The data collected by the data loggers will be sent back to the researchers by one of the following methods (dependant on funding and what each research participant is comfortable with); by teaching the participants to periodically download the data from the devices and emailing it; by asking the participants to air-mail the devices at the end of the data collection period; or by automatically sending the data via the internet (more expensive hardware needed in this case).

A sample of six homes will enable various Earthship designs to be compared. For example more recent designs feature an attached greenhouse with glazed doors and windows adjoining the greenhouse, whereas in older designs the greenhouse was integral with the main living area and was not able to be separated. Another design variation is the use of insulation in the earth-berm. Thus two examples of each of these three variants could be studied enabling comparison and data averaging between the similar designs, and the ability to compare the effects of the different design features.

Study 2: Questionnaire/Interview – "*Earthship General Questionnaire"*

This part of the study aims to gather a variety of information from as many Earthship dwellers as possible via an anonymous *Earthship General Questionnaire*, or, where possible, via an interview which will augment the questionnaire. The interview will be based on the questionnaire but with the possibility of more discussion around the questionnaire topics. It will investigate the nature of Earthship dwellers' lifestyle, their motivations for choosing it, and how the Earthship facilitates it. The scope of the questions are listed in the section 8 Study Plan and Design.

This data will be used to understand the nature of the home, the lifestyle that it enables and the satisfaction or otherwise that this confers to the occupants. The data relating to energy and water systems will be used to calculate energy and water usage which will then be analysed, for example by comparison to national averages.

It is estimated that at least fifty but potentially many more responses are likely for the Earthship General Questionnaire. Assuming there are approximately 2000 currently inhabited Earthships (this is an estimate by Michael Reynolds originator of the

Earthship) a sample size of fifty would be 2.5 percent of the global Earthship community. However, as it is not known how many Earthships exist it is not possible to draw statistical conclusions regarding the results and as such they will be presented as case studies.

4. BACKGROUND

The Earthship is purported to provide a high level of self sufficiency and low running costs in a way that minimises impacts on the environment (Reynolds, 1990). Through the use of a radical design that ingeniously harnesses waste materials, passive heating and cooling systems, in-house food production, wastewater treatment and renewable energy it seems to be possible to provide all the modern amenities enjoyed in a conventional home, yet with a fraction of the resources and energy use and with negligible utilities bills.

If it is as effective as it is claimed, it suggests new strategies for the development of new communities that would enable people to live a sustainable lifestyle, and the possibility of retrofitting existing housing stock with various innovations, for example the greenhouse and greywater treatment system, thereby raising the level of sustainability in the existing built environment. The research may also have relevance to remote indigenous communities that are struggling with unemployment, and lack of fresh food, water, electricity, and proper sanitation.

Given that energy used in Australian homes accounts for approximately 26% of Australia's greenhouse gas emissions (CSIRO, n.d.), and popular construction methods are generally high in embodied energy (Pullen, 2000) and have other impacts arising from the manufacturing techniques of the raw materials (mining, forestry etc), the idea of using old car tyres to build an energy efficient home has many merits: they could help Australians mitigate and adapt to climate change and will help conserve precious resources including water and building materials, whilst simultaneously dealing with a problematic "waste" material.

The research student has substantially completed the requirements for the Master of Architecture degree which has focused on the environmental impacts of the Earthship. He now seeks to upgrade to a Doctorate, with the research proposed in this application forming a major part of the PhD.

Thermal modelling simulations conducted in the course of the Masters degree indicate that the claims regarding the thermal comfort within the Earthship are accurate, however these results need to be validated by measurement of real structures. The small amount of prior research has been limited to single Earthships (Grindley & Hutchinson, 1996; Ip & Miller, 2009; Kruis & Heun, 2007), or has been limited to brief observation time-spans (Grindley & Hutchinson, 1996). Recent design innovations of the Earthship also render these studies somewhat out-dated. In contrast, this proposed study will examine numerous Earthships of various designs comparing the latest innovations with older designs to establish their thermal performance.

In terms of the Earthship occupants' perceptions and motivations regarding this form of architecture, the applicant is not aware of any prior research.

In summary, this proposed research study will extend the existing knowledge regarding the thermal performance and comfort conditions of Earthship architecture providing insights into how Australian housing may benefit from Earthship principles. Secondly, it will develop new knowledge regarding the import issue of behaviour change, revealing the motivations and perceptions of people already leading this pioneering lifestyle, perhaps leading to an affordable, and sustainable, Great Australian Dream (i.e. home ownership).

5. PARTICIPANTS

- Source

Case Studies: Earthship occupants in the Taos, New Mexico, USA region
Interviews: Earthship occupants in the Taos, New Mexico, USA region
Earthship General Questionnaire: Global Earthship community

- Number

Case Studies: approx 6 houses
Interviews: approx 6
Earthship General Questionnaire: Sample of the Global Earthship community (approx 50-100)

- Age range

Head of household age 25 years or over

- Selection & exclusion criteria *(How and by whom will screening be conducted?)*

Candidates for the Case Studies will be sourced by the contact from Earthship Biotecture based on the design of the home and willingness of the home owners for the home to be fitted with various sensors. Participants in the Case Studies have the option to participate in an interview (based on the Earthship General Questionnaire) or do the Earthship General Questionnaire only.

The Earthship General Questionnaire will be available via a website (with consent mechanism on welcome page) for anyone claiming to live in an Earthship, thus it will be self screening. Earthship Biotecture will promote the questionnaire, most probably by word of mouth or email. The researchers may also promote the questionnaire via social media websites or similar.

6. PARTICIPANT RECRUITMENT

- Procedures *(Please explain how you will recruit volunteers onto the study. How will people be approached and asked if they are willing to participate? How and by whom will names and contact details be accessed?)*

The research student has made initial contact with Earthship Biotecture, the architectural and building company that has created the various Earthship communities in Taos. Earthship Biotecture has agreed to assist with the study by recruiting participants within the Earthship communities. Earthship Biotecture will circulate the Participant Information Sheets and Consent Forms to people that live in Earthships. Names and contact details of potential participants will be provided by Earthship Biotecture to the research student who will keep the details confidential.

- Material *(Provide a copy of any advertisements, flyers or other material to be used.)*

Nil

- Payment *(Provide details of and the rationale for any payment or reimbursement to participants.)*

Not applicable. There will be no payments made to participants.

7. PRELIMINARY STUDY (if any)

Not applicable.

8. STUDY PLAN & DESIGN
(Include a detailed description of all planned interactions between researchers and study participants. Include a copy of any questionnaires or interview schedules to be used.)

The scope of the questionnaires is outlined below. The interview will be semi-structured and based on the Earthship General Questionnaire. When the questionnaires are finalised copies will be supplied to HREC.

Scope of Earthship General Questionnaire

- Climate and Site; basic information about where the home is located (roughly – without needing to give an address) and the type of weather conditions it experiences.
- Design aspects including; basic floor-plan, greenhouse design, renewable energy system, water supply, wastewater system, toilet, and construction materials. This information is needed to understand the design features of the home as these are key parameters driving the performance of the home and influencing the perceptions of the occupants.
- Comfort related aspects including; air temperature and humidity (how heating and cooling is achieved, how comfortable the occupants feel during the main seasons), air quality, and sound quality.
- Lifestyle and Behaviour relates to energy use, water use, dealing with household waste, and self-sufficiency initiatives.
- Motivations and Beliefs relates to the occupants beliefs about the state of the environment, the impact of human activity, future availability of resources, and how the occupant thinks they can influence these issues.
- Expenses – aims to roughly quantify utility bills (electricity, water, gas)
- Maintenance - of the various systems and parts of the home, e.g. wastewater system, roof etc in terms of time spent and money spent.
- General background personal data such as approximate age of family members, occupation

Scope of Earthship Daily Comfort Questionnaire

- Perception of comfort

- Actions taken to improve the comfort conditions

9. DRUGS

Not applicable.

10. EFFICACY

(What is known from previous studies regarding the safety and effectiveness of the proposed intervention?)

Not applicable.

11. DATE OF PROPOSED COMMENCEMENT

6 December 2011

12. ETHICAL CONSIDERATIONS

(Provide a clear description of any potential risks to participants (including physical, emotional, social or legal) and the steps that will be taken to address these risks.

It is difficult to imagine any physical, legal or emotional risks arising from the study. A potential social risk is that findings from the questionnaires and interviews may reveal some unusual behaviours employed by Earthship dwellers to save energy, water, improve comfort etc, and consequently people living in Earthships in general may be stigmatised. However, Earthship has received plenty of publicity including a motion picture "Garbage Warrior" so it is unlikely that this study – in which participants will have the option to be anonymous and skip over questions – will cause any additional social unease.

Outline the protocol that will be followed in the eventuality of any adverse event(s).

In the unlikely event that a participant reports any adverse events the research student will discuss with his PhD supervisors and the Human Ethics committee to determine a suitable response and action plan.

Provide details of procedures to maintain participant confidentiality during data collection and reporting of results.

The case studies and interviews will report results in an anonymous fashion based on a description of the home, not by the names of the occupants (address of house will not be given).

The various questionnaires will provide a means for people to supply contact details should they wish to be involved in further research, however all results will be reported in an anonymous fashion.

All questionnaires will be conducted using SurveyMonkey which is password protected and encrypted. Only the researchers named on this form will have access to this website.

Describe how you will you provide detailed information about the study to people and how and when consent will be obtained.

A participant information sheet and consent form will be used to provide detailed information and obtain consent. An info sheet and consent form will be created for each part of the study: Case Studies and the Questionnaire/Interview. The info sheets and consent forms will be provided to participants via email so that potential participants have time to consider their involvement prior to the research commencing. Potential participants will be asked to indicate their intentions via email to confirm cooperation. Hard copy of forms will be provided to potential research participants during the field trip to the USA prior to any research activities.

Include a participant information sheet and a consent form. Information and consent guidelines plus a consent form template can be downloaded from http://www.adelaide.edu.au/ethics/human/guidelines/applications/)

Attached.

13. SAFETY & ECOLOGICAL CONSIDERATIONS

- Radiation, toxicity, biodegradability *(Where radiation exposure is an aspect of the proposal, researchers must comply with the Code of Practice for the Exposure of Humans to Ionizing Radiation for Research Purposes (2005) http://www.arpansa.gov.au/pubs/rps/rps8.pdf and provide specific information set out in Clause 2.1 of the above Code.)*

Not applicable.

- Researcher safety *(Is there any possible risk to the health or safety of the researcher(s)? If so, what precautionary measures will be taken?)*

Not applicable.

14. RESEARCH DATA RECORDING & STORAGE

(Provide details of how the data will be recorded, eg audiotape, videotape, or written notes. Describe how, where and for how long the data will be stored.)

Most of the data will be recorded digitally. The data loggers and online surveys will generate digital data and the audio of interviews will be recorded digitally. Non-digital data such as notes from the interviews will be scanned to convert them to digital format. At the conclusion of the research all the data will be in digital format and it will be archived on CD and stored in a secure office in the School of Architecture Landscape Architecture and Urban Design for seven years.

15. ANALYSIS & REPORTING OF RESULTS

(Describe how the data will be analysed and who will have access to the research data and results. How will the results be published? Will participants receive the results?)

Only the research student and his supervisors will have access to the research data and results. The results will be published in the research student's PhD thesis and most probably in subsequent conference papers and journal publications. Research participants will have access to the results if they elect to be informed of results.

16. OTHER RELEVANT INFORMATION

The proposed research starts in early December 2011 so it would be greatly appreciated if this application could be considered at the earliest convenience of the Low-Risk sub-committee.

17. OTHER ETHICS COMMITTEES TO WHICH PROTOCOL HAS BEEN SUBMITTED

(If the project involves research conducted overseas, give details of any local ethics clearance procedures that apply to it.)

The case studies and interviews are being conducted in the USA whereas the Earthship General Questionnaire is being conducted internationally. Advice from the office of the Human Research Ethics Committee indicates that due to the nature of the research it would be unlikely that there are any issues in relation to the international scope of the project and advised that the project was likely to be assessed as “low risk” but that the application could remain on this proforma.

18. PROPOSED FUNDING SOURCE

(If researchers will receive any personal payment for conducting the study, this must be disclosed to the Committee. If the study has a commercial sponsor, this must be mentioned on the participant information sheet.)

Funded via an Australian Postgraduate Award, personally and or by the School of Architecture, Landscape Architecture and Urban Design.

19. REFERENCES

CSIRO. (n.d.). Zero emission house Retrieved September 29, 2010, from http://www.auszeh.org.au/ZEH%20Brochure_CSIRO.pdf

Grindley, P. C., & Hutchinson, M. (1996). The thermal behaviours of an earthship. *Renewable Energy, 8*(1-4), 154-159. doi: Doi: 10.1016/0960-1481(96)88835-5

Ip, K., & Miller, A. (2009). Thermal behaviour of an earth-sheltered autonomous building – The Brighton Earthship. *Renewable Energy, 34*, 2037-2043.

Kruis, N., & Heun, M. (2007). *Analysis of the performance of earthship housing in various global climates.* Paper presented at the Proceedings of Energy Sustainability 2007, Long Beach, California.

Pullen, S. (2000). Energy use in the construction and operation of houses. *Architectural Science Review*, *43*(2), 3-12.

Reynolds, M. E. (1990). *Earthship: how to build your own*. Taos, New Mexico: Solar Survival Architecture.

A2 - Earthship Comfort Levels Participant Information Sheet

Earthship Comfort Levels

A PhD research project in the School of Architecture by Martin Freney

Information sheet for potential participants

This sheet explains the study so that you can decide whether you want to be involved.

The purpose and outcome of the project

The Earthship Comfort Levels study is part of a larger study titled *Earthship Perceptions and Performance,* which includes another study titled *Earthship General Questionnaire* which will survey a broad range of Earthship issues.

This information sheet relates to the *Earthship Comfort Levels* study. This study will measure the actual comfort conditions (i.e. temperature, humidity and daylighting) inside (up to) six Earthship homes and will ask the occupants to rate the comfort of their home and how they interact with the home to influence the comfort conditions. The results will indicate the capacity of various Earthship designs to provide stable indoor temperatures and adequate daylighting, and will provide insights into how people interact with the Earthship to influence these conditions and how they perceive the comfort level provided.

How you can contribute to the project

Some basic details about the design of your home will be needed, for example, type and amount of roof insulation, glazing type, floor type (material and thickness), basic floor-plan size, ceiling height. Floor plan and section drawings would be most helpful if they are available.

As explained above, the study aims to measure the comfort conditions - temperature, humidity and daylighting - inside Earthship homes. This will be done by fitting your home with various sensors called data loggers. Weatherproof sensors may also be fitted outside the home to measure outside temperature and humidity although this is only needed for one of the homes as the weather conditions will be similar for all homes as they are all in the Taos region.

There are two types of sensors available for this study: "Basic Loggers" and "Internet Connected Loggers". The basic loggers are small white boxes, just a little larger than a match box. They are battery powered - no cables required. The Internet Connected Loggers do require cables and also need a trickle charge (you can still turn off your inverter at night) and need to connect to a spare Ethernet port on your modem/router (please refer to the information about logger hardware options on the following pages for more details).

At the end of the study a delegate from Earthship Biotecture will collect the sensors, and post the sensors back to the researcher in Australia.

It is also important to gauge your perceptions of comfort that your home provides and how you interacted with your home to help modify these conditions – opening and closing windows for example. This should be done consistently by only one family member as peoples' perceptions of comfort differ.

You will be provided with a questionnaire titled *Earthship Daily Comfort* which asks about what you did to alter the comfort conditions and how comfortable you were. Participants will be asked to do the questionnaire for three weeks: one week in winter, one in spring and one in summer.

The questionnaire can be filled out on a paper form that will be provided (and can be posted back to the researcher with the sensors, at the end of the study), or it can be done online via a survey website, whichever you prefer. It is important that you do the questionnaire on a daily basis, however if you miss a day, do not try to remember or guess – it is ok to have some missing days. In particular it will be important to use the questionnaire on days when you use heating or cooling equipment e.g. light a fire, use and air-conditioner. The questionnaire is designed to take less than five minutes per day.

What happens to the data?

The data obtained from the Basic Loggers will be kept confidential and the results will be reported anonymously - your name and address will never be disclosed unless you specifically request it. There is an option on the consent form relating to this (and you can change your mind later by emailing the main researcher directly).

The data obtained from the Internet Connected Loggers will be displayed on a website titled Earthship Monitoring - so it will not be confidential but it will be anonymous; your name and address will never be disclosed unless you specifically request it.

The data will be discussed by the researchers and the results reported to the School of Architecture in the University of Adelaide. The study is part of a PhD so it will also become part of the PhD Thesis which is titled

Lifecycle Assessment of Earthship Architecture and it may be used in publications and presentations.

The data will be stored securely by the School of Architecture for five years in accordance with the *Australian Code for the Responsible Conduct of Research.*

Are there risks?

This research is considered low risk as there is no foreseeable risk of harm or discomfort.

The main risk is taking up your valuable time so the study has been designed to be as efficient as possible.

Although participants in the study may not realise any direct benefit, a possible benefit of the study to the wider community is greater access to information about Earthships that may help potential home owners make more informed decisions about the houses they build or purchase.

If you have any concerns please raise these with me, Martin, or my principal supervisor (see below). You can also contact the independent University of Adelaide Human Ethics Committee (see the attached sheet).

Can you leave the project?

Your participation is completely voluntary and you may withdraw from the study at any time by simply advising the researcher of your intention to do so.

Project funding

This project is funded by an Australian Postgraduate Award, through the Australian Federal Government and the D R Stranks Travelling Fellowship through the University of Adelaide.

Next steps

If you would like to participate;

- read the attached consent form which I will collect from you during my trip to Taos in December 2011. You can sign it after I have answered any questions you may have,
- read the attached information regarding the monitoring hardware options and decide which option you prefer,
- decide which studies you would like to participate in (please also read the *Earthship General Questionnaire* info sheet) and,
- advise Kirsten Jacobsen of Earthship Biotecture of which studies you want to participate in and when you will be available (kirsten@earthship.com)
- If you have more questions please contact…

Main researcher:
Martin Freney
email: martin.freney@adelaide.edu.au
cell: +61 450 555 719
tel: +61 8 8303 3052
US cell:

Principal supervisor:
Associate Professor Terence Williamson
email: terence.williamson@adelaide.edu.au
tel. +61 8 8303 4591

Ethics clearances

University of Adelaide Human Ethics Committee

About the Researcher: Martin Freney

I am currently a research student at the University of Adelaide, writing a thesis about Earthships, trying to quantify their environmental impacts in comparison to other types of homes and other types of lifestyles.

My usual job is as a teacher and researcher at the University of South Australia and in the past I have worked as an industrial (product) designer.

My interest in Earthships escalated in 2008 when I participated in the Earthship Biotecture Internship - working with the crew on the Global Model 1.

I have since been studying Earthship using Life Cycle Assessment which accounts for the whole life cycle "from cradle to grave" i.e. from mining raw materials to eventual demolition. Earthship is likely to fare well in this assessment due to its low operational energy (energy used while people are living in it) and its low embodied energy (energy used to manufacture the construction materials).

Martin's qualifications;
Bachelor of Design (Industrial)

Link to story about Martin's Earthship research.

Earthship Comfort Levels – Hardware Options

There are two hardware options for recording temperature, relative humidity and lighting level. The "Basic Loggers" are small, battery powered devices that can easily go anywhere in the home (see Figure 1). The "Internet Connected Loggers" are more complicated to install and require cables and an internet connection via an Ethernet port on a modem/router (see Figure 3). They are described in more detail below.

There are five sets of the Basic Loggers (for five Earthships), and one set of the Internet Connected Loggers (for one Earthship).

Option 1: Basic Loggers

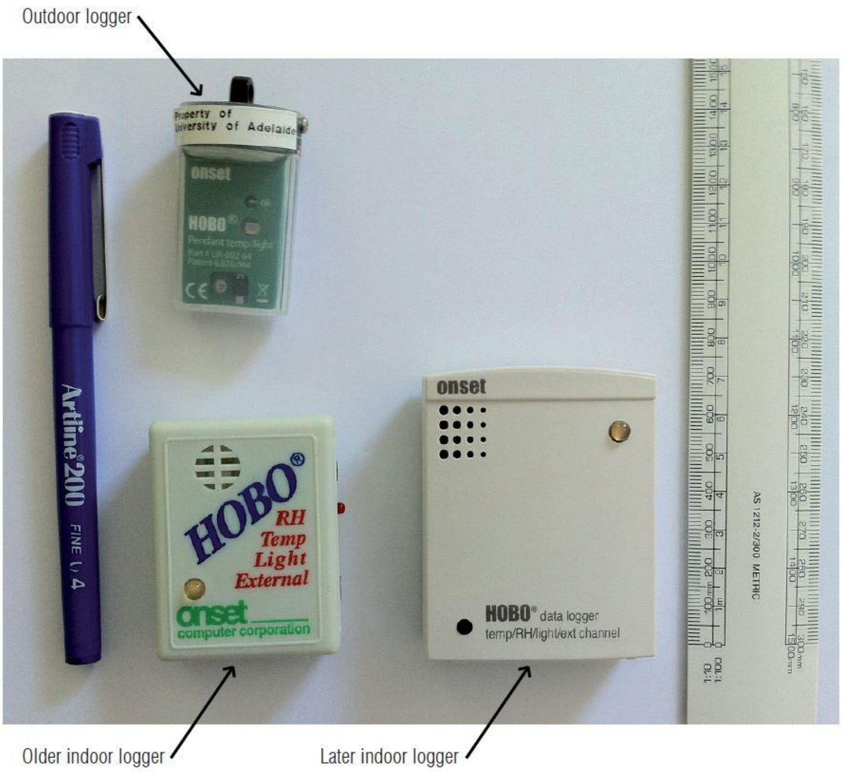

Figure 1 - Basic Temperature, Humidity and Light loggers

The "Older Indoor Logger" and "Later Indoor Logger" do the same thing: measure temperature, relative humidity and light level. They need to be positioned indoors, in a shady place. One will go in the greenhouse (or towards the front of the house) and another will go in the living room. They can be blu-tacked or double sided taped in an unobtrusive place.

The "Outdoor Logger" is intended for use in an earth tube e.g. Global Model Earthship. It is designed to withstand moisture so any condensation in the earth tube will not damage it.

There is a little red light on the side that flashes to indicate that the unit is working properly. You could cover this over (e.g. with blu-tack) if it was annoying.

Setup Time will be approximately 20 minutes.

Returning the Gear

I need you to collect the loggers, and give them to the delegate from Earthship Biotecture who will put them in a pre-paid, self-addressed box which I will supply and take it to the post office. Don't worry if the red light is still flashing – it will keep doing so until it runs out of memory.

Option 2: Internet Connected Loggers

Figure 2 - Remote monitoring system which hooks up to internet

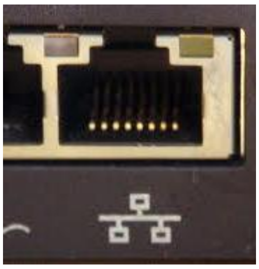

Figure 3 – Ethernet port

This system is designed for remote monitoring via the internet. The “Hobo” white box connects to your router/modem via an Ethernet cable. It is powered by a battery which will last approx one month without power, but it is best to keep it connected to power via the plug pack so that the battery can trickle charge. So it doesn’t matter if power is switched off overnight, and likewise it has plenty of on-board memory so it doesn’t matter if the internet connection is frequently interrupted – as soon as it is resumed it will start uploading again (approx every hour). The size of the uploaded files is very small. Here is a link to a demo webpage that gives an idea of the data you will be able to view.

All the gear on the right side and middle of the photo are sensors (4 x temp/humidity and 1 x light level) that have to plug into the white box via the cables that they are attached to. To avoid tripping hazards, cables will need to be dealt with by hiding them behind furniture, taping to the floor etc - they might be a bit of an "eye-sore" so keep this in mind.

The thing that looks like a stack of white dishes is a “radiation shield” that prevents direct sunlight from hitting the sensor inside: this would cause false readings. This is intended for outdoor temperature/humidity logging and possibly also for the greenhouse (there are two of these shields).

It is intended that the white box be positioned somewhere near the home’s router/modem (e.g. hidden away under a desk) with temperature/humidity sensors in the living room, greenhouse, earth tube (if applicable) and immediately outside the house (in the radiation shield) mounted on a fence post or similar. The light level meter would go in a rear corner of the living room.

Setup time will be approximately 2 hours.

Returning the Gear

Sometime in early December, 2012, Earthship Biotecture will uninstall the equipment for return to the researcher Martin Freney or for installation in another Earthship.

Requirements

- Internet connection
- Router/modem with spare Ethernet port (fig 3).
- Spare wall socket for trickle charge of system's battery, 110 volts.
- Tolerance of unsightly cables.

Diagram of how the gear will be setup

Figure 4 shows the setup for the basic loggers which don't require cables.

Figure 5 shows the setup for the Internet Connected Loggers which do require cables.

Position of loggers is indicative only – we will agree to an unobtrusive place for them.

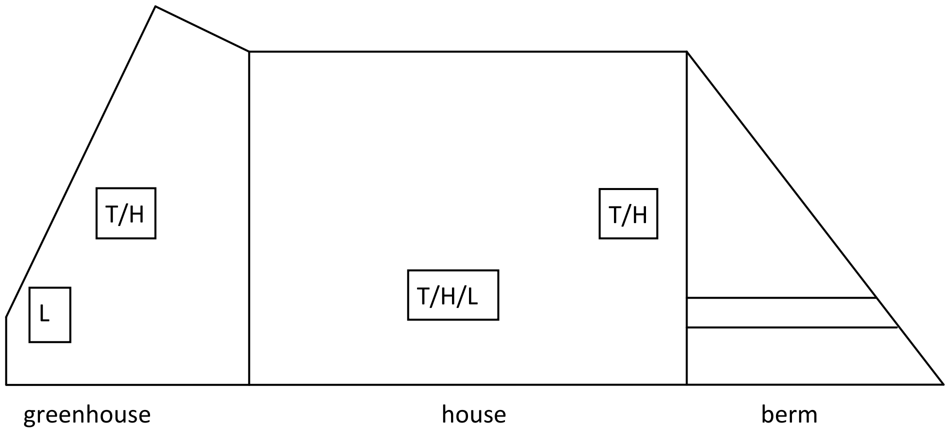

Figure 4 - Basic Loggers

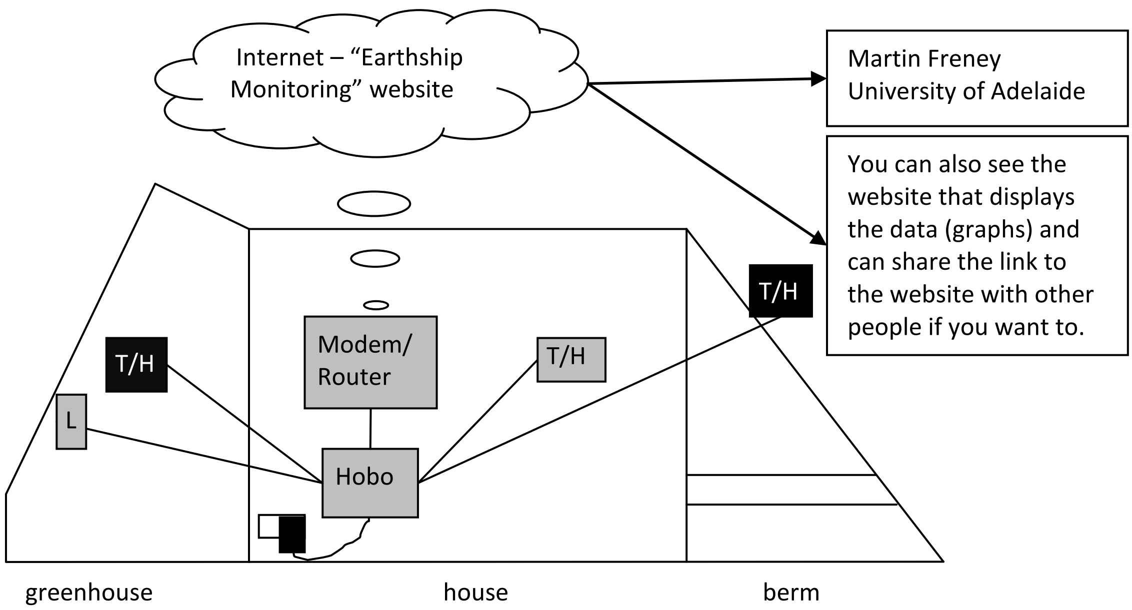

Figure 5 - Internet Connected Loggers

KEY

- T/H – Temperature & Humidity sensor
- T/H/L – Temperature, Humidity and light sensor
- T – "Outdoor" Water proof Temperature sensor
- T/H (black) – Temperature & Humidity sensor with cable and in radiation shield
- T/H (grey) – Temperature, Humidity with cable
- L – Light sensor with cable
- Hobo – "Hobo" white box – plugs into your power outlet and a spare Ethernet port on your modem/router.
- Modem/ Router – Your modem/router
- power outlet with DC pack
- Cable

HUMAN RESEARCH ETHICS COMMITTEE

STANDARD CONSENT FORM
FOR PEOPLE WHO ARE PARTICIPANTS IN A RESEARCH PROJECT

1. I, ……………………………………………………………… *(please print name)*

   consent to take part in the research project entitled:

   Earthship Perceptions and Performance - Earthship Comfort Levels

2. I acknowledge that I have read the attached Information Sheet entitled:

   Earthship Comfort Levels

3. I have had the project, so far as it affects me, fully explained to my satisfaction by the research worker. My consent is given freely.

4. Although I understand that the purpose of this research project is to improve the quality of housing design, it has also been explained that my involvement may not be of any benefit to me.

5. I have been given the opportunity to have a member of my family or a friend present while the project was explained to me.

6. I have been informed that, while information gained during the study may be published, **I will not be identified and my personal results will not be divulged**, OR, **I am willing to be identified in the research results** *(cross out whichever is not applicable).*

7. I understand that I am free to withdraw from the project at any time.

8. I am aware that I should retain a copy of this Consent Form, when completed, and the attached Information Sheet.

……………………………………………………………………………………………..

(signature) *(date)*

A3 - Ethics Approval Letters

THE UNIVERSITY of ADELAIDE

RESEARCH BRANCH
RESEARCH ETHICS AND COMPLIANCE UNIT

BEVERLEY DOBBS
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email: beverley.dobbs@adelaide.edu.au
CRICOS Provider Number 00123M

Applicant: Associate Professor T Williamson

School: School of Architecture Landscape Architecture & Urban Design

Application No: 12652

Project Title: **Earthship perceptions and performance**

THE UNIVERSITY OF ADELAIDE HUMAN RESEARCH ETHICS COMMITTEE

APPROVAL No: H-292-2011

APPROVED for the period until: 31 August 2012

It is noted that this study is to be conducted by Martin Freney, Masters student.

Refer also to the accompanying letter setting out requirements applying to approval.

PROFESSOR GARRETT CULLITY
Convenor
Human Research Ethics Committee

Date: 24 NOV 2011

THE UNIVERSITY of ADELAIDE

RESEARCH BRANCH
RESEARCH ETHICS AND COMPLIANCE UNIT

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CRICOS Provider Number 00123M

24 November 2011

Associate Professor T Williamson
School of Architecture Landscape Architecture & Urban Design

Dear Associate Professor Williamson

APPROVAL No.: **H-292-2011**
PROJECT TITLE: **Earthship perceptions and performance**

I write to advise you that on behalf of the Human Research Ethics Committee I have approved the above project. Please refer to the enclosed endorsement sheet for further details and conditions that may be applicable to this approval.

The ethics expiry date for this project is: 31 August 2012

Participants taking part in the study are to be given a copy of the Information Sheet and the signed Consent Form to retain.

Please note that any changes to the project which might affect its continued ethical acceptability will invalidate the project's approval. In such cases an amended protocol must be submitted to the Committee for further approval.

It is a condition of approval that you **immediately report** anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants
- proposed changes in the protocol; and
- unforeseen events that might affect continued ethical acceptability of the project.

It is also a condition of approval that you inform the Committee, giving reasons, if the project is discontinued before the expected date of completion.

A reporting form is available from the website at http://www.adelaide.edu.au/ethics/human/guidelines/reporting.This may be used to renew ethical approval or report on project status including completion.

Yours sincerely

for **PROFESSOR GARRETT CULLITY**
Convenor
Human Research Ethics Committee

THE UNIVERSITY of ADELAIDE

RESEARCH BRANCH
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CRICOS Provider Number 00123M

17 July 2012

Associate Professor T Williamson
School of Architectur Landscape Architecture & Urban Design

Dear Associate Professor Williamson

PROJECT NO: H-292-2011
Earthship perceptions and performance

Thank you for the annual renewal report and the amendment requested dated 4.7.12 from Mr Freney. I write to advise you that on behalf of the Human Research Ethics Committee I have approved renewal of ethical approval for the project and the amendment request to extend the distribution of the online questionnaire via publicly available email, website and social networking sites as detailed in the email. Thank you for providing the participant information and consent text that will be posted online, and the questionnaire.

The ethical endorsement for the project applies for the period until: 31 August 2015

Please note that any changes to the project which might affect its continued ethical acceptability will invalidate the project's approval. In such cases an amended protocol must be submitted to the Committee for further approval. It is a condition of approval that you immediately report anything which might warrant review of ethical approval including (a) serious or unexpected adverse effects on participants (b) proposed changes in the protocol; and (c) unforeseen events that might affect continued ethical acceptability of the project. It is also a condition of approval that you inform the Committee, giving reasons, if the project is discontinued before the expected date of completion.

A reporting form is available from the Committee's website. This may be used to renew ethical approval or report on project status including completion.

Yours sincerely

PROFESSOR GARRETT CULLITY
Convenor
Human Research Ethics Committee

Appendix B - Miscellaneous

B1 - Earthship Analysis, using Understanding Sustainable Architecture Checklist.

Discourse Issue	Aspects of possible product means	Earthship Analysis notes
Climate Change	Reducing the need for heating and cooling through building form, materials, and control systems.	Yes, earth bermed, high thermal mass walls coupled with operable earth tubes, skylight/vents, windows and blinds obviates the need for heating and cooling.
	Using forms of energy in the operation of the building that do not produce greenhouse gases.	Yes, with the exception of small quantities of propane used to boost solar hot water and for cooking, the typical Earthship is self-sufficient in renewable (solar) energy.
	Using highly energy efficient appliances, water heating and space heating and cooling systems.	Yes, for example use of car stereo systems and computers for entertainment systems. Solar water heating is standard. Appliances are not needed for heating and cooling - not even ceiling fans.
	Using materials and equipment where the use of fuels producing greenhouse gases in their extraction, manufacture and transport is low.	Yes sort of. Many materials are typical to modern architecture and difficult to avoid such as glass and timber. However substantial quantities of “waste” materials that would otherwise be land filled are utilised to form load bearing walls. Of interest was a solar powered mobile power station (a trailer) that was used to provide power to various hand tools and machines. Although this is not specific to Earthship construction, it demonstrates the ethos of Earthship Biotecture. Substantial earthworks, requiring use of an excavator, is a negative.
	Allowing for uncertain future climate.	Yes, earth bermed walls, passive solar design, and operable passive ventilation and shade systems (which could be automated if necessary) enable thermal comfort in a wide variety of climates. Experiments in various climates confirm this.
	Planting trees.	Yes, although large trees that would provide substantial carbon sinks are not able to grow in the Taos environment. Fruit trees were being planted and irrigated with treated black water.

Discourse Issue	Aspects of possible product means	Earthship Analysis notes
Pollution	Reducing waste materials.	There is very little waste generated from construction of the tyre walls – perhaps some off-cuts of steel reinforcing bar. The same is true for the can and bottle walls. The walls actually sequester waste. There is the typical waste generated by timber framing (of the greenhouse and roof).
	Using components that have caused little pollution in extraction, manufacture and transport.	New tyres embody a lot of energy, pollution and resource depletion. However used tyres are "waste". Although they have impacted the environment in their former life, used tyres can be put to good use. To manufacture a used tyre you need to expend vast amounts of fossil fuels driving a car thousands of kilometres until it is worn out! So in this sense using car tyres is not "sustainable". But right now, it is a creative response to huge piles of tyres that cause problems if left lying about. They are notoriously difficult to recycle due to their design parameters: strong and durable in all conditions/climates. They are light weight (for their size) and easy to transport (you can roll them). Although cans and bottles can be reused (glass bottles) or recycled reasonably efficiently, if recycling schemes and facilities are not available they become waste and they end up causing social and environmental problems.
	Using non-polluting energy sources.	Earthships boast "zero utilities bills". Although renewable energy systems embody vast amounts of energy in their manufacture, in their operation they are "non-polluting". Due to the "designed down" systems and appliances, renewable energy systems are of modest size thus reducing the impact in their manufacture. A small amount of propane is used for boosting solar hot water systems and for cooking. Some Earthships also have a fridge that runs on propane.
	Avoiding potential polluted surface water run-off.	The tyre walls are effectively shielded from the elements so it is unlikely that they would contribute to pollution of surface water run-off. If the black water treatment cell (reed bed) was flooded (somehow) this might cause pollution. Earthships catch all the water that falls on the roof and store it in underground cisterns.
	Recycling water.	Earthships are highly efficient at recycling grey water and treating black water which can then be used for irrigation. They are self-sufficient in water with only 8-10" of rainfall annually. This is due to water efficient appliances and the use of sophisticated biological filters within and outside the house.
	Using long-life materials.	The typical composition of a modern Earthship is tyre walls (extreme long life), rendered with adobe or cement (repairable), steel roof (durable), glass greenhouse wall

Discourse Issue	Aspects of possible product means	Earthship Analysis notes
		(durable), can (aluminium) and bottle (glass) internal walls in a matrix of cement, plus some timber for framing the greenhouse, doors, cupboards etc. It is likely that the tyre walls will last hundreds of years.
	Using biodegradable materials.	Ceiling insulation is typically blown-in cellulose fibre. Timber framing will biodegrade.
	Using recyclable materials.	Tyres are reusable but are problematic to recycle. Most other construction materials are recyclable but to what extent their recycling benefits the environment is dependant on many factors; energy required to transport "waste" materials, energy efficiency of the recycling process, and quality of the recycled material ("down cycling" may be an issue).
Resource Depletion	Using renewable resources (e.g. plantation timber, managed regrowth timber, solar energy).	Used tyres and bottles/cans are "renewable" for as long as we persist with driving cars and buying packaged drinks.
	Using plentiful resources (e.g. many building stones, clays, silicon, iron ore).	The main walls are 98.5% dirt and 1.5% used tyres. Adobe render (clay and silicon).
	Very careful, appropriate use of rare and non-renewable resources.	The electronic circuits in some components of the renewable energy system contain rare materials. The lead in the batteries is non-renewable but is readily recycled.
	Building small.	Depends on the client. Typically Earthships have one bathroom, no garage and have an open plan kitchen, living, dining room. Often, the greenhouse can be used as the corridor. Space is used efficiently.
Biodiversity	Avoiding building in places that are particularly significant for biodiversity.	Typically built in the desert on large blocks of land leaving space for creatures and plants.
	Using timber with an authoritative certificate of origin.	Not sure if Earthship Biotecture does this.
	Shifting the use of rainforest timbers to low-volume, high value applications.	Possibly some use of rainforest timbers in the cabinetry.
	Creating landscapes rich in biodiversity.	Yes, the vegetation of the greenhouses and outdoor black water treatment cells attract various types of wildlife, particularly birds and insects. Vegetation on the earth berms

Discourse Issue	Aspects of possible product means	Earthship Analysis notes
		also provide habitat for lizards and insects.
Indigenous flora and fauna	Minimal building footprint.	Although the floor plans are efficient and minimal, the footprint is large due to the earth berm.
	Minimal disturbance to surrounding vegetation.	There is significant disturbance on the actual site as extensive earthworks are needed to level a site and build the earth berm.
	Leaving wildlife movement corridors.	At the "Greater World" community there is a substantial tract of land that is owned in common by the members of the community. Some animals (Elk) migrate through The Greater World Earthship community.
	Designing to avoid bird strikes on windows, wind turbines, etc.	Photovoltaics are used in preference to wind turbines. Windows are on one side of the building only, however bird strikes may be a problem (I don't know).
Society and culture	Using locally-sourced materials.	Used tyres and discarded cans/bottles are reclaimed from the local dump. Adobe render is made from local clays and sands. Timber is grown locally. Cement, steel and glass needs to be imported from further afield.
	Designing to enable the use of locally-sourced skills for construction and future maintenance.	Tyre walls require only minimal maintenance to the render. In New Mexico adobe has been used for centuries so skilful adobe craftspeople are plentiful. With very little training any able bodied person can quickly learn how to "pound" tyres and build "can walls". Tools required are few and inexpensive.
	Adapting existing buildings .	Reynolds has documented how this can be done, however I am not aware of an actual example of this. Theoretically it is possible to retrofit a building with earth bermed Earthship modules at each end provided the house is oriented favourably. The water catchment/distribution/filtering system could be retrofitted to existing houses (by the addition of a greenhouse and additional plumbing).
	Maintaining existing mix of spaces for living, trade and social activities.	The Greater World Earthship community lacks trade and social spaces although this could conceivable evolve, particularly in "The Gravel Pit" – a high density area of The Greater World community.
	Maintaining existing scale and typologies of buildings.	Earthships have a new typology that reflects the functional requirements necessary to encounter natural phenomena such as the stable temperatures 4' below the surface of the earth. The scale is smaller than typical American homes.

Discourse Issue	Aspects of possible product means	Earthship Analysis notes
	Emphasizing public space.	NA.
	Respecting existing built context.	No.
	Using pre-used "blighted" sites rather than green field sites.	An example of this is "The Gravel Pit" a high density development at "The Greater World" Earthship community in Taos, New Mexico. The Gravel Pit is a functioning gravel mine, however it is nearing the end of it's life and has been rehabilitated with plantings, landscaping and numerous Earthships. The nutrients generated via the grey/black water systems facilitates this.
Health	Designing for high fresh air change rate (above minimum requirements).	Yes. Well developed ventilation systems: skylights/vents, greenhouse hopper windows, earth tubes (with insulated doors).
	Using materials with authoritative guarantees of non-toxicity.	Not sure.
	Designing for easy cleaning and maintenance.	Yes, the glazed sunny-side wall (greenhouse) is the only exterior wall that requires maintenance. Adobe interiors can be easily patched when cracking occurs. Dust and crumbs swept off the floor can be deposited nearby in the indoor planter where they will biodegrade and provide nutrients to the plants in the planter.
Comfort	Designing so that the building itself offers internal conditions that are within or approach culturally acceptable limits.	Without active heating or cooling Earthships on Taos achieve 15-25 C temperature range. This is in a climate with a temperature range of -10 to 35 C.
	Using energy-using systems only when appropriate in relation to other sustainability issues.	There are no comfort related energy using systems.
Cost effectiveness	Designing for low imported energy use.	Earthships are totally self sufficient in energy. Reynolds is pessimistic about the longevity of "grids" and is critical of their "poisonous" side effects (pollution).
	Design for low maintenance.	Yes – see Health section above.
Longevity	Adapting and using existing building stock rather than	No. I would argue that with the little time we have remaining (of cheap fossil fuels) a concerted effort to rebuild, from new,

Discourse Issue	Aspects of possible product means	Earthship Analysis notes
	building new.	much of our built environment would be a very sensible use of resources – move to HIGHER ground. Retrofitting existing structures may prove to be highly inefficient resulting in substandard performance, however this may be the only option for many houses.
	Designing for adaptability and future change of use.	The modern Earthship could be easily gutted of internal walls (which are not load bearing) and it could be reconfigured.
	Using long-life materials.	Yes – see above in Pollution section.
	Allowing provision for possible future services.	In modern Earthships the roof could be lifted to install future services. Retrofitting services in tyre walls is also feasible.
	Using measures to protect from place-dependant risks such as bush fires and corrosive seaside air.	In the Australian context, an Earthship could be highly resistant to bush fires with the addition of shutters, or other defence (sprinklers) to the glazed sunny-side wall (greenhouse).
	Designing for low maintenance and easy serviceability.	Low maintenance. Yes – see above in Cost Effectiveness section. Easy serviceability. Yes – components that require maintenance (e.g. batteries, pumps) can be easily accessed, sometimes from within the home.
	Allowing for uncertainty in future climate.	Yes – see above in Climate Change section.

B2 - Paper presented at the International Building Performance Simulation Conference, Chambery, France, 25-28 August 2013

Freney, M., Soebarto, V. & Williamson, T. (2013) Thermal comfort of global model earthship in various European climates.
Presented at: International Building Performance Simulation Conference, Chambery, France, 25-28 August

NOTE:
This publication is included on Appendix pages 28-35 in the print copy
of the thesis held in the University of Adelaide Library.

Appendix C - POE

C1 - Earthship Occupants' Questionnaire

INTRODUCTION & INSTRUCTIONS

INTRODUCTION

This questionnaire is designed to investigate a wide range of issues relating to the Earthship lifestyle. The findings will enable the researcher, Martin Freney a PhD student at Adelaide University, Australia, to estimate the environmental impacts of the Earthship and the Earthship lifestyle compared to other housing types. Another aim of this questionnaire is to gain an insight into how the Earthship lifestyle may differ to more conventional lifestyles.

The questionnaire includes questions about;
- general location of your Earthship,
- construction materials and design of your Earthship.
- indoor comfort conditions: heating, cooling, humidity, lighting, air quality and sound quality.
- maintenance, running costs & insurance
- performance of the off-grid systems
- details of your Earthship systems – energy, water, sewage etc.
- your behaviour in terms of energy use, water use, and food production,
- your motivation for living in an Earthship.
- how many adults & children live in your Earthship

The questionnaire will take at least half an hour and may take longer depending on how much detail you put into your responses and how much research you need to do to answer a question. For example you may need to find out how many kilowatts your solar panels are rated at. However, if you find any questions too time consuming just skip over them and perhaps come back to them if you have time later. It is ok if some of the questions are unanswered.

The questionnaire will be available until 31 October 2012. Results will be published in 2013. Contact martin.freney@adelaide.edu.au to request a copy.

If you have any questions or concerns contact Martin or his supervisor Terence Williamson. Email: terence.williamson@adelaide.edu.au

INSTRUCTIONS

If you are not sure how to answer a question use the “I don’t know” option or skip over the question.

Read each question carefully as some questions alternate between a positive and negative framing.

Ideally, do the questionnaire in one sitting, however if this is not possible observe the following instructions;

1. Complete all questions for the current “page” of the questionnaire;

2. click the “Next” button (at the bottom of the page) which takes you to the next page;

3. then click the “Exit this survey” button (top right of window). This will save the information you entered. Failing to do this will delete any data you entered recently!

4. To return to the unfinished questionnaire use the same link you used to access the questionnaire – it should pick up where you left off provided you are using the same computer (you must use the same computer each time you fill out the questionnaire).

5. If necessary you can change your answers by using the “prev” and "next" buttons to navigate through the survey.

CONSENT

IMPORTANT INFORMATION

I understand that, while information gained during the study may be published, I will not be identified and my personal results will not be divulged.

I understand that once the questionnaire closes on 31 October 2012 I will not be able to withdraw my responses or change my responses.

To accept these conditions and continue the questionnaire please click the "yes I accept" button below.

1. Do you accept the conditions described above?

- ◯ Yes I accept
- ◯ No I don't accept

HOUSE CODE

2. If you are a resident at the Greater World community who participated in the Earthship Daily Comfort Questionnaire (temperature monitoring) please enter your "house code". Otherwise please skip this question.

LOCATION & AGE OF EARTHSHIP

3. What country and city is your Earthship located in/near? (This question is for the purpose of establishing your climate)

City

Country

4. How many years have you been living in your Earthship?

Number of years

DESIGN & CONSTRUCTION

5. The main exterior walls of my Earthship are; (you can check more than one)

- [ ] Made from tires filled with compacted earth
- [ ] Earth bermed (dirt is piled up against the walls)
- [ ] Insulated with "Thermal Wrap" i.e. expanded polystyrene board (or similar) within the berm
- [ ] Made from straw bales
- [ ] Made from other (please specify below)
- [ ] Other (please specify)

6. If your exterior walls are made with tires filled with compacted earth, was the earth compacted via manual labor or with some sort of machine?

- ○ Manual labor
- ○ Machine
- ○ Combination of both

7. The foundations of the exterior walls (e.g. tire walls) of my Earthship are;

- ○ “Natural” uncompacted earth (e.g. ground excavated and levelled)
- ○ Compacted earth (e.g. ground excavated, levelled AND COMPACTED by machine)
- ○ Reinforced Concrete (typical of many house constructions)
- ○ Gravel trench (sometimes used in “natural” house constructions to avoid concrete footings)
- ○ Other (please specify)

8. The soil type that my Earthship is built on is;

- ○ Sand
- ○ Sandy Loam
- ○ Clay
- ○ Clayey Loam
- ○ Loam (40% sand, 40% silt, 20% clay)
- ○ Gravel
- ○ Rock
- ○ I don't know

Other (please specify)

9. What are the other walls (e.g. interior, greenhouse) of your Earthship made from? (you can check more than one e.g. "Aluminum cans" and "cement mortar")

- ☐ Aluminum cans
- ☐ Steel cans
- ☐ Glass bottles
- ☐ Plastic bottles
- ☐ Cement mortar
- ☐ Earth mortar
- ☐ Insulation material
- ☐ Tires
- ☐ Mud brick (adobes)
- ☐ Rammed earth
- ☐ Compressed earth block
- ☐ Light earth (clay and straw)
- ☐ Dry wall timber frame
- ☐ Cob
- ☐ Other (please specify)

10. My roof frame is;

- ○ Timber
- ○ Steel
- ○ Ferro-cement
- ○ Other (please specify)

11. My roof cladding is;

- ○ Timber
- ○ Steel
- ○ Stucco (cement mortar)
- ○ "Green roof" (earth, waterproof membrane etc)
- ○ Zinc
- ○ Aluminum
- ○ Other (please specify)

12. My roof is insulated with the following materials; (you can check more than one)

- [ ] Cellulose fibre
- [ ] Rock wool
- [ ] Glass wool
- [ ] Aluminum foil
- [ ] Expanded Polystyrene board
- [ ] Polyiso board
- [ ] Other (please specify)

13. My floor is made from? (you can check more than one e.g. "flagstone" and "cement mortar")

- [ ] Mud/Compacted earth
- [ ] Flagstone
- [ ] Cement mortar
- [ ] Concrete (unreinforced)
- [ ] Concrete and steel (reinforced)
- [ ] Timber
- [ ] Carpet
- [ ] Insulation material
- [ ] Other (please specify)

SIZE

14. What is the approximate floor area of your Earthship (excluding greenhouse)? (use only one unit of measure)

Square feet

Square metres

15. What is the approximate floor area of your Greenhouse? (use only one unit of measure)

Square feet

Square metres

COMFORT

16. On the whole, do you like or dislike the climate where your house is located? Please try to explain why.

	Like very much	-	-	Neutral	-	-	Dislike very much
Climate	○	○	○	○	○	○	○

Please try to explain why

17. On the whole, how would you describe the conditions in your house during the following times of the year and time of day? (click the button that best corresponds to your perceptions)

	Very comfortable	-	-	Neutral	-	-	Very uncomfortable
Winter during nighttime	○	○	○	○	○	○	○
Winter during daytime	○	○	○	○	○	○	○
Summer during nighttime	○	○	○	○	○	○	○
Summer during daytime	○	○	○	○	○	○	○

COMFORT: HEATING

18. What actions do you take if you feel like it is getting too cold? (you can check more than one)

- [ ] Ensure windows and doors are closed
- [ ] Ensure skylights/roof vents are closed
- [ ] Ensure earth tube vents are closed
- [ ] Ensure blinds/curtains are closed
- [ ] Wear extra clothing
- [ ] Turn heater on
- [ ] Other (please specify)

19. Regarding the previous question, please try to estimate how many minutes per day you spend "sailing" your Earthship to ensure that it doesn't get too cold inside.

20. What kind of active heating system do you have in your Earthship? (you can check more than one)

- [ ] None
- [ ] Gas space heater
- [ ] Built-in electric heater
- [ ] Portable electric heater(s)
- [ ] Heat pump/split-system
- [ ] Open fire
- [ ] Slow combustion stove or pot-belly stove
- [ ] Kerosene heater
- [ ] Other (please specify)

21. If you answered “none” to the previous question, do you think there would ever be the need to install a heater?

- ○ Yes
- ○ No

Please try to explain why

22. If you do not have an active heating system please skip to the next section "Cooling". If you do, which rooms do you usually heat? (you can check more than one)

- [ ] About half the house – the living areas
- [ ] Living room
- [ ] One bedroom
- [ ] All bedrooms
- [ ] Bathroom
- [ ] Kitchen
- [ ] Study/office, etc

Any additional information about the rooms you heat?

23. At what times of the day or night do you usually use heaters during cold weather?

- ○ All the time, day and night
- ○ All the time, except overnight
- ○ Afternoons
- ○ Evenings until bedtime
- ○ Overnight
- ○ Mornings

Any additional information about the use of heaters?

24. How many days in the year do you usually use a heater(s)? (enter a whole number from 0 to 365)

COMFORT: COOLING

25. What actions do you take if you feel like it is getting too hot? (you can check more than one)

- ☐ Ensure windows and doors are open
- ☐ Ensure skylights/roof vents are open
- ☐ Ensure earth tube vents are open
- ☐ Ensure blinds/curtains are closed
- ☐ Wear less clothing
- ☐ Turn cooler on e.g. fan, air conditioner
- ☐ Other (please specify)

26. Regarding the previous question, please try to estimate how many minutes per day you spend "sailing" your Earthship to ensure that it doesn't get too hot inside.

27. Do you have fans in your house? (you can check more than one)

- ☐ No fan(s)
- ☐ Portable fans(s)
- ☐ Ceiling fans(s)

28. What kind of coolers do you have in your house? (you can check more than one)

- ☐ None
- ☐ Earth tubes (e.g. Global Model Earthship)
- ☐ Portable evaporative cooler(s)
- ☐ Fixed evaporative cooler(s) for one or more room(s)
- ☐ Ducted evaporative cooling
- ☐ Reverse cycle air-conditioning for one room(s) e.g. split system
- ☐ Ducted reverse cycle air-conditioning
- ☐ Other (please specify)

29. If “none” do you think there would ever be the need to install a cooler?

- ○ Yes
- ○ No

Please try to explain why

30. If you do not have a cooling system please skip to the next section "Cooling". If you do, which rooms do you usually cool? (you can check more than one)

- ☐ About half the house – the living areas
- ☐ Living room
- ☐ One bedroom
- ☐ All bedrooms
- ☐ Bathroom
- ☐ Kitchen
- ☐ Study/office, etc

Any additional information about the rooms you cool?

31. At what times of the day or night do you usually use coolers during hot weather?

- ◯ All the time, day and night
- ◯ All the time, except overnight
- ◯ Afternoons
- ◯ Evenings until bedtime
- ◯ Overnight
- ◯ Mornings

Any additional information about the use of coolers?

32. How many days in the year do you usually use a cooler(s)? (Enter a whole number from 0 to 365)

HUMIDITY

33. How would you describe the humidity in your Earthship for each season of the year?

	Too dry	-	-	Comfortable	-	-	Too moist
Summer	◯	◯	◯	◯	◯	◯	◯
Fall	◯	◯	◯	◯	◯	◯	◯
Winter	◯	◯	◯	◯	◯	◯	◯
Spring	◯	◯	◯	◯	◯	◯	◯

34. Do you have any problems with mould growing in the house (due to excessive humidity)?

	Lots of mould	-	-	some patches of mould	-	-	No mould
Mould	◯	◯	◯	◯	◯	◯	◯

LIGHTING, AIR & SOUND QUALITY

35. Please indicate the extent to which you agree or disagree with the following statements;

	Strongly agree	Agree	Slightly agree	Neutral	Slightly disagree	Disagree	Strongly disagree
On clear days I don't need to use artificial lighting	○	○	○	○	○	○	○
On overcast days I always use artificial lighting	○	○	○	○	○	○	○
During the night my lighting system provides adequate illumination	○	○	○	○	○	○	○
There is no smell of car tires in or around my Earthship	○	○	○	○	○	○	○
The air inside my Earthship feels and smells fresh	○	○	○	○	○	○	○
There is no echo inside my Earthship	○	○	○	○	○	○	○
Our Earthship is well insulated from outside noise	○	○	○	○	○	○	○

Any additional information about lighting, sound or air quality?

RUNNING EXPENSES & MAINTENANCE

36. Approximately how much do you spend on utility bills per year?

Gas (e.g. propane)	
Electricity	
Water	
Sewage	

37. How often do you need to (or expect to) service or replace parts in your systems?

	month	six months	year	2 years	5 years	10 years	15 years	20 years	30 years	40 years
Replace water filter every...	○	○	○	○	○	○	○	○	○	○
Replace pump every...	○	○	○	○	○	○	○	○	○	○
Replace invertor every...	○	○	○	○	○	○	○	○	○	○
Replace battery charger every...	○	○	○	○	○	○	○	○	○	○
Replace batteries every...	○	○	○	○	○	○	○	○	○	○
Replace solar panels every...	○	○	○	○	○	○	○	○	○	○
Other (please specify) every...	○	○	○	○	○	○	○	○	○	○

Other (please specify)

38. Which parts of your Earthship's structure require maintenance? Please try to indicate how often they need maintenance and what materials are used e.g. "I reseal the floor with 10 gallons of linseed oil every five years".

Exterior Walls	
Interior Walls	
Roof	
Floor	
Windows	
Berm	
Other	

INSURANCE

39. Is your Earthship insured against damage (e.g. from fire, storm etc)?

◯ Yes

◯ No

40. If so, was it difficult to find an insurance company that would insure an Earthship?

	NA	Difficult	-	-	Average	-	-	Easy
level of difficulty	◯	◯	◯	◯	◯	◯	◯	◯

41. Is your insurance premium comparable to similar sized homes?

◯ Yes

◯ No

◯ Don't know

Comments

SYSTEMS PERFORMANCE

42. How does the performance of your Earthship systems compare with the performance of conventional systems? Think about how effective they are at providing you with what you need - enough power, water and sewage treatment. And remember, conventional systems can sometimes let you down too (blackouts, water shortages etc). Please try to explain your answer.

	Much better than conventional system	A little better than conventional system	About the same as conventional system	A little worse than conventional system	Much worse than conventional system
performance of renewable energy system is...	◯	◯	◯	◯	◯
performance of water collection and storage system is...	◯	◯	◯	◯	◯
performance of hot water system is...	◯	◯	◯	◯	◯
performance of wastewater system is...	◯	◯	◯	◯	◯

(After each item:) Please try to explain why

GREENHOUSE

43. Do you have a greenhouse that can be isolated from the main living space as featured in the Global Model Earthship or is your greenhouse integral to the living space?

- ◯ Greenhouse can be isolated
- ◯ Greenhouse is integral (can NOT be isolated)
- ◯ Other (please specify)

[ ]

44. Are the main (exterior) windows single, double or triple glazed?

- ◯ Single glazed
- ◯ Double glazed
- ◯ Triple glazed
- ◯ Other (please specify)

[ ]

45. If you have a glazed partition wall separating the greenhouse from the living space, what type of glazing has been used in this wall?

- ◯ Single glazed
- ◯ Double glazed
- ◯ Triple glazed
- ◯ Other (please specify)

Other (please specify)

[ ]

46. If you know the specification of your glazing please enter it in the box below, otherwise skip this question.

exterior glazing specification [ ]

internal glazing specification (write NA if not applicable) [ ]

47. How do you shade your greenhouse e.g. in the summer? (you can check more than one)

- [ ] NA – no shading devices
- [ ] Fabric blinds
- [ ] Reflective blinds
- [ ] Curtains
- [ ] Other (please specify)

48. If there is anything you would like to mention about your greenhouse please use the box below.

ENERGY SYSTEM

49. Do you have a renewable energy system?

- ◯ Yes
- ◯ No - skip to question 54
- ◯ No - but we buy renewable energy from our electricity retailer - skip to question 54

50. Our renewable energy system is;

- ◯ Off-grid
- ◯ Grid-tied/connected
- ◯ Hybrid (grid-tied but with batteries for off-grid capability)

51. What is your renewable energy system comprised of? (you can check more than one)

- ☐ Solar panels
- ☐ Wind turbine
- ☐ Hydro
- ☐ Bio-mass
- ☐ Backup generator
- ☐ Other (please specify)

____

52. What is the rating of each component of your renewable energy system (in kilowatts. For the generator you have the option to answer in horsepower)?

Solar panels	
Wind turbine	
Hydro	
Bio-mass	
Backup generator (kW)	
Backup generator (horsepower)	
Other (please specify)	

53. If your renewable energy system uses batteries and you know their capacity in Amp Hours please enter this below.

Amp hours	

54. What sort of light bulbs do you use? (you can check more than one)

- [ ] Incandescent
- [ ] Halogen
- [ ] Compact fluorescent
- [ ] LED
- [ ] I don’t know
- [ ] Other (please specify)

55. If there is anything you would like to mention about your renewable energy system please use the box below.

WATER SUPPLY

56. How much water storage capacity do you have? (answer in Gallons or Litres)

Gallons

Litres

57. Aside from the rain/snow that falls on your roof do you have another water supply? (you can check more than one)

- ☐ No other supply
- ☐ Grid supply
- ☐ Well
- ☐ Bore
- ☐ Dam
- ☐ Other (please specify)

58. If there is anything you would like to mention about your water catchment/storage system please use the box below.

HOT WATER SYSTEM

59. What type of hot water system do you have?

- ◯ Solar with gas boost
- ◯ Solar with electric boost
- ◯ Solar with combustion heater boost ("wet back")
- ◯ Other (please specify)

60. If there is anything you would like to mention about your hot water system please use the box below.

WASTEWATER SYSTEM

61. Do you have an on-site wastewater system?

- ◯ Yes
- ◯ No (skip to next section “Toilet”)

62. What is the system comprised of? (you can check more than one)

- ☐ Particle Trap
- ☐ Graywater Planter(s) in the living area
- ☐ Graywater Planter(s) in the greenhouse
- ☐ Graywater Planter(s) outside
- ☐ Blackwater Planter(s) inside
- ☐ Blackwater Planter(s) outside
- ☐ Septic tank
- ☐ Solar septic tank
- ☐ Drainage field/trenches
- ☐ Recirculation pump
- ☐ I don’t know
- ☐ Other (please specify)

63. What is your “recycled” graywater used for? (you can check more than one)

- ☐ Toilet flushing
- ☐ Recirculating back through the indoor planter (irrigation of planter)
- ☐ Irrigating a lawn
- ☐ Irrigating outdoor vegetable garden
- ☐ Irrigating outdoor fruit trees
- ☐ Irrigating outdoor ornamental trees and shrubs
- ☐ Other (please specify)

64. If there is anything you would like to mention about your wastewater system please use the box below.

TOILET

65. What type of toilet do you have?

- ◯ Flush (with recycled graywater from planter)
- ◯ Flush (with fresh water)
- ◯ Composting toilet
- ◯ Other (please specify)

66. If there is anything you would like to mention about your toilet please use the box below.

BATHROOM & LAUNDRY

67. What type of bathing facilities do you have? (you can check more than one)

- ☐ Bath only
- ☐ Shower only
- ☐ Bath and separate Shower
- ☐ Bath with Shower over
- ☐ Japanese bath
- ☐ Spa bath
- ☐ Other (please specify)

68. Do you have laundry facilities in your Earthship or do you use a Laundromat?

- ○ We have a laundry
- ○ We use a Laundromat
- ○ Other (please specify)

69. How do you dry clothes? (you can check more than one)

- ☐ Electric clothes dryer
- ☐ Gas clothes dryer
- ☐ Hang on a line in the house
- ☐ Hang on a line outdoors
- ☐ Other (please specify)

LIFESTYLE / BEHAVIOUR

This section is aimed at understanding how living in an Earthship may be different (or similar) to living in a conventional home in terms of energy use, water use, and food production.

70. Please indicate the extent to which you agree or disagree with the following statements regarding your energy use behaviour.

	Strongly agree	Agree	Slightly agree	Neutral	Slightly disagree	Disagree	Strongly disagree
For high energy activities such as clothes washing I wait for days when my renewable energy system will be working well.	○	○	○	○	○	○	○

71. Only answer this question if you agreed with the previous question. To what extent do you agree or disagree with the following statement

	Strongly agree	Agree	Slightly agree	Neutral	Slightly disagree	Disagree	Strongly disagree
I don't mind having to wait for suitable weather conditions to do high energy activities such as clothes washing.	○	○	○	○	○	○	○

72. Please indicate the extent to which you agree or disagree with the following statements regarding energy saving activities

	Strongly agree	Agree	Slightly agree	Neutral	Slightly disagree	Disagree	Strongly disagree
I am diligent about turning off appliances when they are not in use	○	○	○	○	○	○	○
I am diligent about turning off lights when they are not in use	○	○	○	○	○	○	○

73. Please indicate the extent to which you agree or disagree to the following statements regarding your water use.

	Strongly agree	Agree	Slightly agree	Neutral	Slightly disagree	Disagree	Strongly disagree
I bathe everyday whether I need to or not	○	○	○	○	○	○	○
I have water efficient spouts and shower roses	○	○	○	○	○	○	○
I have designed my garden to be water efficient	○	○	○	○	○	○	○
I bathe more frequently than I would in a "normal" home because I know the water is recycled for toilet flushing and irrigation	○	○	○	○	○	○	○

74. Approximately what percentage of your food do you produce using your recycled wastewater i.e. in your greenhouse or the blackwater planter? (enter a whole number between 0 and 100)

75. Compared to conventional housing your Earthship may have enabled you to lead a very different lifestyle. Thinking about your accommodation and lifestyle prior to living in your Earthship, compared to your Earthship lifestyle right now, to what extent do you agree with the following statements;

	Strongly agree	Agree	Slightly agree	Neutral	Slightly disagree	Disagree	Strongly disagree
The temperatures in my Earthship are MORE COMFORTABLE than my previous home	○	○	○	○	○	○	○
My Earthship lifestyle is MORE EXPENSIVE than my previous lifestyle	○	○	○	○	○	○	○
My Earthship lifestyle is MORE DAMAGING to the environment than my previous lifestyle	○	○	○	○	○	○	○
My Earthship lifestyle is MORE RELAXED than my previous lifestyle	○	○	○	○	○	○	○
My Earthship lifestyle is MORE ENJOYABLE than my previous lifestyle	○	○	○	○	○	○	○
My Earthship lifestyle is MORE HEALTHY than my previous lifestyle	○	○	○	○	○	○	○

MOTIVATION

76. What motivated you to live in an Earthship? (you can check more than one). And if you like, write a few sentences about it in the "Other" box below.

- [ ] Reduce my eco-footprint
- [ ] Reduce my utility bills
- [ ] Become more self-sufficient
- [ ] Other (please specify)

FAMILY COMPOSITION

77. How many people live in your Earthship?

Children

Adults

YOUR CLOSING REMARKS

78. If there is anything else you would like to share about your Earthship experience please use the comments box below.

THANK YOU!

Thank you for taking the time to complete this questionnaire. If you would like to be emailed the results of the study please email martin.freney@adelaide.edu.au to request a copy. Martin's thesis is due for completion in 2013.

C2 - Summary of key data from Earthship Occupants' Questionnaire

Location, years living in home, number & type of occupants

City	Country	Age of Earthship (yrs)	How many people live in your Earthship? - Children	How many people live in your Earthship? - Adults
Peyton, Colorado	USA	10	2	2
Guffey, Colorado	USA	6		1
central	USA	6	2	2
Lithgow	Australia	5		2
Valencia	Spain	4	1	2
Taos, New Mexico	USA	2	1	2
Taos, New Mexico(Greater World Earthship subdivision)	USA	5	0	2
Picton	Canada	1	0	2
Barre, Vermont	USA	4	1	2
Taos, New Mexico	USA	1	1	1
Hot Sulphur Springs, Colorado	USA	4		2
Philo, OH	USA	8	1	2
Manitou Springs, CO (actually El Paso County)	USA	12	0	2
Ramah, New Mexico	USA	12		2
Black Forest, Colorado	USA	18	0	2
Ngaruawahia	New Zealand	3		3

Perceptions of comfort

Respondent #	Climate Pref.	Winter night	Winter day	Summer night	Summer day
1	2	5	1	1	4
2	1	3	1	1	2
3	1	1	1	1	2
4	2	2	2	2	2
5	3	2	1	3	5
6	2	1	1	1	2
7	2	4	2	2	3
8	1	2	1	2	2
9	2	2	2	2	2
10	4	1	1	1	1
11	1	1	1	1	1
12	2	1	1	1	2
13	1	2	1	1	2
14	1	5	3	1	2
15	1	1	1	1	1
16	2	4	1	1	1

Humidity and mould growth

Respondent #	Summer	Fall	Winter	Spring	Mould growth
1	4	4	5	5	4
2	4	4	6	4	5
3	5	4	4	4	7
4	4	4	4	4	4
5	4	4	4	4	7
6	4	4	4	4	7
7	3	5	6	6	4
8	4	4	5	4	5

9	6	4	4	4	4
10	3	4	4	4	7
11	3	3	4	4	7
12	5	4	4	5	7
13	4	4	4	4	7
14	4	4	4	4	7
15	4	4	4	4	7
16	4	4	4	4	4

Lighting, air & sound quality

			Lighting		Air		Sound
Respondent #	Clear Days	Overcast days	Nighttime	Tyre Smell	Fresh smell	Echo	Outside noise
1	1	6	2	2	2	2	2
2	1	4	1	1	1	1	1
3	1	7	1	1	1	1	1
4	2	3	1	1	1	1	1
5	1	6	1	1	1	1	1
6	1	7	1	1	1	1	1
7	2	5	2	2	4	2	2
8	1	6	1	1	1	1	1
9	1	6	1	1	2	1	1
10	1	4	1	1	1	1	1
11	1	5	1	1	1	1	1
12	1	3	1	1	1	1	1
13	1	7	1	1	1	1	1
14	1	4	1	1	1	1	1
15	2	6	2	2	2	2	2
16	1	5	1	1	1	1	2

Annual Running Costs

Respondent #	Gas $	Electricity $	Water $	Sewage $
1	250	150	500	5
2	600	0	0	0
3	50	400*	0	0
4	400	500	0	0
5	78	0	0	0
6	300	0	0	0
7	200	1	1	1
8	300	0	0	0
9	100	0	0	0
10	200	0	0	0
11	300	600*	0	0
12	100	1000*	0	0
13	300	130*	1	20
14	50	0	0	0
15	140	76	0	0
16	300	100	0	0

* grid connected

Systems performance

Respondent #	Country	Energy	Water collection and storage	Hot Water	Wastewater
1	USA	2	4	2	1
2	USA	2	2	1	1
3	USA	2*	1	1	3
4	Australia	3	3	3	NR

5	Spain	4	1	5	3
6	USA	1	2	2	1
7	USA	1	2	3	3
8	Canada	1	3	1	1
9	USA	1	1	3	1
10	USA	1	1	1	1
11	USA	1*	NR	NR	NR
12	USA	1	1	3	1
13	USA	2*	2	1	3
14	USA	1	4	1	1
15	USA	4	1	1	3
16	New Zealand	NR	1	3	NR

highlighted cells indicate non-standard Earthship system

C3 - Earthship Daily Comfort Questionnaire

Earthship Daily Comfort Questionnaire

Evaluation of the Thermal Environment in Earthships

Part of a PhD Research Study by Martin Freney
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Earthship Daily Comfort Questionnaire

Introduction and Instructions

The aim of this survey is to find out what level of thermal comfort your Earthship provides in terms of the temperature and humidity and how you go about influencing these conditions. The data logging study will show what level of comfort your Earthship is capable of producing in a variety of weather conditions, however it is also important to understand how you perceive these comfort levels, how you react to them, and how you influence them. Although this study is only looking at a small number of Earthships the results will provide an insight into the Earthship experience. Providing a better understanding about these issues will enable people unfamiliar or sceptical about Earthships to appreciate what is involved with living in an Earthship.

To achieve this aim, this survey will record some relevant information about how you interact with your Earthship and how you perceive the thermal environment within your Earthship.

To make this study work it is important to;

- not guess or try to remember. If you miss a day don't worry about it - just leave that day blank;
- enter the correct date and time.
- answer all the questions (it should take about 5-10 minutes per day).
- ensure that you have been inside for 30 minutes before you answer the questions - it takes this long for your body to acclimatise to the inside temperature.
- ensure that only one person answers the questions. If more than one family member wants to participate, extra copies of the questionnaire will be provided (or it can be done online).

This survey is designed to record results for three weeks, one in winter, spring and summer. The dates for these weeks will be based on the weather (will wait for a cold week in winter, average week in spring and hot week in summer) so you will be advised when to start the survey (email will be sent). If these dates are not convenient, you can select your own dates.

1. What is your house code? (this is for the purpose of matching these survey results with the data logging results - data will be confidential and results will be reported anonymously).

[ ]

2. In reporting the results of this research can the results from your Earthship be identified? (e.g. "In Earthship 1 the occupants rarely needed to use the heater" - your name and address will not be disclosed)

- ○ Yes
- ○ No

Winter

Day 1 (Winter 2012)

THERMAL ENVIRONMENT QUESTIONS

For the following questions it is important that you have been inside for at least 30 minutes, preferably in a room where a data logger is located.

3. What is the time and date RIGHT NOW?

	MM		DD		YYYY	HH		MM	AM/PM
Time/date		/		/			:		-

4. Which area of the house did you spend most of the last 15 minutes?

- Greenhouse
- Living room
- Other

5. Please indicate how you feel RIGHT NOW at this moment.

	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
At the moment I feel...							

6. Please indicate how you would RATHER be feeling RIGHT NOW at this moment.

	Cooler	No Change	Warmer
At the moment I would like to be...			

7. Please indicate how you feel RIGHT NOW about the air movement in the room you are in?

	very acceptable	moderately acceptable	slightly acceptable	neutral	slightly unacceptable	moderately unacceptable	very unacceptable
At the moment I find the air movement...							

8. I consider the air movement RIGHT NOW to be;

	too much	just right	too little
Air movement is...			

9. I would like;

	more air movement	no change	less air movement
I would like...			

CLOTHING QUESTIONS

10. Which description best describes the type of clothing are you wearing at the moment?

- Very light (e.g. singlet and underwear)
- Light (e.g. light T-shirt and shorts/skirt)
- Regular (e.g. T-shirt/shirt and long pants/long skirt or dress)
- Heavy (e.g. jacket, shirt and pants/dress)

ACTIVITIES QUESTIONS

11. Please indicate whether you have consumed any of the following items within the last 15 minutes.

- ☐ Hot caffeinated drink
- ☐ Hot non-caffeinated drink
- ☐ Cold caffeinated drink
- ☐ Cold non-caffeinated drink
- ☐ Snack or meal

12. Which description best describes your recent activites over the last 30 minutes?

	lying down	seated, quiet	standing, relaxed	walking about or cooking	house cleaning or gardening	exercising
Last 15 minutes	☐	☐	☐	☐	☐	☐
Previous 15 minutes	☐	☐	☐	☐	☐	☐

13. Regarding today, how were the windows, doors, skylights, blinds, etc configured? Use "N/A" for features that are not applicable to your Earthship.

	Open	Closed	Alternating between open and closed	N/A
External Doors	☐	☐	☐	☐
Exterior Windows	☐	☐	☐	☐
Interior Windows (as per Global Model Earthship)	☐	☐	☐	☐
Skylights	☐	☐	☐	☐
Blinds	☐	☐	☐	☐
Curtains	☐	☐	☐	☐
Earth Tube Vents	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐

Other

14. Regarding today, for how many hours did you use the heater or cooler (e.g. gas/wood heater, air conditioner etc)?

	N/A (not installed)	0hr (did not use)	0-1hr	1-2hr	2-3hr	3-4hr	5-6hr	7-8hr	8hr+
heater	○	○	○	○	○	○	○	○	○
cooler	○	○	○	○	○	○	○	○	○

15. Regarding the actions you took today to improve the thermal conditions in your Earthship (opening/closing windows, skylights etc) was this easy or difficult and how long did it take?

	Very easy	Easy	A little difficult	Difficult	Very difficult	N/A, don't know
My actions were...	○	○	○	○	○	○

16. Regarding the actions you took today to improve the thermal conditions in your Earthship how many minutes did it take to do this (opening/closing windows, skylights etc)?

	0 min	1-2 min	2-5 min	5-10 min	10-20 min	20-30 min	30+ min	N/A, don't know
No. of minutes...	○	○	○	○	○	○	○	○

Spring

Day 1 (Spring 2012)

THERMAL ENVIRONMENT QUESTIONS

For the following questions it is important that you have been inside for at least 30 minutes, preferably in a room where a data logger is located.

3. What is the time and date RIGHT NOW?

	MM		DD		YYYY	HH		MM	AM/PM
Time/date	☐	/	☐	/	☐	☐	:	☐	- ▾

4. Which area of the house did you spend most of the last 15 minutes?

- ◯ Greenhouse
- ◯ Living room
- ◯ Other

5. Please indicate how you feel RIGHT NOW at this moment.

	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
At the moment I feel...	◯	◯	◯	◯	◯	◯	◯

6. Please indicate how you would RATHER be feeling RIGHT NOW at this moment.

	Cooler	No Change	Warmer
At the moment I would like to be...	◯	◯	◯

7. Please indicate how you feel RIGHT NOW about the air movement in the room you are in?

	very acceptable	moderately acceptable	slightly acceptable	neutral	slightly unacceptable	moderately unacceptable	very unacceptable
At the moment I find the air movement...	◯	◯	◯	◯	◯	◯	◯

8. I consider the air movement RIGHT NOW to be;

	too much	just right	too little
Air movement is...	◯	◯	◯

9. I would like;

	more air movement	no change	less air movement
I would like...	◯	◯	◯

CLOTHING QUESTIONS

10. Which description best describes the type of clothing are you wearing at the moment?

- ◯ Very light (e.g. singlet and underwear)
- ◯ Light (e.g. light T-shirt and shorts/skirt)
- ◯ Regular (e.g. T-shirt/shirt and long pants/long skirt or dress)
- ◯ Heavy (e.g. jacket, shirt and pants/dress)

ACTIVITIES QUESTIONS

11. Please indicate whether you have consumed any of the following items within the last 15 minutes.

- [ ] Hot caffeinated drink
- [ ] Hot non-caffeinated drink
- [ ] Cold caffeinated drink
- [ ] Cold non-caffeinated drink
- [ ] Snack or meal

12. Which description best describes your recent activites over the last 30 minutes?

	lying down	seated, quiet	standing, relaxed	walking about or cooking	house cleaning or gardening	exercising
Last 15 minutes	☐	☐	☐	☐	☐	☐
Previous 15 minutes	☐	☐	☐	☐	☐	☐

13. Regarding today, how were the windows, doors, skylights, blinds, etc configured? Use "N/A" for features that are not applicable to your Earthship.

	Open	Closed	Alternating between open and closed	N/A
External Doors	☐	☐	☐	☐
Exterior Windows	☐	☐	☐	☐
Interior Windows (as per Global Model Earthship)	☐	☐	☐	☐
Skylights	☐	☐	☐	☐
Blinds	☐	☐	☐	☐
Curtains	☐	☐	☐	☐
Earth Tube Vents	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐

Other

[ ]

14. Regarding today, for how many hours did you use the heater or cooler (e.g. gas/wood heater, air conditioner etc)?

	N/A (not installed)	0hr (did not use)	0-1hr	1-2hr	2-3hr	3-4hr	5-6hr	7-8hr	8hr+
heater	○	○	○	○	○	○	○	○	○
cooler	○	○	○	○	○	○	○	○	○

15. Regarding the actions you took today to improve the thermal conditions in your Earthship (opening/closing windows, skylights etc) was this easy or difficult and how long did it take?

	Very easy	Easy	A little difficult	Difficult	Very difficult	N/A, don't know
My actions were...	○	○	○	○	○	○

16. Regarding the actions you took today to improve the thermal conditions in your Earthship how many minutes did it take to do this (opening/closing windows, skylights etc)?

	0 min	1-2 min	2-5 min	5-10 min	10-20 min	20-30 min	30+ min	N/A, don't know
No. of minutes...	○	○	○	○	○	○	○	○

Summer

Day 1 (Summer 2012)

THERMAL ENVIRONMENT QUESTIONS

For the following questions it is important that you have been inside for at least 30 minutes, preferably in a room where a data logger is located.

3. What is the time and date RIGHT NOW?

	MM		DD		YYYY	HH		MM	AM/PM
Time/date	☐	/	☐	/	☐	☐	:	☐	- ▾

4. Which area of the house did you spend most of the last 15 minutes?

- ◯ Greenhouse
- ◯ Living room
- ◯ Other

5. Please indicate how you feel RIGHT NOW at this moment.

	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
At the moment I feel...	◯	◯	◯	◯	◯	◯	◯

6. Please indicate how you would RATHER be feeling RIGHT NOW at this moment.

	Cooler	No Change	Warmer
At the moment I would like to be...	◯	◯	◯

7. Please indicate how you feel RIGHT NOW about the air movement in the room you are in?

	very acceptable	moderately acceptable	slightly acceptable	neutral	slightly unacceptable	moderately unacceptable	very unacceptable
At the moment I find the air movement...	◯	◯	◯	◯	◯	◯	◯

8. I consider the air movement RIGHT NOW to be;

	too much	just right	too little
Air movement is...	◯	◯	◯

9. I would like;

	more air movement	no change	less air movement
I would like...	◯	◯	◯

CLOTHING QUESTIONS

10. Which description best describes the type of clothing are you wearing at the moment?

- ◯ Very light (e.g. singlet and underwear)
- ◯ Light (e.g. light T-shirt and shorts/skirt)
- ◯ Regular (e.g. T-shirt/shirt and long pants/long skirt or dress)
- ◯ Heavy (e.g. jacket, shirt and pants/dress)

ACTIVITIES QUESTIONS

11. Please indicate whether you have consumed any of the following items within the last 15 minutes.

- [ ] Hot caffeinated drink
- [ ] Hot non-caffeinated drink
- [ ] Cold caffeinated drink
- [ ] Cold non-caffeinated drink
- [ ] Snack or meal

12. Which description best describes your recent activites over the last 30 minutes?

	lying down	seated, quiet	standing, relaxed	walking about or cooking	house cleaning or gardening	exercising
Last 15 minutes	☐	☐	☐	☐	☐	☐
Previous 15 minutes	☐	☐	☐	☐	☐	☐

13. Regarding today, how were the windows, doors, skylights, blinds, etc configured? Use "N/A" for features that are not applicable to your Earthship.

	Open	Closed	Alternating between open and closed	N/A
External Doors	☐	☐	☐	☐
Exterior Windows	☐	☐	☐	☐
Interior Windows (as per Global Model Earthship)	☐	☐	☐	☐
Skylights	☐	☐	☐	☐
Blinds	☐	☐	☐	☐
Curtains	☐	☐	☐	☐
Earth Tube Vents	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐

Other

[ ]

14. Regarding today, for how many hours did you use the heater or cooler (e.g. gas/wood heater, air conditioner etc)?

	N/A (not installed)	0hr (did not use)	0-1hr	1-2hr	2-3hr	3-4hr	5-6hr	7-8hr	8hr+
heater	○	○	○	○	○	○	○	○	○
cooler	○	○	○	○	○	○	○	○	○

15. Regarding the actions you took today to improve the thermal conditions in your Earthship (opening/closing windows, skylights etc) was this easy or difficult and how long did it take?

	Very easy	Easy	A little difficult	Difficult	Very difficult	N/A, don't know
My actions were...	○	○	○	○	○	○

16. Regarding the actions you took today to improve the thermal conditions in your Earthship how many minutes did it take to do this (opening/closing windows, skylights etc)?

	0 min	1-2 min	2-5 min	5-10 min	10-20 min	20-30 min	30+ min	N/A, don't know
No. of minutes...	○	○	○	○	○	○	○	○

Thank you very much for your time!

C4 - Illumination Levels - measured data from three houses

Table Error! No text of specified style in document..**1 – Monthly average, maximum and minimum light levels (lux) at 1pm**

House #	Ave/max/min	Jan	Feb	Mar	Apr	May	Jun	Jul
3	average	448	427	299	148	106	94	101
3	max	667	786	710	355	151	129	151
3	min	129	75	194	54	32	32	32
4	average	142	110	80	77	65	41	42
4	max	215	183	140	140	118	54	54
4	min	32	32	54	32	54	32	32
5	average	278	238	151	101	83	76	75
5	max	334	334	334	161	108	108	108
5	min	65	108	86	32	65	32	32

C5 - Interview Summaries & Transcriptions

C5.1 Interview with Jane (pseudonym) about her Earthship Experience

Martin Freney, 12 December 2011

Summary of Interview

Background

Jane has lived in her Earthship for about one year having previously lived in Nicaragua (tropical climate) and has lived all over the world including Germany.

She has quickly learned to "sail" her new Global Model Earthship, adapting to the Earthship lifestyle and easily meeting the challenges it presents.

Design

The Earthship design is circa 2009, a Global Model, with one bedroom. It is located at The Greater World community outside Taos, New Mexico, USA. It has a 3000 gallon cistern in the berm behind, and has a flushing toilet, shower, bath, laundry (washer only) and a separate greenhouse typical of the Global Model design. It has not heater or cooler. Two earth tubes provide summer cooling and winter cross ventilation (just a little) in the bedroom and the living space/kitchen area.

Thermal Comfort

Jane finds the indoor temperature very comfortable despite having no heater or cooler. She is able to control the indoor temperature by open the doors, greenhouse windows and vents and the earth tubes which enter through the rear wall of the living space. She suspects her Earthship is cooler than others due to being dug into the ground 3 feet deep.

Newly installed screen doors at the ends of the greenhouse have helped her to maintain a more comfortable temperature in the greenhouse.

Energy

Jane has six photovoltaic panels to charge the battery bank plus the usual solar water heating panel. Very occasionally when battery power gets low during extended cloudy periods Jane gets a little anxious about running out of electricity. Consequently she has "backup" appliances that run on propane or are hand-powered to deal with this situation. She is planning to install a wind turbine to generate power during overcast conditions.

She and has learned to save propane by using electrical appliances in times of abundant solar energy.

She has approximately a $100 utility bill for propane plus the usual internet bill but otherwise lives free from bills. She is not worried about the cost of replacement batteries reassured by the experience of other Earthship owners which indicates the batteries may last 20 years.

Water

Jane's 3000 gallon water cistern seems to meet her water use very well although sometimes she does get very close to running out. In times of plenty she flushes the toilet with rain water rather than greywater, and is not super cautious about water use for showers, hand washing etc but during a scarcity of water she adapts her behaviour only flushing the toilet when necessary, turning off the faucet while "soaping up" during hand washing, and flushing the toilet with greywater.

The waste water system works very well – so far so good – although a person who was working in the bathroom for an extended period commented on the smell of the toilet flushing water (greywater) and consequently Jane switched the toilet to fresh water flushing and did not switch it back due to an abundance of fresh water. She doesn't seem to mind cleaning the particle trap every now and then.

She has also discovered that in times of abundant water she doesn't need to be so particular about water conservation and is able to operate the house more "normally" whereas when water is scarce she can still function effectively – and not run out of water - by using water saving techniques e.g. for hand washing and toilet flushing.

She has had to deal with pests in the greenhouse and learn how to do gardening which she manages with the greywater that is used for irrigation.

Transport
Living in the Earthship community Jane is reliant on her car for the 30 mile round trip into town, however she is generally very successful at limiting this trip to once per week when she takes care of chores such as recycling, garbage disposal, grocery shopping and collecting mail.

Motivation and Outlook
Having chosen to live in the Earthship community - The Greater World - she feels reassured that help is never far away in an emergency. She is also pleased that Michael Reynolds has already fought for permission to build Earthships in this area thereby saving her the need to do this if she were to build elsewhere.

The thermal comfort provided by the home and the beautiful scene created by the greenhouse garden and the nearby mountains bring her great joy and contentment. The self sufficient nature of the home is reassuring to her as she knows that she is not subject to the vagaries of utilities prices that are beyond her control. She has been successful with growing a variety of food producing plants as well as beautiful herbs whose fragrance wafts into the living space whenever the doors to the greenhouse are open. She is even trying to grow her own coffee and has ambitions to grow her own tobacco (or was she joking?).

The "spaceship" look of the Earthship does not worry Jane who appreciates function over form, however she appreciates the beauty of traditional materials such as timber and adobe which are prominent inside the home which she has decorated extensively with antiquities from her travels and her own woven tapestries.

Jane's Earthship is unique in that she went to the trouble and expense to have it LEED certified which has enabled her to recoup these costs due to tax concessions/rebates offered to LEED certified homes.

In summary Jane loves living in her Earthship in The Greater World community and is able to enjoy all the modern conveniences such as a washing machine, computer, refrigerator, hot water, shower, and bath yet without the utility bills and the associated environmental impacts that she perceives are associated with utilities infrastructure. She has to be a little careful with water and electricity use at times but she seems to enjoy this challenge perhaps because it is relatively easy for her to meet this challenge and because she has been a conscientious energy saver throughout her life.

NOTES:
It was early afternoon and a snow storm was just starting to blow in after a sunny morning. 12 Dec 2011.

PRELININARY DISCUSSION
(start of audio recording)

J: ...only when there is absolutely no sunshine like just before it started snowing I closed the windows they were open because it was sunny and it was hot in the greenhouse. It didn't last long but... (laugh).

M: But it's lovely in here, I'll get out my thermometer and see what the temperature is right now. (the temperature was 22C).

J: in the greenhouse it is 65(F).

START OF INTERVIEW
M: my first question is about the previous type of house you lived in because I'm building up to what makes it different living in an Earthship compared to your previous house.

J: my previous house was in Managua Nicaragua, stucco construction, composite tile roof meaning a fake terracotta tile, probably cement block covered with stucco but guessing cement block.

M: I've got no idea what the Nicaragua climate is like?

J: hot and humid, tropical.

M: was that a comfortable home to live in, in terms of the temperature?

J: with air conditioning.

M: what about your electricity bill?

J: I didn't pay it. The state department paid it. But let me think... I used the least electricity of anyone and I think my bill was about $600 and the average was about $1000 - $1500.

M: so that was mainly due to the air conditioning I guess? Because that would have been used quite a lot.

J: most people keep it on. But I lived up a mountain and I got a little bit of a breeze so I was able to not use it.

M: and so how has your lifestyle changed now you live in an Earthship?

J: there are no utility bills other than propane. And for most people, since all of mine have been paid for in the last 20 yrs... but I think my son in law who lives in Virginia, I think he pays around $300 a month both in winter and summer, winter for the heat and summer for the ac, and I think sometimes it goes to $400.

M: how much would you be spending on propane per year?

J: last year I was only here from January. I've only been here since last January and I thought I should fill the propane tank before winter came because I didn't know how much I had put in there originally because I didn't live here and I thought oh my god I'm down to 20% I should fill up. And I filled it up and later I found the paperwork and realised I'd used 30 gallons.

M: out of how many gallons?

J: out of 100

M: you had plenty left!

J: I had plenty left and I didn't need to fill up the tank and now I won't need to fill it up for another 10 yr or so. Well at least 5.

M: Wow!

J: the estimate is $100 a year on propane.

M: and that is for cooking and hot water?

J: the hot water is only on demand – when its, foggy, whatever.

M: do you purposely avoid using hot water when its overcast or whatever, or do you generally just go about your business?

J: when you only spend 30 gallons its miniscule. I normally wait until the suns out before I shower unless there is some need to get somewhere. I try not to shower in the late afternoon because then the water is scalding hot so I have to remember to turn it to more cold. And I do the dishes at night.

M: on that same topic, do you do something similar with your energy use. Do you wait for a sunny day to do your washing or...?

J: right, so now its snowing I'm pretty well charged up already because there was sun this morning but I don't know what its going to be like tomorrow or the next day and my batteries will continue to go down if its like this for 2 or 3 days to blinking red (referring to batter charge controller) - something I hate to see, so yes to vacuum, if its like this, I don't use the electric coffee pot or toaster, I use the French press, I use the broilered(?) toast. So I have back up systems, so if its sunny I use the coffee pots, what's the difference! For a long time I didn't and then I thought its free why am I being – you know – from years of being careful of how much electricity I use.

M: its interesting isn't it because when the sun is shining you can kind of use lots and lots of energy and not be frugal about it but when the weather is like this (snowing) and it could be like this for a few days that's when you have to start (being energy conscious), so its quite a challenge really isn't it to the Earthship occupant because sometimes its sort of like yeah...

J: free for all!

M: free for all - and then other times it's quite different the opposite really so that's something I hadn't really thought about before actually. I thought in a way you'd always be being a bit careful but sometimes it is not necessary.

J: well sometimes it is absolutely necessary because why use propane you pay for but it took me a while to get to there. First like you I was just being cheap with my electricity and then I thought you know what I'm paying for propane and some truck has to come and give it to me and the electricity is free out of the sky. Because I had gotten rid of my electric coffee pot and toaster and didn't have a microwave, i only just bought that, why am i doing this (laughs) this is crazy! But it takes time to get to figure out all the bits of it. And I am planning to put on a windmill so that on the days when it is like this for 2 or 3 days my electricity doesn't go down.

M: yeah, there was a bit of wind this morning wasn't there. I saw some of the windmills were turning. OK in terms of the systems, so thermally you're very happy with the way it is performing?

J: it performs as advertised.

M: what is advertised?

J: the house itself will always remain 68 degrees summer or winter. I think my house performs a little better than others in the summer. Because I'm dug down 3 feet and because the only reason I think that is because when people come in who are Earthship people they say ooh this is nice and cool.

M: interesting.

J: so that makes me think it may not be nice and cool in others. Because it gets quite hot out in the greenhouse. I just put in two screen doors so that I could let air come in (to the greenhouse) – you can't open the door here because of snakes and stuff you know – so until the screen doors were in I only had these two vents and two skylights and it made a huge difference to have the screen doors because you often get a small breeze which was just enough to keep it comfortable in there instead of sweating when you walk out there (the greenhouse).

M: how far does the sun actually come in on the winter solstice?

J: in the winter it comes all the way to the couch. But in the summer it only goes like right to the greenhouse dirt.

M: ok so in terms of your energy you said occasionally the red blinking lights are there. Does that happen frequently?

J: twice.

M: twice so far in the last year?

J: this winter. But even when it's blinking red I'm still able to take a shower and have lights so I mean the battery is not happy and it does take - if its blinking red - it does take one and a half days to really get back to full charge.

M: do you have any idea how much, how long the batteries will last and how much it cost to replace them?

J: I don't know how much it will cost to replace them but I know that the Earthship offices have been there for 20 years and they are still using the same batteries.

M: wow that is pretty good!

J: so no matter how much they cost if they last 20 yrs... it's pretty good. And I'm sure they are very expensive (laughs). They're huge.

M: that's good to know. You've already said in weather like this you'll try to conserve energy, what about water?

J: do I conserve water in this kind of weather?

M: well no just tell me about your water use, do you run out of water, what do you do to conserve water if ever or...?

J: I'm careful, I only flush when necessary, although it is greywater I still don't just flush every time I urinate (laughs).

M: sensible yeah I'm like that too.

J: and you know California had a drought for 7 years so you just didn't flush unless it was necessary. I've gotten the washing dishes down to using just a minuscule amount of water to wash and then I rinse them with more fulsome water. I take a pretty short shower. I don't take baths although at this point I'm sure I'm full so I could take a bath but I'm thinking of putting a hot tub in so that way I don't have to be paranoid about using up my water because I just keep heating the same water. And I think that would be the solution.

M: how does that work then, a hot tub that you reheat the water, do you have to discard the water one a week or once a month?

J: no I think a couple of times a year. I think you put something in it to keep it from growing algae or something.

M: salt or something?

J: hopefully not salt because what you don't want to do is dump salt or chlorine into your garden.

M: that's a good point yeah but you don't want to use chlorine either.

J: right

M: I wonder what you use.

J: there's some stuff... I haven't done all my research yet.

M: I'd be interested to know what the solution there is.

J: And of course I'll have to not let anyone know I have one because no one here has a hot tub (laugh) but again I'm from California you know: its like what could be better than a winter snow falling on you watching the sky being in a hot tub. Sounds good to me.

M: yeah does sound good. Now, you've only been here for a year or so but there was a drought last year.

J: there is a drought - it continues, I don't know if it is over yet. I just looked on the radar for the snow, it extends from below Albuquerque just a huge swath so this is going to last. So I don't know if we've had enough rain snow, we had a couple of really big rains but those tend to just run off but I did not run out of water.

M: That's interesting. How much water storage do you have?

J: 3000 gallons. And especially the first year I was very careful with water it was like I turn the faucet on and wet my hands and put soap on them and then I soap up and then I turn it back on again and rinse.

M: that's interesting.

J: I definitely did not want to run out of water. It would be embarrassing to have to buy water. So I was really careful until it started raining and then I can see that my cistern's full because they overflow.

M: back to energy, what's the size of your solar panels or how many panels you have?

J: I have six solar panels for charging, I have one ... you know I tend to forget, I have three other solar panels, and one is I think to heat the ethylene glycol that heats the roof and one is to heat water and I don't know what the other one is.

M: I might ask mike about that.

J: but I also noticed I'm the only one that has all these solar panels. Like most people have the six I have on the outside but they don't have the three in the interior. And I keep forgetting to ask what are those again.

M: yeah ok sounds like something slightly experimental going on.

J: Mike likes to do that. I think I'm the only one that is dug down. You know he emailed me and said do you care if I dig you down 3 feet I want to see how that works. Basically I built the house by email so I said surprise me.

M: and this is the Global Model design, is that right?

J: right. Yeah at the time this was built it was called the Euro but it's morphed into Global so this would be the Global One because it is different style than the Two which has the back hallway.

M: so the Global Two doesn't do that or it does?

J: Global Two does have a back hallway so you don't have to go out into the greenhouse which could be advantageous if it's freezing.

M: or if its really hot?

J: really hot doesn't really bother me.

M: like if you open doors constantly doesn't the heat tend to get in here (the living space)

J: it doesn't really. When it is incredibly hot in the greenhouse and I leave the door open, I usually keep it closed, I usually consider this - the house - that's the pre outside (greenhouse) and the outside, so unless the temperature in the greenhouse is comfortable then I open the doors so then I've got this air flow between the two. But usually the hot air doesn't creep in here or the cold air doesn't creep in. I'm not sure why. These air tubes do leak cold air, you know you put your hand there and you'll feel it if it's windy – its not windy now. And also here I'm not sure why but this is really cold in here (cupboard on north wall in utility area). So when it gets too warm I open this. Lets a little breeze in. I'm not sure why because it seems to be all sealed up.

M: is there anything going up through the roof like chimneys?

J: well there is all the wiring. It doesn't seem to make this room colder. But it does at least make sure that there is always a little tiny bit of air circulation. You know I've been interested in solar housing since the 70s and you know they were disastrous because they were all closed in and people got sick from all the toxins and you know cooking toxins so I do like to have, even if it is just a minuscule trickle of air. And you know the doors (from living space to greenhouse), there is a bit of crack, and in the newer model evidently they have vents up there (above the doors) that you can open and close. But for me it is very comfortable, seldom is it too warm in here in the summer time. Every once in a while it gets to be about 78 – 80 that's just reaching my no comfort zone (laugh).

M: still just ok. And that's when it's 95-100 outside?

J: but you know its not so much how hot it is outside, its more how intense the sun is because it really heats... I mean the second the sun comes up in the morning the greenhouse goes from being 50 degrees to 70 degrees just like (clicking fingers).

M: it's incredible isn't it!

J: It was supposed to be light snow fall. Now I see 2-4 inches. It snows in New Zealand doesn't it up in the mountains at least?

M: Yes it does but actually I'm from Australia.

(Discussion about Australian cities – not transcribed)

M: well Earthships are going to be wonderful I'm sure in bushfires because it is all protected by the berm around there, all you need to do is have some sprinklers or shutters or something out the front here.

J: and something to trickle on the roof. You could even just use those watering hoses the type with all the little holes all along.

M: yeah spraying a bit of water out and keeping the roof cool. Or you can do a green roof with plants growing or something.

J: well the difference between... for that the roof is really part of this design in that it collects your water and I know that for Australia water is an issue as it is here. This is kind of like Australia isn't it?

M: yeah in some parts it is.

J: not much vegetation kind of deserty. So water is going to be an issue, so if you put a green roof on you can't collect as much water. And you want every drop. Because without water you don't exist (laughs)

M: its more important than the electricity isn't it.

J: yeah oh yeah you could live without electricity. I have a turn sewing machine, I have a tea pot and coffee pot a hand grinder I could be quite happy, I weave which is non electric. I could be quite happy without electricity but without water... I would leave the roof. I think this roof design is really good. Because one, it is heated so it melts the snow – guess this wouldn't be an issue in Australia – I have to change a valve so it melts the snow. But the first big rain we got and I would say it rained hard for 2-3 hrs – my tanks were full. That's 3000 gallons because it was *just* getting down to the bottom when it rained.

M: wow so it can potentially fill up pretty quickly.

J: if you have monsoon torrential rains. I don't know how it rains in Australia.

M: up in the tropics we get torrential rains. We had some really bad flooding last year, thousands of people lost their homes because of torrential down pours but in the state where I'm from it is basically a desert and we don't get a whole lot of rain. It comes in the winter and in the summer you don't get much rain at all.

J: well I'm from California, you know it *never* rains in California in the summer and all the rain is in the winter, however in the last couple of year there has been some.

M: its changing.

J: gee you think (laughs)

M: and your waste water system is working ok?

J: apparently

M: it doesn't bother you, it doesn't smell or...?

J: in fact I don't use the top water of the greenhouse very often but like if I'm going somewhere for a week or so I'll top water to make sure that it stays damp and I don't notice any smell at all.

M: what about your toilet water. Your flushing water.

J: well actually I haven't turned over to greywater yet. I need to do that next week. There was a person working in the bathroom and he hated the smell of the greywater so I turned it over.

M: yeah I've noticed in some of the Earthships I've visited that yeah sometimes the toilet smells a little, a little funny, its kind of a sulphurous smell or something like that, so I'm curious to know if these improved designs have addressed that problem.

J: I don't know I really can't answer that. But I have been thinking when I switch it over (to greywater) could I put one of those deodorisers in there or would that be... what kind of disgusting chemicals are in them. Would that be disrupting my septic tank fermentation? I haven't come to that yet. And in fact since we are having so much moisture I may not switch over, I'm full so...

M: yeah that's right if you are not worried about the level in your tanks (cisterns) why switch to greywater for your toilet. Do you have a laundry in you house?

J: I only have a washer and it's the highest rated for electricity and water use so it only uses 6 gallons of water per wash. Its European, bought it in the US but didn't think about the fact that it would be 220 volts because how it was designed its stackable with the dryer on top so the washer plugs into the dryer and then the dryer plugs in and many US households have 220 for the dryer.

M: oh right, didn't know that.

J: yeah well so what in the hell am I gonna do with this thing, it was really expensive, they wouldn't take it back because it wasn't in the original packaging because the guys unpacked it and that's when they realised it was 220. So anyway Amy in the office said why not put a transformer on it. And I've been using a transforming for most of my life, cause I go from country to country. I envisaged something on the top of the washer but they put that in and so when I want to wash I just flip the transformer on do my wash I leave this door open so I remember to turn it off.

M: I notice you have a lot of rugs down. I thought that it was good not to have rugs so that the light coming in would warm up the floor a bit more. Are they always here, you're not putting them out in the summer and taking them away in the winter?

J: no, because where would I put them (laughs) storage is an issue.

J: while we are here do you want to look at the water management system? So you know how it works right? This is the regular water, shower water whatever, and there are two additional filters, and this has got the ceramic filters in there for drinking water and there is a drinking water spigot in the bathroom and in the kitchen. And then this is the water pressure tank and the ethylene glycol.

J: and then this is all the circuit breakers and stuff and you can see I've used up every last bit of space. The refrigerator is 24 volts. I don't know. These are made by hand in Petaluma California so I don't know how easy or difficult, although I would imagine in the Outback (Australian desert) you already have propane refrigerators, and such right?

M: yeah I think so.

J: propane is kind of the old style and these must exist because most RVs have 24 volt refrigerators. They also have propane refrigerators. All these 24 volt light bulbs I think are designed for RVs and they are the CFCs.

M: compact fluorescent.

J: yeah the wiggly ones. These refrigerators are incredibly expensive $3600 and I think that is why some people have propane refrigerators. Yeah but you know it depends on... like this year I want to take it off my taxes. I had to have this house LEED certified. No one else has done that.

M: wow!

J: maybe I'm the only one who is paying taxes I'm not sure (laughs).

M: that's interesting its been LEED certified. What does that entail exactly the LEED certification?

J: I'll tell you I had to submit a binder of stuff to get it LEED certified and they had to install something extra in my system which was like a $1000 could have been $400 but did I want the... I said just do it a $1000 is fine and no one else had ever done it. And I got $8500 back on my house because the solar was $21000 and the federal government gives you a 30% rebate so I got 7000 back from the feds and 2500 back from the state. So and then this year I'm gonna claim the refrigerator and washer which are high energy efficiency, I could claim the roof if I knew how much it cost but (laugh) but I just don't think I can go through it, trying to get Mike to figure out how much the roof cost. I'm not gonna do it.

M: how do you manage transport here because it is a little isolated. Do you have a strategy for minimising the use of the car?

J: I try to only go to town once a week or if I've run out of something and sometimes I'm more successful than others like when they were building I was going into town everyday: oh we need, oh we need,... beer! But since they stopped building the fence... yeah I go like once. I need to go at least once a week because they get annoyed if you don't empty your mail box and pick up packages. But I make lists and try to make sure I get everything done. Do my recycling, get rid of my garbage, go to the grocery store, get rid of my plastic bags.

M: what do you do with things like aluminium cans and glass bottles?

J: those all go to recycling, so cardboard, glass, aluminium, plastic 1 and 2, batteries, um you know phone books.

M: so is there a recycling facility in Taos?

J: in town. Plastic bags go to the grocery store, paper either I burn it because I'm burning something or garbage. So I usually have maybe half a bag a week of garbage that can not be recycled and then I have anything that is organic: coffee grounds, crumbs, egg shells, etc go to the worms and if the worms get too full I have a compost bin.

M: ok good that is all very interesting, and food, are you growing much food in the greenhouse?

J: at the moment no but in the past I was able to grow swiss chard and onions and tomatoes and basil lots and lots of basil it loved to be in the greenhouse, then I tried cucumbers but they got white fly so I pulled them out and I got some peppers but then the other peppers started succumbing to mealybugs so I just ended up pulling everything out of the greenhouse except for the lavender, rosemary and the palm tree. And then using an organic pest control stuff... and now I'm refurbishing so now I'm letting it sit to make sure there are not bugs. And you saw on top of the refrigerator I have all those seedlings started so greenbeans, and sunflowers, and lettuce, and well the tomatoes came up but weren't infected so I didn't pull them out. Do you know what a CSA is?

M: yeah community supported agriculture.

J: yeah and so I got a bunch of tomatoes from him which I canned and they were so good I just, cause when you can you squeeze all the seeds out, so I had this mass of seeds so I threw a bunch of seeds out there and they came up so I'll have tomatoes and bell peppers and onions and swiss chard I just ordered some figs because somebody had a fig tree inside their Earthship and I thought that's a good idea I love figs. Black beans. You know I'm hoping, and I've never really done any gardening and gardening in the greenhouse is challenging.

M: why is that?

J: because bugs get in here. And there were bugs in... this house sat for a year and somebody came and planted ornamental plants and somebody came and watered them but then they had to take out all the plants because they got mealybugs. So I thought I had got... you know I dug out 3 inches of dirt I put brand new sterilised dirt in i thought ok... what do I know about bugs, but they were just hanging out waiting to come up... so now I'm hoping that its under control and now I'm going to use biological controls like little wasps and things. Oh and those little things over there are *coffee* plants. And I'm really hoping... this is my second try at germinating them.

M: wow that would be great to grow your own coffee.

J: can you imagine! So then all I need is tobacco.

M: (laugh) are you allowed to grow tobacco in America? We're not allowed to in Australia, it's illegal.

J: why?

M: I guess it takes taxes away from the government.

J: yeah well there's a big fuck you (laughs) what do I care. At least I'm not growing marijuana. I have no idea but I wouldn't grow it. Are you sure its about taxes or is it because tobacco has a lot of insect predators. If I smoke and then I go out in the garden I have to wash my hands because you can get the mosaic virus on your plants. So as far as I know it is not illegal and there are books about growing your own tobacco.

M: is that the three way valve there right?

J: that I actually don't know why you would turn it off but that's where all the water goes into the greywater cistern. All the water bathroom sink, shower, wash machine all drains in there and goes into the greywater cistern, the kitchen sink by county code can not go into the greywater system and evidently what they've done in a lot of places is after the inspector has checked it then they've switched it (laugh) because its a ridiculous rule but they never switched it on mine so I'm legal.

M: right. Huh.

J: I use little screens in the sinks so no food particles go down, I don't pour grease down there or you know... any gross things.

M: and so that little green trap there you just...

J: it gets water in it.

M: and do you have to scoop any stuff out of there?

J: every now and then something gross like a big glob of soap or something comes out. I don't go feeling around inside of the pipes.

M: well alright getting to the end now. What I'm curious to know, what was your motivation for coming to live in an Earthship?

J: well I've been interested in the environment and its degradation since the late 60s and followed closely all the solar housing kinds of things and I'm from California you know we are the kinda innovators of the US although California have the strictest building codes, I don't know if there are any Earthships in California. I originally was planning on building a house in Costa Rica and although San Jose has fairly decent infrastructure anything outside of that doesn't so I wanted to build a completely self sufficient house with a greywater fishpond and all these other kinds of things, anyway I kind of designed this house in my head and then I thought I wonder if anyone else has done it (laugh). So I got this book called The Natural House, and it had cob, Strawbale, and then I got to the Earthship and it was like wow, somebody has done all the engineering for me. Because I don't know anything about that. So I came here and I stayed a week in a rental.

M: which rental?

J: the Hut. I don't even know if it is still a rental and because I thought before I commit to building one I certainly want to try it. But I wasn't planning on living here on the Earthship community. I was planning on buying a cheap piece of land I mean since you don't need water or electrical or sewage you know I could buy any useless piece of land, and then as I was here in that week I thought about it and I thought, no, do I want to be more remote than this? Do I want to be 80 yr old break my hip and then just lay here and die because I can't get to the neighbours? Do I want to be shovelling snow to get out? So I decided it made more sense to live in the community and it made the most sense to live here where Michael has done all the fighting with the authorities and gotten all the permissions and you know... I thought about Lake Tahoe in California but my ex husband is a contractor and he told me it takes 3-4 yr to get a permit approved for a building. So I said ok well... and you know that means going to hearings and... and you know Michael has done all that. That was not my idea of a nice retirement, hanging out in government offices, I've done that for 20 years. So anyway I wanted a house that was not connected to the grid, I don't know about in Australia but in the United States all the electrical is above ground expect in new subdivisions which is the most ridiculous thing I've ever heard. In Europe its all below ground and it has a double redundancy.

M: so you don't see it.

J: Well it is not so you don't see it but it doesn't get knocked down every time there is a wind storm or you know in California people are sometimes without electricity for 15-20 days because there is all scrub oak and so when it rains hard they break off and the lines go down etc and on the east coast 3 million people were without electricity in this last storm. Why don't these Americans rise up and say... not only occupy wall street but we want our underground utilities! (laugh)

M: that would make sense wouldn't it.

J: I think they wouldn't know any different. I lived in Germany for 7 yr not once did I ever experience a power failure, you know never a blink in my electrical system. I wanted to be free of all of the government control over utilities that's part of it, the other part of it is... I just didn't want to be... I lived in Nicaragua and sometimes my electricity would go off 15 times in an evening, of course when I was on vacation it never went off at all.

M: it was something to do with you.

J: exactly (laugh) to me it just makes sense I mean why use heat if you can build a house that doesn't need it. Why let your water run... I'm in control of how much water I use how much electricity I use and I don't have to pay for it. I mean it was expensive to start with but you know there is no monthly bill, my only monthly bill is the internet. Well car insurance and...

M: oh yeah sure that's nothing to do with the house is it really. And you feel happy and healthy here? Do you feel its got a nice vibe, its bright, comfortable temperature? I guess it would be hard to be miserable in a place like this really?

J: it would be really hard to be miserable, you know most days you have this incredible view of the mountains. Not today unfortunately and it is kind of a bummer when it's like this. But at least its snowing that gives it a little bit more.

M: well its nice to look out onto the greenhouse coz that's nice to look on with some plants and things isn't it?

J: yeah especially when the banana tree gets bigger.

M: yeah oh yeah its a newly planted garden isn't it because of the problem with the pests.

J: well you can see some things that the pests didn't bother, the rosemary the lavender that palm tree which I had to buy special clippers to cut because it is so tough (laugh). You know before the bugs got in the whole thing was planted. So yes it is very nice to look out onto all that greenery and when you open the door in the summer time you get the smell of lavender, basil and sage so it is quite pleasant.

M: lovely.

J: So my next task is... the fence is just finished, I couldn't really plant up there until they were done. So now I need to figure out what to do. In fact something you might be interested in something I bought, they are called Growasis tubs - like "grow oasis". They are these plastic tubs that they are using to reforest the Sahara and so you put your little seedlings in the ground and you put this little wick and this tub over it and then you fill the tub with 4 gallons of water then you put a black plastic thing so it's kind of open like this and then you put over that a white plastic so that any dew collects in there as well and that is all the water they get for one year and then their roots should be established enough so that um... (Ben arrives). So my plan is to put fruit trees all out here in those boxes and then I'm gonna try.

(Chatting with ben about renting the g2 and the cost of the g2 versus Jane's place, fence costs etc.)

M: my last question is about the future of Earthships. What is your thinking on whether Earthship is something that other Americans are going to take on board?

J: my son in law who I must say is an arch republican conservative he calls this my retirement home and he couldn't live like this. He's never been here.

M: there are some prejudices.

J: but he also doesn't believe there is climate change so go figure. So um... but everyone who comes here says this is wonderful and you know the Visitors Center is full everyday, I see 5-10 cars out there everyday but I think people are thinking about... and certainly your age group, I don't see that many old people but I don't hang out there so I don't know, but in terms of the interns that have been here and I've seen three groups I think working on the fence, they are all around in your age range and very excited about not being a part of the same old same old, and you know Earthships can look, I mean you've seen Mike's drawings the ones where he's made them fit into suburban neighbourhoods, I don't know that any one has ever done that. People think they look weird.

M: how do you feel about the look of your home?

J: I don't care (laughs)

M: does that mean...

J: I am function over form. I buy a car because it is the highest safety rating, it gets the best mileage, I do my research to... you know I don't go isn't that a cute little car I think I'll buy that car which unfortunately I suspect most people... otherwise why would they buy those ridiculous mileage, unsafe cars. I feel similarly about the house. It is odd looking if you think about it in terms of what a conventional house looks like.

M: but its not necessarily unattractive either.

J: no. and you know do I wish it was more like some of the other ones with all the frills and yeah, but did you see Nicole and Zac's bathroom - in their bedroom? I would really love to have something like that but I had to figure out what is my budget what do I want to spend etc and so you know this is the low down rock bottom model... and so I figure I can add some cool stuff.

Ben: this is pretty cool.

J: Hilary did that.

M: she did a nice job. She did a lot of the tiling in The Phoenix I think.

J: And she did the Phoenix.

M: right THE Phoenix. (referring to a sculpture of a phoenix's head on the "Phoenix" Earthship)

J: she does beautiful ceramic sculpture. She did the tile work in the G2 all black in a star burst design. She's really very talented. So yeah, I like my house and inside is very different from the outside.

M: it is yeah.

J: the outside is kind of odd looking, spaceship looking, but inside it has the adobe walls, wood, concrete, that's it.

M: ok well that's all I wanted to ask you about. (end of recording)

C5.2 Interview with Ali (pseudonym) about her Earthship Experience

Martin Freney, 11 December 2011

Summary of Interview

Prior to living in an Earthship in the Greater World Earthship Community, Ali grew up in an old three story home built in approximately 1910. It had no insulation, a steam radiator and was either too hot or too cold. She also spent time in a conventional home in Seattle and started her Earthship adventure in 2001 with her husband Doug. They are both architects and Ali worked as an architect for Earthship Biotecture with Mike Reynolds for six years. It took them five years to build their Earthship and in the meantime they lived in various Earthships including the Weaver Earthship at the nearby REACH community (in the mountains). Ali recalls that the Weaver Earthship worked wonderfully in the winter providing excellent comfort levels without the fireplace which was only ever used in the dead of winter for ambiance more than anything. This was a real contrast to the type of home she was accustomed to in which a thermostat would turn on and off, blowing hot air around and making an annoying background noise. One of the things she enjoys about her Earthship is the stable indoor temperature which tends to change gradually.

Ali's time working alongside Reynolds saw the advent of the "Packaged" Earthship, a super simple design, engineered to be cheap, yet effective and easy to build. Ali used this as the template for her Earthship design, although over the years a significant extension has been undertaken to add another bedroom in the form of a two story circular tower built with tyres and insulated on the outside with blown-on foam insulation which is covered in an attractive green coloured render. The use of cement was minimised where possible; for example the bond beam is made from timber rather than the more conventional concrete bond beams used these days.

While the family generally enjoys a good level of thermal comfort, Ali mentioned that there are various micro climates in her home, such as the corridor which is a bit cold, probably due to it connecting with the unusual northern entry through the berm.

The house is small by western standards at 480 square feet (45m2) yet it houses a family of four comfortably due to the efficient layout.

It faces 23 degrees east of south, catching the morning sun. In the upstairs bedroom they need to be vigilant about using the blinds, keeping them down in the summer to block out summer sun and also on winter nights to reduce heat loss, and up during sunny winter days to admit as much solar energy as possible. A gas heater has been installed for space heating although this is very rarely used. They ventilate the house throughout the year to ensure fresh air, although on the coldest winter days they close up the house and are very aware of keeping the outside doors closed as much as possible.

Hot water is supplied by a solar heater with no boost - so if the sun doesn't shine hot water runs out, however this happens rarely due to Taos's sunny climate of 300+ sunny days per year. They are planning to get a gas boosting system one day, but this doesn't seem to be urgent.

The greywater system works well in general even though it is technically a blackwater system as it is receiving wastewater from the kitchen sink. At the time of construction this was permitted but now the codes have become more stringent and kitchen sink waste is defined as black not grey water. One minor problem they have is that the treated greywater that is used for toilet flushing gets a sulphur-like smell. They deal with this by switching the toilet flush to rainwater for a while, which immediately solves the sulphur-odour problem that emanates from the toilet. To more permanently address the problem they have added hydrogen peroxide (which decomposes to water and oxygen and is sometimes used in wastewater treatment plants as an alternative to chlorine[1]) to the water entering the planter, and have also tried flushing the planter periodically with fresh water. Ali explained that these "constructed

1 http://www.h2o2.com/municipal-applications/wastewater-treatment.aspx?pid=146&name=Article-H2S-Control-Headworks-Odor-Control

wetlands" work best if they go through cycles of flooding and drying out - which may not always be what happens in an Earthship.

After some experimentation with various species in the planter they have settled on hardy ornamentals as other plants were not always prospering. Ali puts this down to the design of the Earthship which has vertical glass (typical of the "Packaged" design) and furthermore, her planter extends about 4 feet into the living room, deeper than usual. This makes for a colder than usual planter area which is not always suitable for a wide range of plant species.

Outside, the blackwater botanical cell works well and Ali explains that the conventional leach field they were forced to also install is redundant due to the grey and black water botanical cells using all their wastewater through evapotranspiration. They thought this would be the case and so it was frustrating to be told by officials that they had to tear up their garden to install the two 80ft trenches which comprise the leach field.

Their water collection and storage system works well although due to construction activities requiring lots of water, they have had to haul in water with a truck on a few occasions. Also since the children were born they have been using more water and their 3500 gallon storage (13,250 L) is not quite sufficient necessitating occasional water deliveries. After the September monsoons, they usually have full cisterns (tanks) but by April they can be quite low.

Laundry is done in a Taos Laundromat due to space constraints in the bathroom although provisions have been made for a future washing machine if this becomes a priority; however using the Laundromat helps with water conservation.

Electricity is supplied by 3 x 135W panels = 405W, a tiny system by western standards. Recently they had to replace their batteries (there are eight of them) which cost about US$1000 but this only needs to be done every five years or so. The gas tank is filled less than once per year. The fridge is an ultra efficient Sunfrost model. It is important that they observe the weather and conserve energy by switching off their AC inverter – relying on their DC lighting and fridge circuit only - if there is a string of cloudy days forecast; however, this only happens about 3 or 4 times per year during the winter time. During construction, on occasion they had to use hand tools rather than power tools due to cloudy weather.

The house works well for Ali and her family and Ali thinks it is a great way to bring up kids. She tells a funny anecdote about how her kids thought the municipal dump was a place you got things from (i.e. scrap tyres) rather than a place you got rid of stuff. She loves the way the Earthship connects her to the weather patterns, the seasons and the time of day: all these things take on a new meaning. And she likes the way the Earthship provides a daily incentive for conserving resources, in contrast to conventional homes which deliver a penalty at the end of the quarter – the utility bill. She says "there's an incentive to be conservative with your energy and water... in an earthship if you are not conservative you will realise immediately... there's incentive for behaving in the way I believe in behaving."

The only thing Ali seems to regret somewhat is her family's reliance on the car – for shopping trips and commuting to school and work. She acknowledges this is an issue and explains that they do what they can to car pool and minimise grocery shopping trips. She thinks it would be great if there was a school within the GW Earthship Community as this would help cut down on miles travelled.

When asked about how Earthship ideas will influence future housing Ali replied "I wish a lot quicker!". As an architect Ali has been frustrated by people's resistance to Earthship ideas. She says "people aren't ready for it" in reference to tyre walls and indoor greywater systems, so instead Ali focuses on integrating correct orientation, thermal mass, insulation and perhaps photovoltaics into her architecture. But in conclusion she says "I wish it was more mainstream".

C5.3 Interview with Ray (pseudonym) about his Earthship Experience
Martin Freney, 11 December 2011

Summary of Interview

Background

Ray came to the Greater World Earthship Community in March 2006 as an intern but stayed on as an employee of Earthship Biotecture and has set a cracking pace for developing Earthships: by September 2006 he had built his first. At the time of writing (December 2011) he has built two Earthships in the Gravel Pit: he owns one which he uses as a rental, and another which he sold to fund more plots of land in the Gravel Pit which he plans to develop with more Earthships. The Gravel Pit is an old gravel mine used to built the roads on the GW community and has become a test site for medium density, suburban scale, housing within the GW community, which is otherwise very spread out. The experiment will demonstrate how an old mine site can be rejuvenated by an Earthship development, the scared land being regenerated by the "waste" water and organics that the Earthships produce.

During his internship Ray was commuting back and forth to his dream home in Arizona on weekends – an 8 hour drive. This gave him an insight into the differences between conventional housing and Earthships. The first thing he noticed about the Earthship was they he just felt better being in one. The more he thought about his deluxe dream home in Arizona, the more he realised there were a lot of things that annoyed him about it, whereas the Earthship overcame these annoyances with effective yet cheap and ecological solutions: the artificial lighting that was needed during the daytime in the dream home was not pleasant whereas the natural lighting in the earthship seemed to "charge" Ray with good feelings and made him feel more happy and energetic, and perhaps another thing that Ray was enjoying about the Earthship was the wonderfully stable, comfortable temperature. In his dream home he realised he was tolerating fluctuating temperatures and noise caused by the gas heater which would constantly turn on and off due to the thermostat control. He also felt like the materials used to construct the dream home maybe the cause of winter illnesses, as it had to be shut-up tight in the winter preventing adequate ventilation of VOCs (volatile organic compounds) that were most probably emanating from the carpets and paints. Yet in the Earthship the natural mud plaster and mud floor did not have this potential for VOC emissions. The tyres used in Earthship wall construction didn't bother Ray as he was satisfied that air quality tests of Earthships conducted by the Environmental Protection Agency proved there were no health hazards in the air. And he felt great in Earthships – healthy, happy and energised – and this is obvious during the interview conducted in his rental Earthship.

After 5 and half years living in Earthships Ray has really appreciated the lack of utility bills. Although there is still a small bill for propane used to power the stove and backup hot water it is not much and Ray has plans to use methane from his septic tank to augment the propane supply and reduce his propane bill even further.

Food

Ray is also experimenting with the food production system of the Earthship with a range of innovations that will enable greater food production in the harsh Taos climate. He is building a detached greenhouse with mainly surplus materials that will have highly advanced yet autonomous ventilation system reducing the potential for insect problems. Amongst other innovations it will contain an aquaponics system with vertical growing boxes irrigated by fish pond water enabling him to produce fresh fish and vegetables year round. And he has plans for goats and other livestock too, as he feels that food production is the next frontier that Earthships need to address.

Energy

Ray's first Earthship home was the prototype for what has become Reynolds' Global Model Earthship design. He now offers this home as a rental. It has a 1000W of photovoltaic panels which, in the summer, has the battery bank charged by 10:30am! Hence, the middle of the day is the best time to use up the surplus energy for things like washing clothes or using the electric dryer.

To conserve power at night Ray suggests that guests turn of the inverter which cuts of the Earthship's AC circuit and thereby avoids any "phantom loads" that are inevitably caused by appliances such as televisions, and audio equipment. Lights and refrigerator are powered overnight by the DC circuit with runs directly off the battery bank. Ray suggests no hair dryers, hair curlers or coffee machines in his rental Earthship as these are well known to drain a battery bank.

He decided not to install a wind turbine due to the close proximity of neighbours in the Gravel Pit which is like a mini-suburb (medium density) in the heart of the expansive rural Greater World site. He was concerned about noise pollution that could annoy his neighbours – so he scaled up the size of his solar system to 1000W.

Water

He is not concerned about running out of water as he has sized the roof and storage tanks appropriately: 1200 sq foot roof and 2800 gallons of storage – enough to deal with the six months of drought in Taos. He also has the first water level "observation stem" (branch of clear pipe) which enables him to monitor the water level in his tank and water use conveniently from the comfort of his home. Otherwise he would have to go outside and peer into his water tanks. This enables him to say "hey honey... guess what!? We need to reduce our water consumption from 30 gallons to 27 gallons a day otherwise we're gonna run out!".

His indoor greywater planter copes well with the washing machine and other water use in the home. He explains that it is possible to overtax the system: it depends on how much laundry and how many people are living there. Yet it is engineered to overflow to a septic tank – which Ray has oversized somewhat to deal with extra people or parties. Ray is looking at ways to redirect overflow greywater away from the septic and using it for more productive purposes.

The Future

His enthusiasm for Earthship is motivated by a desire to secure a comfortable home for him and his 18 year old son, in uncertain times: rising energy prices and disruptions are a concern. He relates his recent experience in which the natural gas supply to Taos was cut off for 17 days during the freezing winter. Taos's electricity grid couldn't handle everyone switching to electric heaters and was blacked out. The National Guard soon rolled into the main street of Taos in their Hummers, obviously someone feared that things were going to get out of control, but Ray explained that strong family ties ensured that Taos residents supported each other in this difficult time. Although Earthship Biotecture organised emergency accommodation for people in their Visitors Centre at the Greater World (which was totally unaffected by the gas/power interruption in Taos) no one availed themselves of this charity as they were able to cooperate with family and friends who had wood fires or other backup heating systems to keep them warm.

Ray seems to be optimistic about the future although aware of the potential threats. For example, he is excited about the Tesla electric car he just ordered: so that he has somewhere to dump his excess solar power, and enjoy a sustainable ride into Taos, perhaps to trade some of his organic fish and veggies. But he is also realistic about other people's capacity to accept Earthships. There are barriers such as difficulty getting insurance on an Earthship for example and most people want to be able to leave lights on and have a huge TV. And the thought of a house made of tyres is not acceptable to many people, despite the reassurances of EPA air quality tests. Clearly though, Ray sees the potential in Earthships and the Gravel Pit.

C5.4 Interview with Sarah (pseudonym) about her Earthship Experience
Martin Freney, 12 December 2011

Summary

Background

Prior to Earthship life, Sarah lived in a draughty rental home in Albuquerque, New Mexico, USA which was impossible to keep at a comfortable temperature despite all the typical remedies such as fitting plastic sheeting to windows during the winter and turning the heater up to maximum. Finally getting fed up with her sub standard rental home and wanting to "escape the rat race" Sarah discovered Earthships and decided to move into one.

Design

Sarah's Earthship is of the old design built in the 90s in The Greater World community outside of Taos New Mexico, USA. The design has two U modules which was sufficient for Sarah and her partner although she lives alone now. There is a 3000 gallon cistern at one end and a composing (bucket) toilet in a nearby outhouse built into the berm at the other end. A kitchen is located centrally adjacent the greenhouse glazing with the power organising module in a utility area adjacent the kitchen with a small battery bank accessible above. At one end of the greenhouse there is a large planter dominated by a large fig tree and at the other end of the greenhouse, the other side of the kitchen, there is an elevated shower, about three steps up, surrounded by plants.

Thermal Comfort

Having lived in the house for many years Sarah is very proficient at regulating the indoor temperature by using natural ventilation. This involves "cracking" (opening just a tiny crack) the windows, roof vents, skylights and doors at appropriate times of the day. Very occasionally, during prolonged periods of overcast weather, she uses her heater which is an energy efficient slow combustion heater of Norwegian design. But otherwise she finds the indoor temperature to be very comfortable.

She has identified the source of various drafts and has solved this problem by installing improved weather seals. She is aware of the importance of maintenance to preserve the thermal comfort and has had potential problems rectified by simple maintenance procedures such as tightening the screws that fasten the mullion caps on the greenhouse glazing.

Energy

Sarah never runs out of electricity and she claims to enjoy the challenge of living with only two 220 watt solar panels. She managed this even when she lived with her partner although at times they struggled. The addition of a wind turbine (Airex brand) improved the situation resulting in a well charged battery bank first thing in the morning after a night enjoying music from the standard stereo system (as opposed to the energy efficient DC car stereo systems sported by many Earthships). The biggest electricity use is the refrigerator although this is a highly efficient well insulated design running on DC power (i.e. it is not reliant on the inverter). Sarah's panels are on a tracking rack which she manually adjusts, going outside about four times per day to ensure that it is angled appropriately to optimise solar gain, finally setting it back to the east to catch the morning sun before retiring for the night. Although the wind turbine has needed some maintenance and repairs Sarah considers it to be "no problem" and doesn't mind the swishing noise it makes which she can hear when she is outside.

Sarah's lifestyle is extremely energy efficient with little need for electricity, the little that she requires for refrigeration, stereo, laptop and phone charging are balanced well with her modest renewable energy system.

Water

Likewise, Sarah is extremely water efficient. Generally the 3000 gallon tank is sufficient however during a recent drought it was necessary to have water delivered in a truck. This was mainly used for irrigating trees rather than for domestic purposes. During construction of the home for various activities, e.g. adobe rendering, it was also necessary to truck in extra water.

Sarah doesn't have a bath, preferring the shower which naturally "splash irrigates" the surrounding plants and then drains to the main greywater planter. She does her laundry in town about once a fortnight thereby avoiding the need for a washer and dryer and the associated water and electricity use.

The waste water system works well, perhaps not surprisingly given the fairly low water use. There is no blackwater system due to the composting toilet which does not require water for flushing. A magnificent fruit bearing fig tree grows in the planter along with various other smaller non food producing plants as Sarah is not so keen on "being a farmer".

Transport
Sarah really doesn't like the fact that she is so car dependent and limits her trips to town (a 30 mile round trip) to about 3 per week. On each trip she tries to get as many tasks as possible done so that additional trips are not necessary. She likes the idea of electric cars but is pessimistic about being able to afford one and would prefer a futuristic public transport system.

Motivation and Outlook
Sarah wanted to escape the rat race, and not be subject to increasing utilities costs. She felt life was too fast and uncomfortable in the type of home she could afford. She saw Earthship as the perfect way to enjoy a more relaxed lifestyle. The idea of living in a community with people who could help build the home and maintain it was advantageous and preferable to living alone out in "the boonies". Although she finds the Earthship to be the perfect fit for her, she acknowledges that Earthships may not make everyone as happy as she is and she points to alternative such as Strawbale homes.

NOTES:
It was mid morning and a snow storm was forecast for the afternoon after a sunny morning. 12 Dec 2011.

PRELIMINARY DISCUSSION
Sarah: See how all the water beads up? That's why you oil every six months – religiously. Because it's still doing damage even if its rolling off so that rolls off and it gets all over this and so when I was painting this my friend was helping me, James said don't touch that wall till summer because when you paint it you don't want that water doing that on the paint that you've just put down.

So I'm having to deal with seeing this beautiful red and sealing cement but I know how to see things because you don't build a house for 15 years and not just be able to block things out – all these exposed tyres, I sometimes look at pictures

Marty: where are the exposed tyres?

Sarah: I mean these used to all be exposed and we packed out but still you could see the tyres and you know we were not going to tackle the walls until we'd done all this other stuff, well you just quit seeing it. And friends would come over and say ohhhhh and I'd say know isn't it beautiful and then I'd look at a picture and say oh my god what were they thinking they'd walked in and said oh she lives in tyres but you just don't see it. But I see that back wall now because I painted the front wall when I hadn't painted the front wall. I want to see more of this colour because there's not any colour until you see all the masonry work in the rest of the house.

Start of interview
Marty: this is one of the original design Earthships isn't it? Is it two U's?

Sarah: its just two U's. So this is his original design. We bought this house when it had been partially started we had the floor poured, it had tyres pounded, but not all packed out, we had plastic on the ceiling, plywood roof, I think they tyre pounded the cistern but it wasn't finished and then it was just under here. And so when we bought it at that stage then you clear it all out, OK its two U's and the power cabinet was in that was his original design was to build this box in this corner and on one side is the water and on the other side is the power so that's how he built the original ones, the box is here, and that's all and then we took it over from there. And a guy who has done a lot of building out here did the front face, because the kick up is ridiculous, you don't mess with that unless you know what you are doing. Built the front face, we got the glass in, we did the end walls and as soon as we had doors we moved in. So this was just basically cement slab there was no planter, that was it we just took it over.

M: It's beautiful. So what sort of house did you live in before this one?

S: A big sort of old rambling adobe home in Albuquerque.

M: and how has your lifestyle changed a lot since living in that house, how does this house change your lifestyle in comparison to that one?

S: in that one in Albuquerque your flipping plastic up giant draughty windows and in the winter you have billowing plastic in your living room and it's like oh my god and you've got the heat cranked up that's insane and you're still cold!

M: yeah so you don't have to do that here

S: that's one of the things that absolutely sold me. We came out here , my partner knew about Earthships, she had seen a couple of mike's books and knew someone who knew about them and we came up and we walked into the press office which is the old visitors centre walked in there I took one look around and just the feeling, put my hand on one of those walls, and said this is how we need to live I mean it was just instant, because you know when you live in houses and you're not comfortable for me that's huge I lived in Chicago for 3 years in graduate school and just about died and I just cannot be uncomfortable in my home that's crazy you have to be comfortable in your home whatever it takes so billowing plastic you know and still it was bad still it was uncomfortable so you know to be in the house and say wait a second when this house was designed they were thinking about billowing drafts in horrible windows that don't fit they were thinking about all those things. There is no draft in here. I used to have just kind of crappy weather stripping this makes you appreciate all the fine points so I just had this crappy sort of v weather stripping that we put on the doors, we didn't know, two white girls, what did we know we're trying to build a house, so we put this on and think that will work well when you shut the door like right now on a day like today and you put your hand right here and there was this cold air pouring in and it was like what do we do about that and then Ted said you need this curve there, you take the stops out and you put new stops in a big job but he knew what he was doing.

S: So it's stuff like that I appreciate, I appreciate that all the details make a difference, they all make a difference and you know what all of them do.

M: and you said today that you have a few things cracked open to get a bit of natural ventilation.

S: yeah I don't have this open yet.

M: so the hoppers are closed.

S: but this skylight which is not really a skylight see how it is just cracked a little bit and this one is a skylight and that one's cracked about that much.

M: wow, you've got lovely fresh air coming in.

S: I've got fresh air coming in and then I have to say things that don't work or are a pain in the butt... this is a bizilliion dollar operable window.

M: yeah, doesn't work?

S: well you know it's very heavy it's a Hurd(?) Window that's a good brand but after a while the window starts to sort of sink so that this mechanism can't really handle the weight of it so then I shut it and it gets to a certain point and I have to unlock and I have to go outside and kick the bottom and then it's a nice fit and I come in a lock it.

M: oh that's a rigmarole,

S: so what's really nice about an operable window is it's easy to crack that before you're going out somewhere, or like right now I'd have this cracked, but I don't have this kind of air coming in the winter so I just use this door. On a day like today I do that

M: a couple of shoes in the door.

S: so you know although that a pretty good wind I might not even crack it today I might just use the skylights.

M: there's a bit of wind today that the first wind I've noticed since I've been here.

S: yeah, and that wind is really cold

M: this is a shower here is it that's great

S: that's a shower isn't it great

M: wow!

S: nothing like on a day like today just a little sun and you take a shower right there,

M: how beautiful

S: isn't that great

M: this is terrific

S:you know this has to be the highest thing because it is gravity fed down to the greywater planter so if it's going to be that high we said let's make it a sky shower and we just did this isn't it cool

M: that's really cool yeah I'm really impressed with that.

S: everything is happy right there.

M: so how are those plants irrigated?

S: well I could have put in just a little drain there but I didn't do it

M: nah, so you just do it by hand

S: I just water it once a week

M: I guess they get a bit of a splash

S: they get a splash when you have a shower, and they're succulents so they do well with not a lot of water they like water but they know how to survive without it so they're pretty happy.

S: And this thing is insane, I just took some of those out and stuck them in here and as you can see they've gotten totally out of hand so I imagine going up the shower and being impaled on them. You'd find me in the morning - aaaaah (laughs)

M: oh wow!

S: yeah makes me think see these three little planters right here are going to be fine for some things that come up because when I'm 80 it would be nice to be walking up with a rail.

M: good thinking

M: so in summary your previous house was not so good, pretty drafty in winter

S: it was an old house I'm guessing it was 70-80 yr old built in alb it was adobe and they added rooms on you know and not really designed with anything in mind and you know it had these kinds of windows (sash) and they were ridiculously old and you know and cold air would just pour in everywhere. Now would I have ever lived in that house if it was my house, renting it wasn't much fun but that idea that wouldn't it be nice if you were in a house that you didn't have to go around, because everyone in alb is tacking up plastic in the winter it's like what! You do this every winter, well I did it too.

M: wow!

S: otherwise you're freezing! It's not warm in Albuquerque in the winter its' 30's.

M: so thermally this earthship is performing really well. You said you only need to use the fireplace now and then when the sun doesn't come out

S: I track it, I only had five fires last year, and I had four of them between Christmas and new years when it was grey for 11 days. An Earthship is not fun in the grey. Two days yeah maybe the third morning I'm deciding do I start the fire now and then you have the taste of what it's like to heat your house with wood – this is work! You know you never have an 11 day stretch like that, three days usually in a storm and then it's doing this (sunshine) and you're getting the sun again. But more days than that I'd have a fire either in the morning or at night if I was going to stay up and listen to music or something because I'm not going to sit there with a blanket on - that's stupid. But that is all that's used for. Otherwise, and that's a really efficient one that's the Yertle the Norwegian one, that's a little work horse, they've been making that for a bizilion years, very efficient, very low particulate and you know that will heat a 1000 sq ft but it doesn't' really go round the corner but this gets nice, nice and warm and easy to be in I can sit here and read and not be cold. And that's perfect and then you just wait it out and here comes the sun, it's like yeah, ...

M: how do you go in hot summer weather?

S: oh it's easy for me, I grew up in Phoenix, letting you know, so when I'm hot, its hot, I don't care it doesn't bother me that much, I have both my doors open I have both my hoppers open and honest to god Marty in summer I'll have this like this you know now when I crack it it's like that that's pretty good.

M: it's open about an inch. You can open it all the way up in the summer (SKYLIGHT?)

S: I get plenty of good cool air coming in, well not cool air but at least a wind and then I've got my doors open.

M: it's a bit of a fiddle isn't it?

S: yeah its one of those things I keep thinking I should attend to that. But see now the sun... just this much it is so much warmer.

M: it makes a lot of difference doesn't it.

S: and you feel it immediately, the sun's only been out about an hour and it's really significantly warmer. When they work they really work.

M: what about energy, electricity do you ever run out?

S: no

M: is that your wind turbine out there?

S: yeah, we've only got two 220's and it's not a lot of power but we were finding , and we had it that way for years because you know we sort of mapped out our energy needs what we though and said let's see you know when you're building that's $700 for a panel let's see how we can go with two. It was pretty good but when I really noticed it was winter like a day like today ok , id be out there tracking because our panels are on a rack that I can manually track and that makes a huge difference a huge difference. Also when we first had that poked in for a rack it was kind of low and the panels were about at this level but the parapet on my wall was just high enough that when the panels were really steep in the winter and I have them over like this that parapet was shading my panels and if any part of your panel is shaded you've wrecked the efficiency of your panels so that was a pain in the butt but had it extended - yeah - now it was all perfect not getting any shadow and I spend a lot of time at home luckily I don't have to be at a 40 hr a week job in town or something so I'll go out at 10 o'clock right about now – I'll show you – and the last thing I do at night is turn them for the morning. And you know is that exactly, well I suppose it is , I could just leave them in the middle but I'm here why not do it, plus the fact I love listening to music at nice so I'd love to have power so now see I have em turned up like this and now this is about 10 1030 and this is actually pretty good and then I'll turn it for here at about noon and then I'll just leave it there and then in the afternoon 3 or 4 I'll turn them over here and then I'll have it totally steep like this and turned here for the setting sun. Then I just turn it around and leave it for the morning. And because I'm here I can do that and I think it's kind of fun.

M: and the wind turbine is pretty hassle free?

S: oh it's great, no problem. I mean we never hassle with it. This is the second one. I had one for 4 years and it crapped out just suddenly stopped . but you have to take the tower down take it down but the company airax said yeah you know we have some trouble with this one, we now have a better one that has a really good charge controller in it and they just swapped out and sent me a new one and this one I've had for 4-5 years.

M: this technology just keeps getting better and cheaper

S so you get you know one of those little turbines one year and six years later it's like a whole different technology. I just like being that conscious I like having to supervise I think if comfort is all about unconscious that's too big a price to pay.

M: I'm just going to stand in the sun. is it sort of a bit of a game to you going out and making sure you have the energy in a way is it like..

S no its more about this is what happens... it's probably what happens when you spend a lot of time by yourself but I think about things so I'm thinking about how I think for me the comfort is in feeling this house is totally tuned finely tuned so that it's the most efficient it can be. And underlying all of this I admit it that sort of hideous experience I had in Chicago and I vowed I would never do that again and so everything finely tuned plus isn't there something wonderful like an engine that's finely tuned everything is working just right, that's what it's made to do, that's what these houses are made to do they're made to work exactly right so I love tracking the sun and saying ha ha now look my battery bank is 100% full and its 8 o'clock at night and want to listen to music.

M; can you show me how you monitor your energy levels.

S yeah it's really easy. This is just like a little RV monitor, a little display, that's what I've got right now in my battery banks and this the second little setting, tells me what I've got in amps, so right now I've got right now I've got 7.1 going in so I'm' thinking what s on, my inverter is on, and I'm charging up my phone and so that's what's taking some of the power right now. But still on a fairly in and out cloudy day 7.2 with the inverter on and something going is pretty good. Pretty good. And then the next don't ask me what this is this is amp hours and I've never been able to understand it. Here's the percentage of the battery bank that's charged.

M wow 96 percent.

S now that's biggest difference I saw with my wind turbine. On a winters morning I could come in here and my battery bank could be I the high 90s because all night if it's windy it's keeping the charge going. So in the morning I've got it. Now am I going to use a bunch of power right now, no, but if a storms coming Tuesday and Wednesday is going to be funky for power, if I need to do something like vacuum a rug I'd do that right now because I'd run this down some, the sun is still out I can probably get it up again and it will be fine and then I can go through today with no particular load. I don't use a lot of electricity. I have a sound system that is not the most efficient sound system in the world but I like having the components so it just takes more power. That's ok.

M ok what about water.

S water was horrible this summer, it was very scary, and I'll tell you something, I was talking to Ted about this , there's something for me that there's nothing worse than no water, I don't know you know no power tough shit that really just doesn't bother me at all, I've got little oil lamps that I light in the winter listening to music or reading I will light this oil lamp and that oil lamp just to have a little light in here so that when I come in here I feel like I won't trip on things

M it's a beautiful lamp

S it is pretty huh, it's an old one, old style anyway. But just having those going in here is enough to you know give me, or I'll light a candle on that little table right there, just so there is some light in here, but otherwise I don't have to have lights on I'm not a person who goes on the computer at night and stays on the computer I just don't. So I have plenty of power and when two of us were living here, my partner she liked more she wanted to be on the computer a lot and when we didn't have that wind generator it was clear in the mornings especially in the winter when you'd used the power last night it was going to be low the next morning. So it's pretty cool to use power at night and still be 96 97 % in the morning.

M so you are a big fan of the wind

S I'm a very big fan and here's the good news the wind drives a lot of people crazy. I've heard a hundred million people say oh my brains just scrambled, well first of all tough, you know and when I'm out there doing what I want to do anyway oh well its windy but when I can think that I'm generating power when that's going.

M so when you say the wind drives people crazy do you mean the wind turbine or the wind

S the wind, just wind

M because some people don't like the noise the wind turbines make or they don't like the way they look. Have you had any problems from neighbours?

S well my neighbour has a little airex as well not the spec house Justin's house, and it doesn't have this new charge controller on it so when its 50 mile an hour wind it's going REEEEEEEE and it sounds like somebody is about to land in your front yard, that's a little disturbing but otherwise.

M that problem could be fixed couldn't it

S he'd probably have to get a new turbine with a different charge controller in it and he didn't do that but you know that is noisy when that's going and I'm sure when mines going pretty good that could be... it doesn't bother me and when I'm outside it doesn't bother me but I can understand that somebody might say you know I'd just want to be able to go like this shut my eye and say listen and then that would be annoying.

M what does your fridge run on

S DC. Super super sun frost. Super insulated

M wow look at that

S I can shut this thing off overnight and not worry about it and I used to have to do that Marty when I had less power. When I didn't have the wind turbine, in the winter id shut this thing down because when you are running low on power and that thing goes on it's taking power.

This is super efficient I'm delighted to never unplug it anymore. That was kind of a pain in the butt. And I tended to be more conservative than my partner for instance. She'd say god you're in here in the dark and I'd say well I don't need to have any lights on right now and she wanted to have a light on and I think for her it was like we aren't deprived we should have what we want and I get that but if I'd felt deprived I'd have turned the light on.

M I've been stumbling around the hive for the last week with all the lights out and it gets to the point where you go actually I'm just going to leave a few lights on.

S yeah I mean you know walking around with lamps. Not really.

M nah that's for an emergency.

S I see all these houses out here that are going up and I know mike is really mindful of a sort of conventional view of homes and how to make these homes absolutely scream at somebody I'm not conventional so there are some concessions like walls and hallways and stuff but more is better is what people think and so how many panels on these panels and I'm thinking what are you running what are you using that you have to have that and you know I've got a 1500 w inverter they have 2500watt inverter for what and all those systems have that. We had Danny design this for us, we didn't need that much we don't need a big old power system but there's something about actually this she's been in it for maybe 3 4 week she went back to the middle east and she's coming back and she was talking about more panels and I said live in it, see, I think you're worrying you are going to have enough power and I think people worry about it, but as I say power as I say I don't care but I was going to say , water, last summer was the worst drought I moved here end of 96 and there was a drought in 97 that was pretty bad but this summer and I have trees which are not indigenous so I know I have to keep those trees alive by watering them and there about 8 yr old they need water so this summer I spent... I had 4 load of water delivered this summer and that's 1500 gal my cistern is big (3000 gal) and so I had watered them 4 times and each time it was I was using no water I was saving it all for my trees but when I would water I had to water every two weeks I couldn't let it go and so it was taking a lot of water and in the 14 yr we were building this house we had water delivered twice and both times it was when we were doing the mud or cement plastering using a butt load of water so that's ok we'd run it down and get it delivered because we had to do this work during building and during all those years to have only two loads of water delivered and then one summer four that's how bad it was. And I was talking to Ted there is something so creepy about drought I guess for me it's just the immediate connection you know every little ceratoid every little living thing out there is suffering, everything and it's hard enough for stuff out here with the little amount of water. It was just creepy. So I don't know I just thought I hope every summer isn't like this because I'd have to let some trees go.

M so the water deliveries were mainly for the trees you had enough water

S oh my god I don't use... I don't shower all the time. I just don't. And so I wasn't using the water for me. I was using it for the trees. I give them 15 gal I have 5 gal buckets a whole bunch with a nail hole in the bottom and I put three buckets around every three and I fill them and it slowly seeps into the ground so that's 15 gal times let's see

M so what happens to your black water?

S I don't have black water.

M do you have a composting toilet

S Mmm hmm out in my shed it's a bucket toilet.

M ok

S yeah I don't have black water

M you're not using water for flushing so that's very efficient so it's just kitchen sink and shower.

S so it was all going to the trees and I would just have to let some go. I would have to say that's how it is in nature. Some stuff is just gonna be able to make it in a place. Anyway these trees have no business here. Have a look around the lot next to me there are a couple of pinons like this, that can make it out here but locus trees no I'm sorry and they do pretty well for not being indigenous but would I do it again I think I'd put in Russian olives although they are hideous nasty trees that take over areas and rob them of all the water.

M this fig is doing well.

S yeah this is crazy. We made this planter and we put this dwarf fig in and we thought ok.. look at the size of this trunk. You can see where I've cut

M it doesn't look like a dwarf to me.

S can you imagine the bigger one? You can see where I've cut it. On solstice on the 22nd I'm going to cut everything off so it's just down to that trunk and then in January you start seeing little green stuff and then it does this. But if I didn't cut it down like that at one point it was all the way over here it was taking over the kitchen it's like no, no I can 't have that, but it is so happy here's my recent ???? right here so my intake from my greywater is right here it goes out this way, I can't every imagine what the root system of this is like but it is using so efficiently the amount of greywater I have in this planter that during the winter when I cut that down I'm gonna have to,.. this is my well so you know it is coming down through the baffles and then dropping down into the little well but I have a gauge so I can see when the water is too high in here and then I will use this hose and I'll water my berm out there to get rid of the greywater because that uses so much water when it's got vegetation on it that I never have to check my greywater so it's quite amazing how much water its using. Right now this is dry. But after Christmas I'll have to be thinking check my greywater level.

M what do you do for laundry.

S I go into town and use the Laundromat.

M would you do that once per week

S every two weeks. And you know luckily I have the time to do that. If you are really busy it is a pain in the butt. But for me it's easy. Because you know I'm glad they are leasing me their water and their power, I don't have to have a washer and dryer.

M that's a good way to think about it. I like that. What about transportation, do you do a weekly trip into town.

S: I try to limit the number and as I say I'm fortunate I don't have to be there all the time but I may go in 3 days per week and then when I go in I have a list of 6 places to go 6 things to do because I'm not gonna go in everyday, I don't want to go in everyday, and if there's one thing I hate about living here I hate that I have to drive a car.

M: would you mind if you had batteries in your car running on solar power?

S: oh I'd love it, I'd never be able to afford it but I'd love that but I can't stand that I'm having to go what is it 30 miles when I go in and come back and every time I do that you know it's just like I'm living so in tune with the world and nature our here and then I'm getting in my flipping car and then driving like that it's just you know I want pneumatic tubes I'm trying to get a grass roots movement going here you know like at the bank you go to the little drive in teller and you open the tube you put your thing in and it goes pneumatically, I want to travel like that, get in and then I'm in Taos and somebody takes me out at the other end.

M: I notice in the planter you have your fig tree is that the only kind of food producing thing?

S: yeah I'm not a farmer. I don't want to be a farmer. I love the figs and I'm just getting my last ones off now and that's been producing since summer. So that's killer. But I'm lucky I can afford to buy someone else's food and they can be the farmers so I do the CSAs and farmers market. I wish I lived in town so I could go to the farmers market every week early in the morning id love that but no I don't see my life are having to produce my own food – how fortunate is that?

M: it's very fortunate

S: it's very fortunate so I don't have to. I've had things, we've had cherry tomatoes around the shower, that's great but you know white flies like them too so now I get to live with white flies in order to get cherry tomatoes.

M: it's a trade off isn't it

S: it is and even this thing I love it , thank you very much for all the figs, I have to climb around this thing once a week religiously with spray bottle with don dishwashing soap nothing else will do and water and spray all the leaves because this gets spider mites and we spent 9 yr trying to figure out, organic sprays, organic systemic, predator wasps, all this shit and about this time every year this thing looked horrible, all the leaves were really brown and a bunch of them had withered already.

M: it's beautiful now. It looks so healthy.

S: "Don" dishwashing soap and water keeps it healthy. But once a week, so I'm up here like this and it has to be when the sun has gone down because you don't want the leaves to be wet in the sun, walking around, I just did it last night, I'll be here with my spray bottle and I'm kind of anal so I'm getting every leaf, so I work my way around them and I get up on the kitchen counter, but that is what it takes. And I won't have a sick plant to make me just feel ... and it was so hard every year to see those spider mites starting up on here and say god cant' stay ahead of em so it's really great when it's a healthy plant.

M what about materials used to build the house, obviously we've got the tyres and the bottles but I thought you might have some recycled or salvaged timbers and things like that

S do you know what this is? Feel it

M its cardboard

S this is the most labour intensive, cheapest, but we rag painted each one we verthaned each one and then my partner made a template and we put a template on each one and we scored one side and turned it over and scored the other side accordion folded it and then fitted it. Ridiculous amount of labour.

M You sealed it with something or other to stop mold or something did you?

S well verathane on top of the paint. Mostly you just put a sealer on it. But it's exposed; it's not going to last forever.

M how old is it?

S maybe 6 yrs

M its holding up remarkably well.

S and here's the great thing about using it a fixture like that you just get out the exacto knife and you cut a hole, yeah, that was really great, in fact when I had to get my seal and I had to get these stupid smoke detectors put in I just cut holes to expose the box and then when the box was up there, there was a little channel right there that was exposed I just cut a piece of cardboard and stuck it up there – easy! No tools or anything major. Yeah so that's a cheap material, what else, I think one of the coolest materials they use in these houses is lathe, I think lathe is the best, you can do so much shit with it, look at that, this was where when mike had all the plumbing done in this house because it was done when we moved in or it was almost done this is pvc that goes up here and this was for a laundry room, and so that would have been for a washer and dryer hook-up and so we were never gonna have a washer and dryer... lathe, lathe and sort of sculpture around there and then plaster it and the pvc is still in there but we didn't have to tear it out or cut it off but it's just like bye bye.

M cool hide it all away.

S so I love lathe. I think it's the greatest it makes for... oh this, this is lathe,

M and is this adobe plaster

S yes mud plaster

M: not cement

S: no no no mud plaster but this was cement plaster many times because we had lots and our friends kept saying why are you doing all that cement well we had a lot of tyres the way the tyres were in here and with pack out you have to come out pretty far and we did a coat of cement and another coat of cement and the guys out here said you 're doing way too many coats before your colour coat. But it makes for a good wall. But that's just lathe and this is can wall right here because when we did that we thought what could go here and it's like fake built and then we just built this can wall in front of it.

M: do you know what is insulating the roof

S: yeah 4" of rigid and then I think maybe that last, I dunno what goes above the rigid on the rooves, rigid and then maybe just plywood and some PBM. I think, I think that is all it is I think it is just 4" of rigid.

M: do you have a floorplan?

S: you know I thought of this when I heard from Kirsten and then you said the things you were going to be asking, I leant all my plans to an architecture student in Albuquerque and she of course didn't give them back, I'm hoping she still has them. That was about 3 months ago.

M: maybe if you could follow up on her.

S: what do you need in the floorplan, I have just the basic floorplan the 2 u, what do you need?

M: just the dimensions

S: this is 18 wide (skipping over the conversation regarding the measurements of the home – see floorplan).

M: so the last thing I want to ask you about is what was your motivation for living in an Earthship, I've already explained your previous experience you had some bad experience with previous houses

S: I really think there was a point, I was 47 and I was thinking you know I'm looking at coming up 102 I'm way too old so I'm looking at half way having lived my life, so how do you suddenly make it different cause I remember being in that rambling little house the cost is only gonna go up utilities were only gonna go up the rent will go up the cost of food would go up and I looked around and I saw people and I thought this is the flipping rat race this that flipping deal where you get in it and everything is increasing in cost so you have to go faster and I just don't want to live another half of my life like that. I don't. And this was the perfect... at least you know my idealised version of it, I didn't really know what it would be like to live out here but knowing that you are in a dwelling that was efficient and you wouldn't have high utility cost and you wouldn't be on the grid and at the mercy of the gas co and PNM that was really something that absolutely stuck about living like this. And I think too, knowing that it was a community where people were living like this not so much that I needed like minded neighbours but I wanted to know if when we were building and we ran into some problem there was somebody out here, and like Ted is such a great guy he'd come over and say "I'd blah blah blah" and I can't imagine building this in the middle of the boonies with no resources so it made sense that people were building houses like this and you could share your knowledge about it.

M: what do you think about Earthships and how they fit into the future of housing do you see this as a solution that lots of people are going to take up in the future as utility prices rise or do you think there are too many things about it that people are not going to be able to deal with.

S: I think people are going to be looking for alternatives to the conventional stuff but I don't think an Earthship is the only alternative: Strawbale, pumice crete, and one of the cool things about people out here, I don't know if it's going on in other parts of the world, but right here in Taos county people are thinking alternative they are not building the same fucking stick houses they've always built, they aren't, so there are lots of ways I think people could go, maybe everyone wouldn't go for an Earthship, that's ok, I don't want anybody in an Earthship who's unhappy because it's an Earthship, they should find something that works for them but I think that the feeling... at least seeing it is kind of fake up here because we're surrounded by people who are thinking this way and who are thinking about alternatives to conventional stuff, other places in the country they aren't thinking like that, there are places in the world they aren't thinking like that so it's kind of a pretend little kind of a fantasy in a way. There are so many people who are thinking this way – up here. So I don't know. I'm not one for dogma and so I think to be honest with you Marty that there is this sort of one mindedness about Earthships being the only solution, no they aren't, there are many ways to do things more efficiently. Now frankly standing right here talking to you like this with the sun on the side of my face feeling this warm and it's so flipping cold out there and I'm thinking are you kidding, who would do anything but live in an Earthship, but not everybody has this same connection with it but for me, perfect.

M: so you seem pretty happy and healthy in your Earthship.

S: sure

M: loving it

S: yeah yeah.

M: it's the vibe I get from you.

S: it's a total good fit. When people find their fit, they're happy and you can deal with other stuff as long as you feel like - yeah - and for me it's this, it's this right here. It really is.

M: ok that's pretty much all the questions I wanted to ask you Sarah thank you very much.

C5.5 Interview with Michael Reynolds, by Martin Freney

27 July 2009, Adelaide, Australia

Synopsis

Reynolds has recently developed a "Global" prototype of housing in the extreme hot/cold climate in New Mexico USA over 40 years using original techniques developed by him and his construction crew. He is currently demonstrating how to build this model all over the world, "tweaking" it as he goes, to adapt to local climates.

In an effort to drive the cost of housing down, Reynolds is also developing Earthship Village Ecologies (EVE) which is a model for developing Earthship communities based on what he has learnt from the three communities that he has established in New Mexico USA. By avoiding the cost of electricity, water and sewage infrastructure (and to a certain degree roads) he is able to develop land cheaply – he claims that half the cost of a house and property is the infrastructure costs – and combined with free materials he is able to deliver Earthships for the same price as equivalent conventional housing. However, the Earthship boasts a zero utilities bill with the exception of approx $100 pa gas bill. Reynolds hides the cost of the renewable energy, water and sewage systems within the overall cost essentially providing no option to buyers other than to "go green". Thus, over the life time of the house, the Earthship would save the owner many thousands of dollars of utilities bills, even when replacement batteries are factored into the costing.

He has recently received substantial funds from the state of New Mexico via Governor Bill Richardson to build a new educational facility on the main community (the Greater World) and another development called Sustainable Energy Experiences (SEE) in which families will be able to stay a couple of nights for an eco-holiday with an educational twist. With the SEE project he is proposing an extensive greenhouse that will link up existing and new Earthships creating an Amazon like jungle with food producing fish ponds and vegetable and fruit gardens.

An interesting hypothesis is that by "taking one foot out of the economy" via renewable water and energy, food production and communities working together to build homes for each other, people can transcend the grip of the economy over their lives and avoid the worst of future financial crises. He says the Earthship "takes care of you" as opposed to a normal house which you have to continuously feed in the form of utilities bills.

Frustrated by the slow progress being made with legislation (which he has tried to change through the correct channels, after being shut down for defying them) he proposes using an legal/political mechanism common to many countries call the Executive Order to enforce top down rapid change in terms of relaxing building regulations on specific "test sites" to enable experimentation with sustainable housing. He argues that carbon neutral, sustainable buildings must proliferate rapidly if we are to avoid catastrophic damage to our life support systems which he defines as the environment and the economy. He argues that failure is an important learning experience and thus the test sites will enable experiments to proceed safely with appropriate monitoring. He says;

"The dangers of doing sustainable housing slightly imperfectly are not nearly as severe as not doing it at all."

In terms of research Reynolds to prefers to just do it, and there is currently very little empirical evidence. He mentioned that the Brighton (UK) Earthship has had some studies conducted.

He claims that they have proved themselves in bush fires, and in earthquakes.

Transcription of Interview

MF: Mike thanks for agreeing to be interviewed. If you could start by outlining what it is you hope to achieve while in Australia and how your ideas could help Australian people.

MR: Well , Australia as well as any country, I'm hoping to, one, by going to other countries I've found similarities with our country, similarities with all countries, its and education for me, to further evolve this thing that we're doing, which is a sustainable housing prototype that is applicable on a global level and will lower the carbon footprint of human life on the planet. So I go to other countries to not only learn myself but to take what we have learned. Because we've been doing it for four decades, to take what we have learned and start applying it, and see if, one, if people want the ideal that we are talking about and two, if their country, their climate, their system will allow it, and I'm learning on both of those levels but overall I'm seeing every country wants to go green, they want to take steps to be sustainable, they understand it, the regular person on the street pretty much gets it, but the doors aren't open in terms of the legal system of allowing it.

MF: Great OK. You've been successful in your home state of New Mexico USA with introducing a sustainable development testing sites act with a view to accelerating the development of sustainable architecture, while you've been in Australia you've been agitating for this to be implemented here too, US, Australia and many developed countries have building codes that are arguably over restrictive and are preventing or retarding sustainable outcomes, and I'm also aware that there is a tyre building code in New Mexico could you talk a little about the process that you undertook in challenging these laws and then changing them.

MR: Well, I was learning the process as I went, along, I was naïve I was ignorant, I didn't know what I was getting into when I started doing this 40 yrs ago, also as I was doing it the codes and regulations grew up around me getting more and more stringent every year, when I started there wasn't much, so my first reaction was ignore it. Well, I got busted. My second reaction was fight it. I got defeated ultimately, you know, I fought some good battles but I'm fighting a whole state , a whole country, so I got crucified basically and it took a lot of energy to fight it. So my next approach was to infiltrate them and join them in their own methods, and become an influence basically play their game, go and get involved with law making and make new laws, I was successful at that but as that was going on the situation that I was observing and dealing with – the deterioration of the planet and its ability to sustain people increased exponentially and even though I was successful and saw that I could continue to be successful at playing the game that is out there with the rules and changing them and doing it the way of the status quo so to speak, it wasn't fast enough, it took too long, so it put me all into another emergency, yes that could work but we don't have time for that now, so its like the minute you get something patched in a dam another hole breaks out that is even more severe, so what we are seeing here is things are changing faster than that method will allow, even though that method was successful. OK, next scenario, I did learn enough about the legal regulatory system which is very similar in all countries that I stumbled on a method that is used for radical quick change in times of emergency and that is the Executive order. Every governor in the US has used it, every President has used it, and all leaders of all countries have used it ,one form or another of it, at different times and so I'm seeing that that is the only way to hand down an Executive Order to the more local administrators and governing people that can't break the rules themselves – they must follow the law it's not their fault – to hand down from the top a way of opening doors, those people will then be authorised to enable and fast track green building.

MF: So the Sustainable Development Test Site Act is going to bring about positive change through allowing green building to start happening in various places, so could you give an insight into what you anticipate will happen and perhaps what happens after the Sustainable Development Test Site Act, what needs to happen after that for sustainable houses to become mainstream?

MR: The test site act allows testing, in other words it basically paints the picture of this - because of fear because of fear of doing something wrong, if a politician or a commission or a council changes a law and allows a new type of thing to happen and in this case we're talking about many new types of things, cause we're talking building methods, energy methods, electricity methods, water methods, sewage methods, material methods, we're talking about a world of different things that need to be approached to get us into a different way of living on this planet. That is way risky and would take a huge amount of time – we just don't have it – so the testing site allows it to be taken not as an immediate change but an immediate experiment – it's a test and if the test proves encouraging and positive, it will take on its own life, people will demand it, if something works its going to make it – but it gives us the chance to trial and error things and find out what works and it gives us a chance to move forward rather than waiting to move until authorisation is there which takes forever in the bureaucracy of every country and so that is what the testing site is aimed at doing is causing action now – on a limited basis but still happening now, feedback goes into the society on the successes and failures and bear in mind that we constantly want to emphasise failure as a positive thing, failure is what you learn from and in a way it's a form for failure, maybe there'll be failures, maybe there won't but in the real world, failure is not acceptable. Here in these test sites it is acceptable because it is a method of learning. So that is what the test site is aimed at doing and then once those are out there in every state in every country in every town, city, there'll be more of them, they'll be limited at first but there will more of them and basically what you are doing is you are slowly transitioning - have you seen those signs where a billboard or whatever and it says once thing and then a cube changes and another cube changes and after enough cubes changes you can see that it is staring to say something else. It's another commercial that's the way this could work, it'll change cube at a time, you see it would be difficult to change the whole billboard all at once, you know to turn the whole billboard it's a giant piece of work up there, but changing little cubes is really mechanically easy and that's exactly what this does, changing little spots is mechanically easy for a legal system – its bite sized – you can ask people to take bite sized steps but if you ask them to take a giant step its risky, they can't really conceive of how to do it, so what I'm saying is, it's the old thing if you can go an inch you can go a mile. It's putting things into a comprehendible size that they are manageable easily – you can turn them on, turn them off, you can get out there and see its not working - turn it off. If you do something for the whole country and its not working you've got a mess. So it's these little learning experiences that will ultimately end up in change.

MF: OK. You mentioned having the ability to have some failures and that failure is a positive thing, I guess would it be your view that this experiment we've been doing for the last 50-60 years, conventional housing has been a bit of a failure in terms of ecology.

MR: It is failing now. That brings me to this (holding up a short strip of paper). Here is conventional housing and this is the system that we use in this world for decades or centuries. Due to population and the amount of fossil fuels and the nature of the situation this works. With more people and more garbage and more fuel being taken it starts to weaken (longer strip of paper, drooping a bit). And more and more it weakens more, but it's the same system - it's over, it doesn't work. The same system can work with certain numbers and certain time frames. A log cabin that is very inefficient and has cloths on the windows instead of thermal glass and whatever, if it is surrounded by tons of wood to burn and the guy has plenty of time, that system works, it even keeps him in shape as he's doing it. But multiply it by ten, by one thousand, by one million and you've go a problem. Somebody once said, if you had an invention or a way or an idea, multiply that idea by the number of people on the planet and see if it's still valid. So a good way to look at that is to take a tree as an idea. Multiply the tree times however many people there are on the planet and what you've got is a *beautiful* planet enhanced and gorgeous and sustaining itself naturally, take an automobile and multiply by the number of people on the planet, consuming fuel like a ravenous beast taking up the landscape with roads, endless issues… there's the answer. So the housing and the methods that we have weren't failures in a certain range of time and numbers, but they are now, and so what we're looking for one is to apply that philosophy of the ways we do things now must be following the ways that of things that can be successful in terms of billions and that is like trees and really in fact a lot of the answers I've looked for in developing sustainable housing, I look to trees for guidance, because a billion trees does nothing but enhance the planet and so a billion sustainable homes should enhance the planet, and I'm talking in everyway, how built, what put off, what they take, how they breathe and give and exchange with the planet, what materials they take, the quality of life, there's a lot of factors there. That's why it's taken me 40 years to even get something that works reasonably well, because you're not just dealing with shelter and structure, you're dealing with energy and thermal dynamics and electricity and water and sewage and biology and physics, and production of food even, so you're dealing with so many issues , the sustainable home we call the Earthship is actually addressing every one of the major problems that a country has, and here it is on a cellular level and a Mickey Mouse little business can address these, yes it took 40 years, so if the approach is right can you imagine the resources behind a country the size of Australia that can build tall buildings and cars and roads and whatever, if they addressed it in the proper way it would just – it would go off the charts – it would be fantastic. If all countries addressed these issues, and I even project these issues beyond - into politics - because if every person on the planet in each country could do this on their own (and poor countries could be helped by rich countries) but if each country took care of its people totally first and foremost - what would there be to fight about?

MF: It's a good point Mike I like that. You're message is reaching more people since the release of Garbage Warrior and your constant appearances in the media and on architectural television shows such as Grand Designs, or rather that was an Earthship inspired feature on Grand Designs, but the point is that your message is getting to more and more people, and more and more people are switching to the idea of being more self sufficient. Are you able to gauge the uptake of this idea through your book sales and online sale of plans?

MR: That, but also just the requests that we get to do things, build homes, communities, speaking, whatever, yeah, we're able to gauge that it is definitely on a major crescendo and we've experience crescendos and then it'll cool down. The crescendos always link with something that happens on the planet, like when Y2K happened, and global warming started, or when gas prices when up about a year ago, as something global happens, people start looking to sustainable ways, and then everything levels off and gets complacent again and then it falls down and then it goes back up with the next one but this one this time I think people are aware that it is a limited planet and they have been made aware by many things – the TV is constantly putting out specials on melting ice caps and pollution and shortages of water and crises, I don't think it's going to go down, it may not even slow up, if any thing its got a curve like this (up, exponential), so yeah we are noticing it for sure, and see I'm noticing that level of interest, but I'm also noticing that if you really do the research you'll find that the level of interest is still not congruent with the level of change on the planet which is going off the charts, and so the level of interest if very encouraging but it is still lagging behind, it is like a buffalo is chasing you, you are managing to run away from it but it is gaining on you, your moving fast, faster than you've ever moved but it is still moving faster and its gaining on you.

MF: So I assume that this Sustainable Development Test Site Act, you're hoping that this is really going to increase that rate of change with people – once they know they can start doing this its going to hopefully match the rate of change on the planet in terms of the negative consequences to the planet.

MR: Well I did think that, but now I don't anymore. It is a step but to get that act to be enacted its going to take an Executive Order and it may be that the Executive Order needs to even streamline the language that's in the act and just make it a bit more rapid-fire, quick, instant instantaneous because yes I had high hope and do have high hopes for the Sustainable Development Test Site Act but I'm seeing that even it will be too slow, we need and Executive Order that says fast track carbon neutral building permits now. I'm talking about a permit in a matter of hours if its carbon neutral. I've been through the law and the writing of the law and the voting on the law and all that and there will be so many what ifs but the point is the fast tracking of carbon neutral permits, people will be worrying about people taking advantage of that just to build a piece of junk with no permit, when I say the fast tracking of carbon neutral permits that means you're making a carbon neutral building, that means you can't hook up to any grids, that limits you right there, no developer is going to take advantage of this mandate and build a piece of junk that has no utilities because nobody is going to buy it. You have got to be a serious carbon neutral builder to take advantage of this, or you have to be a serious home owner who wants to simply take care of their family and is willing to take the risk, because it is really a shoot first ask questions later policy, you could build it right now and its going to start taking care of you within the next few months when you get it done, we're going to allow you to do that right away however its going to have language written into it – the Executive Order – that allows the authorities to come and analyse and scrutinise what you are doing to see if you've got a little nuclear power plant in your basement or something like that or if you are discharging funky sewage on the ground or something like that, and also in regard to that there is going to be language written into it, that's what they wanted in New Mexico and we're going to carry it throughout the world is, yes you can do this but there are a couple of restrictions, codes if you will about this, one is that you can't take water from the aquifers, you can't mess with the state engineered water usage of the country, you are taking water from the sky only, or the air, or some other means of condensation, or whatever, not from the conventional means of extracting water, that is one thing that is a given, another thing is that all liquid waste is contained if you're talking about a giant storage vat then you're probably going to have to top it later and dump it somewhere we'll you're probably going to get busted - later, but it allows you to present your ideas out there and use them for yourself and it is shoot first ask questions later and questions will be asked later, so its not just a carte blanche everybody do what they want anarchy, it is a *controlled* escape from the confines of something that isn't working.

MF: OK. You mentioned to me yesterday that you have some plans to setup some online training resources like some videos and other information to assist – I think you were planning to assist particularly builders to learn how to do this but also people who want to learn, I think you called it the permit pathway. Do you want to talk about that?

MR: Yeah, we actually have launched this with my staff, and what we are talking about is, well first of all we are going to do a series of videos, something like YouTube with them, on our site and YouTube, people put amazing amount of information and entertainment gets out to millions of people via this media so we're going to take advantage of it and we're going to address this situation that I have seen this all around the world, this dilemma of, why we're not building more green buildings is due to permitting, like if all the soldiers in all the armies in all the world would put down their weapons and pick up tools and start building sustainable housing we would have peace on earth and we'd really start living, but the reason they won't do that is because they can't get permits (laugh). It's really that ridiculous, so I'm going to paint the picture on YouTube of this dilemma and talk about the Executive Order and how it's written and get copies of it available downloaded so that this concept is presented. At the same time we're putting together a package of step 1, 2 – maybe up to 30 steps, that will guide people through how to get into green building. It's got to be designed right, drawn right, permitted, funded, its insurmountable to the common person who doesn't know anything about building to have to face that, so its like a big battle board and map and you're coming in from the east, from the west, and then your going to surprise them from the north, that is how were playing it, were not just fighting one battle, we're saying ok there's something to achieve by this direction, something to achieve by this direction, something to achieve by that direction, so we're going to do them all at once, so another one we're doing is putting out this Global model that we know will work in 80% of climates on the globe that are inhabited and we're just going to try to get them built so that people can walk in them. In other words were going to go to the country, were going to build the building and train other people to build them so that like automobiles you can go down to the show room and buy one and walk in it, you know if you buy a Toyota its already permitted its already meeting the emissions rules and everything, you just walk in and buy it, that is really the way to do it, were not a giant corporation, so we can't put them out fast enough so were doing a website that is probably going to be incorporated into our Earthship website and it's going to take people through step by step and they pay as they go, obviously we have to make this a business that supports itself, were not funded, so rather than people risking a lot of money before if they know if they can even do it, we take them through for a $50 conversation and then the next step may cost $100, the next step may cost $300 but each time they are gaining ground and they haven't invested a huge amount, they won't invest a huge amount until they have gained enough ground to be worthy of that huge amount, and the huge amount due to volume if we do this right will be less than the huge amount that it would take to hire an architect to design the building and that's another thing I've found out is that many architects are professing to be green these days but there is really the, the… if an architect has done one or two sort of half way green projects its going to be expensive for you to hire them to do it, because they are going to be doing everything for the first time or the second time, what we want to do is make it like automobiles, mass produced, and that's the way it is with us after 40 years, is everything were doing we've done hundreds and hundreds of time, so there's no doubt on price, no doubt on performance, we want to bring that kind of thing to people so were really dealing with about 3 or 4 different ways of attacking the issue of making sustainable buildings happen faster on the planet.

MF: OK. To take a guess, how many Earthships are on the planet right now?

MR: I'd say approaching 2000, maybe half of them we've had something directly to do with the other half has been like the Grand Designs one, they've trained with us, got our books and then gone off and done their own thing, and we appreciate when they don't call it an Earthship just in case they aren't taking advantage of everything we've learned and they make a mistake which is easily doable and of course we're the ones that talk about failure being positive, so we make enough of our own mistakes that we don't want to absorb yours too (laugh).

MF: and so if someone wanted to call their house an Earthship, would you expect them to have consulted with you in some way or bought your plans or what's the…?

MR: If they want to actually call it an Earthship we have to be directly involved with design, drawing and building, but based on an Earthship like grand designs earth, what did he call it, a ground home, based on Earthship, that's a compliment, that's basing it on a bunch of research that we've done and based on Earthship is fine, it just makes it clear that this guy did it based on Earthship and he screwed this up but its not an Earthship so its not the Earthship people who'll take the blame for that so to speak and affect our credibility because our credibility is important in that it allows us to go further faster.

MF: And there's no legal impediment to people calling it an Earthship, it's not trademarked or anything?

MR: It is trademarked in the US and now were working on it in other countries, it's kind of expensive, we don't bother with patenting it because we want people to use it but we want people to respect the use of the word Earthship and Biotecture because we coined them and they would be words... I mean Earthship is getting out there but Biotecture was invented after it and its passed it actually, Biotecture is a science now, Biotecture is a method of living and it's talked about all over Europe, people are opening companies, they opened one in Ireland called Biotecture Ireland, our word, but in a way that's good, it's a concept of living that involves biology and physics rather than nuclear power plants and so that's good, but yeah we will be getting trademark at least so we can decide how we want to control the use of it.

MF: And if this idea takes off in the future can you foresee a time when used tyres actually cost money to buy, and what do we do when the tyres start becoming scarce?

MR: well first of all I don't see tyres as the only answer, see, I'm just so amazed at how once people in massive numbers millions of brains get together on the same thought , my prediction is that before we run out of tyres, if it got so successful that we were threatening to use tyres up faster than we were producing them which is a *phenomenal* thing right now so we are not in any danger of that any time in the near future, but if we got so lucky that we were using them faster than producing them, that would mean that there would be so many brains on the planet thinking this way in terms of thermal mass somebody would come up with something better anyway – the collective mind will take over and take care of us.

MF: We're making 20 million waste tyres per year in Australia, so that is enough for 20,000 homes a year at 1000 tyres per home, that is a pretty substantial number of homes.

MR: That doesn't take into consideration the amount of tyres already out there,

MF: That's right there is a stock pile.

MR: But it will be a while before that comes into play. If and when it does I think by then resilient mass will be, resilient structural mass will be such a thing in everybody's brain that we'll come up with better ways to do it. But still as long as there are cars, see I can project all kinds of things in the future, I can see the cars of the future may not even have wheels, they are skating across the earth – we wouldn't need highways – we'd still need paths on which to direct them – but not pavement so to speak, so obviously I've seen enough out of the human race to know that once they have got a concept of something they'll come up with two dozen ways to do it, and automobile tyres at this point in time happen to be – there is no question in my mind – the best way to achieve structural resilient thermal mass. And if you add a few other qualities to that, structural resilient thermal mass that is indigenous to the whole planet, that is environmentally friendly to use, of course it's environmentally friendly to reuse tyres. There's no product at this point in time that has those qualities and that is also low tech and easy to use so you know we took people who had never pounded a tyre before but by the end of the day they were all tyre pounders - that 's that, and it was good for them, and there's a certain level of good energy after that's been done, so it's a good thing right now, and there's not really anything you can find negative about it, you can bring up some negative aspects but they can be easily squelched.

MF: OK. I'd like to talk now about construction and design issues, to start with, what other construction methods are you familiar with, and were you the originator of the tyre wall idea?

MR: Yes, it happened, it didn't just come on as a light bulb, I was building with beer cans so therefore I was in this frame of mind of using by products of our society to build with, and that had its own reasons, and the first energy crunch hit in the early 70s and I said ok they're talking about storing water in houses in 55 gallon drums and some old scientist once told me that you should build your house over a big pond and that would be thermal mass, and I started observing what is thermal mass: rock and stone and water and concrete is a little bit, its ok but it is not as dense as some of the others, what can you build with, dirt, adobe, but that's only allowed in certain areas because it can crumble and crack, its good but its not going to meet major standards I didn't think, and it wouldn't work in damp climates and on and on, so I looked around and said what else is there that we have millions of on this planet and it's not trees because that's insulation, wood is really vulnerable and burnable, termites, and I stumbled onto tyres and I built a few buildings just *stuffing* dirt into tyres not even pounding it and they still *exist*. I've got one in the picture tonight, and its just *stuffed* and I built three or four buildings just stuffing it, and then we started beating it in a little more with a hand held mallet and then we went wow man lets just go ape shit on this and we started with the sledge, so it evolved in the context of our situation so we basically developed it and then there's been many take offs on it , after some of our books came out somebody wrote a book on it, what they wanted to do was take it into a very conventional looking building and they tried and … it didn't get that far with them.

MF: was that Ed Paschich?

MR: It might be, he's out of New Mexico.

MF: He wrote the Tire House book.

MR: Yeah, they wrote some books and so its been taken off on several times since we did our first applications of it, so yeah, I don't believe there was anything like on the planet like that until we did it.

MF: So you didn't see it in a book, - you came to it on your own.

MR: We stumbled onto it ourselves just by trial and error by looking around. And we have the procedure, I've got pictures of tonight of the two first ones, actually I don't have the first one because it fell over, failure, the first one I stacked them up, I should have pictures of it though, but I stacked them up like lifesavers and filled them full of liquid mud…

MF: in columns not like bricks

MR: in columns yeah, and didn't snap to the interlacing of it, it just fell over, I actually got it to work but, you know, then I thought why don't we just stuff them and interlace them like concrete block and on and on and on, so I've got the awkward weird strange looking evolution of it in history.

MF: Wow – I look forward to seeing that. So you mentioned the beer cans, what about… you're an architect but did you experience any other construction methods before you got into the beer cans and tyres?

MR: I was briefly, I just got out of school , while I was in college I went to school on a co-op program where you work 3 months and then you go to school 3 months, it takes longer to get through but you can pay your own way, my parents didn't have any money so I had to pay my own way through school that way, and so your work was largely in architectural offices in the early days of your schooling you were an office boy but as you got halfway through it you became a draftsman and a designer and I worked in architects offices for the whole 6 years I was going to school, well I saw from that I don't want to do this shit, you know, I don't want that, so by the time I got out I was pretty sceptical on that whole thing, I almost quit and became an artist, because I needed more money than I could make so I was painting – I got good grades in painting – so I even had a gallery and sold paintings right off the easel so I almost quit and decided to paint but I wanted… a painting was decoration, you could make a message maybe in a painting but I liked the relevance of buildings but not the way they were happening so I didn't know what the hell I was going to do, and besides I was getting ready to get drafted, so I went to New Mexico to race motorcycles and get injured and avoid the draft, well I ended up getting a teaching job and then I started seeing these broadcasts on the news about clear cutting timber and I started sinking into all that and the cans being thrown all over the streets and highways so that's how it started and I had done some adobe buildings and some wood buildings and that was ok and being an architect for myself was what I did almost immediately, I got to do that, but I wanted… I saw something happening little by little, but I saw… I think buildings should be more in response to the environment rather than a fucking masturbation of an architect, that's what I started seeing architecture as…, I read an article once I'd love to find it but some woman wrote it, I think she was an architect, wrote it long ago, and I related to it immensely, she talked about the ancient architects being pretty much priests, they designed the temples, the pyramids, all aligned with the stars and the Pleiades and the planets and the sun and they tuned us into the universe via our buildings and housing was just of the people, people built their own houses, but the major buildings were designed by these architect priests that took the peoples' minds and linked them with the universe and it was an amazing position of the architect and then she said now days architects are she called them impotent puppets of the economy, clients just want to make the cheapest building they can and architects are just impotent creatures that just manipulate the square footage and blah blah blah, and use recall and whatever they're either that way or a few of the ones, I guess you'd call them lucky, I don't even think they're lucky I think they're pathetic but, that get extreme budgets to make these super super expensive buildings which in my opinion are just masturbations, and it's a waste of money… a lot of them don't even work very well at all some are kind of arty farty to the point of being a nice experience to be in or whatever but they are all super inefficient and certainly not green and a lot of them get ugly real quick and don't work and some of the ones that are still getting good commissions have buildings have buildings out there that are just pathetic pieces of shit so the whole architecture is like whatever on it, so I'm after something that is different, that's why its really good that I fell into the word Biotecture because - it came about because I wasn't allowed to use the word architecture in my work in New Mexico after they busted me and they said you cant even use the name architect or the word architecture in any of your business, so I said ok fuck you I'll make Biotecture and I did that kind of for that reason but then I went wait a second this is really what I believe in, this is it, and now its been picked up and they're teaching Biotecture courses and stuff, its pretty interesting.

MF: OK. Maybe if we digress a little bit from the construction, design issues because you started talking about priests… I've got the sense from some of your books, in particular one of your earlier books A Coming of Wizards, where you talk about some of the spiritual, metaphysical influences, and you've brought this up again in your latest coffee table book *Journey Part 1*, do you want to say anything about that because I guess it is not the kind of thing that comes out of a public lecture.

MR: (laugh) It could but its just too much pragmatic, you don't want to waste the time philosophising when you can talk about something pragmatic that can be done tomorrow, its more of a reflecting on things but it is, yeah I'm, ah, I don't, ah, what I think happened, what I think is the situation is, ah, I grew up in Kentucky and Indiana and went to school and was poor and blah blah blah and wanted to get the hell out of there and I got the hell out of there, when I came to New Mexico I was just like mountains and wide open desert and rainbows in the sky and stars and I just got opened I think, and I got away from the crap that was even in those days 40 odd years ago still was oppressive sort of, but its just a matter of chance that I just got awe stricken by the beauty of the world when I went to New Mexico and it just, it opened up my senses or whatever, I'm trying to make this as un-cosmic as I can (laugh), it just opened up my senses and things came in, you know, and the things that came in they hit me and never let me go, it still have hanging right beside my bed the colour picture, because I love the colours in the picture itself, of the four wizards, I see it every day, its like it made a lasting effect and yeah, I did put it in the first book and now in the journey book again, because I hadn't done any colour and it is still is an everyday part of my life and I don't know why those things … that stuff happened about 40 yr ago – the wizard stuff happened about 40 years ago - and of course some of it had to do, I'm sure, I was open but I stimulated myself , you know I did every kind of drug and everything you can think of but not on a regular, you know my rule was I never bought anything, if someone gave it to me I would do it, and so I did it all but nothing serious I was never stoned for weeks at a time, I did some peyote and mushrooms and whatever, but ah, one thing that did have an effect, its in that Journey book, was putting that coffer up on top of the pyramid and that I saw in old Lemuria which was the city before Atlantis its even more legendary or mythical but there was a picture, it wasn't a photograph it was a drawing, of a pyramid with a priest had an alter not an alter but just like an alter on top of the pyramid which is from all the pyramid experiments why its definitely - there is something going on up there a vortex of some kind of energy at different times, almost like tuning a television, with sky and stars and everything are, there's something going on up there so I built a coffer on top of a third story building, perfectly made pyramid, and strapped myself in it for every full moon and then watched the full moon come up, I'd be up there for an hour before and after the moon came straight across in our case the southern sky and it would be full as hell and be coming right across and I'd be strapped in a coffer up on top of a pyramid doing what you call gazing and I would gaze at the full moon, keeping my eyes not even blinking, and it would literally burn a hole all the way through my skull and out the back, I'm sure that was a treatment so to speak that opened things or whatever so that's about the only unnatural I guess - if you want to call it that - thing that happened. I saw things about where we are here that there's no way I could not act on it. Whatever it takes, I took me way beyond money, I see money as a tool to use to get somewhere, I'll never be without it, I know how to make it, and I will always make as much as I need but beyond that I use it to do whatever with this whole movement so to speak so it's a… it's a force – that's what it is. It's a force that I'm almost… I can't turn it off, I can't shut it down I can't stop, and I don't want to, and its fun, I'm not some victim of it or something, I'm having a damn good time doing this, but it's also… there's no way I'd ever stop.

MF: On the topic of money, you've just been quite successful recently with getting some funding from Bill Richardson, he's who?

MR: he's the governor of New Mexico who's been an ambassador to a couple of the last presidents in terms of going to other countries and trying to make peace over this or that so he's a global figure but he's the governor of New Mexico and he actually ran for president and he was then actually asked by Obama to be the secretary of commerce but then they always, whenever someone gets asked to do something they run their whole history out, and he had some questionable business things which I think they just overdo all of that stuff and he said rather than go through all of the dirty laundry situation I'll just step down and ask somebody else, but anyway he's a great man and good man - he's real, and he gave me 300 grand to build an education facility, he likes what we are doing enough that he wanted to fund a building that would show it to the public, and now our public officials in our county have asked me to go back to him and get more to add an addition onto it and we did and it looks like we have a really good chance of getting that, and a state senator, I mean a national senator, we have state senators and then the ones that go to Washington, one of our Washington senators from New Mexico wrote a letter of recommendation for getting this second batch of money, he basically said this is a worthy cause, give it to them, he's a well respected senator, Tom Sudore, in Washington so we've got some politicians that are not just bozos, they're high up there, appreciating and believing in what we're doing, so we're in a good position.

MF: That's great. Coming back to the design and construction, a common criticism of pounding tyres seems to be that it looks very labour intensive and it might give you a bad back or some kind of RSI so the question is often why don't you use machines and, why do you persist with the manual tyre pounding?

MR: I have nothing against doing it by machine, and I've done 40,000 tyres in my life, right in that vicinity and I'm not crippled. I have had both shoulders orthoscopically dealt with, rotator cuff injuries, but that was from in Scotland carrying a piece of plywood, it got caught in the wind and ripped my shoulder and the other one was from jumping the concrete posts in Paris, in the rain I slipped off of one and landed on my shoulder so tyre pounding hasn't fucked my shoulders, but I think that amount of physical activity is really good for you, I don't think there are very many people on the planet that will ever pound 40,000 tyres but pounding enough to make your own house and help a few other people do theirs, its not going to hurt you, people go to the spa and do a whole lot worse, and pay for it, so I'm saying the reason I haven't pursued the mechanisation of it, is because me and our whole crew actually love to do it and when you do it all day, I pounded whatever 6 or 8 tyres yesterday and at your request let other people do it, but on a day when our crew goes out to get a job done, I'll pound 25 or 30 tyres, and they all do too, at the end of that day we are just jelly rolled in terms of oxygen deprivation and its just so much fun to be that way, and we *love* it so we have no desire to mechanise it, although somebody wanted to and they weren't as physically adept or whatever, that's fine, but I haven't been inspired to pursue that direction, I have nothing against pursuing that direction but I haven't been inspired to do that.

MF: What do you think of the practice of removing one side wall of the tyre to make compaction easier?

MR: I don't buy it because one, it just slows up the process, if you've got a really good a really good tool you can do it in 5-10 mins but hell I can pound a tyre in 5-10 mins so its not necessary to do it and also if the casing is kept intact and you beat the earth into it and it swells then that automatically keeps it dense, the other way you have to tamp it from above and then you have the compression, you're taking away a tiny bit of the structural integrity which I think will come to play in the coefficient of friction in an earthquake, and things like that, so I don't buy it, it's not necessary, it takes longer, it takes more equipment, and its not quite as good. It's so good that tyre walls are so good that it doesn't really harm it that much but it's certainly not as good, I'm probably the world's expert on tyre walls, and I would have to say that that is not as good structurally.

MF: I've tried it and I've noticed that the tyre goes out of round.

MR: Yeah, it goes a little funky, but it's still very forgiving and whatever but why do it?

MF: In terms of energy Earthships rely on gas for cooking, for hot water boosting, and sometimes to power a fridge, do you see this as being a weakness and if not, why not?

MR: Well, no I don't see it as being a weakness, they rarely use gas for a refrigerator, the gas is used for cooking and backup hot water and so I already have in mind ways to eliminate that and we will be doing that , since that question does get asked a lot, we will be doing a few buildings that don't use anything, just to show, for instance cooking can easily be done from a solar oven and microwave and on days you can't use your solar oven you use your microwave which can run off the solar and wind power system and hot water can be backed up with storage from a resistance windmill, a resistance vertical axis windmill that is constantly, with a bit of a break on creating heat and the heat's taken down into the water in exchange, so those things can be done, the reason we don't do them on a grand scale right now is that they're such a small amount of usage that we make them the last things that we dealt with and frankly we have had so many other battles that we haven't taken that one on, but like I say, it is in the works right now, but no the reason I don't see it as a weakness is, ok, that gets you down to a 90% energy free building except for those 10%, if you want to call it 10 it probably isn't even that much, so I just project that figure, if every building in the world got to be 90% less use of energy and fuel we'd be ok anyway. You could just say 90 is the cut off point. But just for philosophical reasons we will take it all the way. How could that possible called a weakness, a weakness is really a weird word to use for it, but we will address it simply to keep that from happening because it is a stigma, that's what it is.

MF: so what would the typical gas utility bill be for an Earthship?

MR: A hundred dollars a year or less on a two bedroom home, I'd say, it used to be 47 but fuel has gone up, now it's a hundred dollars a year. When you say 100 dollars a year total annual utility bill that is a screaming success, right there, you can stop right there, but we can take it all the way.

MF: And so what about, batteries, they eventually die, if you factored in replacing the batteries every x years, would you need to be putting away 100 bucks a year for that as well?

MR: Well let's see the ultimate battery situation is 1000 dollars a battery for 6 batteries so that is 6000 dollars. They last 20 years if you treat them right. We used to use the 7 year battery but now we use the 20 year battery. So do the math… they get down to 25 dollars a month you have to put away for a new set of batteries. So $25 a month is what it would cost to replace batteries and so that is a fact, but that's just like the thing we were talking about before, what I have observed is you can reach in and find out things like that that are going to be replaced or whatever, of course if you are buying conventional utilities, hell they're going to go up $25 anyway, every one of them, if there even going to be available, but I think there is one thing about it and I agree I think batteries are the weakness of our buildings because batteries are not great technology yet, but they're going to get better, there's no question that they'll get better, but *what this does* to people and me too, I've experienced it, is when you get in a home that does everything for itself, that puts you in a different frame of mind, that puts you in an independent empowered position, if you get there by hook or by crook, you will find other ways to get there, because you'll appreciate that circumstance so much, so it just shows you that, I don't need a nuclear power plant in my life and I won't have it, so batteries are bad but not as bad as a nuclear power plant and so you know that batteries are not super rocket science, they are being improved all the time and now there is impetus to improve them because of the battery powered cars so that's going to keep happening, so what I'm saying is just getting there, to being off of all grids, anyway you can, puts you in the frame of mind that you see a whole lot of other stuff, and its like, I used to draw this thing on the wall, like a person is here, and they're going to come up here and here's a plateau they're going to get to, it takes a line of sight, the plateau is blocking your line of sight for something that is over here, and over here, and you're blocked you can't see, lets make this plateau a little higher, so what I'm saying is unless you go up to here if you stay down here you don't see what is even possible out here, you're totally blocked from knowing that there is a peak with gold on it out here, you can't see it until you get to here. So here is sustainable housing here, sustainable housing shows you things you would have never seen unless you went there, and so you go to off -grid housing how ever you can and then you're going to see basically.

MF: You mentioned to me yesterday you were talking about really energy efficient lighting and you've been talking about microwave and solar ovens, designing down reduced energy requirements to power these appliances, that is going to tie in with new battery technology.

MR: yeah all of that. I've got such hope for what's possible, and see even my first efforts, they're evolving now, but my first efforts were to try and make enough solar power to make life as we know it. Well, wait a second, I can change life as we know it to meet that half way, and so that's where I'm at now, so what I'm saying is Jesus, if I change life as we know it which is doable and I make independent power and energy and water, I mean the sky is the limit on the quality of life for people and the planet. If people have less stress to live, then they're going to treat each other and the planet nicer.

MF: When you say life as we know it are you talking about peoples' attitudes and behaviour about using energy and water or…?

MR: Yeah, life as we know it, people wash their cars, leave the hose running, leave the lights on, you go into a normal room and there's an entertainment centre on using power just waiting for somebody to start using it for real, and heating and fans and lights… there's this ghost load of power just being consumed even when you're in Mexico, all that shit stays on, when you go on a vacation, whatever, so when you change those kinds of usage patterns as well as the devices themselves, LED lights who gives a shit about LED lights until we started making our own power, now they're really coming on, now they're just coming on they're getting way better all the time, they used to be pathetic, but now they are getting pretty good, so I know now that I can light a room for $300 with LED lights, and independent of my power systems, see so what I'm thinking of doing, I'm going to take each room and light it up for $300 independent of the other rooms, so maybe I'll have 5 rooms that's 1500 buck s and then I'll spend another 5 grand maybe on an AC converted system to run some appliances and I've got my power centre down to 75 hundred. 65 75 hundred compared to 25 grand to make a power system capable of dealing with life as we know it. So those kinds of things are out there. So I mean I could just block myself in a room and work as hard as I can with a crew building what I'm figuring out at the same time for the next 15 years and still not go anywhere near as far as you can go in terms of taking this… this is scratching the surface of an amazing new world. This is what it is.

MF: You mentioned some costs there, in terms of costs, can you talk a little bit about comparing that to a conventional house and how you've tried to integrate your systems into the cost to encourage people to get into this type of technology.

MR: When I do something that I think should be done, I don't care what it looks like and I don't care what it costs and people just raise their eyebrows, both at what it looks like - what the hell is that, and you spent a fortune on that, how can that be anything that anybody wants, well you cant do something right the first time its going to look what its going to look like and its going to cost whatever, I don't care, I try to get people to understand that, you're first attempt is going to cost whatever, its sacrifice if you want to get anywhere, and usually the first demo in a country costs more than the replications, and don't count on the first demo being a model for costs, it's just getting a demo there at all costs, so I didn't care what they looked like and what they cost and when they started working good, then I started realising and seeing and addressing the issue that ok I've got to make these palatable to some extent, and so I try and make them palatable, I mean other people could make them more palatable than me, cause I'm just not that inspired to go for what the look already is, because I don't like it that much, so I'd rather just have a whole new look, Dr Seuss or whatever, and so that's one thing, but the cost is - what I found out is, these systems do cost a lot, I don't even what people to know how much they cost so I just put them into the building, and by virtue of the building itself being a very forgiving low tech easy to build way to build, the building itself is actually 20% cheaper than conventional building, so if you built an Earthship and hooked it up onto the grid it would probably would use less of everything, it would be still good, but it cost 20% less but that gave me the way of concealing the systems, so now through all these expensive systems in there and the Earthship costs the same of other housing, and its pretty true in every country, the Earthship can be built for the same price you're paying for a similar quality of house and even in some places, less, and its still cheaper because the living expense of utilities then gets added onto your living expense and in an Earthship it doesn't so the initial house investment costs the same and the operation is nothing compared to something continuing to increase if its available at all.

MF: OK, now moving onto Adelaide, where we have a temperate Mediterranean climate, water shortages, bushfires, heatwaves, electricity blackouts, also termites, what types of design features would an Earthship for the Adelaide plains have, and also what about the Adelaide hills where you were yesterday, where it gets a little bit frosty but no snow?

MR: Well in that we have developed the Earthship for 40 years in an extremely hot and extremely cold climate, we have a basic prototype, and so the way I look at is it is like an automobile engine, the automobile engine for a Porsche is the same concept as that for a Toyota 4WD truck, the Toyota 4WD truck is geared differently, has different chassis, to do what it does but it still has the same concept of engine as the Porsche which is meant to go 130mph down the highway and handle like a breeze but not to haul big loads and whatever, so its geared differently, so basically what you are doing is tuning an automobile engine differently for different uses. The Earthship basic concept of encountering the phenomenon at hand give you your utilities and your life, is the same just like the gasoline engine is the same, we simply take, and we made this universal, we've struggled to get this universal design together that we in fact call the Global design, so here in Adelaide I would take the Global design and tweak it slightly for different things, easy to tweak it for termites, add a few this and that to avoid the termite situation very much similar to conventional practices on avoiding termites but we can even take it further, and then in the hills it would probably be little different than out on the plains, but we are still talking about the basic design being the most appropriate one, and most appropriate also because of economics, and I've had a lot of people have the money to hire me to do a total custom Earthship, but I always tell them yeah we can get it all shapely and beautiful and everything but it isn't going to work any better than the Global model, the Global model is the best I can do, it looks like what it looks like and its priced what its priced which is the same as conventional housing of a similar quality but its got everything thought out, if I have to think of all that again I'm not even going to be able to get any price to do it as good as I did the Global over 40 years, over 40 years I've got a relationships and sizes and everything right with, see you can't , that's the thing that is important, you can't think about one part of this building without thinking about 6 or 8 others at the same time yeah you can extend the roof but what is that going to do, you can change the angle of the greenhouse, but how's that going to effect the temperature in the winter the temp in the summer the growth area of the plants the volume of the air in the greenhouse that you have to either heat or cool… the lighting of the building that you're trying to keep maximised, everything is inter-related and it causes you to have to think in layers, you have to think in probably 8 different layers to even begin to mess with this design, and I'll get people who say why can't I do this, well there is about 8 reasons if not a dozen why that is there, this is here because that, because that, because that, you change it you change other things, and I've let people talk me into that because I couldn't get to all of the reasons, and so they talked me into making a change and then as we're building it I'm going oh fuck, this isn't going to work now because of that, so the Global design is the way the truth and the light, I will always struggle with people to try and say let's use this and let's just tweak it slightly but let's don't redesign because it's going to be too involved and there is too much of a chance of screw-up on some other aspect of it.

MF: OK, and this is what you've documented in your book *comfort in any climate* – correct?

MR: the Global design came after it, the *comfort in any climate* was a step of evolution from vol 1-3 but the Global went on further. Like just in Montana, we increased the tube length from 20 to 30 feet because we've all experienced the tubes at 20 feet, yeah they put out some cool air, it's pretty nice, Montana it was fucking cold there, why, it's 30 feet and a little deeper, alright! You can't learn that stuff in any other way other than just doing it, that's my whole reasons for the test site situation, you can calculate your ass off, and pull out facts of this and facts of that but there is nothing better than *doing it* and setting down beside it and having it blow cold air in your face, and oh my god, that influenced everybody, so its constantly improving and it will constantly improve, but I'm just like, I'd don't care how much somebody is going to pay me, I don't want to do it, I'm almost like a my way or the highway person, you want to reinvent the wheel that we've invented, be my guest, I don't need money bad enough to go through the mental anguish of trying to fight through it with you, I know what works and maybe call me arrogant, call me whatever, I've been called it all, I don't care.

MF: OK, thanks Mike. You've done some experiments with straw bales in terms of insulating tyre walls, and straw bale building is starting to take off in Australia and in Adelaide and I just wondered if you could talk a little about your experiments and we were talking earlier about what happens when tyres eventually run out, would straw bales perhaps be capable of replacing the tyres but still using a lot of the other Earthship principles like greenhouses and the long east west floor plan?

MR: well, the answer to that is no in my mind. I always preface straw bale conversations with I appreciate straw bale construction because it is organic because, it is renewable, and it's a good thing, but I would never do it, I did a few times, but a building needs to have storage of temperature, straw bales don't store temperature, there's two things you want to look at, one is the storage that dense mass can achieve of temperature, and the other is trapping that temperature , via insulation, straw bales are insulation, they are not mass, so straw bale building will hold a temperature for longer than a building that is not insulated, but it won't hold it for a long time like mass will, so if you're going to go to the trouble to build a building, and you could figure our a way to get mass into it, I would get mass into it, so I would say that straw bales wont replace (thermal) mass buildings, they are there because they are green in that they are renewable building method but there's a lack of understanding there in terms of people not understanding that buildings need to be built with mass, I mean you have to have mass on the inside to eliminate fuel, straw bale buildings always need backup heat, a more minimal amount of it, but they need more backup heat, but we're building buildings that don't need *any* backup heat, and its coming to that, so straw bale buildings are a… if we ran out of tyres we'd have to come up with another mass way to build, and we are, I'm sure like we said before that people will come up with something. I've used straw bales for insulation on the outside of tyres and it was successful but I'm doing it again and this time its with volcanic pumice, I did it and so why am I not doing it again, well I guess I'm seeing that this is better, I did the nautilus with a tyre wall and then I laid up blue perimeter insulation about that far, and then I stacked straw bales, I purchased the straw bales – and that's one thing, they're expensive now when I did it they were 2 dollars a piece and now they are 6-7 a piece or more, so first of all they are expensive, but second you put them in and latch and attach them to the tyres and then you've got to wire chicken wire them or stucco net them or whatever and then you've got plaster on them with something that is rainproof and whatever, some people used to put plastic over them but that locks in the moisture, and so they now just plaster right on them and let them breathe but you still have the vulnerability issue when there is a lot of rain, you have to have the eaves to cover them really, you don't really have parapets with straw bale to have water setting on them, so they are a little bit vulnerable they are expensive and they are not mass and so the tyre building I'm doing now for the EVE project, I thought of straw bales but it just wasn't that impressive to me and I wanted something a little bit more substantial, and so I put a course of tyres out there, and I got real impressed with these glass bottles laid in mud and then spacing that out this far from the tyres and filling with volcanic pumice, rigid insulation scraps, Styrofoam, all kinds of stuff, it opened me up to have a combination of natural and found materials, secondary materials, and the bottles laid in mud are really cool because they are substantial, the rain will erode the first half inch or so but the glass protects the rest of the mud after you eat in a half an inch, and that's another thing, the plaster on the straw bales it just cracks more and more and more every year, but the bottle and mud wall just gets a little more character every year, the glass will never go away, and the mud can only erode so far and I've noticed that we've done quite a lot of these bottle and mud walls and they just look better every year, whereas plaster looks worse every year, even over cans, even over tyres, I'm not that thrilled with plaster. And I'm thinking of just veneering buildings with something else that is just more durable. Plaster is just not a really lifetime permanent thing. Every place I've used it or seen it used, after a decade or so it is starting to look pretty shitty, whereas some things like brick and bottles and mud and whatever, not just mud plaster but mud mortar, what I'm getting at is I am looking for finishes on a building that will look better every year, they wear in not out.

MF: I like it. Perhaps before we leave that topic do you think the types of methods you are talking about there with insulating the tyre walls rather than using the earth berm, is that going to be more applicable in high density urban areas.

MR: Yeah, that's one of the reasons I'm playing with it is because I get that question a lot. Areas where you don't have a shit load of land you can't bury, you've got to achieve a similar thermal situation which is mass inside, insulation outside, so there is still a super thick wall but its not going to increase the footprint of the building by anymore that a metre, metre and a half something like that. So we definitely have to pursue that to illustrate that this method can be build in high density situation. We're not going to build a hundred story building this way but you can certainly build 3 even 4 story building this way.

MF: As part of my research I'm planning to do a life cycle analysis of tyre walls, stand alone electricity and water systems, and compare them with conventional forms of wall construction and power and water supply systems, are you aware of any similar life cycle analysis studies.

MR: Well when we did, early on, maybe 10 years ago, maybe not quite that, anyway we went to Scotland and there was a group called SCI, sustainable something initiatives, forget what it was, I don't think they even exist anymore, but they got us over there to do an Earthship and of course had a lot of experts over there, and we got it watered down, it wasn't thrilling but we had fun, it was good, they actually did some calculations but I don't know how real it was, but that's the only calculations. We've had people put thermometers in the wall and ambient air and stuff, but we've done no real studies like that, I'm just like a pure, you know, proof is in the pudding type person, to me when I've got a building that's 70-72 year round, Fahrenheit, which is whatever it is Celsius but obviously that is a stable temperature in the comfort zone, that to me was it, I don't need to know much more than that, I think I see the validity in it when your talking about ok if you can illustrate that this building through facts and figures, that you can advertise through facts and figures that it has got zero or less carbon footprint, that's a good thing, but you can kind of logically look at it and deduct that, so it is something that I think is a valid thing to do, but I would rather pursue, still making the building better and better and better rather than presenting an argument for why it is better, but I see the validity in doing that.

MF: Yeah, and so you're saying that you've observed that the temperature remains in a comfort zone, is this just by checking the thermometer daily or something like that?

MR: Yeah we usually have a thermometer in the ambient space, out in the greenhouse, and outside, so you can look at 30 below zero F outside and 72 inside and when have that you've got a functioning building.

MF: Has there been any research on how Earthships would perform in an earthquake like on a shake table or...

MR: No, we've been approached to do that a lot of times, but it costs like 35 grand, the only thing we have there is, which you've probably seen the engineer report, that mentioned that its resilient and its got a good coefficient of friction and would probably perform very well in an earthquake. See we used to say that the tyre wall wouldn't burn because of the thing of wadding a piece of paper up and having air all around it and trying to light a book, buy logic we would say a tyre wall wouldn't burn, but we had not proof until one went through a forest fire and it didn't burn. So it is the same thing on the earthquake, when you try to imagine how a tyre wall can crack, the plaster on it can crack, but how can a tyre wall crack? It can't, and so unless the earthquake epicentre goes right through and just tears the earth open and breaks it, the tremor even a 9 point is not going to cause it to crack, and when we are building in an error that we know is prone to major earthquake we go for round shapes, fully round, because they are obviously a round shape made of rubber, it is about the best thing you can get for an earthquake. So again no testing just logic and ultimately one of these days there will be some, however there was an Earthship that we didn't build in around LA county in California, that did go through that earthquake and engineers came out and looked at it afterwards, and it was all like Jesus this thing looks pretty good, a lot of other buildings and bridges had fallen down, so we do have that… I should document that more and get more information on it, but word got back to me that engineers from around the area actually went to observe that building because buildings around it were destroyed and it wasn't.

MF: Wow that is really interesting. Now could we talk a little bit about your Earthship communities because I see that as being a really important and interesting aspect of what you are doing. Perhaps if you could talk a little bit about the financing of these and the by-laws and how people are affording these, and are they able to sell their Earthships easily, and also, if you could talk a little bit about what is going on now, you've mentioned the EVE project and your new educational facility.

MR: The communities were initiated because we had started observed that we've got buildings that don't need infrastructure, and developers of a subdivision would tell you, anyone would still tell you, they'll tell you that half of the expense of a home is the site development, the roads, the power, the water, the sewage, the developers developing homes and land, placing homes on it and building homes and selling the turnkey project *half the cost is in site development*. So we said wait a second, this is why started doing communities, we said wait a second, we've got buildings that don't need site development, they'll go on any site, they don't need infrastructure, let's just cut the price in half right now, lets just buy a chunk of land and that's what I did, I bought a chuck of land at REACH then I did it at STAR, I bought a chunk of land and I said ok, here's how much this land cost me, I'm going to charge, you know, 5% more, I'm going to sell memberships to this piece of land and I'm going to charge 5-10% more as a whole to pay me for my time which is still miniscule and so membership to a piece of land, I didn't put in roads or nothing. I said get a 4WD vehicle and we'll just create the roads, I'll place where I want them to be, because I want all of your money to go to your house, and then we'll teach you on somebody else's house, how to build your house, so I had people going by the highway and pulling in giving me a $100 down and starting to build their house the next day – *it was fantastic!* People were getting housing like that (clicking fingers) and it worked and the government wasn't even doing that, they were building their own house themselves, and so it's like we were putting housing into the hand of people – it was fucking thrilling, so I got busted then on everything, because you are supposed to put in roads, and utilities and I said but we don't need utilities but they said you're going to have to put them in anyway, so I fought that and I won, but anyway the idea was to cut the price of housing, because I made a drawing in court for the judge I said your honour here is a person, and here is their home and here is Mt Everest between them and their home, and that's made up of land price, well, survey, realtor, banker, lawyer, bringing in power, water, sewage, you know like no wonder a person can't afford a house, I said your honour what I want to do I want to do this, I want to take that away and make it so people can get their house, and I said the governments not even doing that, so that's why we started the communities and, we lost, but we did gain, so now I just go into every battle knowing I'm going to lose something but I'm going to gain something, but you're not going to ever win everything. We won the ability to continue these to build these building, we got variances for all the systems we didn't have to put in utilities, but we had to survey all the land and put in the roads and do the archaeology studies and all this other stuff and so it drove it all up to being expensive, not expensive but close to being as expensive as regular buildings, and then we had to give them what they wanted in addition to what we wanted, it was a watered down version of what we really believed in but it was really good to have gotten at least that far, and so the communities now are… they shut the REACH one down, because there is no way they're going to approve a community on a slope that steep they can't get emergency vehicles there blah blah blah blah blah, so the houses that are there, people can still occupy but we can't build more,

MF: they can't be sold can they?

MR: yeah, they can be sold, they just can't build any more. The Greater World is a happening community. Its got about half of the people in it that its designed for, its really cool because it has the circular lots, and they don't touch each other and so the animals – I've got a picture of that – I've got a picture of elk, sand hill cranes, and lizards and stuff all cruising through the community because nobodies' lot touches the other lot and so we are settling amongst the animals rather than displacing them and I think that is the way the whole rest of the planet should be settled. Nowhere should we just go in and clear out and put in a subdivision and pave and lawns and everything that was there is *wiped out* – that's the way development is. It's not that way. We go in and make these little circles, and the people are essentially in cages and everything that is there still stays there.

MF: and are they circular for ease of surveying?

MR: well that's really a cheap way to survey because all you have to do is locate the point and the radius, boom you're done, but they're mainly circles because we want the elk and the lizards and the coyotes to still be able to go through, and the grass and the snakes and everything to be there, you can't ever do anything here, so we are amongst what was there, not replacing what was there, that's the rationale for that and that's the way they are. And so the Greater World is happening good, STAR is another one just the size of the Greater World but its got 7 miles of really bad road, again, it didn't bother me, get a 4WD vehicle and you're in and out, and I'm even talking about getting hover craft and selling them with the house, because its just an extra 25 grand for a hover craft and then you don't have to worry about the roads, so we're going on with STAR, its more remote and probably about the time we get really into it the road will get paved part way out there, but part of it is going through easement of private land, and I would have to do it, it means a million dollars, I don't have a million dollars, so STAR is going slower as a matter of fact we aren't selling any lots at STAR until I get the subdivision thing done, so the communities were started out to own the land in common to take the cost out of the land and cut the price of housing in half but now we at least have cheaper lots and the price of housing is down but not what we really wanted, we wanted housing to be like I said, walk in put down 100$ and start building your home. That was the ideal that we started with and it got squelched.

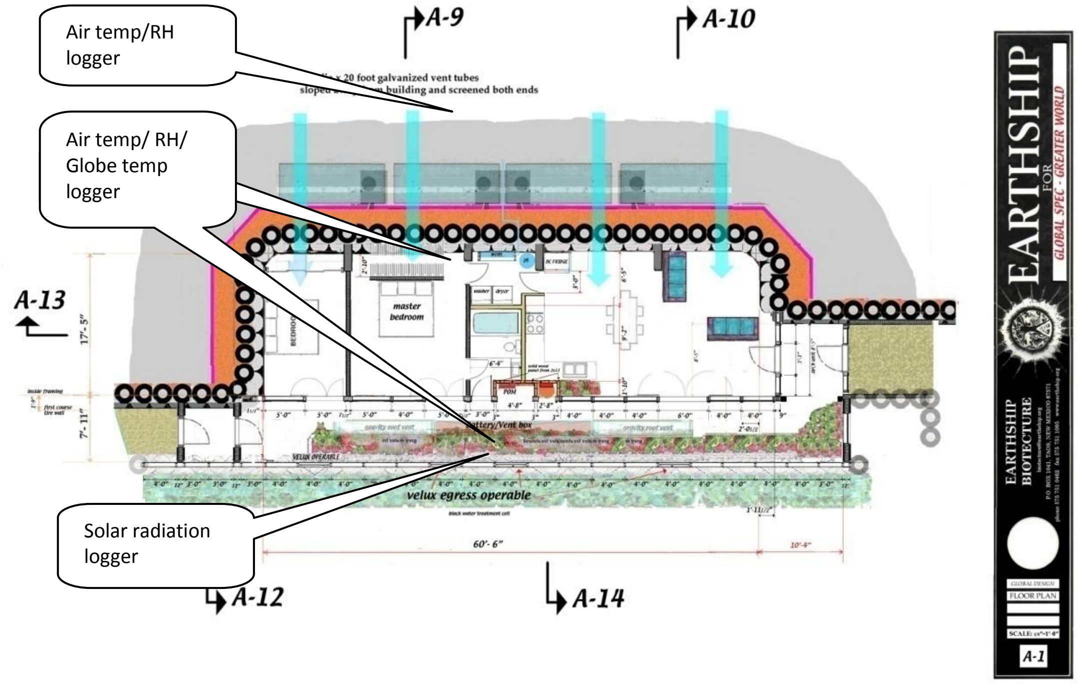
MF: If you just talk a little about you're plans for the future, you've mentioned EVE and also other developments in the pipeline, you've mentioned something in Oslo, the mushroom I think you called it.

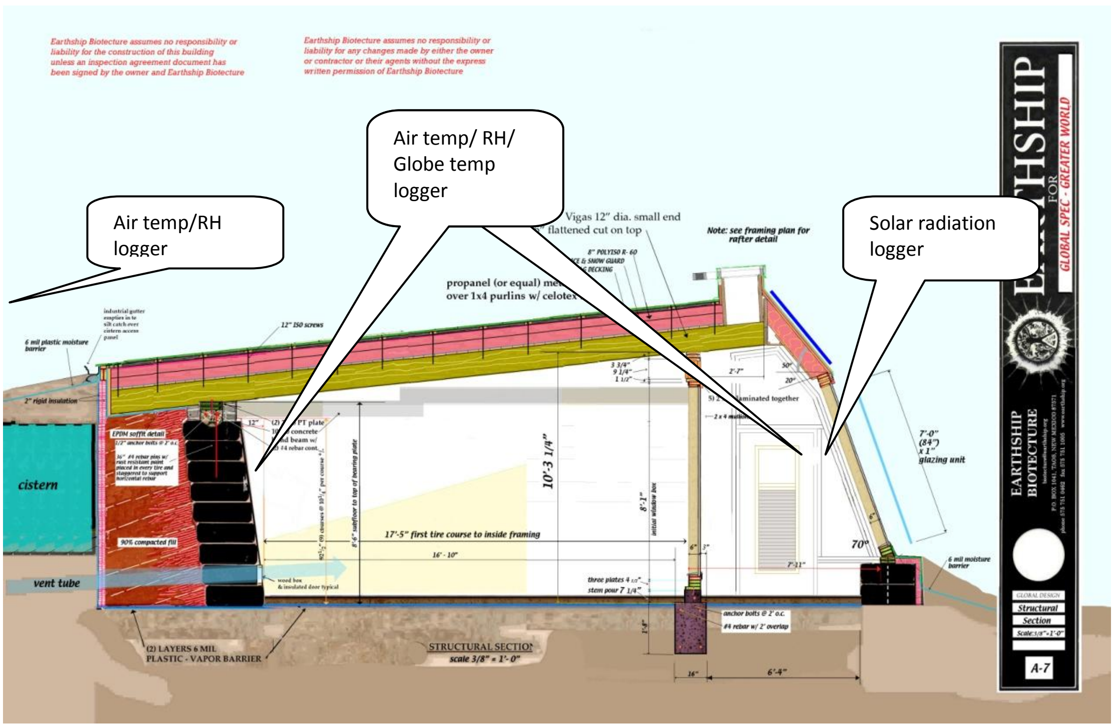
MR: EVE got inspired by... I'm starting to see and I see it many times over it comes through my head, like we've got the thing that we were working for in terms of a building we've got it, we've got a building that is pretty much carbon zero, has pretty much no utility dependency its there for the people, its priced in the same ball park, and I keep saying not that it won't improve but we've made it to that point as far as having the product. So then I start saying what else do people need, well I got this winter when we were in Holland we had the economic crisis where people lost their homes, they lost their jobs, regular people like you and me lost everything, due to economics being… the economy, the sustenance of people is subject to the economy so I decided with EVE that I wanted to make a stab at making the sustenance not be subject to the economy, because we are already half way there in that we don't need utilities we don't need water, we don't need power, we don't need sewage, we're growing our own food, we've already taken one foot out of the economic clamp so to speak so why should sustenance at all be subject to the economy, and also I noticed that people tend to, some of them, want to be kind of clustered together, I've heard people say even out at the greater world, you've seen how far the buildings are apart, a single woman said she felt isolated out there, and even though she loved her Earthship that she built herself and got for practically nothing she just felt isolated, she wanted to be with more people, single people especially, but even couples with kids, there's some people that want to live together and it does have its advantages and that and the fact that I'm trying to make it so people can not have to have the ability to borrow 300 grand to build a house which we get paid to do it but still I'm wanting that not to be the case, so EVE is aimed at making the sustenance of life available to people for a teeny fraction of what it costs to build your own house and attacking the economy and its grip on people and so the idea there is we have sustainable building, we're going to experiment with making it more sustainable with more techniques so we're going to make it a testing site so that we can take all of these new ideas and evolutions of what we are already doing and make it cheaper in terms of the building but then we're going to cluster together all of those buildings that are there at the architects' office and the round ones too and the rental units on the east and the press office, and make that into a compound for 25 people, it's a shit load of work to do, we're going to link it all together with a food producing, fish producing jungle Amazon greenhouse water running through it and everything, and birds flying around, and create a whole world that is worthy of visiting - by the public too - and that's going to take a lot of work, so we're going to put people in it that want to work on it, that want to build it. It's also going to involve a garage that converts vehicles to veggie oil for those people, we're going to be minimising their trips to town because their job is there, their home is there, and most of their food is there and when they do go to town they are going to be running on veggie oil. So its like all of that together if we take fuel, food, utilities and housing out of the economic equation because they are going to pay a teeny amount of money as rent, that's what we're going to buy materials with, but they are going to work and trade for living there, and how ever long they work is how many months they clock up that they can live there, and there is 5 or 6 years of work there at least for that amount of people and it will slowly start off and increase and who knows it may just keep increasing. We're going to learn from that and setup a model, and we're calling it Earthship Village Ecologies (EVE) and that model then we're going to take all over the world, just like we're taking the Earthship all over the world, and that is our way of getting back to ok, we walk in put down a couple of hundred bucks, inflation happens, walk in put down 2 or 3 hundred bucks, and you can start living, and working and eating and shitting and showering you know, it's like we're trying to make a walk in life that… - lots of people can get 2 or 3 hundred bucks together, you can join this walk in life for 2 or 3 hundred bucks and then you might have to pay a little bit each month to rent, but it takes a lot more 2 or 3 hundred bucks a month to live, everything is provided for that, employment, and so say a person comes along with 10 grand in their pocket, how long can you live off 10 grand at 2 or 3 hundred bucks a month, and then we filter some of them out and throw them into a work crew and they make a few grand and come back, we're going to play that off of the real world, greater world community situation, but it's a method of taking everything we know. See there we can combine systems, one power system is going to do half the building another one is going to do the other half and it's a huge building and we're going to do this individual room power and some other things that I've been thinking about but the overall objective is taking it one step further, we've got power, water, sewage, food, comfortable shelter, we've got fuel *and* we're not subject to the economy, the economy is for TVs, motorcycles, things like that, and computers, you're sustenance of life should not be subject to the economy. So we are playing that game with EVE. So that is one thing going on, we have it going on at different levels, the governor gave us the money for the educational facility, so now we're getting money for a project called SEE that is in addition to the education facility, that is Sustainable Energy Experiences, it's funded by the department of Energy, Minerals and Natural Resources in the state of New Mexico and they want to show conservation of energy and so we're taking all the Earthship concepts of course that show that, just like the Phoenix, but what were doing is making it a four unit nightly rental so four different people or families can stay in these four units and experience all of this, tilapia growing and grapefruits and bananas growing and grapes and food and heating and cooling and solar power and water harvesting, they can live with it for a day or two, and experience it rather than just seeing pictures of it on the wall like at the visitors centre and so that project is going on. They'll pay big bucks, not as big as, we'll make it 10% cheaper than a Holiday Inn or whatever, we'll make it cheaper but it's an education at the same time, that's playing the real game, and from that kind of stuff we are able to play the EVE game - which is trying to escape the game. So it is sort of like robbing from the rich and giving to the poor, only we're not giving anything to the poor, we're making them earn it, and we're not stealing from the rich, we're giving something to them, but we're playing one game to finance another game, it's a multilayered situation there and then we're doing projects around the world like the Oslo mushroom is, we're going to charge them an arm and a leg, it's an art piece, we're going to charge 'them a million dollars if we can get away with it, they want a four story mushroom that will be an icon for the city, and they want to emphasis the recycling of bottles which they produce a shit load of and they want it to be solar powered in terms of the lights inside that shine through the bottles, that's their green statement, so it's a big hoopla but its not a sell out because it is attacking a few of the principles so we will make bank on it. So we have all these different levels that all have to have a certain level of priority of what its about, we won't just do anything, but we're doing some things to make money and then we're doing some things with that money and it's all about furthering on different levels, it's all about coming in from the east, coming in from the west, surprising them from the south, and making them think that that's what their facing and then all of sudden we come in from the north, so its like we've got a map of the reality laid out and we're attacking that reality from four different directions.

MF: Alright Mike, we better call and end to this because we've got to see Brett and George, but thanks very much for that.

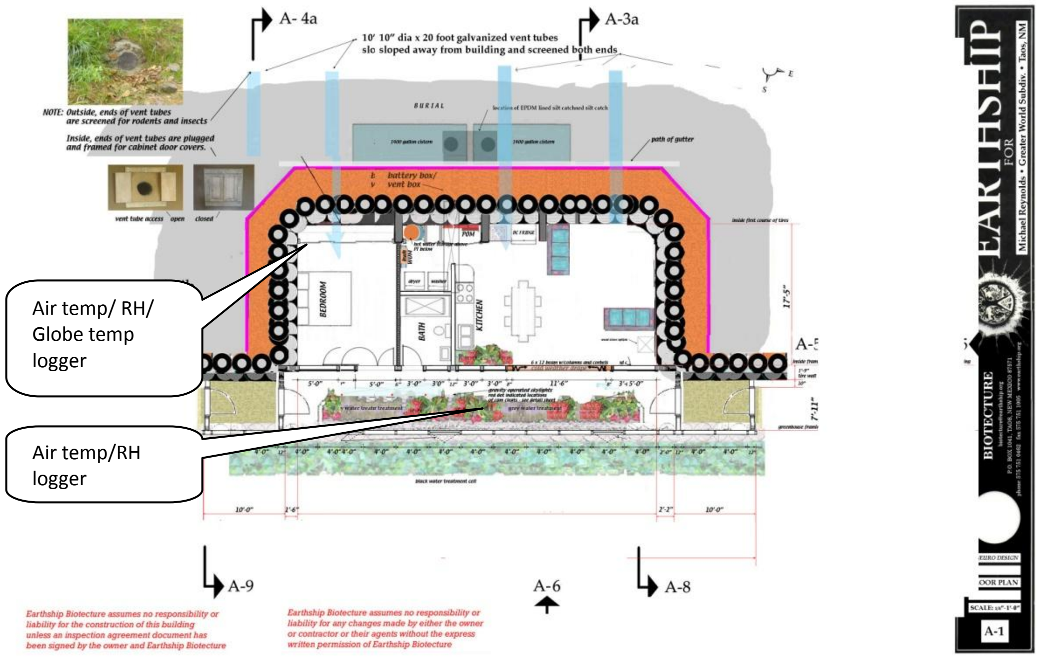
C6 - Monitored Houses and Logger Locations

House #1 Floor Plan





House #2 Floor Plan



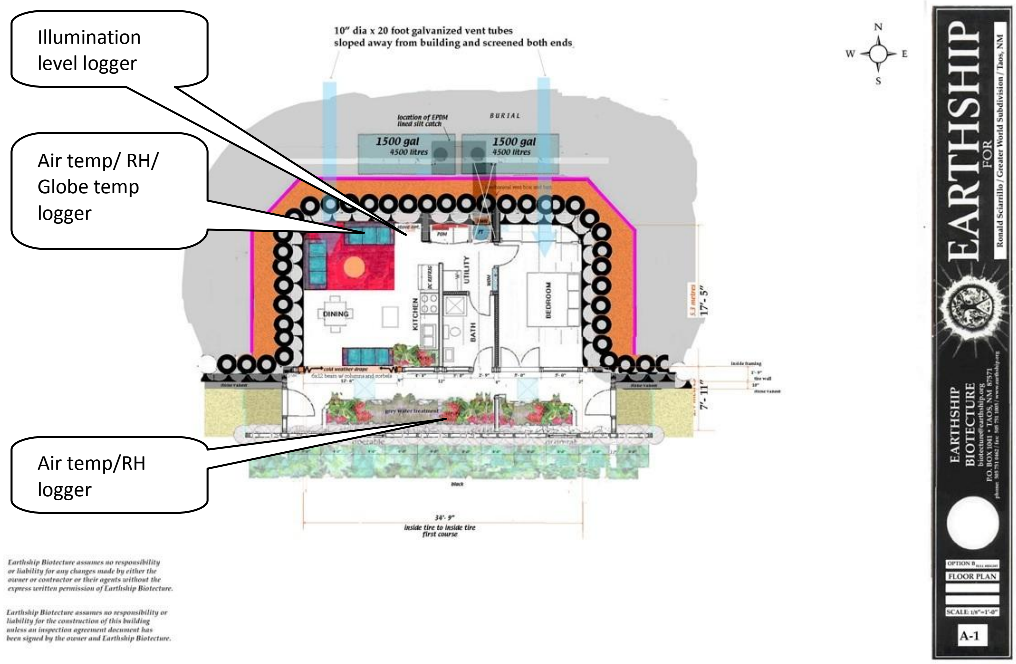
Refer to House #4 for section view – identical design

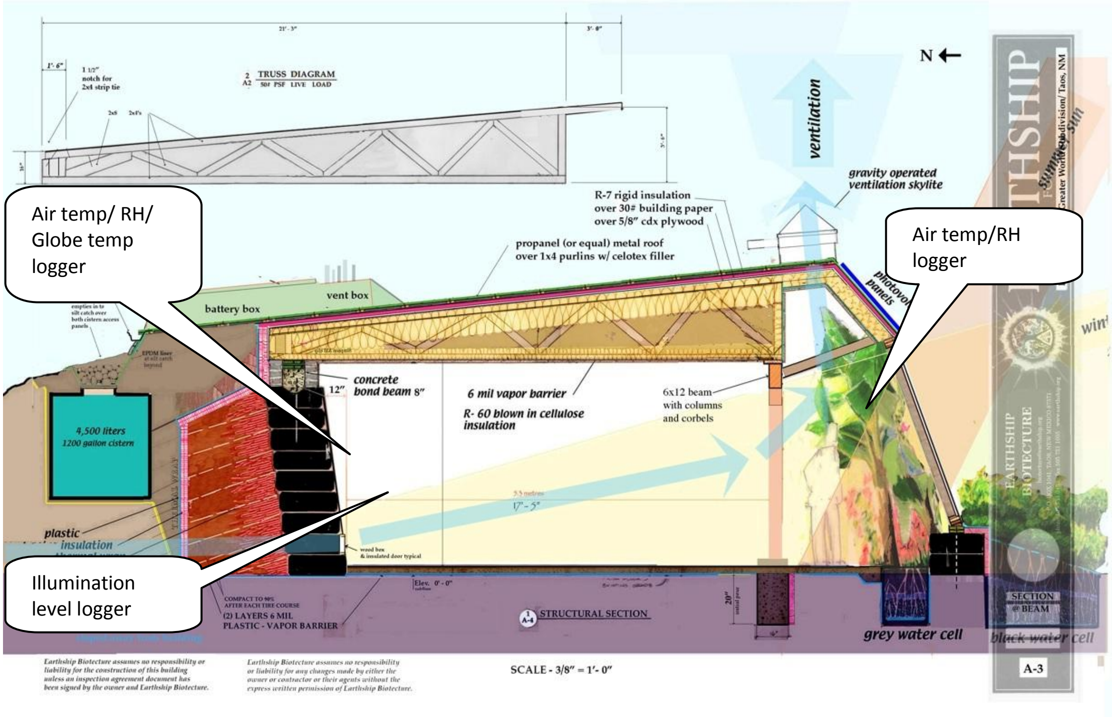
House #3 Floor Plan

Refer to House #2 – identical design

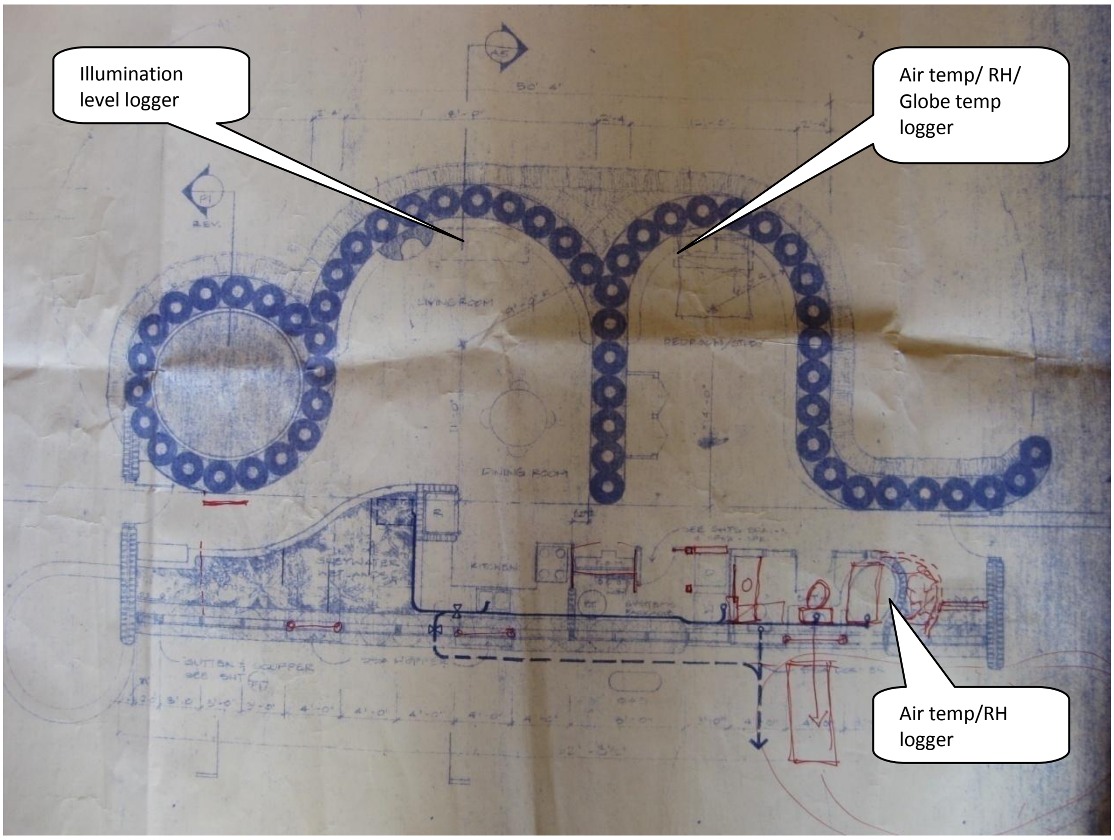
Refer to House #4 for section view – identical design

House #4 Floor Plan

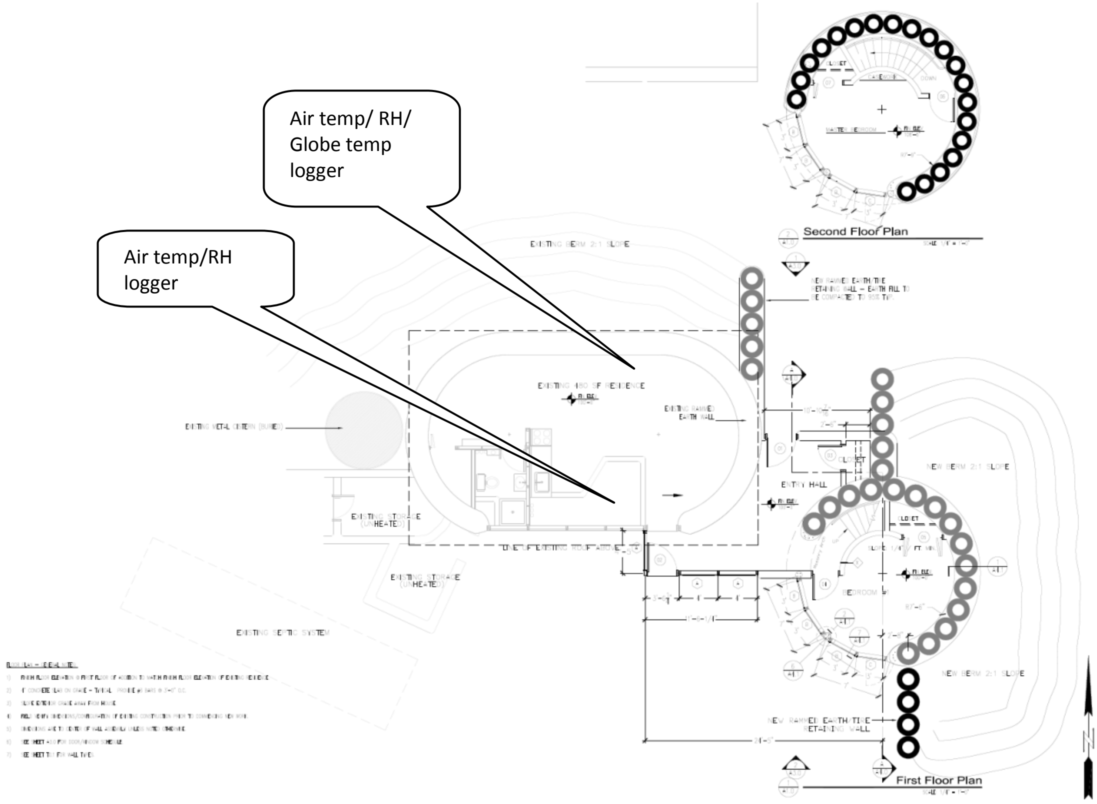




House #5 Floor Plan



House #6 Floor Plan

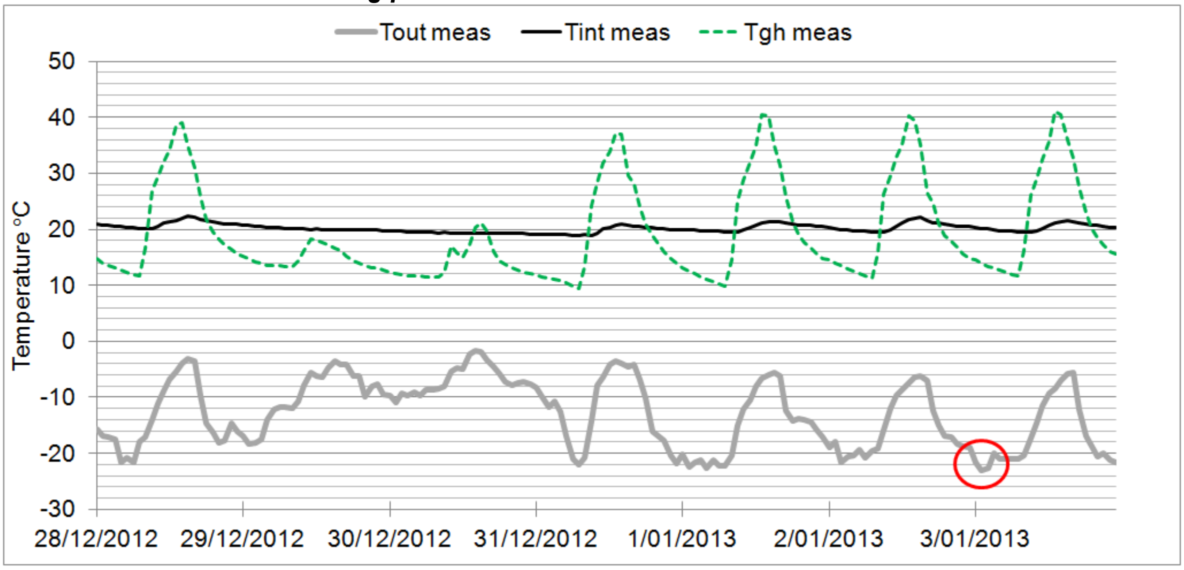


C7 - Additional monitoring results

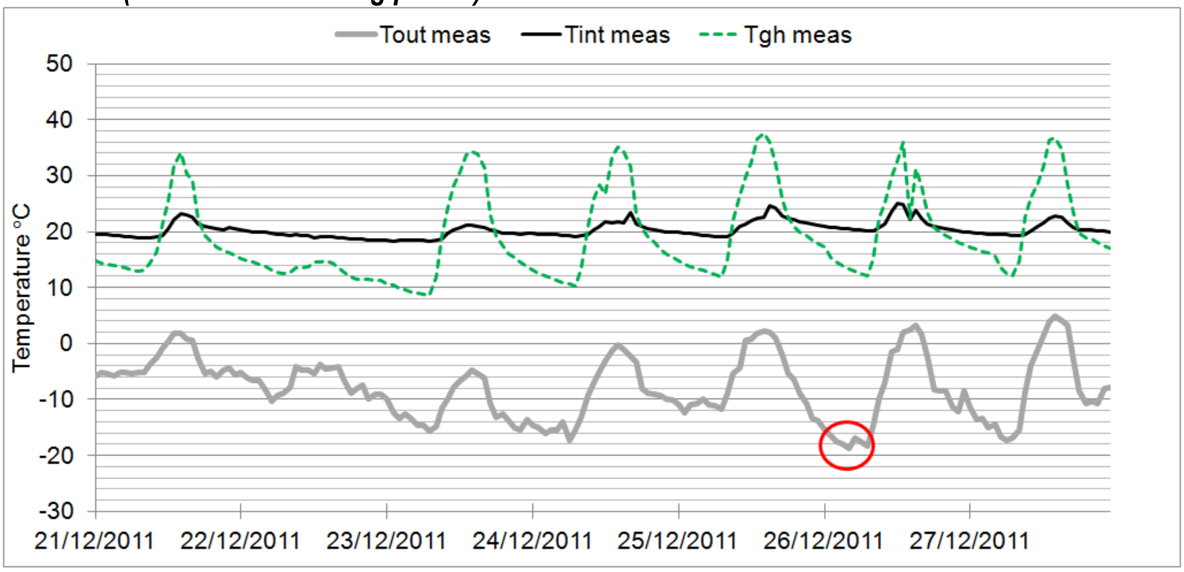
Note: red circles indicate the maximum or minimum temperature recorded during the 7 month or 12 month monitoring period.

Winter week with coldest day of year, all houses

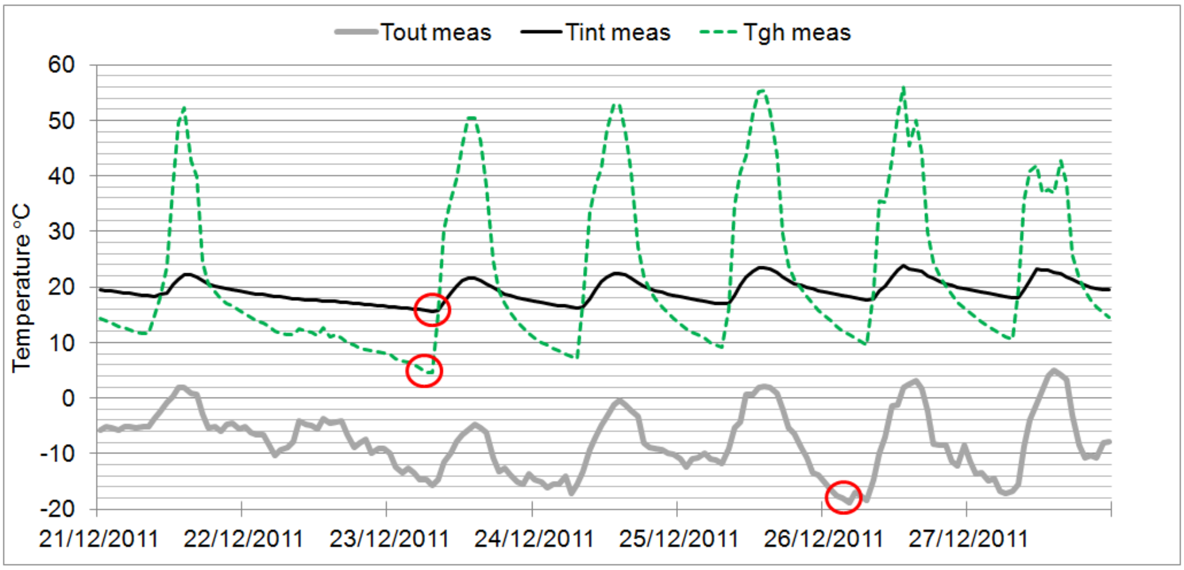
House #1 12 month monitoring period



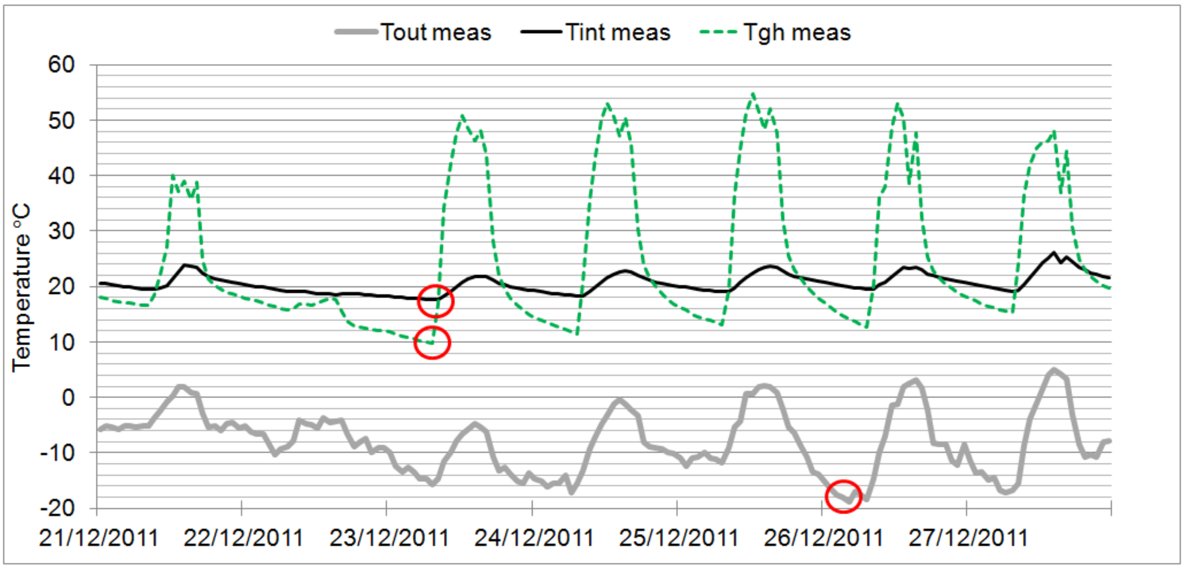
House #1 (standard monitoring period)



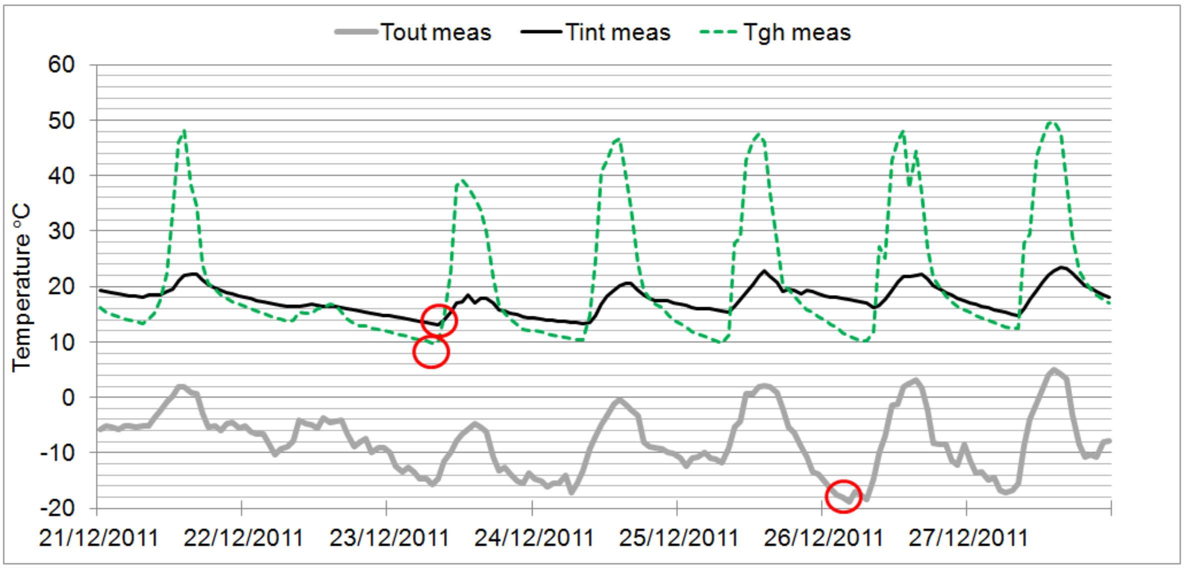
House #2



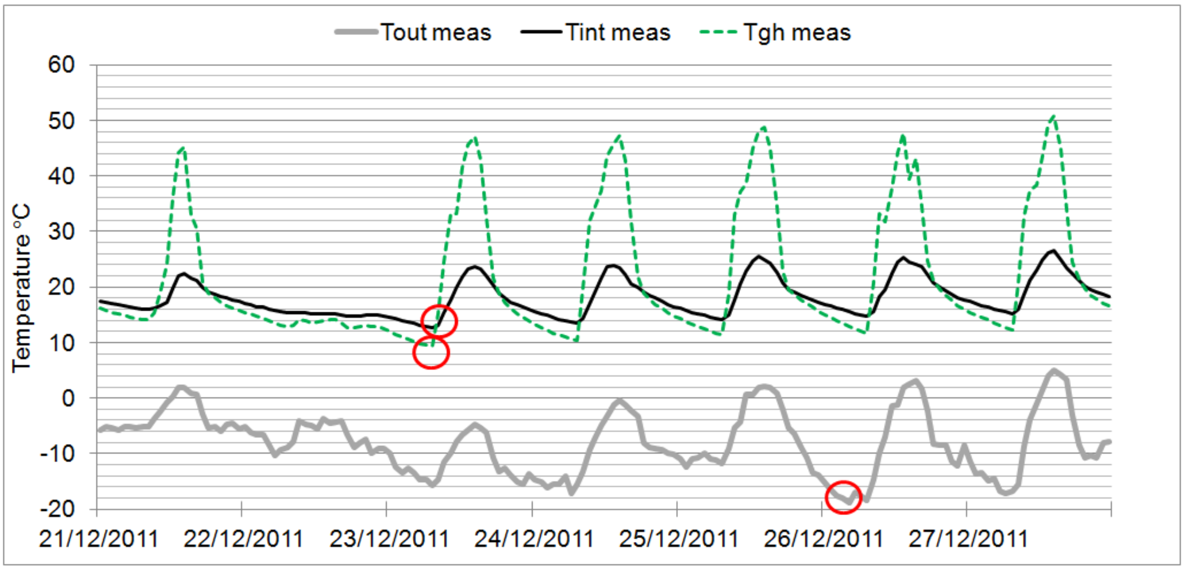
House #3



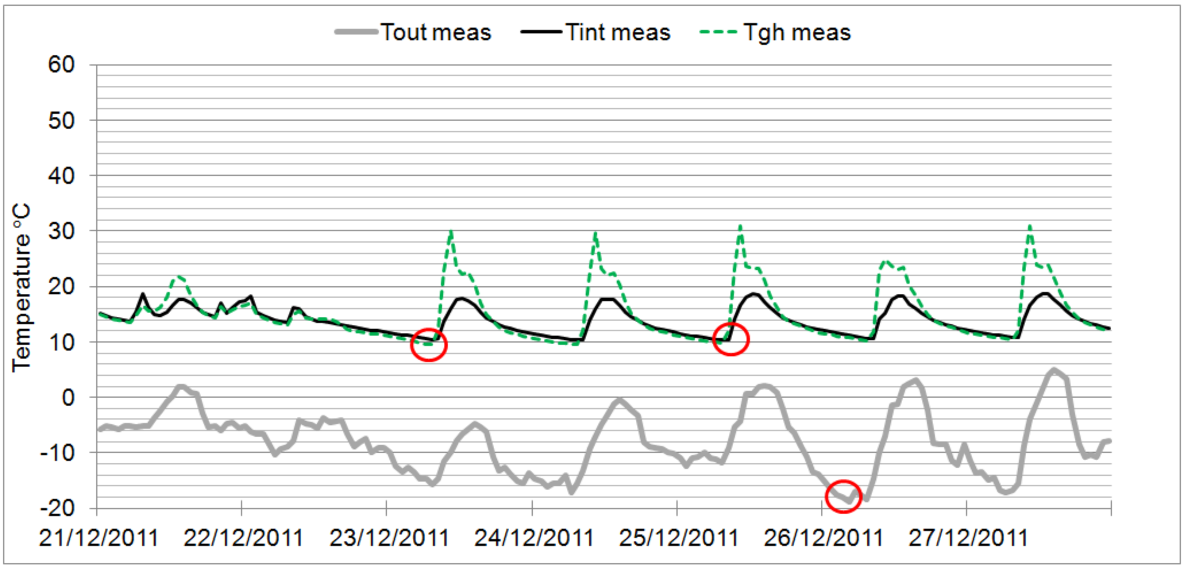
House #4



House #5

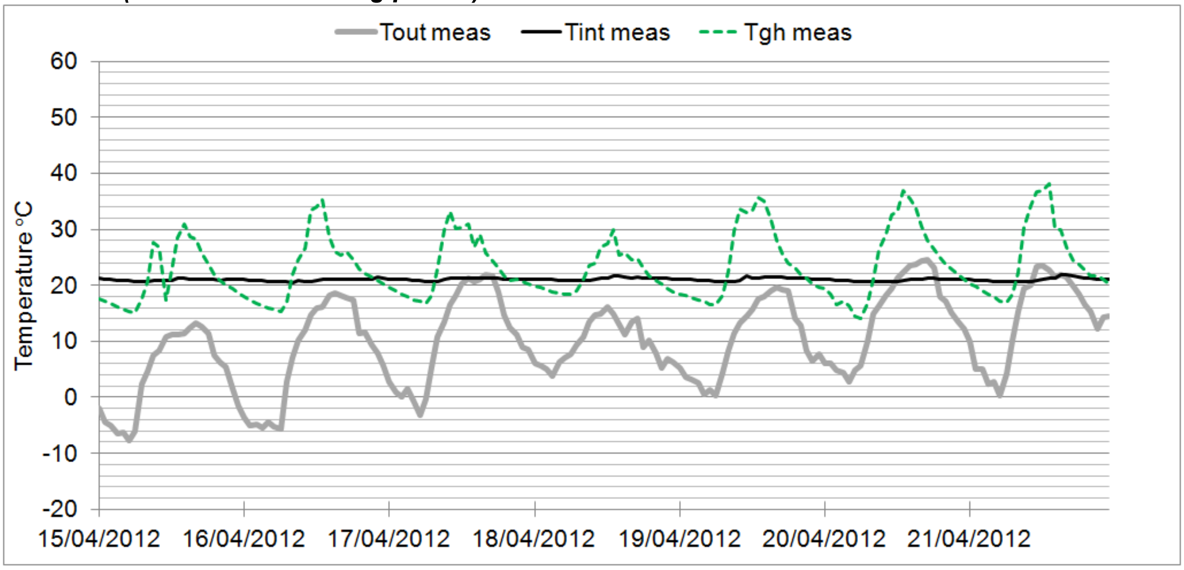


House #6

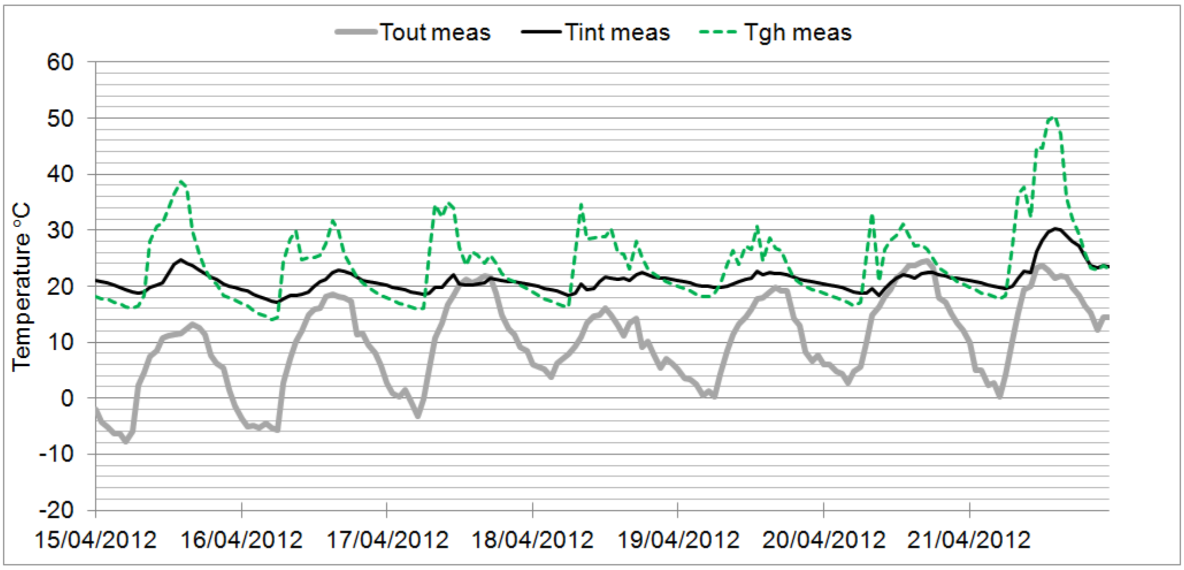


Spring week, all houses

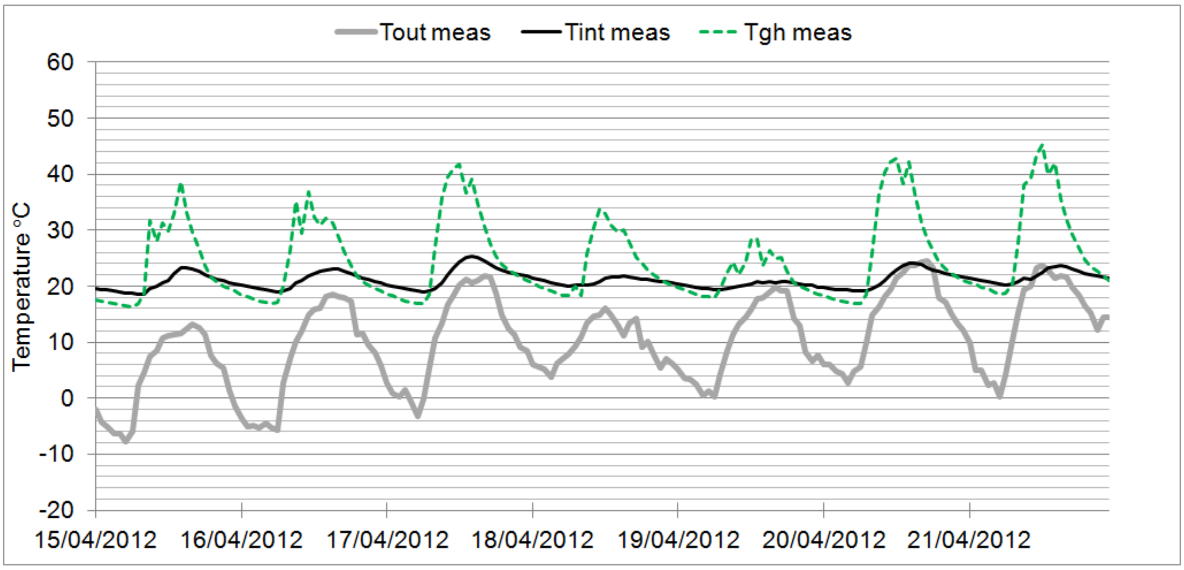
House #1 (standard monitoring period)



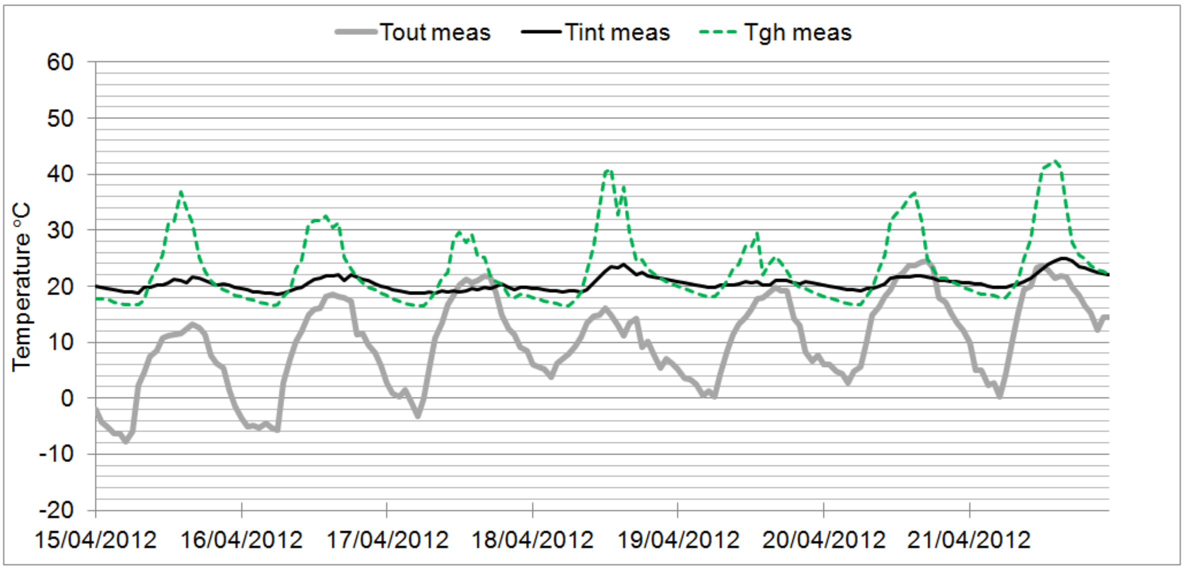
House #2



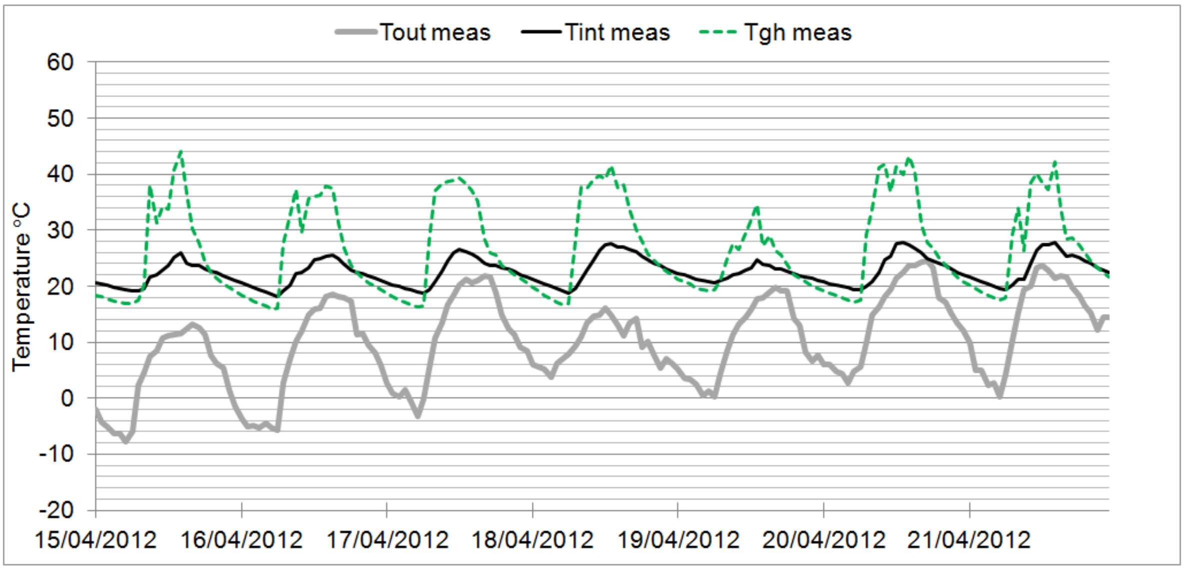
House #3



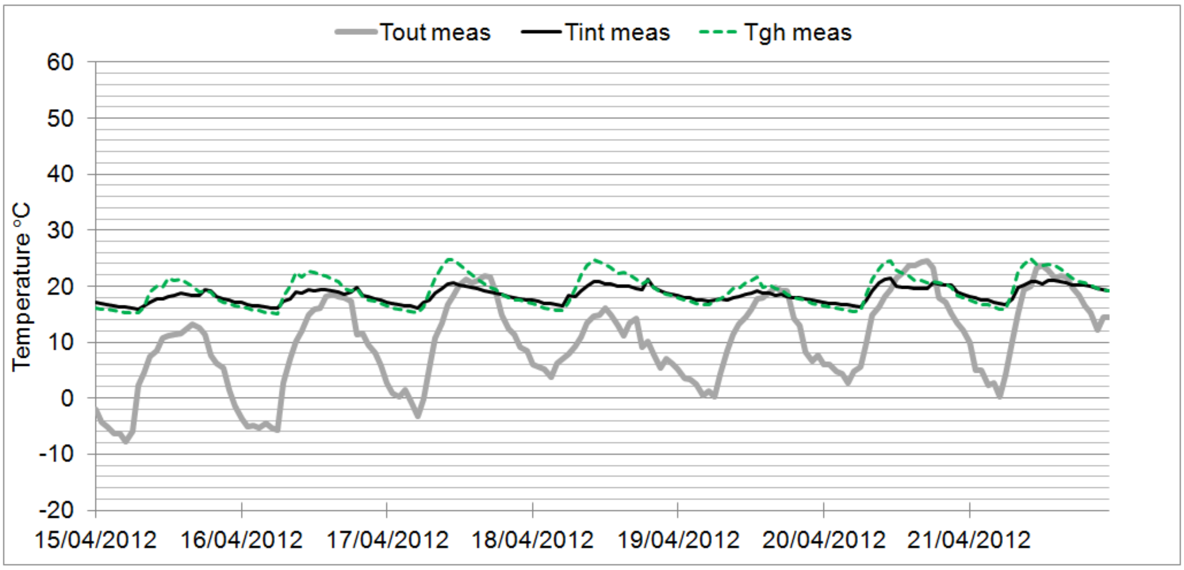
House #4



House #5

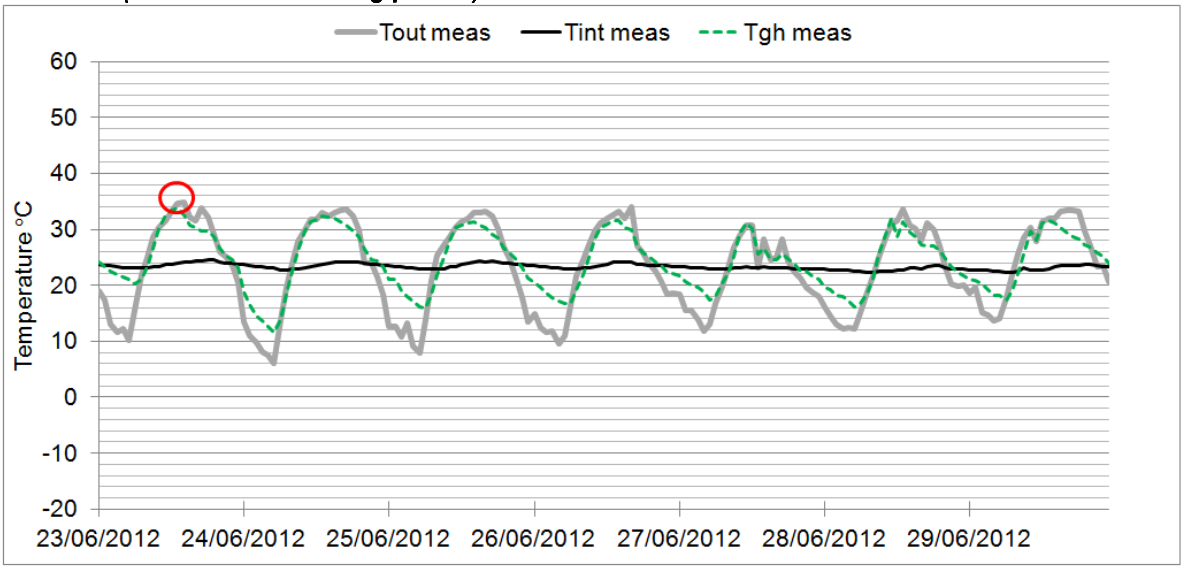


House #6

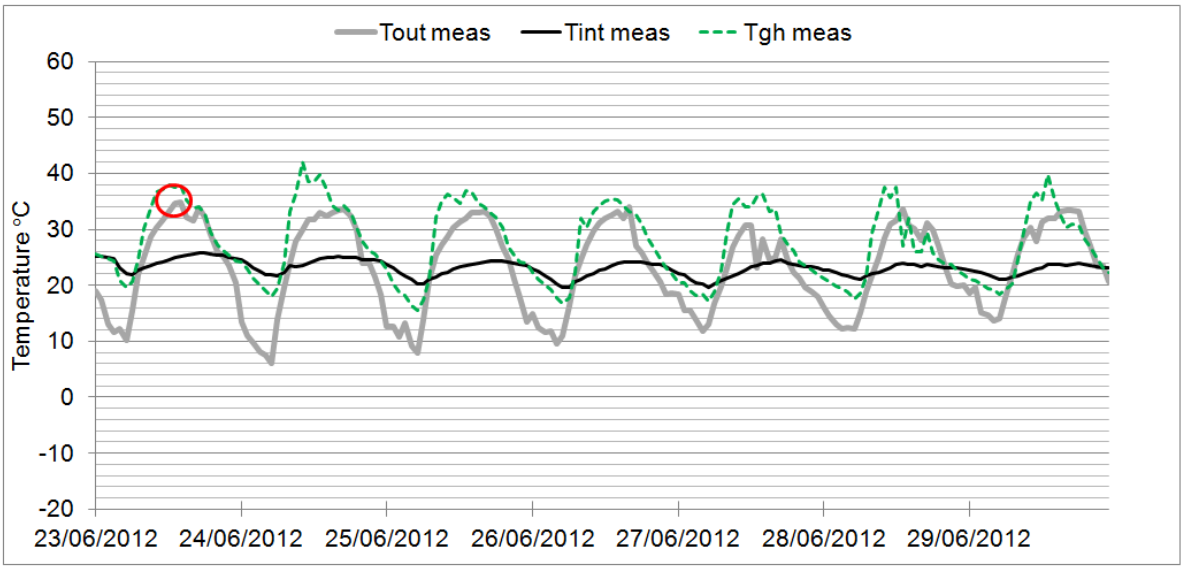


Summer week with hottest day of year, all houses

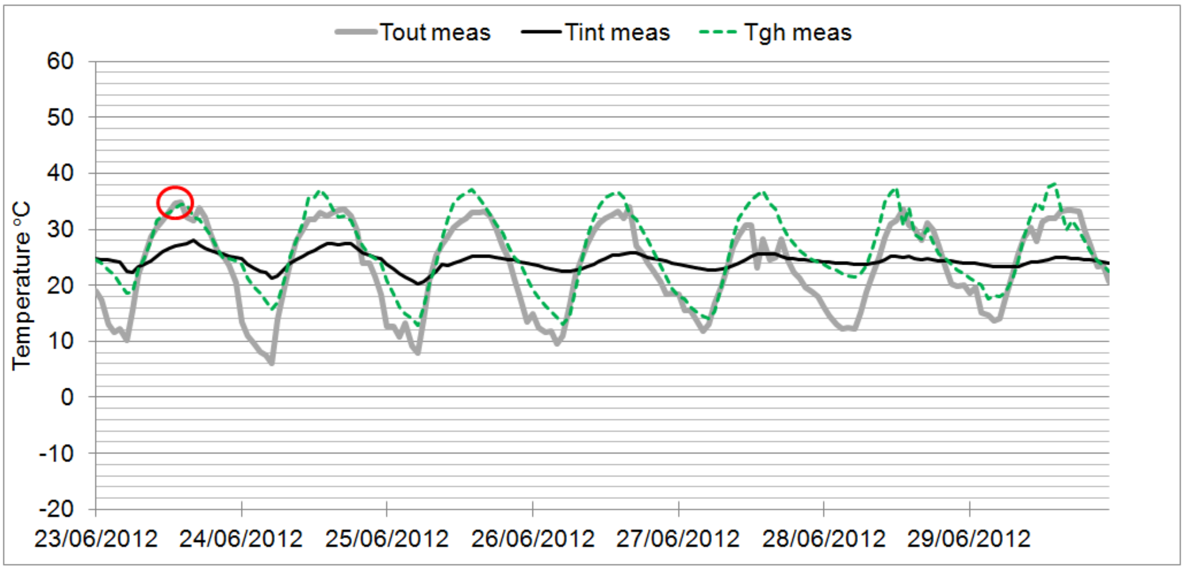
House #1 (standard monitoring period)



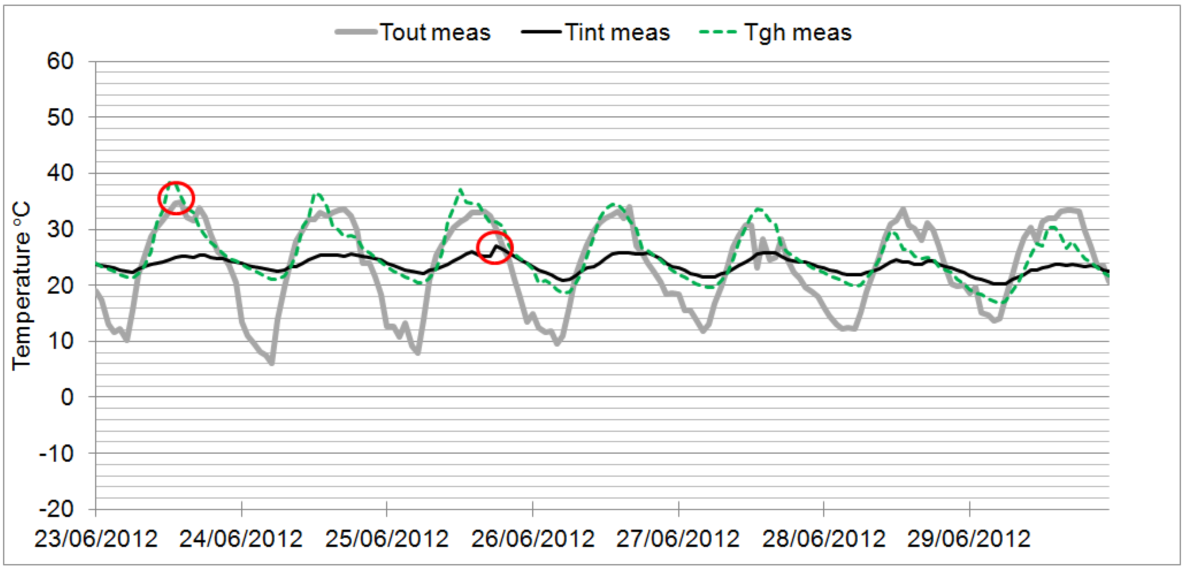
House #2



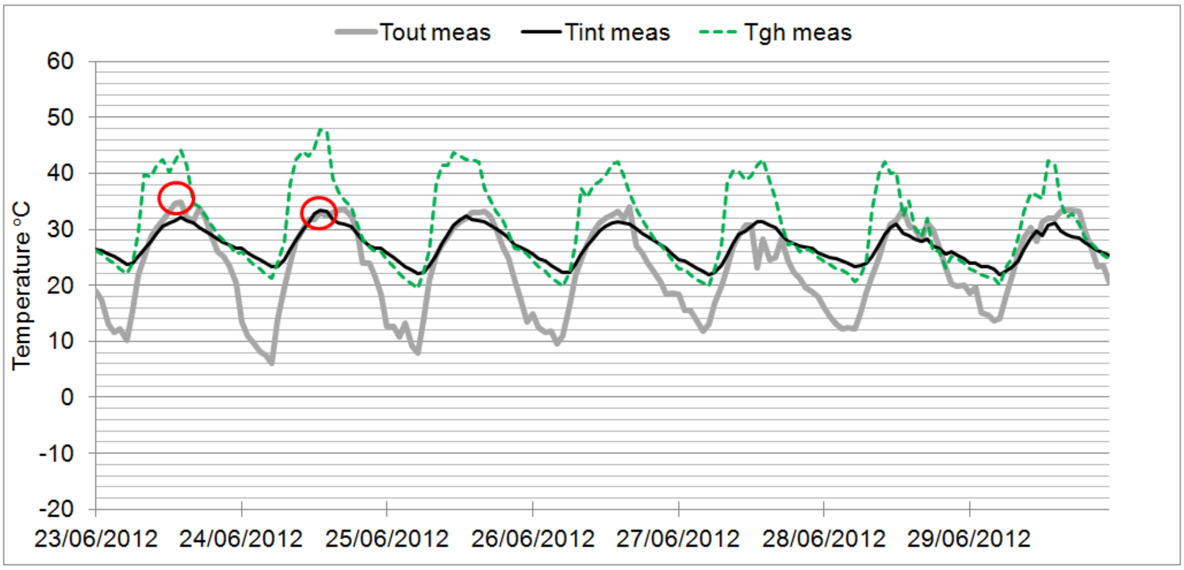
House #3



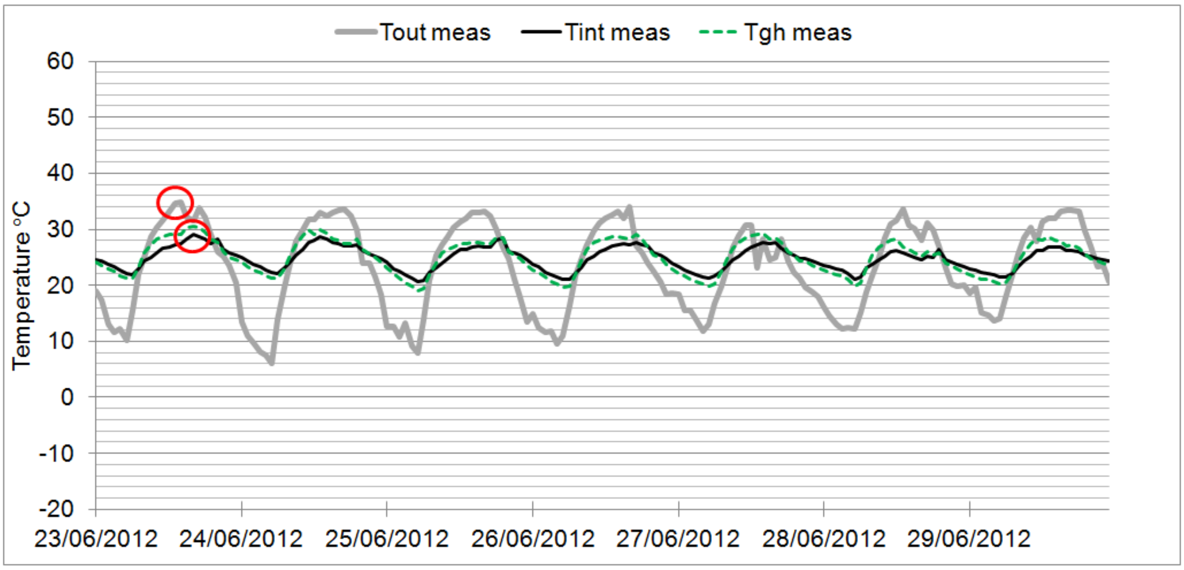
House #4



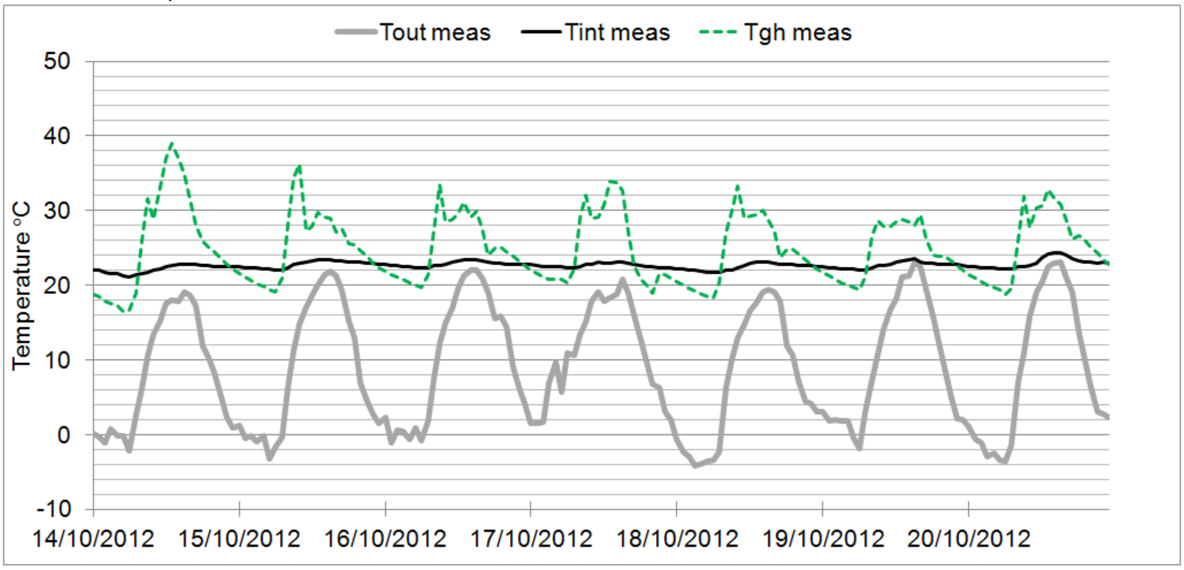
House #5



House #6

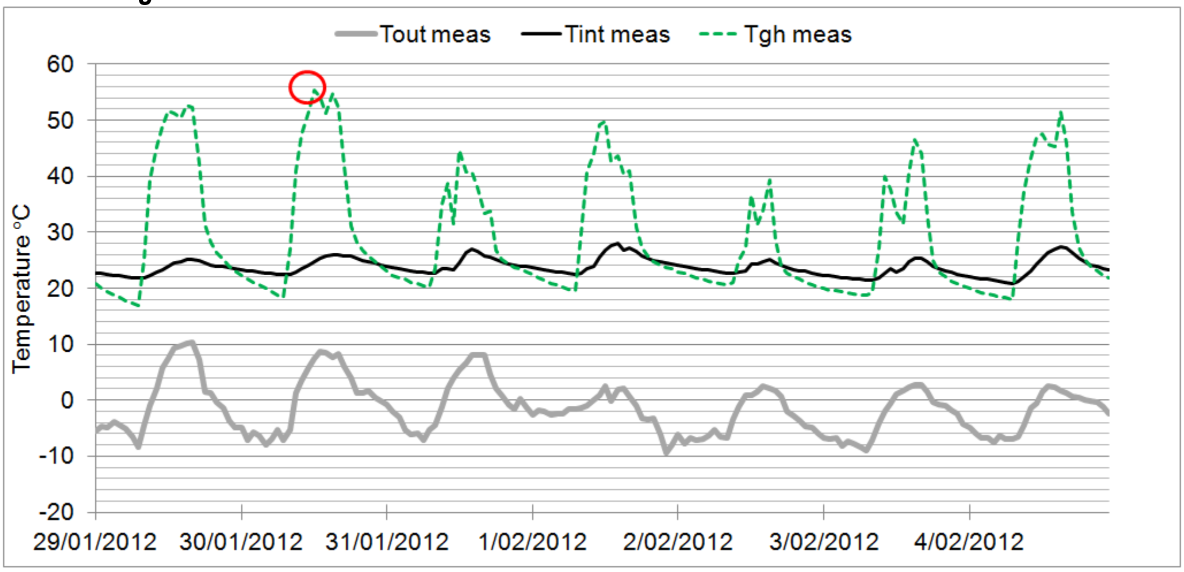


Autumn week, House #1

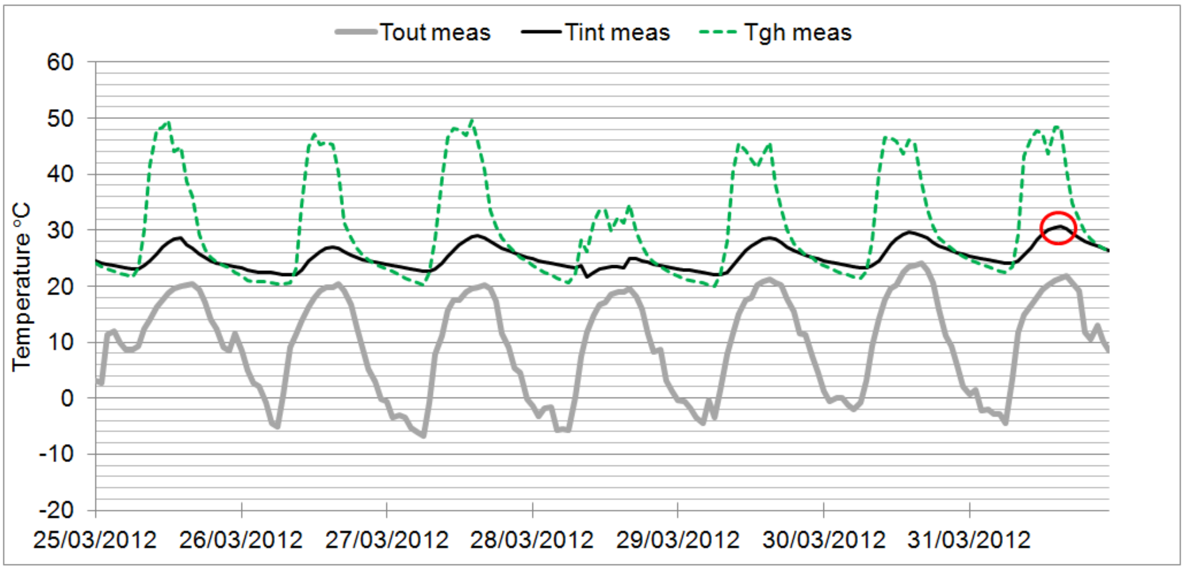


Miscellaneous Weeks showing Tint and Tgh max/min where they don't occur in the max/min outdoor temperature weeks

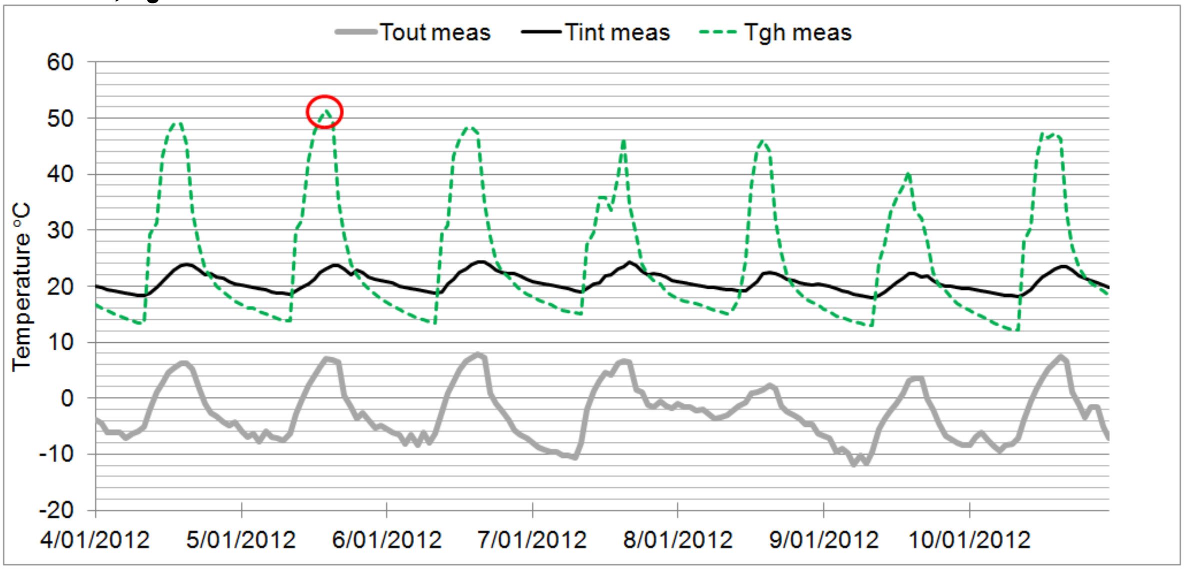
House #3 Tgh max



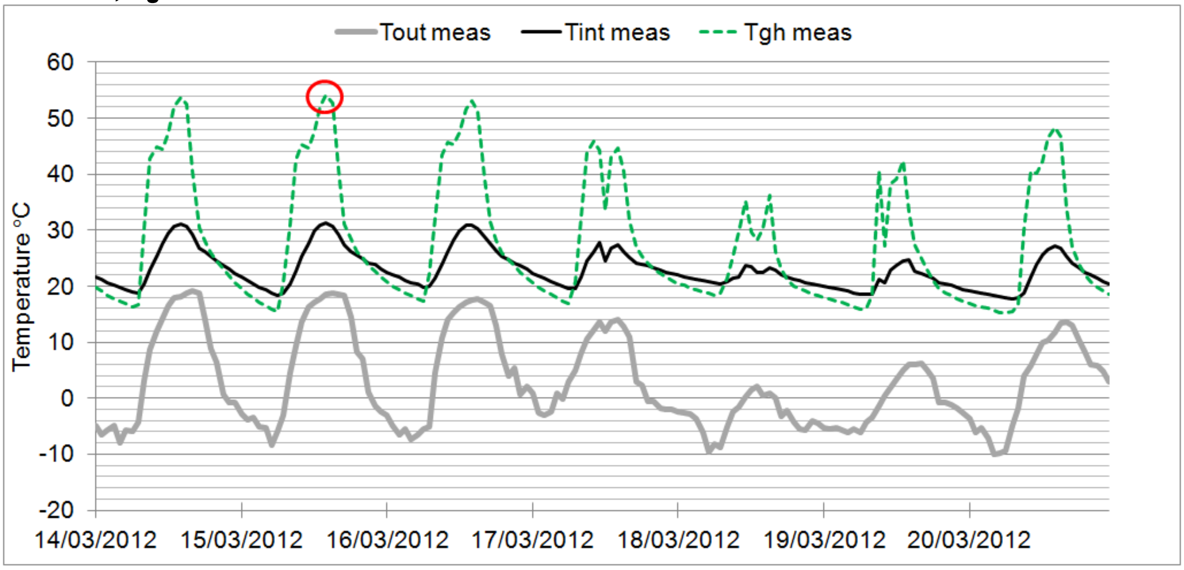
House #3 Tint max



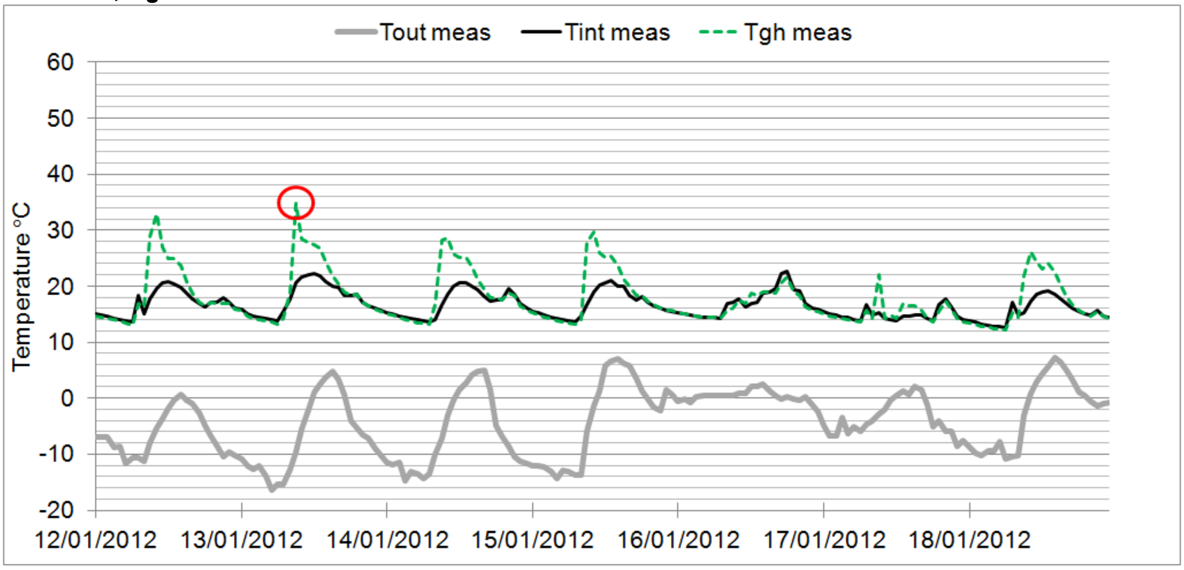
House #4, Tgh max



House #5, Tgh max



House #6, Tgh max



C8 - Ground Temperatures

Calculated Under-slab Ground Temperatures for Adelaide, Kent Town using Tground (not calibrated)

Month	Outdoor Mean Monthly Air Temperature °C	Typical, above ground home °C	Earth-sheltered (bermed) home °C
January	23.2	20.7	19.9
February	23.3	21.2	20.8
March	20.8	20.5	19.8
April	17.6	18.8	19.2
May	14.6	17.4	18.0
June	12.1	15.4	16.6
July	11.4	14.8	16.6
August	12.5	15.4	16.5
September	14.4	16.6	17.4
October	16.7	17.5	17.8
November	19.6	18.1	18.4
December	21.3	19.6	19.7

Calculated Under-slab Ground Temperatures for Adelaide, Kent Town using TgroundES (calibrated)

Month	Outdoor Mean Monthly Air Temperature °C	Typical, above ground home °C	Earth-sheltered (bermed) home °C
January	23.2	24.1	23.7
February	23.3	24.3	23.8
March	20.8	22.5	22.2
April	17.6	20.4	20.4
May	14.6	18.7	18.9
June	12.1	18.1	18.3
July	11.4	18	18.2
August	12.5	17.9	18.1
September	14.4	18.4	18.4

October	16.7	19.6	19.5
November	19.6	21.5	21.2
December	21.3	22.7	22.3

Results – with Berm, Adelaide Climate

Annual Harmonic Transfer Functions – With berm (heat flow down)

Component	U-value	Transfer Modulus Γ	Lag (days)	Internal Admittance Y	Lead (days)
Core concrete slab, and 1m soil Soil 1200mm ρ=1900 kg/m3 * k=1.0 c=810 Concrete 100mm ρ=2400kg/m3 * k=1.44 c=880 Resi = 0.16	0.70 4.4	0.70 4.4	6.1 0.1	0.72 4.4	9.6 0.1
Edge of slab, path length 5.0m Rese = 0.04	0.20 0.25* .17** 0.2*** 0.25****	0.15 0.22 .10 .14 0.17	68.2 46 91 79 79	0.54 0.51 .55 .6 0.75	47.2 46 47 47 47

First row of results is for calculating gtemp at 1m down
*Second row of results 20130110, 4m heat path for underslab temp (no dirt)
** third row of results 20130110, 6m heat path for underslab temp (no dirt)
*** fourth row of results 20130110 , 6m heat path for underslab temp (no dirt) with 1.2 conductivity for soil (instead of 1)
**** fifth row of results, 6m heat path for underslab temp (not dirt) with wet berm assumption for Taos.

Annual Harmonic Transfer Functions – Without berm (heat flow down)

Component	U-value	Transfer Modulus Γ	Lag (days)	Internal Admittance Y	Lead (days)
Core concrete slab, and 1m soil Soil 1100mm ρ=1900 kg/m3 * k=1.0 c=810 Concrete 100mm ρ=2400kg/m3 * k=1.44 c=880 Resi = 0.16	0.75 4.4*	0.75 4.4	5.2 0.1	0.76 4.4	8.2 0.1
Edge of slab, path length 2.8m* Rese = 0.04	0.35 0.11*	0.34 0.10	23.6 46	0.49 0.23	35.6 46

First row of results is for calculating gtemp at 1m down

*Second row of results is underslab (no dirt layer). Edge with 1.8m “thickness” of earth (heat flow path length), K= 1.2.

Appendix D - LCA

D1 - LCA Results: Elementary Flows and Characterisation

Elementary Flows for External Wall

Table D1.1 - Comparison of Elementary flows greater than 1%, External Walls per linear metre of wall (“E+02” means “ x100” E-05 means “/100 000”, etc)

Substance	Compart-ment	Unit	BV 5/90/5	BV 60/15/25	CBI	ESI CanR	ESIB CanR	ESIB CanL	ESIB CanL inc Foot	MB	RBV	RE	REI	SB	TFC
Carbon dioxide, biogenic	Soil	kg CO2-eq	-1.5E+01	-1.5E+01	-2.1E+00	-1.6E-05	-1.1E+00	-1.3E+01	-1.3E+01	-2.1E+00	-1.5E+01	-2.1E+00	-2.1E+00	-8.3E+00	-1.7E+01
Carbon dioxide, fossil	Air	kg CO2-eq	2.7E+02	1.9E+02	2.9E+02	9.1E+01	1.3E+02	1.8E+02	3.0E+02	8.5E+01	2.8E+02	1.5E+02	1.9E+02	1.2E+02	1.3E+02
Methane, biogenic	Air	kg CO2-eq	6.9E+00	6.9E+00	1.0E+00	3.2E-02	8.3E-01	6.2E+00	6.2E+00	9.6E-01	7.1E+00	9.7E-01	9.9E-01	3.8E+00	7.9E+00
Methane, fossil	Air	kg CO2-eq	3.9E+00	3.7E+00	1.2E+01	8.7E+00	1.2E+01	1.3E+01	1.5E+01	1.8E+00	4.2E+00	3.3E+00	1.0E+01	2.6E+00	3.5E+00
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC 11-eq	1.1E-07	9.6E-08	8.6E-08	4.5E-08	9.0E-08	1.2E-07	1.6E-07	3.3E-08	1.1E-07	7.0E-08	7.4E-08	6.2E-08	3.6E-08
Hydrocarbons, chlorinated	Air	kg CFC 11-eq	-6.5E-09	1.1E-09	4.5E-08	4.8E-08	6.5E-08	6.5E-08	6.6E-08	5.9E-10	5.3E-06	-2.2E-08	2.0E-08	1.3E-09	5.2E-06
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC 11-eq	2.2E-07	2.0E-07	2.2E-07	1.1E-07	2.1E-07	6.4E-07	7.3E-07	7.5E-08	2.2E-07	1.3E-07	1.5E-07	1.3E-07	9.4E-08
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC 11-eq	1.8E-06	1.6E-06	2.3E-06	8.1E-07	1.3E-06	1.6E-06	2.6E-06	7.9E-07	1.8E-06	1.5E-06	1.6E-06	1.3E-06	8.0E-07
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC 11-eq	1.7E-08	1.5E-08	5.8E-07	6.3E-07	8.4E-07	8.5E-07	8.6E-07	6.2E-09	1.7E-08	7.6E-09	5.7E-07	9.6E-09	9.6E-09
Carbon monoxide	Air	kg C2H4-eq	2.0E-02	1.6E-02	1.5E-02	4.2E-03	8.8E-03	1.6E-02	2.2E-02	5.9E-03	2.0E-02	1.0E-02	1.1E-02	1.4E-02	1.3E-02
Carbon monoxide, biogenic	Air	kg C2H4-eq	3.1E-03	3.1E-03	4.6E-04	3.7E-04	7.1E-04	1.9E-03	2.0E-03	4.2E-04	3.1E-03	4.3E-04	4.4E-04	1.6E-03	3.6E-03
Carbon monoxide, fossil	Air	kg C2H4-eq	7.9E-03	4.2E-03	2.9E-03	1.9E-03	2.7E-03	3.3E-03	4.1E-03	6.9E-04	7.8E-03	1.1E-03	2.2E-03	1.2E-03	8.4E-04
Formaldehyde	Air	kg C2H4-eq	5.2E-03	2.2E-03	8.4E-05	-1.4E-05	3.6E-06	9.5E-04	9.9E-04	3.5E-05	5.0E-03	4.6E-05	5.1E-05	5.4E-05	1.2E-04
Methane, biogenic	Air	kg C2H4-eq	2.0E-03	2.0E-03	2.9E-04	9.3E-06	2.4E-04	1.8E-03	1.8E-03	2.8E-04	2.0E-03	2.8E-04	2.8E-04	1.1E-03	2.3E-03
Methane, fossil	Air	kg C2H4-eq	1.1E-03	1.0E-03	3.4E-03	2.5E-03	3.3E-03	3.6E-03	4.3E-03	5.1E-04	1.2E-03	9.5E-04	2.9E-03	7.4E-04	9.9E-04
Pentane	Air	kg C2H4-eq	4.8E-05	8.3E-05	5.9E-02	6.5E-02	8.8E-02	8.7E-02	8.7E-02	4.0E-05	5.3E-05	-5.1E-05	5.9E-02	6.7E-05	5.0E-05
Propylene glycol	Air	kg C2H4-eq	2.5E-02	2.5E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.2E-02	0.0E+00	0.0E+00	0.0E+00	2.8E-02
Sulfur dioxide	Air	kg C2H4-eq	6.3E-03	4.4E-03	9.7E-03	6.1E-03	8.9E-03	1.2E-02	1.4E-02	1.7E-03	6.7E-03	2.4E-03	7.8E-03	2.7E-03	2.9E-03
Ammonia	Air	kg PO4--- eq	4.5E-03	4.8E-03	1.3E-03	2.9E-04	2.3E-03	3.9E-03	4.5E-03	4.4E-04	9.2E-03	-1.6E-04	-1.3E-04	6.6E-04	5.3E-03
COD, Chemical Oxygen Demand	Water	kg PO4--- eq	3.9E-03	3.5E-03	4.9E-03	4.7E-03	1.0E-02	1.1E-02	1.3E-02	1.2E-03	4.2E-03	1.8E-03	3.1E-03	1.7E-03	4.0E-03
Nitrogen oxides	Air	kg PO4--- eq	1.0E-01	8.2E-02	1.0E-01	3.5E-02	5.7E-02	8.1E-02	1.3E-01	3.4E-02	1.0E-01	7.0E-02	8.2E-02	5.3E-02	6.3E-02
Phosphate	Water	kg PO4--- eq	1.7E-02	1.6E-02	2.0E-02	9.3E-03	2.0E-02	2.9E-02	3.7E-02	6.5E-03	1.8E-02	1.1E-02	1.3E-02	1.1E-02	7.9E-03
Phosphorus	Water	kg PO4--- eq	4.6E-05	4.6E-05	2.0E-03	2.1E-03	3.9E-03	3.9E-03	3.9E-03	2.7E-05	4.6E-05	4.7E-05	2.0E-03	3.7E-05	3.9E-05

Substance	Compart-ment	Unit	BV 5/90/5	BV 60/15/25	CBI	ESI CanR	ESIB CanR	ESIB CanL	ESIB CanL inc Foot	MB	RBV	RE	REI	SB	TFC
Occupation, arable, non-irrigated	Raw	Ha.years	1.5E-05	1.5E-05	1.9E-06	3.2E-05	1.5E-04	1.4E-04	1.4E-04	7.2E-07	1.8E-05	1.5E-06	1.5E-06	1.1E-06	2.7E-05
Occupation, forest	Raw	Ha.years	2.9E-04	2.9E-04	3.9E-05	2.9E-05	6.0E-05	1.4E-04	1.4E-04	3.9E-05	3.9E-04	3.9E-05	3.9E-05	1.5E-04	4.3E-04
Occupation, forest, intensive	Raw	Ha.years	4.5E-04	4.5E-04	8.9E-04	1.6E-04	1.8E-04	2.4E-04	6.6E-04	2.9E-04	4.4E-04	5.6E-04	5.9E-04	3.8E-04	4.4E-04
Occupation, forest, intensive, normal	Raw	Ha.years	2.1E-04	2.1E-04	3.9E-04	7.2E-05	8.6E-05	8.7E-03	8.9E-03	1.3E-04	2.1E-04	2.4E-04	2.5E-04	1.8E-04	2.0E-04
Occupation, forest, intensive, short-cycle	Raw	Ha.years	2.3E-03	2.3E-03	2.8E-04	6.9E-04	1.1E-03	1.6E-03	1.6E-03	2.8E-04	2.3E-03	2.8E-04	2.8E-04	1.1E-03	2.7E-03
Occupation, traffic area, road network	Raw	Ha.years	7.4E-05	6.4E-05	3.7E-05	2.9E-05	4.8E-05	4.7E-05	6.4E-05	1.7E-05	7.2E-05	3.9E-05	4.1E-05	3.8E-05	1.7E-05
Occupation, urban, green areas	Raw	Ha.years	2.4E-04	2.0E-04	3.5E-04	1.0E-04	1.4E-04	2.5E-04	3.7E-04	9.0E-05	2.6E-04	9.6E-05	1.4E-04	1.2E-04	1.7E-04
Water, cooling, unspecified natural origin/m3	Raw	m3 H2O	2.7E-01	2.5E-01	2.0E+00	1.9E+00	2.7E+00	2.8E+00	3.0E+00	1.3E-01	3.1E-01	2.1E-01	1.9E+00	1.9E-01	2.1E-01
Water, process, unspecified natural origin/kg	Raw	m3 H2O	8.2E-02	8.2E-02	1.6E-01	-1.3E-01	-1.5E-01	2.1E-01	2.9E-01	5.3E-02	9.7E-02	1.0E-01	1.1E-01	6.9E-02	9.2E-02
Water, river	Raw	m3 H2O	5.8E-02	5.2E-02	5.9E-02	3.2E-02	9.0E-01	9.1E-01	9.4E-01	1.9E-02	5.8E-02	3.8E-02	4.8E-02	3.5E-02	2.2E-02
Water, unspecified natural origin /kg	Raw	m3 H2O	1.8E-01	1.8E-01	3.8E-02	6.4E-01	1.3E+00	1.1E+00	1.1E+00	2.9E-01	1.8E-01	1.2E+00	1.3E+00	7.4E-01	5.8E-02
Water, unspecified natural origin/m3	Raw	m3 H2O	5.7E-01	1.2E+00	3.1E+00	9.6E-01	1.2E+00	1.4E+00	2.9E+00	1.2E+00	9.3E-01	3.1E-01	4.5E-01	1.4E+00	1.5E+00
Cardboard waste	Waste	kg	0.0E+00	0.0E+00	0.0E+00	1.1E+01	1.5E+01	1.4E+01	1.4E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Mineral waste	Waste	kg	1.5E+01	1.4E+01	5.4E+01	8.4E+00	9.6E+00	1.4E+01	4.0E+01	1.6E+01	1.5E+01	1.8E+01	1.8E+01	2.1E+01	1.5E+01
Waste, final, inert	Waste	kg	1.1E+02	2.3E+02	1.0E+02	4.0E+01	4.9E+01	6.4E+01	1.1E+02	3.0E+01	1.0E+02	1.1E+02	1.2E+02	4.5E+01	9.5E+01
Waste, unspecified	Waste	kg	1.2E+00	1.2E+00	2.9E+00	6.1E-01	7.1E-01	7.6E-01	1.6E+00	6.3E-01	2.0E+00	6.4E-01	6.7E-01	1.1E+00	1.4E+00
Coal, 29.3 MJ per kg, in ground	Raw	MJ LHV	9.6E+01	9.6E+01	2.4E+02	4.5E+01	4.8E+01	7.8E+01	1.9E+02	7.7E+01	1.2E+02	1.5E+02	1.6E+02	1.0E+02	9.5E+01
Coal, hard	Raw	MJ LHV	4.9E+01	4.5E+01	5.1E+01	2.1E+01	3.3E+01	3.6E+01	6.0E+01	1.9E+01	4.9E+01	3.1E+01	3.3E+01	3.3E+01	2.1E+01
Energy, from biomass	Raw	MJ LHV	5.1E+01	5.1E+01	1.9E+00	8.8E+01	1.2E+02	1.2E+02	1.2E+02	1.9E+00	3.8E+01	1.9E+00	1.9E+00	7.4E+00	6.8E+01
Energy, from wood	Raw	MJ LHV	7.3E+01	7.3E+01	9.8E+00	7.3E+00	1.5E+01	3.6E+01	3.6E+01	9.7E+00	7.4E+01	9.7E+00	9.7E+00	3.9E+01	8.5E+01
Energy, gross calorific value, in biomass	Raw	MJ LHV	3.1E+01	3.1E+01	6.0E+01	1.3E+01	3.6E+01	2.3E+02	2.5E+02	1.9E+01	3.0E+01	3.7E+01	4.1E+01	2.6E+01	2.9E+01
Energy, kinetic (in wind), converted	Raw	MJ LHV	4.4E+01	3.6E+01	6.7E+01	2.6E+01	3.5E+01	4.0E+01	6.4E+01	1.7E+01	4.7E+01	1.9E+01	2.7E+01	2.3E+01	3.0E+01
Gas, natural, 36.6 MJ per m3, in ground	Raw	MJ LHV	1.3E+03	8.3E+02	8.5E+02	2.7E+02	3.5E+02	4.4E+02	8.0E+02	2.6E+02	1.4E+03	4.1E+02	4.7E+02	3.6E+02	5.2E+02
Gas, natural/m3	Raw	MJ LHV	3.9E+01	3.5E+01	3.9E+01	1.6E+01	2.5E+01	2.7E+01	4.5E+01	1.4E+01	3.9E+01	2.5E+01	2.7E+01	2.5E+01	1.7E+01
Oil, crude	Raw	MJ LHV	1.5E+02	1.4E+02	1.8E+02	6.6E+01	1.0E+02	1.1E+02	1.9E+02	6.5E+01	1.5E+02	1.2E+02	1.3E+02	1.1E+02	6.7E+01
Oil, crude, 42 MJ per kg, in ground	Raw	MJ LHV	6.3E+02	5.1E+02	8.4E+02	2.6E+02	4.2E+02	5.2E+02	9.4E+02	3.5E+02	6.4E+02	5.3E+02	5.7E+02	4.8E+02	3.1E+02
Oil, crude, 42.7 MJ per kg, in ground	Raw	MJ LHV	2.5E+02	2.1E+02	3.5E+02	1.1E+02	1.8E+02	2.2E+02	3.9E+02	1.4E+02	2.6E+02	2.2E+02	2.3E+02	2.0E+02	1.3E+02

Substance	Compart-ment	Unit	BV 5/90/5	BV 60/15/25	CBI	ESI CanR	ESIB CanR	ESIB CanL	ESIB CanL inc Foot	MB	RBV	RE	REI	SB	TFC
Uranium	Raw	MJ LHV	5.9E+01	5.2E+01	4.5E+01	2.4E+01	3.7E+01	3.8E+01	5.9E+01	1.8E+01	5.9E+01	3.8E+01	4.0E+01	3.4E+01	2.0E+01
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	CTUh	1.6E-09	1.6E-09	1.4E-09	5.2E-10	7.7E-10	1.2E-09	1.8E-09	5.3E-10	1.7E-09	8.1E-10	9.4E-10	1.1E-09	1.5E-09
Formaldehyde	Air	CTUh	1.3E-07	5.7E-08	2.2E-09	-3.3E-10	1.4E-10	3.4E-08	3.5E-08	9.0E-10	1.3E-07	1.3E-09	1.4E-09	1.3E-09	2.7E-09
Benzene	Air	CTUh	1.7E-10	9.5E-11	1.1E-10	4.5E-11	6.2E-11	7.9E-11	1.2E-10	2.9E-11	1.7E-10	4.1E-11	6.5E-11	4.4E-11	3.1E-11
Carbon disulfide	Air	CTUh	3.9E-09	3.9E-09	4.6E-09	1.9E-09	2.8E-09	4.1E-09	6.0E-09	1.5E-09	4.0E-09	1.4E-09	1.6E-09	2.5E-09	2.2E-09
Formaldehyde	Air	CTUh	1.7E-09	7.3E-10	2.8E-11	-4.3E-12	1.5E-12	3.9E-10	4.0E-10	1.2E-11	1.7E-09	1.6E-11	1.8E-11	1.7E-11	3.6E-11
Hexane	Air	CTUh	6.8E-11	5.8E-11	8.6E-11	3.9E-11	6.1E-11	5.1E-11	9.2E-11	3.3E-11	6.9E-11	5.5E-11	5.9E-11	4.8E-11	3.6E-11
Parathion	Soil	CTUh	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.8E-10	3.8E-10	3.8E-10	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Styrene	Air	CTUh	-4.3E-14	2.2E-14	9.1E-11	1.0E-10	1.3E-10	1.3E-10	1.3E-10	1.8E-14	-3.4E-14	-1.9E-13	9.0E-11	6.3E-14	4.8E-14
Xylene	Air	CTUh	4.1E-11	3.6E-11	7.4E-11	2.2E-11	3.2E-11	3.9E-11	7.4E-11	2.6E-11	4.1E-11	3.8E-11	4.2E-11	3.6E-11	2.4E-11
Chlorothalonil	Soil	CTUe	9.0E-02	8.9E-02	1.6E-01	3.7E-02	4.2E-02	5.4E-02	1.3E-01	5.8E-02	8.8E-02	1.1E-01	1.1E-01	7.7E-02	8.2E-02
Cumene	Water	CTUe	4.8E-02	4.9E-02	9.5E-02	2.7E-02	2.5E-02	3.1E-02	7.4E-02	3.2E-02	4.7E-02	5.3E-02	6.3E-02	4.2E-02	4.5E-02
Formaldehyde	Air	CTUe	2.7E-01	1.1E-01	4.3E-03	-7.1E-04	1.9E-04	5.0E-02	5.2E-02	1.8E-03	2.6E-01	2.4E-03	2.6E-03	2.8E-03	6.0E-03
Metolachlor	Soil	CTUe	1.5E-02	1.3E-02	1.3E-02	6.0E-03	8.6E-02	1.1E-01	1.1E-01	5.0E-03	1.5E-02	1.1E-02	1.2E-02	9.0E-03	5.6E-03
Parathion	Soil	CTUe	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.1E+01	1.1E+01	1.1E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Phenol	Water	CTUe	5.6E-02	5.0E-02	8.8E-02	2.8E-02	4.1E-02	5.2E-02	9.3E-02	3.2E-02	5.6E-02	5.4E-02	6.1E-02	4.5E-02	3.5E-02

Characterisation Results for Impacts of External Wall

Table D1.2 - Characterisation results, external walls (1lm)

Impact category	Unit	BV	BV EOL60/15/25	CBI	ESI CanR	ESIB CanR	ESIB CanL	ESIB CanL inc Foot	MB cem rend	RBV	RE	REI	SB	TFC	TFC no CO2 seq
Global Warming Potential	kg CO_2-eq	2.67E+02	1.89E+02	3.00E+02	9.88E+01	1.41E+02	1.91E+02	3.12E+02	8.64E+01	2.83E+02	1.49E+02	1.96E+02	1.19E+02	1.27E+02	1.44E+02
Ozone depletion	kgCFC 11-eq	2.17E-06	1.98E-06	3.26E-06	1.67E-06	2.51E-06	3.32E-06	4.53E-06	9.21E-07	7.53E-06	1.69E-06	2.42E-06	1.52E-06	6.17E-06	6.17E-06
Photochemical oxidation	kg C_2H_4	7.18E-02	5.95E-02	9.37E-02	8.13E-02	1.13E-01	1.28E-01	1.39E-01	1.03E-02	1.00E-01	1.65E-02	8.58E-02	2.22E-02	5.31E-02	5.31E-02
Eutrophication	kg PO4--- eq	1.27E-01	1.07E-01	1.34E-01	5.22E-02	9.72E-02	1.34E-01	1.89E-01	4.25E-02	1.37E-01	8.30E-02	1.01E-01	6.71E-02	8.06E-02	8.06E-02
Land use	Ha.years	3.70E-03	3.63E-03	2.04E-03	1.13E-03	1.91E-03	1.14E-02	1.21E-02	8.64E-04	3.74E-03	1.22E-03	1.31E-03	2.02E-03	4.07E-03	4.07E-03
Water Use	M3 H2O	1.24E+00	1.81E+00	5.43E+00	3.46E+00	5.88E+00	6.49E+00	8.25E+00	1.66E+00	1.67E+00	1.92E+00	3.79E+00	2.43E+00	1.87E+00	1.87E+00
Solid waste	kg	1.23E+02	2.48E+02	1.63E+02	6.04E+01	7.57E+01	9.30E+01	1.65E+02	4.75E+01	1.21E+02	1.29E+02	1.42E+02	6.81E+01	1.13E+02	1.13E+02
Embodied energy LHV	MJ LHV	2.93E+03	2.24E+03	2.77E+03	9.51E+02	1.42E+03	1.94E+03	3.21E+03	1.01E+03	3.04E+03	1.62E+03	1.77E+03	1.47E+03	1.56E+03	1.56E+03

Impact category	Unit	BV	BV EOL60/15/25	CBI	ESI CanR	ESIB CanR	ESIB CanL	ESIB CanL inc Foot	MB cem rend	RBV	RE	REI	SB	TFC	TFC no CO2 seq
Human toxicity, cancer	CTUh	1.35E-07	5.93E-08	4.64E-09	9.53E-10	1.93E-09	3.65E-08	3.83E-08	1.59E-09	1.32E-07	2.33E-09	3.19E-09	2.64E-09	4.46E-09	4.46E-09
Human toxicity, non-cancer	CTUh	5.99E-09	4.87E-09	5.18E-09	2.12E-09	3.57E-09	5.34E-09	7.39E-09	1.64E-09	6.12E-09	1.61E-09	1.97E-09	2.77E-09	2.43E-09	2.43E-09
Ecotoxicity	CTUe	5.26E-01	3.62E-01	4.22E-01	1.16E-01	1.09E+01	1.10E+01	1.12E+01	1.52E-01	5.40E-01	2.65E-01	2.92E-01	2.08E-01	2.18E-01	2.18E-01

Elementary Flows for Thermal Envelope

Table D1.3 - Comparison of Elementary flows greater than 1%, Thermal Envelope (“E+02” means “ x100” E-05 means “/100 000”, etc)

Substance	Compart-ment	Unit	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH Base Case	ESIB GH lowEE	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
Carbon dioxide, biogenic	Soil	kg CO2-eq	-3.01E+03	-2.89E+03	-2.31E+03	-5.10E+03	-6.42E+03	-6.01E+03	-2.31E+03	-2.90E+03	-2.31E+03	-2.31E+03	-2.59E+03	-3.27E+03
Carbon dioxide, fossil	Air	kg CO2-eq	1.87E+04	2.50E+04	2.58E+04	1.19E+04	2.81E+04	1.55E+04	1.06E+04	2.56E+04	1.61E+04	1.79E+04	1.84E+04	1.54E+04
Methane, biogenic	Air	kg CO2-eq	1.37E+03	1.32E+03	1.06E+03	2.32E+03	2.95E+03	2.76E+03	1.05E+03	1.33E+03	1.05E+03	1.06E+03	1.18E+03	1.49E+03
Methane, fossil	Air	kg CO2-eq	4.05E+02	4.50E+02	8.10E+02	5.48E+02	1.06E+03	7.91E+02	2.86E+02	4.65E+02	4.05E+02	7.07E+02	3.94E+02	4.28E+02
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC 11-eq	7.79E-06	1.06E-05	9.60E-06	7.32E-06	1.61E-05	1.24E-05	6.02E-06	1.06E-05	7.62E-06	7.83E-06	8.55E-06	5.72E-06
Hydrocarbons, chlorinated	Air	kg CFC 11-eq	2.17E-07	-7.36E-08	2.21E-06	1.80E-06	3.34E-05	3.36E-05	1.01E-07	2.38E-04	-5.54E-07	1.32E-06	2.77E-07	2.30E-04
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC 11-eq	3.40E-05	3.91E-05	3.89E-05	3.35E-05	7.58E-05	5.50E-05	2.97E-05	3.91E-05	3.29E-05	3.40E-05	3.54E-05	3.08E-05
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC 11-eq	1.34E-04	1.76E-04	1.98E-04	1.17E-04	2.31E-04	1.74E-04	1.00E-04	1.76E-04	1.46E-04	1.50E-04	1.55E-04	1.09E-04
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC 11-eq	1.90E-06	2.23E-06	2.75E-05	2.31E-05	3.62E-05	3.53E-05	1.40E-06	2.25E-06	1.66E-06	2.68E-05	1.91E-06	1.75E-06
Methane, tetrachloro-, CFC-10	Air	kg CFC 11-eq	8.43E-06	8.91E-06	9.02E-06	9.13E-06	1.05E-05	9.38E-06	7.28E-06	8.98E-06	7.71E-06	8.04E-06	8.13E-06	8.32E-06
Carbon monoxide	Air	kg C2H4-eq	2.18E+00	2.48E+00	2.28E+00	2.51E+00	4.13E+00	2.79E+00	1.61E+00	2.49E+00	1.92E+00	1.98E+00	2.23E+00	2.09E+00
Carbon monoxide, biogenic	Air	kg C2H4-eq	5.72E-01	5.49E-01	4.32E-01	9.71E-01	1.19E+00	1.15E+00	4.29E-01	5.50E-01	4.31E-01	4.31E-01	4.84E-01	6.28E-01
Carbon monoxide, fossil	Air	kg C2H4-eq	3.40E-01	5.91E-01	3.69E-01	1.57E-01	3.16E-01	2.45E-01	1.01E-01	5.87E-01	1.33E-01	1.81E-01	2.90E-01	1.15E-01
Formaldehyde	Air	kg C2H4-eq	2.01E-01	3.73E-01	1.47E-01	3.35E-02	9.38E-02	3.71E-02	3.11E-02	3.68E-01	3.23E-02	3.26E-02	1.46E-01	3.60E-02
Methane, biogenic	Air	kg C2H4-eq	3.92E-01	3.77E-01	3.02E-01	6.64E-01	8.42E-01	7.88E-01	3.01E-01	3.79E-01	3.01E-01	3.01E-01	3.38E-01	4.27E-01
Methane, fossil	Air	kg C2H4-eq	1.16E-01	1.29E-01	2.31E-01	1.57E-01	3.03E-01	2.26E-01	8.17E-02	1.33E-01	1.16E-01	2.02E-01	1.13E-01	1.22E-01
Pentane	Air	kg C2H4-eq	9.80E-03	1.01E-02	2.65E+00	2.27E+00	3.76E+00	3.79E+00	7.50E-03	1.03E-02	6.00E-03	2.65E+00	1.10E-02	1.03E-02
Propylene glycol	Air	kg C2H4-eq	1.84E+00	1.61E+00	5.10E-01	4.54E-02	9.95E-01	3.04E-01	x	2.08E+00	x	x	5.10E-01	1.52E+00

Substance	Compart-ment	Unit	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH Base Case	ESIB GH lowEE	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
Sulfur dioxide	Air	kg C2H4-eq	5.75E-01	7.31E-01	8.83E-01	5.83E-01	1.69E+00	1.06E+00	3.97E-01	7.50E-01	4.74E-01	7.13E-01	5.74E-01	4.92E-01
Ammonia	Air	kg PO4---eq	4.13E-01	3.71E-01	2.29E-01	8.99E-02	4.86E-01	2.97E-01	7.90E-02	4.52E-01	8.09E-02	8.22E-02	1.99E-01	3.73E-01
COD, Chemical Oxygen Demand	Water	kg PO4---eq	3.84E-01	4.27E-01	4.72E-01	3.44E-01	9.99E-01	7.24E-01	2.49E-01	4.41E-01	3.12E-01	3.72E-01	3.33E-01	4.31E-01
Nitrogen oxides	Air	kg PO4---eq	8.60E+00	1.04E+01	1.05E+01	7.23E+00	1.51E+01	9.70E+00	5.77E+00	1.06E+01	8.22E+00	8.78E+00	8.29E+00	7.98E+00
Phosphate	Water	kg PO4---eq	1.70E+00	2.10E+00	2.23E+00	1.61E+00	3.73E+00	2.92E+00	1.35E+00	2.11E+00	1.64E+00	1.75E+00	1.83E+00	1.47E+00
Occupation, forest	Raw	Ha.years	5.39E-02	5.17E-02	4.03E-02	9.27E-02	1.12E-01	1.09E-01	4.03E-02	5.60E-02	4.03E-02	4.03E-02	4.56E-02	6.34E-02
Occupation, forest, intensive	Raw	Ha.years	4.15E-02	4.52E-02	6.50E-02	2.04E-02	5.64E-02	2.47E-02	2.63E-02	4.49E-02	4.80E-02	4.93E-02	4.25E-02	4.55E-02
Occupation, forest, intensive, normal	Raw	Ha.years	2.49E-01	2.51E-01	2.59E-01	2.54E-01	6.27E-01	3.15E-01	2.43E-01	2.51E-01	2.52E-01	2.52E-01	2.50E-01	2.51E-01
Occupation, forest, intensive, short-cycle	Raw	Ha.years	4.13E-01	3.95E-01	3.04E-01	6.92E-01	8.37E-01	8.18E-01	3.04E-01	3.92E-01	3.04E-01	3.04E-01	3.42E-01	4.57E-01
Occupation, urban, green areas	Raw	Ha.years	2.08E-02	2.48E-02	2.96E-02	1.40E-02	3.72E-02	1.27E-02	1.19E-02	2.55E-02	1.61E-02	1.80E-02	1.95E-02	2.02E-02
Water, cooling, unspecified natural origin/m3	Raw	m3 H2O	3.33E+01	3.82E+01	1.15E+02	9.23E+01	2.44E+02	2.22E+02	2.75E+01	4.01E+01	3.36E+01	1.08E+02	3.48E+01	3.35E+01
Water, process, unspecified natural origin/kg	Raw	m3 H2O	8.45E+00	9.90E+00	1.35E+01	1.63E+00	6.54E+01	-1.18E+01	6.44E+00	1.06E+01	1.04E+01	1.07E+01	9.38E+00	9.75E+00
Water, river	Raw	m3 H2O	4.70E+00	6.13E+00	6.16E+00	4.57E+00	6.87E+01	6.65E+01	3.65E+00	6.11E+00	4.59E+00	5.04E+00	5.11E+00	3.73E+00
Water, unspecified natural origin /kg	Raw	m3 H2O	8.06E+00	1.32E+01	6.78E+00	1.03E+02	1.71E+02	1.67E+02	7.83E+01	1.31E+01	7.73E+01	7.90E+01	3.85E+01	4.61E+00
Water, unspecified natural origin/m3	Raw	m3 H2O	9.23E+01	8.77E+01	2.03E+02	5.89E+01	1.91E+02	9.70E+01	6.90E+01	1.04E+02	8.94E+01	9.55E+01	1.24E+02	1.37E+02
Cardboard waste	Waste	kg	x	x	x	3.94E+02	5.45E+02	6.04E+02	x	x	x	x	x	x
Mineral waste	Waste	kg	1.48E+03	1.68E+03	3.45E+03	6.68E+02	1.22E+03	8.82E+02	8.86E+02	1.70E+03	1.83E+03	1.84E+03	1.98E+03	1.61E+03
Waste, final, inert	Waste	kg	1.04E+04	1.09E+04	1.08E+04	8.21E+03	1.20E+04	1.01E+04	6.46E+03	1.07E+04	1.03E+04	1.08E+04	8.21E+03	1.10E+04
Waste, unspecified	Waste	kg	1.39E+02	1.40E+02	2.14E+02	8.08E+01	1.66E+02	1.39E+02	7.28E+01	1.57E+02	1.01E+02	1.03E+02	1.34E+02	1.44E+02
Coal, 26.4 MJ per kg, in ground	Raw	MJ LHV	4.08E+03	4.12E+03	3.92E+03	3.04E+03	1.43E+04	2.15E+03	3.49E+03	5.56E+03	3.46E+03	3.53E+03	4.30E+03	5.83E+03
Coal, 29.3 MJ per kg, in ground	Raw	MJ LHV	7.66E+03	9.46E+03	1.58E+04	4.37E+03	1.68E+04	5.67E+03	5.41E+03	1.04E+04	1.13E+04	1.17E+04	9.77E+03	8.56E+03
Coal, hard	Raw	MJ LHV	3.22E+03	4.38E+03	4.47E+03	2.79E+03	5.34E+03	3.95E+03	2.28E+03	4.39E+03	3.14E+03	3.22E+03	3.69E+03	2.51E+03
Energy, from biomass	Raw	MJ LHV	6.66E+03	6.36E+03	4.18E+03	8.16E+03	1.01E+04	1.02E+04	4.18E+03	5.80E+03	4.18E+03	4.18E+03	4.43E+03	8.01E+03
Energy, from wood	Raw	MJ LHV	1.35E+04	1.29E+04	1.01E+04	2.32E+04	2.80E+04	2.73E+04	1.01E+04	1.29E+04	1.01E+04	1.01E+04	1.14E+04	1.48E+04
Energy, gross calorific value, in biomass	Raw	MJ LHV	7.82E+03	8.10E+03	9.43E+03	6.83E+03	1.87E+04	1.02E+04	6.82E+03	8.08E+03	8.22E+03	8.39E+03	7.90E+03	8.06E+03

Substance	Compart-ment	Unit	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH Base Case	ESIB GH lowEE	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
Energy, kinetic (in wind), converted	Raw	MJ LHV	3.59E+03	4.34E+03	5.35E+03	2.48E+03	4.61E+03	2.89E+03	1.95E+03	4.46E+03	2.79E+03	3.14E+03	3.38E+03	3.43E+03
Gas, natural, 36.6 MJ per m3, in ground	Raw	MJ LHV	8.16E+04	1.13E+05	9.31E+04	4.17E+04	7.69E+04	4.39E+04	3.77E+04	1.15E+05	5.35E+04	5.62E+04	7.13E+04	6.13E+04
Gas, natural/m3	Raw	MJ LHV	2.55E+03	3.45E+03	3.46E+03	2.17E+03	4.15E+03	3.04E+03	1.80E+03	3.45E+03	2.49E+03	2.55E+03	2.86E+03	2.00E+03
Oil, crude	Raw	MJ LHV	1.01E+04	1.36E+04	1.49E+04	8.58E+03	1.63E+04	1.22E+04	7.26E+03	1.36E+04	1.10E+04	1.12E+04	1.18E+04	7.96E+03
Oil, crude, 42 MJ per kg, in ground	Raw	MJ LHV	4.53E+04	5.99E+04	6.93E+04	3.52E+04	7.10E+04	4.95E+04	3.46E+04	6.05E+04	5.08E+04	5.25E+04	5.35E+04	3.79E+04
Oil, crude, 42.7 MJ per kg, in ground	Raw	MJ LHV	1.84E+04	2.43E+04	2.84E+04	1.45E+04	2.93E+04	2.06E+04	1.43E+04	2.45E+04	2.10E+04	2.17E+04	2.20E+04	1.55E+04
Uranium	Raw	MJ LHV	3.44E+03	4.96E+03	4.33E+03	3.09E+03	5.99E+03	4.48E+03	2.47E+03	4.93E+03	3.36E+03	3.45E+03	3.87E+03	2.35E+03
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	CTUh	2.23E-07	2.30E-07	2.20E-07	3.17E-07	4.35E-07	3.83E-07	1.63E-07	2.30E-07	1.87E-07	1.93E-07	2.05E-07	2.37E-07
Formaldehyde	Air	CTUh	5.41E-06	9.87E-06	4.04E-06	1.07E-06	3.01E-06	1.22E-06	1.03E-06	9.72E-06	1.07E-06	1.07E-06	4.00E-06	1.14E-06
Benzene	Air	CTUh	9.36E-09	1.45E-08	1.15E-08	5.04E-09	8.11E-09	6.33E-09	3.82E-09	1.43E-08	5.43E-09	6.51E-09	8.77E-09	4.94E-09
Carbon disulfide	Air	CTUh	3.72E-07	4.48E-07	4.81E-07	3.25E-07	6.34E-07	4.73E-07	2.70E-07	4.54E-07	3.06E-07	3.16E-07	3.89E-07	3.38E-07
Formaldehyde	Air	CTUh	6.81E-08	1.25E-07	5.04E-08	1.27E-08	3.56E-08	1.43E-08	1.21E-08	1.23E-07	1.25E-08	1.26E-08	5.00E-08	1.35E-08
Hexane	Air	CTUh	5.35E-09	6.78E-09	7.64E-09	4.45E-09	5.13E-09	7.57E-09	3.98E-09	6.83E-09	5.70E-09	5.86E-09	5.96E-09	4.67E-09
Chlorothalonil	Soil	CTUe	8.17E+00	9.05E+00	1.23E+01	4.65E+00	1.14E+01	5.84E+00	5.58E+00	8.99E+00	9.39E+00	9.64E+00	8.53E+00	8.75E+00
Cumene	Water	CTUe	6.38E+00	6.83E+00	8.91E+00	5.27E+00	8.21E+00	5.33E+00	4.95E+00	6.80E+00	6.87E+00	7.28E+00	6.60E+00	6.74E+00
Formaldehyde	Air	CTUe	1.04E+01	1.93E+01	7.63E+00	1.74E+00	4.88E+00	1.93E+00	1.62E+00	1.90E+01	1.69E+00	1.70E+00	7.56E+00	1.87E+00
Metolachlor	Soil	CTUe	1.51E+00	1.89E+00	1.78E+00	1.43E+00	8.45E+00	7.25E+00	1.26E+00	1.88E+00	1.55E+00	1.57E+00	1.62E+00	1.26E+00
Parathion	Soil	CTUe	x	x	x	x	7.38E+02	7.38E+02	x	x	x	x	x	x
Phenol	Water	CTUe	5.28E+00	6.33E+00	7.75E+00	4.41E+00	9.06E+00	6.68E+00	4.11E+00	6.35E+00	5.87E+00	6.19E+00	5.85E+00	4.94E+00

Characterisation Results for Impacts of Thermal Envelope

Table D1.4 - Characterisation results, thermal envelope

Impact category	Unit	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH Base Case	ESIB GH lowEE	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
Global Warming Potential	kg CO2-eq	1.78E+04	2.42E+04	2.57E+04	9.84E+03	2.69E+04	1.31E+04	9.83E+03	2.49E+04	1.55E+04	1.76E+04	1.77E+04	1.44E+04
Ozone Depletion	kg CFC 11-eq	1.88E-04	2.39E-04	2.88E-04	1.93E-04	4.06E-04	3.22E-04	1.46E-04	4.77E-04	1.97E-04	2.30E-04	2.11E-04	3.88E-04
Photochemical Oxidation	kg C_2H_4-eq	6.39E+00	7.05E+00	8.03E+00	7.51E+00	1.36E+01	1.05E+01	3.06E+00	7.58E+00	3.56E+00	6.66E+00	4.86E+00	5.61E+00
Eutrophication	kg PO4--- eq	1.13E+01	1.35E+01	1.38E+01	9.50E+00	2.12E+01	1.45E+01	7.58E+00	1.37E+01	1.04E+01	1.12E+01	1.08E+01	1.04E+01
Land use	Ha.years	7.92E-01	7.85E-01	7.11E-01	1.08E+00	1.71E+00	1.31E+00	6.33E-01	7.87E-01	6.68E-01	6.72E-01	7.12E-01	8.49E-01
Water Use	m3 H2O	1.51E+02	1.61E+02	3.48E+02	2.62E+02	7.44E+02	5.44E+02	1.86E+02	1.80E+02	2.17E+02	3.01E+02	2.16E+02	1.91E+02
Solid waste	kg	1.21E+04	1.29E+04	1.46E+04	9.41E+03	1.41E+04	1.18E+04	7.49E+03	1.27E+04	1.23E+04	1.29E+04	1.04E+04	1.29E+04
Embodied energy LHV	MJ LHV	2.20E+05	2.81E+05	2.74E+05	1.59E+05	3.04E+05	2.02E+05	1.36E+05	2.84E+05	1.90E+05	1.97E+05	2.16E+05	1.89E+05
Human Toxicity, cancer	CTUh	5.69E-06	1.02E-05	4.34E-06	1.44E-06	3.53E-06	1.67E-06	1.22E-06	1.00E-05	1.29E-06	1.33E-06	4.26E-06	1.41E-06
Human Toxicity, non-cancer	CTUh	4.69E-07	6.11E-07	5.76E-07	3.63E-07	7.42E-07	5.46E-07	3.00E-07	6.17E-07	3.44E-07	3.61E-07	4.69E-07	3.76E-07
Ecotoxicity	CTUe	3.65E+01	4.89E+01	4.43E+01	2.09E+01	7.87E+02	7.69E+02	2.07E+01	4.91E+01	2.97E+01	3.09E+01	3.48E+01	2.82E+01

Elementary Flows for Energy System

Table D1.5 - Comparison of Elementary flows greater than 1%, Energy Systems ("E+02" means " x100" E-05 means "/100 000", etc)

Substance	Compartment	Unit	Off-Grid Energy System	South Australian Grid Energy
Carbon dioxide, fossil	Air	kg CO2-eq	4.38E+04	9.06E+04
Methane, fossil	Air	kg CO2-eq	7.84E+02	4.93E+03
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CFC 11-eq	1.35E-07	2.22E-05
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC 11-eq	2.37E-05	2.60E-06
Hydrocarbons, chlorinated	Air	kg CFC 11-eq	5.42E-05	1.60E-06
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC 11-eq	2.55E-04	1.85E-05
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC 11-eq	1.71E-04	4.35E-05
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC 11-eq	1.89E-04	1.62E-05
Methane, dichlorodifluoro-, CFC-12	Air	kg CFC 11-eq	7.84E-06	1.31E-05
Methane, tetrachloro-, CFC-10	Air	kg CFC 11-eq	5.41E-05	9.45E-06
Benzene	Air	kg C2H4-eq	2.49E-01	1.38E-03
Carbon monoxide	Air	kg C2H4-eq	7.37E-01	3.95E+00
Carbon monoxide, fossil	Air	kg C2H4-eq	7.72E-01	8.52E-02
Hexane	Air	kg C2H4-eq	2.52E-01	1.89E-01
Methane	Air	kg C2H4-eq	5.20E-02	1.20E-01

Substance	Compartment	Unit	Off-Grid Energy System	South Australian Grid Energy
Methane, fossil	Air	kg C2H4-eq	2.24E-01	1.41E+00
Sulfur dioxide	Air	kg C2H4-eq	1.76E+00	1.40E-01
COD, Chemical Oxygen Demand	Water	kg PO4--- eq	7.12E-01	2.04E+00
Nitrogen	Water	kg PO4--- eq	9.79E+00	1.13E-02
Nitrogen oxides	Air	kg PO4--- eq	3.89E+01	3.81E+01
Phosphate	Water	kg PO4--- eq	3.60E+01	1.49E+00
Occupation, forest, intensive, normal	Raw	Ha.years	2.30E-02	2.90E-03
Occupation, urban, green areas	Raw	Ha.years	7.14E-04	4.19E-01
Water, cooling, unspecified natural origin/m3	Raw	m3 H2O	5.49E+02	4.41E+01
Water, river	Raw	m3 H2O	7.01E+02	3.20E+00
Water, unspecified natural origin/m3	Raw	m3 H2O	2.95E+01	5.53E+01
Water, well, in ground	Raw	m3 H2O	1.44E+01	5.82E-01
ash	Waste	kg	6.86E-01	3.72E+02
Rejects	Waste	kg	3.39E-02	1.29E+01
Waste, final, inert	Waste	kg	4.15E+02	1.89E-04
Energy, kinetic (in wind), converted	Raw	MJ LHV	4.63E+02	7.83E+04
Energy, potential (in hydropower reservoir), converted	Raw	MJ LHV	1.10E+04	7.12E+03
Gas, natural, 36.6 MJ per m3, in ground	Raw	MJ LHV	3.00E+05	9.36E+05
Oil, crude, 42 MJ per kg, in ground	Raw	MJ LHV	1.81E+05	2.23E+04
Oil, crude, 42.7 MJ per kg, in ground	Raw	MJ LHV	7.36E+04	4.85E+02
Benzene	Air	CTUh	1.44E-07	1.97E-09
Benzene, ethyl-	Air	CTUh	3.62E-09	9.06E-09
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	CTUh	1.36E-07	3.33E-08
Formaldehyde	Air	CTUh	6.01E-07	1.74E-07
Carbon disulfide	Air	CTUh	4.07E-05	7.33E-07
Benzene	Water	CTUe	2.52E+00	1.44E-01
Benzene, chloro-	Water	CTUe	6.86E-01	4.15E-01
Benzene, ethyl-	Water	CTUe	3.89E-01	1.89E-02
Carbon disulfide	Air	CTUe	2.01E+00	3.63E-02
Chlorothalonil	Soil	CTUe	9.42E+00	2.20E+00
Cumene	Water	CTUe	2.15E+00	3.67E-01
Formaldehyde	Air	CTUe	1.11E+00	6.87E-01
Naphthalene	Water	CTUe	6.61E-01	4.37E-03
p-Cresol	Water	CTUe	6.61E-01	4.36E-03

Substance	Compartment	Unit	Off-Grid Energy System	South Australian Grid Energy
Phenol	Water	CTUe	1.03E+01	4.29E-01
Phenol, 2,4-dimethyl-	Water	CTUe	6.96E-01	4.59E-03
Toluene	Water	CTUe	1.82E+00	3.71E-02
Xylene	Water	CTUe	1.32E+00	3.73E-02

Characterisation Results for Impacts of Energy System

Table D1.6 - Characterisation results, energy systems

Impact category	Unit	Off-Grid energy system 5kWh/day with LPG backup	Grid power use, ADL, 5kWh/day with NG backup
Global Warming Potential	kg CO_2-eq	4.50E+04	9.63E+04
Ozone Depletion	kg CFC 11-eq	7.56E-04	1.28E-04
Photochemical Oxidation	kg C2H4-eq	4.41E+00	5.99E+00
Eutrophication	kg PO4--- eq	8.65E+01	4.21E+01
Land Use & Transformation	Ha.years	3.67E-02	4.27E-01
Water Use & Depletion	m3 H2O	1.30E+03	1.10E+02
Solid Waste	kg	4.19E+02	3.85E+02
Embodied Energy LHV	MJ LHV	5.73E+05	1.06E+06
Human Toxicity, Carcinogenic	CTUh	9.03E-07	2.22E-07
Human Toxicity, Non-Carcinogenic	CTUh	4.09E-05	7.87E-07
Eco Toxicity	CTUe	3.55E+01	4.62E+00

Elementary Flows for Water Supply System

Table D1.7 - Comparison of Elementary flows greater than 1%, Water Supply System ("E+02" means " x100" E-05 means "/100 000", etc)

Substance	Compart-ment	Unit	Off-Grid Earthship System inc Shed	Grid Water Supply, ADL
Carbon dioxide, fossil	Air	kg CO2-eq	9.61E+03	3.55E+04
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CFC 11-eq	1.75E-06	1.20E-05
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC 11-eq	1.30E-06	1.52E-06
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC 11-eq	5.29E-06	1.04E-05
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC 11-eq	2.46E-05	2.44E-05
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC 11-eq	1.40E-06	8.79E-06
Methane, dichlorodifluoro-, CFC-12	Air	kg CFC 11-eq	1.03E-06	7.09E-06
Methane, tetrachloro-, CFC-10	Air	kg CFC 11-eq	4.65E-06	5.66E-05

Substance	Compart-ment	Unit	Off-Grid Earthship System inc Shed	Grid Water Supply, ADL
Carbon monoxide	Air	kg C2H4-eq	9.45E-01	2.21E+00
Carbon monoxide, fossil	Air	kg C2H4-eq	3.18E-02	4.79E-02
Ethene	Air	kg C2H4-eq	2.39E-01	1.94E-03
Methane	Air	kg C2H4-eq	1.95E-02	3.54E-02
Methane, fossil	Air	kg C2H4-eq	6.02E-02	5.33E-02
Nonane	Air	kg C2H4-eq	2.75E-01	6.61E-09
Propene	Air	kg C2H4-eq	8.68E-02	7.71E-04
Sulfur dioxide	Air	kg C2H4-eq	1.04E-01	1.74E-01
COD, Chemical Oxygen Demand	Water	kg PO4--- eq	2.16E-01	1.12E+00
Nitrogen oxides	Air	kg PO4--- eq	2.34E+00	3.97E+00
Phosphate	Water	kg PO4--- eq	4.17E-01	8.54E-01
Phosphorus, total	Water	kg PO4--- eq	3.54E-02	1.34E-01
Occupation, forest, intensive	Raw	Ha.years	4.95E-03	1.06E-03
Occupation, forest, intensive, normal	Raw	Ha.years	3.37E-03	2.00E-03
Occupation, urban, green areas	Raw	Ha.years	3.37E-02	2.26E-01
Water, unspecified natural origin/m3	Raw	m3 H2O	7.97E+01	2.85E+04
ash	Waste	kg	3.32E+01	2.01E+02
Mineral waste	Waste	kg	1.02E+02	8.47E+00
Waste, final, inert	Waste	kg	3.59E+02	9.27E-02
Waste, solid	Waste	kg	1.13E+02	6.85E-07
Waste, unspecified	Waste	kg	3.09E+02	1.15E-01
Energy, kinetic (in wind), converted	Raw	MJ LHV	5.95E+03	5.74E+04
Energy, potential (in hydropower reservoir), converted	Raw	MJ LHV	8.94E+02	3.87E+03
Gas, natural, 36.6 MJ per m3, in ground	Raw	MJ LHV	8.40E+04	2.40E+05
Oil, crude	Raw	MJ LHV	1.97E+03	2.68E+03
Oil, crude, 42 MJ per kg, in ground	Raw	MJ LHV	9.03E+03	1.96E+04
Oil, crude, 42.7 MJ per kg, in ground	Raw	MJ LHV	3.02E+03	6.00E+03
Benzene	Air	CTUh	8.49E-09	7.29E-09
Benzene, ethyl-	Air	CTUh	8.58E-10	5.15E-09

Substance	Compart-ment	Unit	Off-Grid Earthship System inc Shed	Grid Water Supply, ADL
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	CTUh	2.32E-08	2.33E-08
Formaldehyde	Air	CTUh	1.38E-07	1.20E-07
Methane, tetrachloro-, CFC-10	Air	CTUh	3.06E-10	3.72E-09
Propylene oxide	Water	CTUh	3.41E-09	2.75E-10
Acrolein	Air	CTUh	2.46E-09	1.73E-08
Carbon disulfide	Air	CTUh	1.26E-07	4.10E-07
Methane, tetrachloro-, CFC-10	Air	CTUh	1.01E-09	1.23E-08
Benzene	Water	CTUe	2.50E-01	2.51E-01
Benzene, chloro-	Water	CTUe	3.75E-02	2.25E-01
Chlorothalonil	Soil	CTUe	1.05E+00	1.33E+00
Cumene	Water	CTUe	2.13E+00	2.77E-01
Formaldehyde	Air	CTUe	2.83E-01	2.26E-01
Metolachlor	Soil	CTUe	1.26E-01	4.10E-02
Phenol	Water	CTUe	1.30E+00	9.01E-01
Propylene oxide	Water	CTUe	2.38E-01	1.91E-02
Toluene	Water	CTUe	8.29E-02	1.55E-01
Xylene	Water	CTUe	6.32E-02	1.14E-01

Characterisation results for Water Supply System

Table D1.8 - Characterisation results, water collection system

Impact category	Unit	Earthship System inc Shed	Grid Water Supply, ADL
Global Warming Potential	kg CO_2-eq	9.95E+03	3.60E+04
Ozone Depletion	kg CFC 11-eq	4.02E-05	1.22E-04
Photochemical Oxidation	kg C_2H_4-eq	1.80E+00	2.59E+00
Eutrophication	kg PO4--- eq	3.07E+00	6.17E+00
Land Use & Transformation	Ha.years	4.34E-02	2.32E-01
Water Use & Depletion	m3 H2O	3.46E+02	2.85E+04
Solid Waste	kg	9.18E+02	2.17E+02
Embodied Energy LHV	MJ LHV	1.11E+05	3.35E+05
Human Toxicity, Carcinogenic	CTUh	1.79E-07	1.62E-07
Human Toxicity, Non-Carcinogenic	CTUh	1.41E-07	4.51E-07
Eco Toxicity	CTUe	5.93E+00	3.90E+00

Elementary Flows for Wastewater System

Table D1.9 - Comparison of Elementary flows greater than 1%, Wastewater Systems ("E+02" means " x100" E-05 means "/100 000", etc)

Substance	Compartment	Unit	Off-Grid Earthship Wastewater System	Sewer Use, ADL
Carbon dioxide, fossil	Air	kg CO2-eq	2.82E+03	1.02E+04
Methane, fossil	Air	kg CO2-eq	2.89E+01	3.19E+02
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC 11-eq	2.57E-06	1.00E-05
Hydrocarbons, chlorinated	Air	kg CFC 11-eq	8.92E-06	9.48E-07
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC 11-eq	5.15E-06	3.89E-04
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC 11-eq	3.80E-05	1.88E-04
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC 11-eq	3.83E-07	1.14E-05
Carbon monoxide	Air	kg C2H4-eq	2.00E-01	1.61E-01
Carbon monoxide, biogenic	Air	kg C2H4-eq	5.70E-04	3.86E-02
Carbon monoxide, fossil	Air	kg C2H4-eq	4.24E-02	6.20E-01
Ethane	Air	kg C2H4-eq	5.70E-04	3.06E-02
Ethene	Air	kg C2H4-eq	1.96E-01	1.95E-02
Methane, fossil	Air	kg C2H4-eq	8.26E-03	9.10E-02
Nonane	Air	kg C2H4-eq	2.25E-01	2.02E-06
Propene	Air	kg C2H4-eq	6.94E-02	4.98E-03
Sulfur dioxide	Air	kg C2H4-eq	6.36E-02	3.89E-01
COD, Chemical Oxygen Demand	Water	kg PO4--- eq	6.11E-02	3.66E+00
Nitrogen oxides	Air	kg PO4--- eq	1.17E+00	2.98E+00
Nitrogen, total	Water	kg PO4--- eq	1.73E-03	7.99E+00
Phosphate	Water	kg PO4--- eq	4.27E-01	4.10E+00
Phosphorus, total	Water	kg PO4--- eq	4.51E-03	1.52E+01
Occupation, arable	Raw	Ha.years	1.00E+00	x
Occupation, urban, green areas	Raw	Ha.years	5.35E-03	3.21E-02
Water, cooling, unspecified natural origin/m3	Raw	m3 H2O	4.51E+01	2.68E+01
Water, lake	Raw	m3 H2O	2.72E-02	8.47E+00
Water, river	Raw	m3 H2O	1.35E+00	3.09E+01
Water, unspecified natural origin /kg	Raw	m3 H2O	9.10E+01	2.00E-04
Water, unspecified natural origin/m3	Raw	m3 H2O	1.84E+01	4.29E+01
Water, well, in ground	Raw	m3 H2O	5.73E-01	1.86E+01
ash	Waste	kg	5.47E+00	2.85E+01
Waste, final, inert	Waste	kg	3.49E+02	8.92E-03
Coal, brown	Raw	MJ LHV	3.12E+02	1.99E+03
Coal, brown, 10.0 MJ per kg, in ground	Raw	MJ LHV	x	2.76E+04

Substance	Compartment	Unit	Off-Grid Earthship Wastewater System	Sewer Use, ADL
Coal, hard	Raw	MJ LHV	1.18E+03	1.84E+04
Energy, kinetic (in wind), converted	Raw	MJ LHV	8.21E+02	5.65E+03
Energy, potential (in hydropower reservoir), converted	Raw	MJ LHV	4.69E+02	2.26E+03
Gas, natural, 36.6 MJ per m3, in ground	Raw	MJ LHV	3.07E+04	3.80E+02
Gas, natural/m3	Raw	MJ LHV	9.52E+02	5.20E+04
Oil, crude	Raw	MJ LHV	3.39E+03	2.12E+04
Oil, crude, 42 MJ per kg, in ground	Raw	MJ LHV	1.16E+04	2.01E+03
Oil, crude, 42.7 MJ per kg, in ground	Raw	MJ LHV	4.65E+03	8.45E+02
Uranium	Raw	MJ LHV	1.39E+03	6.14E+03
Benzene	Air	CTUh	4.15E-09	6.68E-09
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	CTUh	1.35E-08	2.56E-07
Ethene, chloro-	Air	CTUh	7.03E-09	2.82E-09
Formaldehyde	Air	CTUh	7.83E-08	1.74E-07
Carbon disulfide	Air	CTUh	1.51E-07	1.36E-06
Atrazine	Soil	CTUe	2.16E-02	3.84E-01
Benzene	Water	CTUe	3.22E-01	8.03E-01
Chlorothalonil	Soil	CTUe	4.98E-01	6.10E-01
Cumene	Water	CTUe	1.92E+00	7.40E+00
Formaldehyde	Air	CTUe	1.48E-01	3.22E-01
Formaldehyde	Water	CTUe	5.09E-02	1.95E-01
Metolachlor	Soil	CTUe	3.35E-01	1.08E-01
Phenol	Water	CTUe	1.03E+00	1.58E+00
Toluene	Water	CTUe	1.27E-01	1.18E-01
Xylene	Water	CTUe	9.65E-02	1.24E-01

Characterisation results for Wastewater System

Table D1.10 - Comparison of characterisation results, wastewater systems

Impact category	Unit	Earthship Wastewater System	Sewer Use, ADL
Global Warming Potential	kg CO_2-eq	2.89E+03	1.06E+04
Ozone Depletion	kg CFC 11-eq	6.52E-05	6.04E-04
Photochemical Oxidation	kg C_2H_4-eq	8.39E-01	1.46E+00
Eutrophication	kg PO4--- eq	1.69E+00	3.41E+01
Land Use & Transformation	Ha.years	1.01E+00	5.62E-02

Impact category	Unit	Earthship Wastewater System	Sewer Use, ADL
Water Use & Depletion	m3 H2O	1.59E+02	1.28E+02
Solid Waste	kg	3.57E+02	2.86E+01
Embodied Energy LHV	MJ LHV	5.80E+04	1.41E+05
Human Toxicity, Carcinogenic	CTUh	1.11E-07	4.49E-07
Human Toxicity, Non-Carcinogenic	CTUh	1.63E-07	1.39E-06
Eco Toxicity	CTUe	4.86E+00	1.20E+01

Elementary Flows for Whole House

Table D1.11 - Comparison of Elementary flows greater than 1%, Whole House ("E+02" means " x100" E-05 means "/100 000", etc)

Substance	Compart-ment	Unit	BV LW CONV 20	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH lowEE	ESIB GH Base Case	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
Carbon dioxide, biogenic	Soil	kg CO2-eq	-3.01E+03	-3.01E+03	-2.89E+03	-2.31E+03	-5.10E+03	-6.01E+03	-6.42E+03	-2.31E+03	-2.90E+03	-2.31E+03	-2.31E+03	-2.59E+03	-3.27E+03
Carbon dioxide, fossil	Air	kg CO2-eq	3.13E+05	2.46E+05	1.71E+05	1.66E+05	7.75E+04	7.37E+04	8.64E+04	8.35E+04	1.69E+05	1.69E+05	1.58E+05	1.62E+05	1.66E+05
Methane, biogenic	Air	kg CO2-eq	1.58E+03	1.53E+03	1.42E+03	1.16E+03	2.36E+03	2.79E+03	2.98E+03	1.09E+03	1.43E+03	1.16E+03	1.16E+03	1.28E+03	1.60E+03
Methane, fossil	Air	kg CO2-eq	2.09E+03	1.65E+03	1.32E+03	1.65E+03	1.61E+03	1.82E+03	2.09E+03	1.39E+03	1.32E+03	1.30E+03	1.54E+03	1.25E+03	5.94E+03
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kg CFC 11-eq	1.01E-04	6.72E-05	3.88E-05	3.69E-05	6.36E-06	3.77E-06	4.71E-06	8.80E-06	3.78E-05	4.05E-05	3.62E-05	3.74E-05	4.04E-05
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC 11-eq	2.97E-05	2.65E-05	2.60E-05	2.47E-05	3.48E-05	3.96E-05	4.32E-05	3.38E-05	2.58E-05	2.32E-05	2.29E-05	2.38E-05	2.05E-05
Hydrocarbons, chlorinated	Air	kg CFC 11-eq	8.89E-06	6.47E-06	4.11E-06	6.24E-06	6.49E-05	9.66E-05	9.64E-05	6.34E-05	2.42E-04	3.79E-06	5.35E-06	4.39E-06	2.34E-04
Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC 11-eq	5.07E-04	4.81E-04	4.62E-04	4.60E-04	3.01E-04	3.20E-04	3.41E-04	2.99E-04	4.62E-04	4.58E-04	4.55E-04	4.58E-04	4.54E-04
Methane, bromotrifluoro-, Halon 1301	Air	kg CFC 11-eq	5.19E-04	4.57E-04	4.43E-04	4.60E-04	3.52E-04	4.04E-04	4.60E-04	3.40E-04	4.41E-04	4.18E-04	4.13E-04	4.19E-04	3.76E-04
Methane, chlorodifluoro-, HCFC-22	Air	kg CFC 11-eq	8.62E-05	6.18E-05	4.11E-05	6.48E-05	2.17E-04	2.27E-04	2.28E-04	1.97E-04	4.04E-05	4.21E-05	6.41E-05	4.00E-05	4.19E-05
Methane, dichlorodifluoro-, CFC-12	Air	kg CFC 11-eq	6.02E-05	4.04E-05	2.36E-05	2.25E-05	1.58E-05	1.44E-05	1.48E-05	1.72E-05	2.30E-05	2.46E-05	2.21E-05	2.28E-05	2.45E-05
Methane, tetrachloro-, CFC-10	Air	kg CFC 11-eq	1.01E-04	8.72E-05	7.54E-05	7.46E-05	6.68E-05	6.59E-05	6.70E-05	6.60E-05	7.51E-05	7.52E-05	7.36E-05	7.42E-05	7.56E-05
Carbon monoxide	Air	kg C2H4-eq	1.77E+01	1.33E+01	9.32E+00	8.80E+00	4.90E+00	4.79E+00	6.13E+00	4.39E+00	9.18E+00	9.09E+00	8.49E+00	8.91E+00	9.19E+00
Carbon monoxide, biogenic	Air	kg C2H4-eq	6.23E-01	6.19E-01	5.92E-01	4.75E-01	1.01E+00	1.18E+00	1.23E+00	4.64E-01	5.93E-01	4.74E-01	4.74E-01	5.28E-01	6.72E-01

Substance	Compart-ment	Unit	BV LW CONV 20	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH lowEE	ESIB GH Base Case	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
Carbon monoxide, fossil	Air	kg C2H4-eq	1.35E+00	1.23E+00	1.37E+00	1.14E+00	1.01E+00	1.08E+00	1.15E+00	9.59E-01	1.36E+00	9.20E-01	9.51E-01	1.06E+00	8.89E-01
Hexane	Air	kg C2H4-eq	6.18E-02	2.69E-01	2.68E-01	2.72E-01	2.88E-01	2.97E-01	2.94E-01	2.87E-01	2.68E-01	2.65E-01	2.64E-01	2.64E-01	2.34E-01
Methane	Air	kg C2H4-eq	3.18E-01	2.76E-01	2.04E-01	1.99E-01	1.18E-01	1.12E-01	1.58E-01	1.22E-01	2.05E-01	1.98E-01	1.87E-01	1.92E-01	2.16E-01
Methane, biogenic	Air	kg C2H4-eq	4.52E-01	4.36E-01	4.06E-01	3.31E-01	6.74E-01	7.97E-01	8.51E-01	3.12E-01	4.08E-01	3.32E-01	3.30E-01	3.67E-01	4.58E-01
Methane, fossil	Air	kg C2H4-eq	5.97E-01	4.73E-01	3.76E-01	4.71E-01	4.61E-01	5.21E-01	5.98E-01	3.96E-01	3.76E-01	3.71E-01	4.41E-01	3.56E-01	1.70E+00
Pentane	Air	kg C2H4-eq	4.78E-02	4.23E-02	3.76E-02	2.68E+00	2.32E+00	3.84E+00	3.81E+00	6.26E-02	3.76E-02	3.39E-02	2.67E+00	3.83E-02	3.78E-02
Propylene glycol	Air	kg C2H4-eq	1.84E+00	1.84E+00	1.61E+00	5.10E-01	4.54E-02	3.04E-01	9.95E-01	x	2.82E+00	x	x	5.10E-01	2.26E+00
Sulfur dioxide	Air	kg C2H4-eq	1.70E+00	1.78E+00	1.76E+00	1.90E+00	2.50E+00	2.96E+00	3.59E+00	2.33E+00	1.77E+00	1.52E+00	1.73E+00	1.60E+00	1.23E+00
COD, Chemical Oxygen Demand	Water	kg PO4--- eq	1.32E+01	1.03E+01	7.67E+00	7.51E+00	1.64E+00	1.78E+00	2.05E+00	1.78E+00	7.59E+00	7.75E+00	7.41E+00	7.48E+00	7.72E+00
Nitrogen	Water	kg PO4--- eq	6.92E-02	5.23E-02	3.86E-02	4.06E-02	9.80E+00	9.90E+00	9.89E+00	9.80E+00	3.83E-02	3.93E-02	3.79E-02	3.72E-02	3.89E-02
Nitrogen oxides	Air	kg PO4--- eq	3.16E+01	5.87E+01	5.52E+01	5.50E+01	5.00E+01	5.20E+01	5.74E+01	4.91E+01	5.52E+01	5.35E+01	5.32E+01	5.29E+01	5.40E+01
Nitrogen, total	Water	kg PO4--- eq	8.11E+00	8.08E+00	8.05E+00	8.04E+00	2.40E-02	2.10E-02	2.71E-02	2.62E-02	8.05E+00	8.05E+00	8.04E+00	8.05E+00	8.04E+00
Phosphate	Water	kg PO4--- eq	1.27E+01	1.07E+01	9.19E+00	9.18E+00	3.85E+01	3.96E+01	4.05E+01	3.84E+01	9.13E+00	8.88E+00	8.70E+00	8.85E+00	8.45E+00
Phosphorus, total	Water	kg PO4--- eq	1.63E+01	1.59E+01	1.56E+01	1.56E+01	1.02E-01	7.27E-02	8.64E-02	1.27E-01	1.56E+01	1.56E+01	1.56E+01	1.56E+01	1.56E+01
Occupation, arable	Raw	Ha.years	6.80E-01	6.80E-01	6.80E-01	7.60E-01	3.01E+00	4.74E+00	4.74E+00	2.61E+00	6.80E-01	6.90E-01	7.20E-01	7.60E-01	6.80E-01
Occupation, forest	Raw	Ha.years	5.39E-02	5.39E-02	5.17E-02	4.03E-02	9.28E-02	1.09E-01	1.12E-01	4.04E-02	5.60E-02	4.03E-02	4.03E-02	4.56E-02	6.34E-02
Occupation, forest, intensive	Raw	Ha.years	4.45E-02	4.39E-02	4.72E-02	6.69E-02	2.85E-02	3.27E-02	6.44E-02	3.44E-02	4.68E-02	5.00E-02	5.12E-02	4.45E-02	4.75E-02
Occupation, forest, intensive, normal	Raw	Ha.years	2.69E-01	2.65E-01	2.63E-01	2.71E-01	2.82E-01	3.43E-01	6.55E-01	2.71E-01	2.63E-01	2.63E-01	2.63E-01	2.61E-01	2.63E-01
Occupation, forest, intensive, short-cycle	Raw	Ha.years	4.13E-01	4.13E-01	3.95E-01	3.04E-01	6.92E-01	8.18E-01	8.37E-01	3.04E-01	3.92E-01	3.04E-01	3.04E-01	3.42E-01	4.57E-01
Occupation, urban, green	Raw	Ha.year	1.93E+00	1.30E+00	7.63E-01	7.27E-01	1.18E-01	6.73E-02	9.18E-02	1.65E-01	7.44E-01	7.95E-01	7.15E-01	7.38E-01	7.94E-01

Substance	Compart-ment	Unit	BV LW CONV 20	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH lowEE	ESIB GH Base Case	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
areas		s													
Water, cooling, unspecified natural origin/m3	Raw	m3 H2O	2.62E+02	1.98E+02	1.46E+02	2.18E+02	9.52E+02	1.08E+03	1.10E+03	8.92E+02	1.45E+02	1.45E+02	2.11E+02	1.40E+02	1.42E+02
Water, river	Raw	m3 H2O	5.04E+01	4.61E+01	4.33E+01	4.31E+01	7.08E+02	7.70E+02	7.72E+02	7.08E+02	4.32E+01	4.21E+01	4.19E+01	4.22E+01	4.07E+01
Water, unspecified natural origin/m3	Raw	m3 H2O	2.62E+04	2.61E+04	2.61E+04	2.62E+04	1.94E+02	2.25E+02	3.19E+02	2.10E+02	2.61E+04	2.61E+04	2.61E+04	2.61E+04	2.61E+04
ash	Waste	kg	1.80E+03	1.24E+03	7.66E+02	7.65E+02	1.43E+02	1.06E+02	2.04E+02	2.00E+02	7.48E+02	7.97E+02	7.27E+02	7.35E+02	8.01E+02
Mineral waste	Waste	kg	1.49E+03	1.49E+03	1.69E+03	3.46E+03	7.74E+02	9.88E+02	1.32E+03	9.92E+02	1.71E+03	1.84E+03	1.85E+03	1.99E+03	1.63E+03
Waste, final, inert	Waste	kg	1.04E+04	1.04E+04	1.10E+04	1.08E+04	9.33E+03	1.12E+04	1.31E+04	7.58E+03	1.08E+04	1.03E+04	1.09E+04	8.25E+03	1.10E+04
Waste, unspecified	Waste	kg	1.41E+02	1.41E+02	1.42E+02	2.17E+02	3.91E+02	4.49E+02	4.76E+02	3.83E+02	1.77E+02	1.04E+02	1.05E+02	1.36E+02	1.64E+02
Coal, brown, 10.0 MJ per kg, in ground	Raw	MJ LHV	2.76E+04	2.76E+04	2.76E+04	2.76E+04	-1.27E+02	-1.27E+02	-1.27E+02	-1.27E+02	2.76E+04	2.76E+04	2.76E+04	2.76E+04	2.76E+04
Coal, hard	Raw	MJ LHV	3.50E+04	3.10E+04	2.83E+04	2.81E+04	5.95E+03	6.77E+03	8.16E+03	5.79E+03	2.82E+04	2.74E+04	2.69E+04	2.75E+04	2.63E+04
Energy, kinetic (in wind), converted	Raw	MJ LHV	3.74E+05	2.56E+05	1.56E+05	1.49E+05	2.18E+04	1.30E+04	1.47E+04	3.04E+04	1.52E+05	1.62E+05	1.47E+05	1.51E+05	1.61E+05
Energy, potential (in hydropower reservoir), converted	Raw	MJ LHV	3.61E+04	2.54E+04	1.66E+04	1.60E+04	1.48E+04	1.42E+04	1.83E+04	1.55E+04	1.65E+04	1.67E+04	1.55E+04	1.59E+04	1.67E+04
Gas, natural, 36.6 MJ per m3, in ground	Raw	MJ LHV	2.06E+06	1.68E+06	1.14E+06	1.08E+06	5.23E+05	4.73E+05	5.06E+05	5.70E+05	1.12E+06	1.13E+06	1.04E+06	1.08E+06	1.34E+06
Gas, natural/m3	Raw	MJ LHV	6.77E+04	6.36E+04	6.07E+04	6.04E+04	4.68E+03	5.20E+03	6.31E+03	4.64E+03	6.06E+04	6.00E+04	5.95E+04	6.00E+04	5.92E+04
Oil, crude	Raw	MJ LHV	5.31E+04	4.61E+04	4.35E+04	4.43E+04	1.61E+04	1.92E+04	2.32E+04	1.53E+04	4.33E+04	4.13E+04	4.05E+04	4.14E+04	3.79E+04
Oil, crude, 42 MJ per kg, in ground	Raw	MJ LHV	1.10E+05	2.71E+05	2.71E+05	2.79E+05	2.37E+05	2.50E+05	2.72E+05	2.38E+05	2.71E+05	2.63E+05	2.62E+05	2.64E+05	8.36E+04
Oil, crude, 42.7 MJ per kg, in ground	Raw	MJ LHV	2.68E+04	9.84E+04	1.04E+05	1.08E+05	9.54E+04	1.01E+05	1.10E+05	9.52E+04	1.04E+05	1.00E+05	1.01E+05	1.01E+05	2.26E+04
Benzene	Air	CTUh	5.82E-08	6.04E-08	7.83E-08	6.63E-08	1.76E-07	1.81E-07	1.88E-07	1.71E-07	7.76E-08	4.26E-08	4.65E-08	5.55E-08	3.57E-08
Dicofol	Water	CTUh	x	x	x	x	-1.22E-06	-1.22E-06	-1.22E-06	-1.22E-06	x	x	x	x	x
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	CTUh	6.36E-07	5.89E-07	5.52E-07	5.40E-07	4.92E-07	5.54E-07	6.06E-07	3.43E-07	5.51E-07	5.13E-07	5.12E-07	5.26E-07	5.58E-07
Formaldehyde	Air	CTUh	6.32E-06	6.51E-06	1.08E-05	4.92E-06	1.87E-06	2.01E-06	3.80E-06	1.85E-06	1.06E-05	1.98E-06	1.96E-06	4.89E-06	1.66E-06
Carbon disulfide	Air	CTUh	5.27E-06	4.18E-06	3.31E-06	3.27E-06	4.14E-05	4.14E-05	4.16E-05	4.14E-05	3.28E-06	3.24E-06	3.10E-06	3.21E-06	3.24E-06
Chlorpyrifos	Water	CTUh	x	x	x	x	-1.87E-06	-1.87E-06	-1.87E-06	-1.87E-06	x	x	x	x	x
Dicofol	Air	CTUh	x	x	x	x	-9.67E-07	-9.67E-07	-9.67E-07	-9.67E-07	x	x	x	x	x
Dicofol	Water	CTUh	x	x	x	x	-1.13E-05	-1.13E-05	-1.13E-05	-1.13E-05	x	x	x	x	x
Bifenthrin	Water	CTUe	x	x	x	x	-9.16E+03	-9.16E+03	-9.16E+03	-9.16E+03	x	x	x	x	x
Carbendazim	Water	CTUe	x	x	x	x	-5.27E+04	-5.27E+04	-5.27E+04	-5.27E+04	x	x	x	x	x
Chlorpyrifos	Water	CTUe	x	x	x	x	-2.29E+04	-2.29E+04	-2.29E+04	-2.29E+04	x	x	x	x	x
Dicofol	Water	CTUe	x	x	x	x	-1.05E+03	-1.05E+03	-1.05E+03	-1.05E+03	x	x	x	x	x

Characterisation results for Whole House

Table D1.12 - Characterisation results for all Thermal Envelopes

Impact category	Unit	BV LW CONV 20	BV LW CONV	BV TM	CBI TM	ESI lowEE	ESIB GH lowEE	ESIB GH TM (Base Case)	MB MB	RBV TM	RE RE	REI RE	SB TM	TFC LW
Global Warming Potential	kg CO2-eq	3.16E+05	2.48E+05	1.72E+05	1.68E+05	7.71E+04	7.28E+04	8.66E+04	8.44E+04	1.70E+05	1.70E+05	1.60E+05	1.63E+05	1.72E+05
Ozone Depletion	kg CFC 11-eq	1.42E-03	1.23E-03	1.12E-03	1.15E-03	1.06E-03	1.18E-03	1.26E-03	1.03E-03	1.35E-03	1.09E-03	1.09E-03	1.08E-03	1.27E-03
Photochemical Oxidation	kg C2H4-eq	2.55E+01	2.10E+01	1.68E+01	1.74E+01	1.51E+01	1.77E+01	2.07E+01	1.11E+01	1.79E+01	1.37E+01	1.60E+01	1.44E+01	1.73E+01
Eutrophication	kg PO4--- eq	8.32E+01	1.05E+02	9.68E+01	9.63E+01	1.01E+02	1.05E+02	1.12E+02	1.00E+02	9.68E+01	9.45E+01	9.38E+01	9.38E+01	9.49E+01
Land Use & Transformation	Ha.years	3.45E+00	2.80E+00	2.24E+00	2.21E+00	4.25E+00	6.15E+00	6.54E+00	3.45E+00	2.23E+00	2.18E+00	2.13E+00	2.23E+00	2.34E+00
Water Use & Depletion	m3 H2O	2.66E+04	2.65E+04	2.63E+04	2.65E+04	1.91E+03	2.17E+03	2.37E+03	1.84E+03	2.63E+04	2.64E+04	2.65E+04	2.64E+04	2.64E+04
Solid Waste	kg	1.39E+04	1.33E+04	1.36E+04	1.53E+04	1.12E+04	1.35E+04	1.58E+04	9.28E+03	1.35E+04	1.31E+04	1.36E+04	1.11E+04	1.37E+04
Embodied Energy LHV	MJ LHV	2.86E+06	2.57E+06	1.92E+06	1.86E+06	9.81E+05	9.58E+05	1.06E+06	1.02E+06	1.90E+06	1.88E+06	1.78E+06	1.83E+06	1.85E+06
Human Toxicity, Carcinogenic	CTUh	7.10E-06	7.24E-06	1.15E-05	5.62E-06	1.29E-06	1.50E-06	3.36E-06	1.10E-06	1.13E-05	2.60E-06	2.60E-06	5.54E-06	2.31E-06
Human Toxicity, Non-Carcinogenic	CTUh	5.60E-06	4.53E-06	3.67E-06	3.56E-06	2.65E-05	2.66E-05	2.68E-05	2.66E-05	3.64E-06	3.48E-06	3.34E-06	3.49E-06	3.41E-06
Eco Toxicity	CTUe	6.91E+01	7.95E+01	8.65E+01	8.15E+01	-8.66E+04	-8.59E+04	-8.59E+04	-8.66E+04	8.69E+01	6.77E+01	6.81E+01	7.22E+01	5.01E+01

D2 - Characterisation Factors

Global Warming

Impact Category				
Global Warming	kg CO2 eq			
Compartment	Sub compartment	Substance	Factor	Unit
Air	(unspecified)	Carbon dioxide	1	kg
Air	(unspecified)	Carbon Dioxide Equivalent	1	kg
Soil	(unspecified)	Carbon dioxide, biogenic	-1	kg
Air	(unspecified)	Carbon dioxide, fossil	1	kg
Air	(unspecified)	Carbon dioxide, land transformation	1	kg
Air	(unspecified)	Chlorinated fluorocarbons, hard	7100	kg
Air	(unspecified)	Chlorinated fluorocarbons, soft	1600	kg
Air	(unspecified)	Chloroform	25	kg
Air	(unspecified)	Dinitrogen monoxide	310	kg
Air	(unspecified)	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	1200	kg
Air	(unspecified)	Ethane, 1,1,1-trichloro-, HCFC-140	100	kg
Air	(unspecified)	Ethane, 1,1,1-trifluoro-, HFC-143a	3800	kg
Air	(unspecified)	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	4500	kg
Air	(unspecified)	Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	580	kg
Air	(unspecified)	Ethane, 1,1-difluoro-, HFC-152a	150	kg
Air	(unspecified)	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	7000	kg
Air	(unspecified)	Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	1800	kg
Air	(unspecified)	Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	90	kg
Air	(unspecified)	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	440	kg
Air	(unspecified)	Ethane, chloropentafluoro-, CFC-115	7000	kg
Air	(unspecified)	Ethane, hexafluoro-, HFC-116	9200	kg
Air	(unspecified)	Ethane, pentafluoro-, HFC-125	3400	kg
Air	(unspecified)	Methane	21	kg
Air	(unspecified)	Methane, biogenic	21	kg
Air	(unspecified)	Methane, bromochlorodifluoro-, Halon 1211	4900	kg
Air	(unspecified)	Methane, bromotrifluoro-, Halon 1301	4900	kg
Air	(unspecified)	Methane, chlorodifluoro-, HCFC-22	1600	kg
Air	(unspecified)	Methane, chlorotrifluoro-, CFC-13	13000	kg
Air	(unspecified)	Methane, dichloro-, HCC-30	9	kg
Air	(unspecified)	Methane, dichlorodifluoro-, CFC-12	7100	kg
Air	(unspecified)	Methane, fossil	21	kg
Air	(unspecified)	Methane, tetrachloro-, CFC-10	1300	kg
Air	(unspecified)	Methane, tetrafluoro-, CFC-14	6500	kg
Air	(unspecified)	Methane, trichlorofluoro-, CFC-11	3400	kg

Ozone Depletion

Impact Category				
Ozone Depletion	kgCFC 11-eq			
Compartment	Sub compartment	Substance	Factor	Unit
Air	(unspecified)	Ethane, 1,1,1,2-tetrafluoro-2-bromo-, Halon 2401	0.25	kg
Air	(unspecified)	Ethane, 1,1,1-trichloro-, HCFC-140	0.12	kg
Air	(unspecified)	Ethane, 1,1,1-trifluoro-2,2-chlorobromo-, Halon 2311	0.14	kg
Air	(unspecified)	Ethane, 1,1,2-trichloro-	0.12	kg
Air	(unspecified)	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	1	kg
Air	(unspecified)	Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	0.12	kg
Air	(unspecified)	Ethane, 1,2-dibromotetrafluoro-, Halon 2402	6	kg
Air	(unspecified)	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	0.94	kg
Air	(unspecified)	Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	0.07	kg
Air	(unspecified)	Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	0.02	kg
Air	(unspecified)	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	0.02	kg
Air	(unspecified)	Ethane, chloropentafluoro-, CFC-115	0.44	kg
Air	(unspecified)	Hydrocarbons, chlorinated	0.00617	kg
Air	(unspecified)	Methane, bromo-, Halon 1001	0.38	kg
Air	(unspecified)	Methane, bromochlorodifluoro-, Halon 1211	6	kg
Air	(unspecified)	Methane, bromodifluoro-, Halon 1201	1.4	kg
Air	(unspecified)	Methane, bromotrifluoro-, Halon 1301	12	kg
Air	(unspecified)	Methane, chlorodifluoro-, HCFC-22	0.05	kg
Air	(unspecified)	Methane, dibromodifluoro-, Halon 1202	1.3	kg
Air	(unspecified)	Methane, dichlorodifluoro-, CFC-12	1	kg
Air	(unspecified)	Methane, monochloro-, R-40	0.02	kg
Air	(unspecified)	Methane, tetrachloro-, CFC-10	0.73	kg
Air	(unspecified)	Methane, trichlorofluoro-, CFC-11	1	kg
Air	(unspecified)	Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	0.03	kg
Air	(unspecified)	Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	0.02	kg

Photochemical Oxidation

Impact Category				
Photochemical Oxidation	kg C2H4			
Compartment	Sub compartment	Substance	Factor	Unit
Air	(unspecified)	1-Butanol	0.62	kg C2H4-eq / kg
Air	(unspecified)	1-Butene	1.079	kg C2H4-eq / kg
Air	(unspecified)	1-Butene, 2-methyl-	0.771	kg C2H4-eq / kg
Air	(unspecified)	1-Butene, 3-methyl-	0.671	kg C2H4-eq / kg
Air	(unspecified)	1-Hexene	0.874	kg C2H4-eq / kg
Air	(unspecified)	1-Pentene	0.977	kg C2H4-eq / kg
Air	(unspecified)	1-Propanol	0.561	kg C2H4-eq / kg
Air	(unspecified)	2-Butanol	0.4	kg C2H4-eq / kg
Air	(unspecified)	2-Butanone, 3-methyl-	0.364	kg C2H4-eq / kg
Air	(unspecified)	2-Butanone, 3,3-dimethyl-	0.323	kg C2H4-eq / kg
Air	(unspecified)	2-Butene (cis)	1.146	kg C2H4-eq / kg
Air	(unspecified)	2-Butene (trans)	1.132	kg C2H4-eq / kg
Air	(unspecified)	2-Butene, 2-methyl-	0.842	kg C2H4-eq / kg
Air	(unspecified)	2-Hexanone	0.572	kg C2H4-eq / kg
Air	(unspecified)	2-Hexene (cis)	1.069	kg C2H4-eq / kg
Air	(unspecified)	2-Hexene (trans)	1.073	kg C2H4-eq / kg
Air	(unspecified)	2-Methyl-1-propanol	0.36	kg C2H4-eq / kg
Air	(unspecified)	2-Pentanone	0.548	kg C2H4-eq / kg
Air	(unspecified)	2-Pentene (cis)	1.121	kg C2H4-eq / kg
Air	(unspecified)	2-Pentene (trans)	1.117	kg C2H4-eq / kg
Air	(unspecified)	2-Propanol	0.188	kg C2H4-eq / kg
Air	(unspecified)	3-Hexanone	0.599	kg C2H4-eq / kg
Air	(unspecified)	3-Pentanol	0.595	kg C2H4-eq / kg
Air	(unspecified)	4-Methyl-2-pentanone	0.49	kg C2H4-eq / kg
Air	(unspecified)	Acetaldehyde	0.641	kg C2H4-eq / kg
Air	(unspecified)	Acetic acid	0.097	kg C2H4-eq / kg
Air	(unspecified)	Acetone	0.094	kg C2H4-eq / kg
Air	(unspecified)	Alcohol, diacetone	0.307	kg C2H4-eq / kg
Air	(unspecified)	Benzaldehyde	-0.092	kg C2H4-eq / kg
Air	(unspecified)	Benzene	0.218	kg C2H4-eq / kg
Air	(unspecified)	Benzene, 1-propyl-	0.636	kg C2H4-eq / kg
Air	(unspecified)	Benzene, 1,2,3-trimethyl-	1.267	kg C2H4-eq / kg
Air	(unspecified)	Benzene, 1,2,4-trimethyl-	1.278	kg C2H4-eq / kg
Air	(unspecified)	Benzene, 1,3,5-trimethyl-	1.381	kg C2H4-eq / kg

Air	(unspecified)	Benzene, 3,5-dimethylethyl-	1.32	kg C2H4-eq / kg
Air	(unspecified)	Benzene, ethyl-	0.73	kg C2H4-eq / kg
Air	(unspecified)	Butadiene	0.851	kg C2H4-eq / kg
Air	(unspecified)	Butanal	0.795	kg C2H4-eq / kg
Air	(unspecified)	Butane	0.352	kg C2H4-eq / kg
Air	(unspecified)	Butane, 2,2-dimethyl-	0.241	kg C2H4-eq / kg
Air	(unspecified)	Butane, 2,3-dimethyl-	0.541	kg C2H4-eq / kg
Air	(unspecified)	Butanol, 2-methyl-1-	0.489	kg C2H4-eq / kg
Air	(unspecified)	Butanol, 2-methyl-2-	0.228	kg C2H4-eq / kg
Air	(unspecified)	Butanol, 3-methyl-1-	0.433	kg C2H4-eq / kg
Air	(unspecified)	Butanol, 3-methyl-2-	0.406	kg C2H4-eq / kg
Air	(unspecified)	Butyl acetate	0.269	kg C2H4-eq / kg
Air	(unspecified)	Carbon monoxide	0.027	kg C2H4-eq / kg
Air	(unspecified)	Carbon monoxide, biogenic	0.027	kg C2H4-eq / kg
Air	(unspecified)	Carbon monoxide, fossil	0.027	kg C2H4-eq / kg
Air	(unspecified)	Chloroform	0.023	kg C2H4-eq / kg
Air	(unspecified)	Cumene	0.5	kg C2H4-eq / kg
Air	(unspecified)	Cyclohexane	0.29	kg C2H4-eq / kg
Air	(unspecified)	Cyclohexanol	0.518	kg C2H4-eq / kg
Air	(unspecified)	Cyclohexanone	0.299	kg C2H4-eq / kg
Air	(unspecified)	Decane	0.384	kg C2H4-eq / kg
Air	(unspecified)	Diethyl ether	0.445	kg C2H4-eq / kg
Air	(unspecified)	Diethyl ketone	0.414	kg C2H4-eq / kg
Air	(unspecified)	Diisopropyl ether	0.398	kg C2H4-eq / kg
Air	(unspecified)	Dimethyl carbonate	0.025	kg C2H4-eq / kg
Air	(unspecified)	Dimethyl ether	0.189	kg C2H4-eq / kg
Air	(unspecified)	Dodecane	0.357	kg C2H4-eq / kg
Air	(unspecified)	Ethane	0.123	kg C2H4-eq / kg
Air	(unspecified)	Ethane, 1,1,1-trichloro-, HCFC-140	0.009	kg C2H4-eq / kg
Air	(unspecified)	Ethanol	0.399	kg C2H4-eq / kg
Air	(unspecified)	Ethanol, 2-butoxy-	0.483	kg C2H4-eq / kg
Air	(unspecified)	Ethanol, 2-ethoxy-	0.386	kg C2H4-eq / kg
Air	(unspecified)	Ethanol, 2-methoxy-	0.307	kg C2H4-eq / kg
Air	(unspecified)	Ethene	1	kg C2H4-eq / kg
Air	(unspecified)	Ethene, dichloro- (cis)	0.447	kg C2H4-eq / kg
Air	(unspecified)	Ethene, dichloro- (trans)	0.392	kg C2H4-eq / kg
Air	(unspecified)	Ethene, tetrachloro-	0.029	kg C2H4-eq / kg
Air	(unspecified)	Ethene, trichloro-	0.325	kg C2H4-eq / kg

Air	(unspecified)	Ethyl acetate	0.209	kg C2H4-eq / kg
Air	(unspecified)	Ethylene glycol	0.373	kg C2H4-eq / kg
Air	(unspecified)	Ethyne	0.085	kg C2H4-eq / kg
Air	(unspecified)	Formaldehyde	0.519	kg C2H4-eq / kg
Air	(unspecified)	Formic acid	0.032	kg C2H4-eq / kg
Air	(unspecified)	Heptane	0.494	kg C2H4-eq / kg
Air	(unspecified)	Hexane	0.482	kg C2H4-eq / kg
Air	(unspecified)	Hexane, 2-methyl-	0.411	kg C2H4-eq / kg
Air	(unspecified)	Hexane, 3-methyl-	0.364	kg C2H4-eq / kg
Air	(unspecified)	Isobutane	0.307	kg C2H4-eq / kg
Air	(unspecified)	Isobutene	0.627	kg C2H4-eq / kg
Air	(unspecified)	Isobutyraldehyde	0.514	kg C2H4-eq / kg
Air	(unspecified)	Isopentane	0.405	kg C2H4-eq / kg
Air	(unspecified)	Isoprene	1.092	kg C2H4-eq / kg
Air	(unspecified)	Isopropyl acetate	0.211	kg C2H4-eq / kg
Air	(unspecified)	m-Xylene	1.108	kg C2H4-eq / kg
Air	(unspecified)	Methane	0.006	kg C2H4-eq / kg
Air	(unspecified)	Methane, biogenic	0.006	kg C2H4-eq / kg
Air	(unspecified)	Methane, dichloro-, HCC-30	0.068	kg C2H4-eq / kg
Air	(unspecified)	Methane, dimethoxy-	0.164	kg C2H4-eq / kg
Air	(unspecified)	Methane, fossil	0.006	kg C2H4-eq / kg
Air	(unspecified)	Methane, monochloro-, R-40	0.005	kg C2H4-eq / kg
Air	(unspecified)	Methanol	0.14	kg C2H4-eq / kg
Air	(unspecified)	Methyl acetate	0.059	kg C2H4-eq / kg
Air	(unspecified)	Methyl ethyl ketone	0.373	kg C2H4-eq / kg
Air	(unspecified)	Methyl formate	0.027	kg C2H4-eq / kg
Air	(unspecified)	Nitric oxide	-0.427	kg C2H4-eq / kg
Air	(unspecified)	Nitrogen dioxide	0.028	kg C2H4-eq / kg
Air	(unspecified)	Nonane	0.414	kg C2H4-eq / kg
Air	(unspecified)	o-Xylene	1.053	kg C2H4-eq / kg
Air	(unspecified)	Octane	0.453	kg C2H4-eq / kg
Air	(unspecified)	p-Xylene	1.01	kg C2H4-eq / kg
Air	(unspecified)	Pentanal	0.765	kg C2H4-eq / kg
Air	(unspecified)	Pentane	0.395	kg C2H4-eq / kg
Air	(unspecified)	Pentane, 2-methyl-	0.42	kg C2H4-eq / kg
Air	(unspecified)	Pentane, 3-methyl-	0.479	kg C2H4-eq / kg
Air	(unspecified)	Propanal	0.798	kg C2H4-eq / kg
Air	(unspecified)	Propane	0.176	kg C2H4-eq / kg

Air	(unspecified)	Propane, 2,2-dimethyl-	0.173	kg C2H4-eq / kg
Air	(unspecified)	Propene	1.123	kg C2H4-eq / kg
Air	(unspecified)	Propionic acid	0.15	kg C2H4-eq / kg
Air	(unspecified)	Propyl acetate	0.282	kg C2H4-eq / kg
Air	(unspecified)	Propylene glycol	0.457	kg C2H4-eq / kg
Air	(unspecified)	Propylene glycol methyl ether	0.355	kg C2H4-eq / kg
Air	(unspecified)	Propylene glycol t-butyl ether	0.463	kg C2H4-eq / kg
Air	(unspecified)	s-Butyl acetate	0.275	kg C2H4-eq / kg
Air	(unspecified)	Styrene	0.142	kg C2H4-eq / kg
Air	(unspecified)	Sulfur dioxide	0.048	kg C2H4-eq / kg
Air	(unspecified)	Sulfur monoxide	0.048	kg C2H4-eq / kg
Air	(unspecified)	t-Butyl acetate	0.053	kg C2H4-eq / kg
Air	(unspecified)	t-Butyl alcohol	0.106	kg C2H4-eq / kg
Air	(unspecified)	t-Butyl ethyl ether	0.244	kg C2H4-eq / kg
Air	(unspecified)	t-Butyl methyl ether	0.175	kg C2H4-eq / kg
Air	(unspecified)	Toluene	0.637	kg C2H4-eq / kg
Air	(unspecified)	Toluene, 2-ethyl-	0.898	kg C2H4-eq / kg
Air	(unspecified)	Toluene, 3-ethyl-	1.019	kg C2H4-eq / kg
Air	(unspecified)	Toluene, 3,5-diethyl-	1.295	kg C2H4-eq / kg
Air	(unspecified)	Toluene, 4-ethyl-	0.906	kg C2H4-eq / kg
Air	(unspecified)	Undecane	0.384	kg C2H4-eq / kg

Eutrophication

Impact Category				
Eutrophication	kg PO4--- eq			
Compartment	Sub compartment	Substance	Factor	Unit
Air	(unspecified)	Ammonia	3.50E-01	kg
Soil	(unspecified)	Ammonia	3.50E-01	kg
Water	(unspecified)	Ammonia	3.50E-01	kg
Air	(unspecified)	Ammonium carbonate	1.20E-01	kg
Air	(unspecified)	Ammonium nitrate	7.40E-02	kg
Soil	(unspecified)	Ammonium nitrate	7.40E-02	kg
Air	(unspecified)	Ammonium, ion	3.30E-01	kg
Soil	(unspecified)	Ammonium, ion	3.30E-01	kg
Water	(unspecified)	Ammonium, ion	3.30E-01	kg
Water	(unspecified)	COD, Chemical Oxygen Demand	2.20E-02	kg
Air	(unspecified)	Nitrate	1.00E-01	kg
Soil	(unspecified)	Nitrate	1.00E-01	kg
Water	(unspecified)	Nitrate	1.00E-01	kg
Air	(unspecified)	Nitric acid	1.00E-01	kg
Soil	(unspecified)	Nitric acid	1.00E-01	kg
Water	(unspecified)	Nitric acid	1.00E-01	kg
Air	(unspecified)	Nitric oxide	2.00E-01	kg
Water	(unspecified)	Nitrite	1.00E-01	kg
Soil	(unspecified)	Nitrogen	0.42	kg
Water	(unspecified)	Nitrogen	4.20E-01	kg
Air	(unspecified)	Nitrogen dioxide	1.30E-01	kg
Air	(unspecified)	Nitrogen oxides	1.30E-01	kg
Soil	(unspecified)	Nitrogen oxides	1.30E-01	kg
Water	(unspecified)	Nitrogen oxides	1.30E-01	kg
Air	(unspecified)	Nitrogen, total	4.20E-01	kg
Soil	(unspecified)	Nitrogen, total	4.20E-01	kg
Water	(unspecified)	Nitrogen, total	4.20E-01	kg
Air	(unspecified)	Phosphate	1.00E+00	kg
Soil	(unspecified)	Phosphate	1.00E+00	kg
Water	(unspecified)	Phosphate	1.00E+00	kg
Air	(unspecified)	Phosphoric acid	9.70E-01	kg
Soil	(unspecified)	Phosphoric acid	9.70E-01	kg
Water	(unspecified)	Phosphoric acid	9.70E-01	kg
Air	(unspecified)	Phosphorus	3.06E+00	kg
Soil	(unspecified)	Phosphorus	3.06E+00	kg
Water	(unspecified)	Phosphorus	3.06E+00	kg
Air	(unspecified)	Phosphorus pentoxide	1.34E+00	kg
Soil	(unspecified)	Phosphorus pentoxide	1.34E+00	kg
Water	(unspecified)	Phosphorus pentoxide	1.34E+00	kg
Air	(unspecified)	Phosphorus, total	3.06E+00	kg
Soil	(unspecified)	Phosphorus, total	3.06E+00	kg
Water	(unspecified)	Phosphorus, total	3.06E+00	kg

Land Use & Transformation

Impact Category				
Land Use & Transform.	ha a			
Compartment	Sub compartment	Substance	Factor	Unit
Raw	(unspecified)	Occupation ; arable	1	ha a
Raw	(unspecified)	Occupation ; arid arable	1	ha a
Raw	(unspecified)	Occupation ; forest	1	ha a
Raw	(unspecified)	Occupation ; pasture and meadow ; intensive	1	ha a
Raw	(unspecified)	Occupation ; urban ; continuously built	1	ha a
Raw	(unspecified)	Occupation, arable	1	ha a
Raw	(unspecified)	Occupation, arable, integrated	1	ha a
Raw	(unspecified)	Occupation, arable, intensive	1	ha a
Raw	(unspecified)	Occupation, arable, non-irrigated	1	ha a
Raw	(unspecified)	Occupation, arable, non-irrigated, diverse-intensive	1	ha a
Raw	(unspecified)	Occupation, arable, non-irrigated, fallow	1	ha a
Raw	(unspecified)	Occupation, arable, non-irrigated, monotone-intensive	1	ha a
Raw	(unspecified)	Occupation, arable, organic	1	ha a
Raw	(unspecified)	Occupation, arid arable	1	ha a
Raw	(unspecified)	Occupation, construction site	1	ha a
Raw	(unspecified)	Occupation, dump site	1	ha a
Raw	(unspecified)	Occupation, dump site, benthos	1	ha a
Raw	(unspecified)	Occupation, dump site, radioactive	1	ha a
Raw	(unspecified)	Occupation, dump site, radioactive, high	1	ha a
Raw	(unspecified)	Occupation, dump site, radioactive, low-medium	1	ha a
Raw	(unspecified)	Occupation, forest	1	ha a
Raw	(unspecified)	Occupation, forest, extensive	1	ha a
Raw	(unspecified)	Occupation, forest, intensive	1	ha a
Raw	(unspecified)	Occupation, forest, intensive, clear-cutting	1	ha a
Raw	(unspecified)	Occupation, forest, intensive, normal	1	ha a
Raw	(unspecified)	Occupation, forest, intensive, short-cycle	1	ha a
Raw	(unspecified)	Occupation, hardwood production	1	ha a
Raw	(unspecified)	Occupation, heterogeneous, agricultural	1	ha a
Raw	(unspecified)	Occupation, industrial area	1	ha a
Raw	(unspecified)	Occupation, industrial area, benthos	1	ha a
Raw	(unspecified)	Occupation, industrial area, built up	1	ha a
Raw	(unspecified)	Occupation, industrial area, vegetation	1	ha a
Raw	(unspecified)	Occupation, mineral extraction site	1	ha a
Raw	(unspecified)	Occupation, oil and gas extraction site	1	ha a
Raw	(unspecified)	Occupation, other forest production	1	ha a
Raw	(unspecified)	Occupation, pasture and meadow	1	ha a
Raw	(unspecified)	Occupation, pasture and meadow, extensive	1	ha a
Raw	(unspecified)	Occupation, pasture and meadow, intensive	1	ha a
Raw	(unspecified)	Occupation, pasture and meadow, organic	1	ha a
Raw	(unspecified)	Occupation, permanent crop	1	ha a
Raw	(unspecified)	Occupation, permanent crop, fruit	1	ha a
Raw	(unspecified)	Occupation, permanent crop, fruit, extensive	1	ha a
Raw	(unspecified)	Occupation, permanent crop, fruit, intensive	1	ha a
Raw	(unspecified)	Occupation, permanent crop, fruit, organic	1	ha a
Raw	(unspecified)	Occupation, permanent crop, vine	1	ha a
Raw	(unspecified)	Occupation, permanent crop, vine, extensive	1	ha a
Raw	(unspecified)	Occupation, permanent crop, vine, intensive	1	ha a
Raw	(unspecified)	Occupation, pipelines	1	ha a
Raw	(unspecified)	Occupation, softwood production	1	ha a

Raw	(unspecified)	Occupation, traffic area	1	ha a
Raw	(unspecified)	Occupation, traffic area, rail embankment	1	ha a
Raw	(unspecified)	Occupation, traffic area, rail network	1	ha a
Raw	(unspecified)	Occupation, traffic area, road embankment	1	ha a
Raw	(unspecified)	Occupation, traffic area, road network	1	ha a
Raw	(unspecified)	Occupation, traffic area, sea transport	1	ha a
Raw	(unspecified)	Occupation, unknown	1	ha a
Raw	(unspecified)	Occupation, urban, continuously built	1	ha a
Raw	(unspecified)	Occupation, urban, discontinuously built	1	ha a
Raw	(unspecified)	Occupation, urban, green areas	1	ha a
Raw	(unspecified)	Occupation, water bodies, artificial	1	ha a
Raw	(unspecified)	Occupation, water bodies, inland	1	ha a
Raw	(unspecified)	Occupation, water bodies, sea	1	ha a
Raw	(unspecified)	Occupation, water courses, artificial	1	ha a

Water Use & Depletion

Impact Category				
Water Use	m3			
Compartment	Sub compartment	Substance	Factor	Unit
Raw	(unspecified)	Water, cooling	1	m3
Raw	(unspecified)	Water, cooling, drinking	1	t
Raw	(unspecified)	Water, cooling, river	1	t
Raw	(unspecified)	Water, cooling, salt, ocean	1	t
Raw	(unspecified)	Water, cooling, surface	1	t
Raw	(unspecified)	Water, cooling, unspecified natural origin/kg	1	t
Raw	(unspecified)	Water, cooling, unspecified natural origin/m3	1	m3
Raw	(unspecified)	Water, cooling, unspecified/kg	1	t
Raw	(unspecified)	Water, cooling, well, in ground	1	t
Raw	(unspecified)	Water, cooling/kg	1	t
Raw	(unspecified)	Water, cooling/m3	1	m3
Raw	(unspecified)	Water, drinking	1	t
Raw	(unspecified)	Water, fresh	1	m3
Raw	(unspecified)	Water, from Victorian catchments	1	m3
Raw	(unspecified)	Water, lake	1	m3
Raw	(unspecified)	Water, mining, unspecified natural origin/m3	1	m3
Raw	(unspecified)	Water, process and cooling, unspecified natural origin	1	m3
Raw	(unspecified)	Water, process, drinking	1	t
Raw	(unspecified)	Water, process, river	1	t
Raw	(unspecified)	Water, process, salt, ocean	1	t
Raw	(unspecified)	Water, process, surface	1	t
Raw	(unspecified)	Water, process, unspecified natural origin/kg	1	t
Raw	(unspecified)	Water, process, unspecified natural origin/m3	1	m3
Raw	(unspecified)	Water, process, well, in ground	1	t
Raw	(unspecified)	Water, reticulated supply	1	m3
Raw	(unspecified)	Water, river	1	m3
Raw	(unspecified)	Water, stormwater	1	t
Raw	(unspecified)	Water, surface	1	t
Raw	(unspecified)	Water, unspecified natural origin /kg	1	t
Raw	(unspecified)	Water, unspecified natural origin/kg	1	t
Raw	(unspecified)	Water, unspecified natural origin/m3	1	m3
Raw	(unspecified)	Water, well, in ground	1	m3
Raw	(unspecified)	Water, well, in ground /kg	1	t
Raw	(unspecified)	Water, well, in ground/m3	1	m3

Solid Waste

Impact Category				
Solid Waste	kg			
Compartment	Sub compartment	Substance	Factor	Unit
Waste	(unspecified)	Aluminium waste	1	kg
Waste	(unspecified)	Asbestos	1	kg
Waste	(unspecified)	ash	1	kg
Waste	(unspecified)	Calcium fluoride waste	1	kg
Waste	(unspecified)	Cardboard waste	1	kg
Waste	(unspecified)	Cathode iron ingots waste	1	kg
Waste	(unspecified)	Cathode loss	1	kg
Waste	(unspecified)	Chemical waste, inert	1	kg
Waste	(unspecified)	Chemical waste, regulated	1	kg
Waste	(unspecified)	Chemical waste, unspecified	1	kg
Waste	(unspecified)	Chromium waste	1	kg
Waste	(unspecified)	Coal tailings	1	kg
Waste	(unspecified)	Copper waste	1	kg
Waste	(unspecified)	Dross	1	kg
Waste	(unspecified)	Dust, unspecified	1	kg
Waste	(unspecified)	Glass waste	1	kg
Waste	(unspecified)	gypsum	1	kg
Waste	(unspecified)	Iron waste	1	kg
Waste	(unspecified)	Jarosite	1	kg
Waste	(unspecified)	limestone	1	kg
Waste	(unspecified)	Metal waste	1	kg
Waste	(unspecified)	Mineral waste	1	kg
Waste	(unspecified)	Mineral waste, from mining	1	kg
Waste	(unspecified)	Monasite	1	kg
Waste	(unspecified)	Neutralized Acid Effluent	1	kg
Waste	(unspecified)	non magenetic fines	1	kg
Waste	(unspecified)	Oil waste	1	kg
Waste	(unspecified)	Packaging waste, paper and board	1	kg
Waste	(unspecified)	Packaging waste, plastic	1	kg
Waste	(unspecified)	Packaging waste, steel	1	kg
Waste	(unspecified)	Packaging waste, unspecified	1	kg
Waste	(unspecified)	Packaging waste, wood	1	kg
Waste	(unspecified)	Plastic waste	1	kg
Waste	(unspecified)	Polyethylene waste	1	kg
Waste	(unspecified)	Polyvinyl chloride waste	1	kg
Waste	(unspecified)	Production waste	1	kg
Waste	(unspecified)	Production waste, not inert	1	kg
Waste	(unspecified)	Rejects	1	kg
Waste	(unspecified)	Rejects, corrugated cardboard	1	kg
Waste	(unspecified)	Slags	1	kg
Waste	(unspecified)	Slags and ashes	1	kg
Waste	(unspecified)	Soot	1	kg
Waste	(unspecified)	Steel waste	1	kg
Waste	(unspecified)	Stones and rubble	1	kg
Waste	(unspecified)	Tails	1	kg
Waste	(unspecified)	Tin waste	1	kg
Waste	(unspecified)	Tinder from rolling drum	1	kg
Waste	(unspecified)	Waste in bioactive landfill	1	kg
Waste	(unspecified)	Waste, final, inert	1	kg

Waste	(unspecified)	Waste, fly ash	1	kg
Waste	(unspecified)	Waste, from construction	1	kg
Waste	(unspecified)	Waste, from incinerator	1	kg
Waste	(unspecified)	Waste, household	1	kg
Waste	(unspecified)	Waste, industrial	1	kg
Waste	(unspecified)	Waste, Inert	1	kg
Waste	(unspecified)	Waste, inorganic	1	kg
Waste	(unspecified)	Waste, limestone	1	kg
Waste	(unspecified)	Waste, Shedder dust	1	kg
Waste	(unspecified)	Waste, sludge	1	kg
Waste	(unspecified)	Waste, solid	1	kg
Waste	(unspecified)	Waste, to incineration	1	kg
Waste	(unspecified)	Waste, toxic	1	kg
Waste	(unspecified)	Waste, unspecified	1	kg
Waste	(unspecified)	Wood and wood waste	1	t
Waste	(unspecified)	Wood, sawdust	1	kg
Waste	(unspecified)	Zinc waste	1	kg

Embodied Energy LHV

Impact Category		Source: Australasian Unit Process LCI v 2.02		
Embodied Energy LHV	MJ LHV			
Compartment	Sub compartment	Substance	Factor	Unit
Raw	(unspecified)	bagasse	8.7	kg
Raw	(unspecified)	Biomass, feedstock	1	MJ
Raw	(unspecified)	Coal, 13.3 MJ per kg, in ground	13.3	kg
Raw	(unspecified)	Coal, 18.0 MJ per kg, in ground	18	kg
Raw	(unspecified)	Coal, 18.5 MJ per kg, in ground	18.5	kg
Raw	(unspecified)	Coal, 19.5 MJ per kg, in ground	19.5	kg
Raw	(unspecified)	Coal, 20.0 MJ per kg, in ground	20	kg
Raw	(unspecified)	Coal, 20.5 MJ per kg, in ground	20.5	kg
Raw	(unspecified)	Coal, 21.5 MJ per kg, in ground	21.5	kg
Raw	(unspecified)	Coal, 22.1 MJ per kg, in ground	22.1	kg
Raw	(unspecified)	Coal, 22.4 MJ per kg, in ground	22.4	kg
Raw	(unspecified)	Coal, 22.6 MJ per kg, in ground	22.6	kg
Raw	(unspecified)	Coal, 22.8 MJ per kg, in ground	22.8	kg
Raw	(unspecified)	Coal, 23.0 MJ per kg, in ground	23	kg
Raw	(unspecified)	Coal, 24.0 MJ per kg, in ground	24	kg
Raw	(unspecified)	Coal, 24.1 MJ per kg, in ground	24.1	kg
Raw	(unspecified)	Coal, 26.4 MJ per kg, in ground	26.4	kg
Raw	(unspecified)	Coal, 27.1 MJ per kg, in ground	27.1	kg
Raw	(unspecified)	Coal, 28.0 MJ per kg, in ground	28	kg
Raw	(unspecified)	Coal, 28.6 MJ per kg, in ground	28.6	kg
Raw	(unspecified)	Coal, 29.0 MJ per kg, in ground	29	kg
Raw	(unspecified)	Coal, 29.3 MJ per kg, in ground	29.3	kg
Raw	(unspecified)	Coal, 30.3 MJ per kg, in ground	30.3	kg
Raw	(unspecified)	Coal, 30.6 MJ per kg, in ground	30.6	kg
Raw	(unspecified)	Coal, brown	12	kg
Raw	(unspecified)	Coal, brown, 10.0 MJ per kg, in ground	10	kg
Raw	(unspecified)	Coal, brown, 14.1 MJ per kg, in ground	14.1	kg
Raw	(unspecified)	Coal, brown, 14.4 MJ per kg, in ground	14.4	kg
Raw	(unspecified)	Coal, brown, 15 MJ per kg, in ground	15	kg
Raw	(unspecified)	Coal, brown, 15.0 MJ per kg, in ground	15	kg
Raw	(unspecified)	Coal, brown, 7.9 MJ per kg, in ground	7.9	kg
Raw	(unspecified)	Coal, brown, 8.0 MJ per kg, in ground	8	kg
Raw	(unspecified)	Coal, brown, 8.1 MJ per kg, in ground	8.1	kg
Raw	(unspecified)	Coal, brown, 8.2 MJ per kg, in ground	8.2	kg
Raw	(unspecified)	Coal, brown, 9.9 MJ per kg, in ground	9.9	kg
Raw	(unspecified)	Coal, feedstock, 26.4 MJ per kg, in ground	26.4	kg
Raw	(unspecified)	Coal, hard	24	kg
Raw	(unspecified)	Energy, from ADO	1	MJ
Raw	(unspecified)	Energy, from Auto gasoline-leaded	1	MJ
Raw	(unspecified)	Energy, from Auto gasoline-unleaded	1	MJ
Raw	(unspecified)	Energy, from Aviation gasoline	1	MJ
Raw	(unspecified)	Energy, from Aviation turbine fuel	1	MJ
Raw	(unspecified)	Energy, from bagasse	1	MJ
Raw	(unspecified)	Energy, from biomass	1	MJ
Raw	(unspecified)	Energy, from brown coal briquetts	1	MJ
Raw	(unspecified)	Energy, from coal	1	MJ
Raw	(unspecified)	Energy, from coal byproducts	1	MJ
Raw	(unspecified)	Energy, from coal, brown	1	MJ
Raw	(unspecified)	Energy, from coke	1	MJ

Raw	(unspecified)	Energy, from Fuel oil	1	MJ
Raw	(unspecified)	Energy, from gas, natural	1	MJ
Raw	(unspecified)	Energy, from geothermal	1	MJ
Raw	(unspecified)	Energy, from Heating oil	1.00E+00	MJ
Raw	(unspecified)	Energy, from hydro power	1.00E+00	MJ
Raw	(unspecified)	Energy, from hydrogen	1.00E+00	MJ
Raw	(unspecified)	Energy, from IDF	1.00E+00	MJ
Raw	(unspecified)	Energy, from Lighting kerosene	1	MJ
Raw	(unspecified)	Energy, from liquified petroleum gas, feedstock	1	MJ
Raw	(unspecified)	Energy, from LPG	1	MJ
Raw	(unspecified)	Energy, from Natural gas	1	MJ
Raw	(unspecified)	Energy, from oil	1	MJ
Raw	(unspecified)	Energy, from peat	1	MJ
Raw	(unspecified)	Energy, from Petroleum products nec	1	MJ
Raw	(unspecified)	Energy, from Power kerosene	1	MJ
Raw	(unspecified)	Energy, from solar	1	MJ
Raw	(unspecified)	Energy, from sulfur	1	MJ
Raw	(unspecified)	Energy, from tidal	1	MJ
Raw	(unspecified)	Energy, from Town gas	1	MJ
Raw	(unspecified)	Energy, from uranium	1	MJ
Raw	(unspecified)	Energy, from waves	1	MJ
Raw	(unspecified)	Energy, from wood	1	MJ
Raw	(unspecified)	Energy, geothermal	1	MJ
Raw	(unspecified)	Energy, gross calorific value, in biomass	0.904761905	MJ
Raw	(unspecified)	Energy, in Solvents	1	MJ
Raw	(unspecified)	Energy, kinetic (in wind), converted	1	MJ
Raw	(unspecified)	Energy, potential (in hydropower reservoir), converted	1	MJ
Raw	(unspecified)	Energy, recovered	1	MJ
Raw	(unspecified)	Energy, unspecified	1	MJ
Raw	(unspecified)	Gas, natural, 30.3 MJ per kg, in ground	30.3	kg
Raw	(unspecified)	Gas, natural, 31.65 MJ per m3, in ground	31.65	m3
Raw	(unspecified)	Gas, natural, 35 MJ per m3, in ground	35	m3
Raw	(unspecified)	Gas, natural, 35.0 MJ per m3, in ground	35	m3
Raw	(unspecified)	Gas, natural, 35.2 MJ per m3, in ground	35.2	m3
Raw	(unspecified)	Gas, natural, 35.9 MJ per m3, in ground	35.9	m3
Raw	(unspecified)	Gas, natural, 36.6 MJ per m3, in ground	36.6	m3
Raw	(unspecified)	Gas, natural, 38.8 MJ per m3, in ground	38.8	m3
Raw	(unspecified)	Gas, natural, 39.0 MJ per m3, in ground	39	m3
Raw	(unspecified)	Gas, natural, 42.0 MJ per m3, in ground	42	m3
Raw	(unspecified)	Gas, natural, 46.8 MJ per kg, in ground	46.8	kg
Raw	(unspecified)	Gas, natural, 50.3 MJ per kg, in ground	50.3	kg
Raw	(unspecified)	Gas, natural, 51.3 MJ per kg, in ground	51.3	kg
Raw	(unspecified)	Gas, natural, feedstock, 35 MJ per m3, in ground	35	m3
Raw	(unspecified)	Gas, natural, feedstock, 35.0 MJ per m3, in ground	35	m3
Raw	(unspecified)	Gas, natural, feedstock, 46.8 MJ per kg, in ground	46.8	kg
Raw	(unspecified)	Gas, natural/m3	35	m3
Raw	(unspecified)	Gas, off-gas, 35.0 MJ per m3, oil production, in ground	35	m3
Raw	(unspecified)	Gas, off-gas, oil production, in ground	35	m3
Raw	(unspecified)	Gas, petroleum, 35 MJ per m3, in ground	35	m3
Raw	(unspecified)	Methane	35.9	kg
Raw	(unspecified)	Mining gas, 30 MJ per kg	30	kg
Raw	(unspecified)	Oil, crude	45	kg
Raw	(unspecified)	Oil, crude, 38400 MJ per m3, in ground	38400	m3
Raw	(unspecified)	Oil, crude, 41 MJ per kg, in ground	41	kg

Raw	(unspecified)	Oil, crude, 41.0 MJ per kg, in ground	41	kg
Raw	(unspecified)	Oil, crude, 41.9 MJ per kg, in ground	41.9	kg
Raw	(unspecified)	Oil, crude, 42.6 MJ per kg, in ground	42.6	kg
Raw	(unspecified)	Oil, crude, 42.7 MJ per kg, in ground	42.7	kg
Raw	(unspecified)	Oil, crude, 42.8 MJ per kg, in ground	42.8	kg
Raw	(unspecified)	Oil, crude, 43.4 MJ per kg, in ground	43.4	kg
Raw	(unspecified)	Oil, crude, 44.0 MJ per kg, in ground	44	kg
Raw	(unspecified)	Oil, crude, 44.6 MJ per kg, in ground	44.6	kg
Raw	(unspecified)	Oil, crude, 45.0 MJ per kg, in ground	45	kg
Raw	(unspecified)	Oil, crude, feedstock, 41 MJ per kg, in ground	41	kg
Raw	(unspecified)	Oil, crude, feedstock, 42 MJ per kg, in ground	42	kg
Raw	(unspecified)	Secondary wood	15.3	kg
Raw	(unspecified)	Uranium	451000	kg
Raw	(unspecified)	Uranium ore, 1.11 GJ per kg, in ground	1110	kg
Raw	(unspecified)	Uranium, 2291 GJ per kg, in ground	451000	kg
Raw	(unspecified)	Uranium, 336 GJ per kg, in ground	336000	kg
Raw	(unspecified)	Uranium, 451 GJ per kg, in ground	451000	kg
Raw	(unspecified)	Uranium, 560 GJ per kg, in ground	451000	kg
Raw	(unspecified)	Water, barrage	0.01	kg
Raw	(unspecified)	Water, through turbine	0.01	l
Raw	(unspecified)	Wood and cardboard waste	15.3	kg
Raw	(unspecified)	Wood and wood waste, 10.5 MJ per kg	15.3	kg
Raw	(unspecified)	Wood, feedstock	15.3	kg
Raw	(unspecified)	Wood, unspecified, standing/kg	15.3	kg
Raw	biotic	Biomass	15	kg
Raw	in ground	Energy, from oil	1	MJ
Raw	in ground	Energy, from uranium	1	MJ
Raw	in ground	Oil, crude, 42 MJ per kg, in ground	42	kg

Human Toxicity, Carcinogens
Too many factors to list (3819). Refer to digital file: *Characterisation and Normalisation Factors.xlsx*

Human Toxicity, Non-Carcinogens
Too many factors to list (3027). Refer to digital file: *Characterisation and Normalisation Factors.xlsx*

EcoToxicity
Too many factors to list (7905). Refer to digital file: *Characterisation and Normalisation Factors.xlsx*

D3 - Off-grid renewable electricity system

(system A was the basis for the LCA)

NATURAL TECHNOLOGY SYSTEMS
ENERGY CONSULTANTS
120 PROSPECT RD., PROSPECT, S.A. 5082
bp solar Distributor
PHONE: (61-8) 8344 7298
FAX: (61-8) 8269 7167
EMAIL: 27honeysuckle@msn.com.au
WEB: www.naturaltechnology.com.au
BCSE Accreditation F558 Hybrid and Solar

DIESEL REBATE SAMPLE SYSTEMS – SMALL

The following system designs are examples of systems we can offer. Our staff on application will make an individual assessment of your requirements.

SYSTEM A – Loads of 3-5kWh per day – System Voltage 24VDC

1 X SELECTRONIC SP/PRO 3.5 kW INVERTER/CHARGER
12 X SONNENSCHEIN A620 960 AMP BATTERIES
8 X BP SOLAR 4190T – 190 Watt SOLAR PV MODULES
1 X BP SOLAR PL60 REGULATOR SYSTEM CONTROLLER (incl. 200A shunt)
1 X SOLAR ARRAY FRAME FOR ROOF OR GROUND MOUNT
1 X MATERIALS AND INSTALLATION ex-ADELAIDE

COST: $31,896 incl. GST ex-ADELAIDE

SYSTEM B – Loads of 2kWh per day – System Voltage 24VDC

1 X LATRONICS LS 3024 3 kW INVERTER
1 X BATTERY CHARGER AT12/45
12 X SONNENSCHEIN A620 - 600 AMP BATTERIES
4 X BP SOLAR 4190T 170 Watt SOLAR PV MODULES
1 X BP SOLAR PL60 REGULATOR SYSTEM CONTROLLER (incl. 200A shunt)
1 X SOLAR ARRAY FRAME FOR ROOF
1 X MATERIALS AND INSTALLATION ex-ADELAIDE

COST: $21,383 incl. GST ex-ADELAIDE

OPTION: 300W WIND TURBINE

1 X AIR INDUSTRIAL 300W 24V TURBINE incl. STOP SWITCH
1 X 14m MAST/GIN POLE TOWER COMPLETE
1 X INSTALLATION ex-ADELAIDE

COST: $7,950 incl. GST ex-ADELAIDE

D4 - Personal Communication regarding LCA

Email from Stephen Dobson of Ramtec regarding rammed earth construction

From: Stephen Dobson [mailto:mail@ramtec.com.au]

Sent: Wednesday, 23 February 2011 5:18 PM

To: martin.freney@adelaide.edu.au

Subject: Re: Rammed Earth: Life Cycle Assessment study

Hi Martin,

I do recall you.

Here is some up-to-date info on rammed earth construction...from measurements made on walls that we built last week.

Here are figs to quantify the use of machinery used to make the wall; e.g. bobcat for proportioning and mixing and delivering and lifting materials, plus the engine that drives the pneumatic tamper.

Bobcat tank holds 70litres of diesel. It lasts one week (of 5 or 6 days). It is used 3 to 3.5 avge to 4 hours per day. In one day there is 15 sq metres of face wall area of 300mm thick rammed earth built. This is on a good day. Hard walls can result in lower outputs, but this lower output of wall built is matched by more time spent messing around with complex formwork.

A few hours of Bobcat use time go into setting the job up at the start and cleaning up at the end of each job. Say 4 hrs at start and 6 hrs at end ...for a hypothetical job of 150 face sq m of 300m thick walls.

One tamper at a time is used. Fuel consumption currently is 20litres (with a nice aircompressor) of diesel per week for 5 or 6 days and the compressor operates about 4 or 5 hours per day (for that 15 sq m of 300mm thick wall).

Water consumption. About 400 to 500 litres of water is used in the RE production process to give 6 sq m of 300mm thick wall. This 500litres is peak summer. Average 400litres. In winter the figure would be nearer to 300litres.

You should compare water usage as it is very high with say concrete but low with RE and water too is a very valuable commodity.

I will send you an invitation to a free lecture that may interest you.

Regards

Stephen

Stephen Dobson, Ramtec Pty Ltd.

PO Box 84,Cottesloe, Western Australia, 6911.
Tel: 08-93845777
Fax:08-93851308
Mob: 0419956819
Email: mail@ramtec.com.au
Website: www.ramtec.com.au

On Tue, Feb 22, 2011 at 1:06 PM, Martin Freney <martin.freney@adelaide.edu.au> wrote:

Hi Stephen,

I met you at the EBAA conference last year and I got the impression that you may be able to answer some of my questions about rammed earth...

I'm studying under Terry Williamson and Veronica Soebarto, doing a master of architecture, writing a thesis regarding the environmental impacts of various types of walls, one of which is rammed earth. Hoping you can help out with some up-to-date info on rammed earth construction.

My methodology (life cycle assessment) relies on accurate information regarding the amounts of materials and the associated processes, in particular the energy consumption.

Perhaps there is a book you recommend? My main reference is The Rammed Earth House by David Easton. From this I have managed to glean enough info regarding the materials involved but I need more detailed info on the production process. I need to be able to quantify the use of machinery used to make the wall; e.g. bobcat for mixing and lifting materials, pneumatic tamper. Of course is can be done without machinery but it's not done that way now! So for a modern build, what is your estimate of the energy/fuel needed to build a wall e.g.

- how many hours, per cubic meter of wall, is the bobcat needed?
- how many hours, per cubic meter of wall, is the tamper needed (how many tampers) – what is the fuel consumption of the air compressor?

Any advice greatly appreciated!

Cheers,

Martin Freney

Masters Candidate

School of Architecture, Landscape Architecture and Urban Design

The University of Adelaide

Email from William Kaggwa re: tyre wall footings

From: William Kaggwa [mailto:wkaggwa@civeng.adelaide.edu.au]
Sent: Thursday, 4 August 2011 4:34 PM
To: martin.freney@adelaide.edu.au
Subject: Re: Tyre Wall Discussion

Martin,

That is a correct reflection of our discussions. I would add "probably" or "likely" to the numerical values of pressures though.

William

On 4/08/2011 4:16 PM, Martin Freney wrote:

Dear William,

It was a pleasure talking with you about the tyre wall of an "Earthship". Thank you very much for taking the time to discuss this with me. I think I will be more able to have an intelligent discussion with a structural engineer now.

I've written down the main points to make sure I've understood correctly. I'd like to quote you on this (and put this email in the appendix of my thesis), so if you would be so kind as to check that the following is correct that would be much appreciated.

The tyre wall is very similar to adobe bricks – the binder in this case is the tyre "container", the main material is compacted earth.

In most soil types the tyre wall would NOT require footings, with the exception of highly reactive clay typical on the Adelaide Plains (and some areas in the Adelaide Hills).

A footing made of stabilised soil or gravel, width and depth equal to the diameter of the tyre (at least 600mm deep), would be an adequate footing for the tyre wall in highly reactive clay.

In Adelaide's highly reactive clay, lifting is usually the problem.

200kPa is needed to suppress the upwards heave of highly reactive clay. An Earthship construction would be in the order of 60-80kPa and would dampen the movement but not prevent it.

A concrete or rammed earth floor would be preferable to floor boards as the later will dry out the under-floor soil and exacerbate the tendency for moisture to migrate under the house.

Preventing the soil around the house from drying out helps prevent heaving of highly reactive clay. Regular irrigation is a good idea.

The earth-berm will help prevent the soil under the wall from drying out.

Plastic sheet laid underground to direct water away from the wall/house will help prevent heaving of highly reactive clay.

Rather than attempt to water proof the tyre wall it would be better to provide good drainage (vertical layer of gravel adjacent tyre wall with slotted pipe slightly below ground level and geofabric placed between gravel and backfill) and good surface water run-off management (e.g. plastic sheet laid underground to direct water away from the wall).

Best regards,

Martin Freney
Masters Candidate
School of Architecture, Landscape Architecture and Urban Design
The University of Adelaide
Ph: +61 8 8303 3052
Fax: +61 8 8303 4377
e-mail: martin.freney@adelaide.edu.au

Glenn Turner email 19 December 2012 – Stratco Shed

From: Glenn Turner [mailto:glenn.turner@stratco.com.au]
Sent: Wednesday, 19 December 2012 4:19 PM
To: Martin Freney (martin.freney@adelaide.edu.au)
Subject: Domestic Shed Weight

Hi Martin,

Below is the approximate weight of steel required for a standard domestic shed with the following parameters:

Size: 6.9m wide x 12.3m long x 2.7m wall height

Pitch: 15°

Wind Classification: N2

Portal Frames: 150mm C-section at approximately 3m centres.

Purlins/girts: 75mm C-sections

Roofing: 0.42mm BMT (base metal thickness) CGI

Walling: 0.35mm BMT Superdek

Doors: No doors considered (The average weight of a roller door for a domestic shed as about 100kg so feel free to add this weight if required)

Approximate Shed Weight: 1500kg

If you are interested in further details on the shed designs refer to the Stratco web site:

http://stratco.com.au/products/garages/types/gable_homeshed/gable_homesheds.asp

Feel free to give me a call if you require any further information for your project.

Best Regards,

Glenn Turner
Stratco (Aust) Pty Ltd
(Tel): (08) 8349-5555
(Fax): (08) 8262-9688
E-Mail: glenn.turner@Stratco.com.au

Emails from Matthew Ward and Jarrod Ison - Solar Hot Water Systems

From: Ward, Matthew [mailto:matthew.ward@edwards.com.au]
Sent: Tuesday, 7 May 2013 4:11 PM
To: Martin Freney
Cc: 'Martin Freney'
Subject: RE: Quantities of materials in SHWS

Hi Martin,

Please note the following:

For a 2 collector system you will need to double the weights that I have highlighted below. The weights listed are for a single collector.

The copper pipe (½", 20) listed below is not supplied with the heater but is fitted by the installer during installation.

Let me know if you need anything further.

Best Regards,

Matthew Ward
National Technical Officer/Trainer - Service
Rheem Australia Pty Ltd

PH: (08) 9351 4632
FAX: (08) 9351 8034

From: Ison, Jarrod
Sent: Tuesday, 7 May 2013 02:34 PM
To: Martin Freney; Ward, Matthew
Cc: 'Martin Freney'
Subject: RE: Quantities of materials in SHWS

Martin,

Apologies for the delay. Here are material weights for a Rheem system with ground mounted tank, 511325/2NPT (325L tank, 2 x NPT collectors)

Tank & Ground Kit:

Mild Steel	67.2kg
Colorbond Steel	16.5kg
Polyurethane	5.5kg
Brass	2.5kg
Vitreous Enamel	0.5kg
Polystyrene	0.2kg
Pump, controller & various electrical components	~3kg

Collectors & Roof Kit:

Copper	3.65kg
Aluminum	2.76kg
Glass	15.6kg
Colorbond	1.34kg
Zincallume	11.00kg

Brass	1.7kg
Copper pipe (½", 20m)	6.7kg

I believe I got everything! Thanks to Matt for the collector info.

Regards,

Jarrod

From: Martin Freney [mailto:martin.freney@internode.on.net]
Sent: Friday, 3 May 2013 5:32 PM
To: Ward, Matthew
Cc: 'Martin Freney'; Ison, Jarrod
Subject: RE: Quantities of materials in SHWS

Hi Matt,

Thanks very much for the prompt reply. This is exactly the data I need. Thanks again.

Cheers,

Martin

From: Ward, Matthew [mailto:matthew.ward@edwards.com.au]
Sent: Friday, 3 May 2013 4:35 PM
To: Martin Freney; Ison, Jarrod
Cc: Martin Freney
Subject: RE: Quantities of materials in SHWS

Hi Martin,

Here are the details of the major components of the Edwards L32 Australis Series 2 system. The L32 system consists of a 300L stainless steel tank, 2 x Australis solar collectors and a parts kit.

Material	Mass (kg)
Colorbond Steel	42.50
Stainless Steel	39.00
Glass	31.2
Copper	9.10
Polyurethane	6.75
Aluminum	5.52
Brass	1.50

Please let me know if we can be of any further assistance.

Best Regards,

Matthew Ward
National Technical Officer/Trainer - Service
Rheem Australia Pty Ltd

PH: (08) 9351 4632
FAX: (08) 9351 8034

From: Martin Freney [mailto:martin.freney@adelaide.edu.au]
Sent: Thursday, 2 May 2013 09:49 AM
To: Ison, Jarrod; Ward, Matthew

Cc: Martin Freney
Subject: Quantities of materials in SHWS

Hi Jarrod and Matt,

Thanks for speaking with me this morning.

As I mentioned on the phone I am doing a Life Cycle Assessment (LCA) on solar hot water systems and need to know the approximate quantities (mass) of the materials used in their manufacture e.g. glass, stainless steel, galv steel, aluminium, copper, polystyrene, etc. I am not so concerned with small quantities of materials such as silicone caulking, cardboard packaging etc although if that info is readily available please include it. I am interested in the typical domestic 2 panel, 300L capacity system.

Matt offered to supply some data on an Edwards model and Jarrod, I assume you'll be supplying data on a Rheem system.

Also if you know of any LCA studies on SHWS I would be interested to know about it. My literature review has turned up very little.

If you want to clarify anything my mobile number is 0450 555 719.

Thanks in advance!

Cheers,

Martin Freney
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Fax: +61 8 8313 4377
e-mail: martin.freney@adelaide.edu.au

Email Matthew Ward, Solar Fraction in Adelaide

From: Ward, Matthew [mailto:matthew.ward@edwards.com.au]
Sent: Monday, 13 May 2013 3:40 PM
To: Martin Freney; Ison, Jarrod
Cc: 'Martin Freney'
Subject: RE: Quantities of materials in SHWS

Hi Martin,

I don't have anything official but an old handbook that was put together years ago by Edwards Solar Hot Water states the following solar contribution factors for major centres:

	Alice Springs	Cairns	Brisbane	Sydney	Canberra	Melbourne	Hobart	Adelaide	Perth
Solar Contribution Factor	0.7	0.7	0.65	0.6	0.55	0.5	0.45	0.6	0.65

Best Regards,

Matthew Ward
National Technical Officer/Trainer - Service
Rheem Australia Pty Ltd

PH: (08) 9351 4632
FAX: (08) 9351 8034

From: Martin Freney [mailto:martin.freney@internode.on.net]
Sent: Monday, 13 May 2013 01:42 PM
To: Ward, Matthew; Ison, Jarrod
Cc: 'Martin Freney'
Subject: RE: Quantities of materials in SHWS

Hi Matt and Jarrod,

I have another question:

What is the solar fraction for a solar hot water system in Adelaide? By this I mean what percentage of energy is derived from the sun?

Someone told me 65% but can you confirm that, and or direct me to any information for Adelaide (and perhaps other capital cities).

Regards,

Martin

Email from Hugh Hocking, Adelaide Resource Recovery
From: Hugh Hocking [mailto:hugh.hocking@arr.net.au]
Sent: Monday, 13 May 2013 4:39 PM
To: 'Martin Freney'
Subject: RE: recycling house materials

I can only answer for ARR where all bricks are crushed. You are correct though, Ol Red Brick do re-use bricks.

Regards

Hugh

ADELAIDE RESOURCE RECOVERY

Hugh Hocking
Sales & Marketing Manager
Adelaide Resource Recovery
0403 923 824

www.arr.net.au

From: Martin Freney [mailto:martin.freney@internode.on.net]
Sent: Monday, 13 May 2013 3:31 PM
To: 'Hugh Hocking'
Subject: RE: recycling house materials

Hugh,

Thanks very much for the prompt reply. This is very useful info.

I just want to query one thing: bricks

Some bricks must be getting reused e.g. The Old Red Brick Company where I've bought second hand bricks. Do you think it would be fair to say 5% get reused and 95% recycled?

Regards,

Martin

From: Hugh Hocking [mailto:hugh.hocking@arr.net.au]
Sent: Monday, 13 May 2013 2:59 PM
To: 'Martin Freney'
Subject: RE: recycling house materials

Martin,

See below…

Regards

Hugh

Hugh Hocking
Sales & Marketing Manager
Adelaide Resource Recovery
0403 923 824

www.arr.net.au

From: Martin Freney [mailto:martin.freney@internode.on.net]
Sent: Monday, 13 May 2013 11:57 AM
To: hugh.hocking@arr.net.au
Cc: 'Martin Freney'
Subject: recycling house materials

Hi Hugh,

You suggested I email you regarding my questions about recycling materials from homes:

What percentage of the following house construction materials would you expect to end up being reused/recycled/landfilled at the end of a house's life? To show you what I mean I'll make some guesses and you can correct me:

Concrete 0% reused/ 90% recycled/ 10% landfilled actually 0/99/1 as we only landfill the bare minimum that comes in concrete loads as the orange DPC plastic, timber etc are still recycled elsewhere.
Steel 0/90/10 0/100/0
Aluminium 0/90/10 0/100/0
Brick 20/70/10 0/100/0
Gyprock 0/0/100 0/20/80 some gyprock has been added to timber to produce a mulch product..
Compressed cement fibre board 0/0/100 0/50/50 we will crush cement fibreboards with concrete or brick to produce non-critical rubbles when required
Sarking (reflective foil) 0/0/100 0/0/100
Polystyrene (insulation) 0/0/100 0/0/100
Fibreglass wool (insulation) 0/0/100 0/0/100

Perhaps you can only comment on the brick and concrete but if you have any suggestions about where to find info on the others that would be very helpful.

Many thanks.

Cheers,

Martin Freney
PhD student
University of Adelaide
School of Architecture and Built Environment

Mob: 0450 555 719

Appendix E - Research Data / Files on CD ROM

NOTE:
This appendix is on a CD included with the print copy of the thesis held in the University of Adelaide Library.

E1.0 - Occupants' Questionnaire data

E1.1 - Daily Comfort Questionnaire data

E2.0 - Taos Earthship Monitoring data

E2.1 - Thermal Modelling DesignBuilder files

E2.2 - Thermal Modelling results spreadsheets

E3.0 - Life Cycle Assessment SimaPro database files

E3.1 - Life Cycle Assessment results spreadsheets

E3.2 - Life Cycle Assessment SolidWorks 3D Modelling files

E3.3 - Life Cycle Assessment Bill of Materials/Processes results spreadsheet