Carbon footprint and embodied energy assessment of roof covering materials

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Abstract The residential building sector regularly satisfies a diverse range of housing needs whilst addressing respective capital-cost considerations. Designers and builders must also be aware of the environmental implications of their design specifications; the work here adds to a body of knowledge concerned with carbon footprint and embodied energy demand, specifically through an examination of alternative roof covering materials. A life-cycle assessment (LCA) has been carried out, within a West Australian context, to compare impacts for the roof-specification options of: clay-tile; concrete-tile; and, sheet-metal. In locations where recycling facilities are unavailable and thus disregarded, it is found that clay tiles have the lowest carbon footprint of 4.4 t of CO_2 equivalent (CO_2 e-) and embodied energy demand of 52.7 Mega Joule (MJ) per 100 m^2, while sheet-metal roofing has the highest carbon-footprint (9.85 t of CO_2 e-), with concrete roof tiles having the highest embodied-energy demand (83 MJ). Findings confirm that a sheet-metal roof can obtain significant carbon and embodied energy saving benefits (i.e. 71-73%) compared to clay tile or concrete roof covers through ongoing encouragement of recycling strategies and increased local recycling facilities able to embrace residual cradle-to-cradle material re-use.

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Introduction

The construction industry globally consumes 40% of natural materials, 40% of the total primary energy, 15% of the world's fresh water resources, generates 25% of all wastes and emits 40-50% of GHG (Ding, 2014); the design team is thus charged to adopt an environmentally responsible approach to their design solutions and construction materials' specification choices.

The building sector is responsible for 20% of Australia's total energy demand and 23% greenhouse gas (GHG) emissions (Lawania and Biswas, 2016). It is projected that 460,000 new houses will be constructed in Western Australia (WA) by 2030, which will necessarily increase demand for construction materials and impact energy usage (NHSC, 2011). Without due consideration of environmentally-conscious specification choices, the construction industry in Western Australia will experience significant GHG emissions increases; there will be depletion of finite resources, and landfill over flow. This will result in a challenging situation requiring ongoing federal government and local authorities' 'green' tendering guidelines and not least, requires respective design-teams and builders to make informed decisions when specifying materials.

Life-cycle assessment (LCA) is a decision-making tool that can assist stakeholders in identifying opportunities to make sustainability gains for built assets by selecting the most environmentally-friendly option (Seidel, 2016). It quantifies and accesses the inputs and outputs affecting environmental performance associated with a product, process or activity throughout its life-cycle (Whyte, 2012) . Whilst the LCA technique is somewhat commonly available, uptake by industry remains still limited. Case-study examples such as those presented here can be argued to increase the profile of LCA application and, by extension, encourage a more sustainable design process (Crawford et al., 2016).

Roofing accounts for 6% of a low-rise building's volume and, typically, 7% of a residential building's GHG emissions (from mining to material production) (Lawania and Biswas, 2018). Saiz conducted an LCA of a so-called 'green' roof in Madrid, finding that its low solar absorbance resulted in a reduced level of energy demand for the building (Saiz et al. 2015). Chenani (2014) similarly determined the environmental performance of two lightweight 'green' roof systems and found that an environmental impact reduction, through layers' configurations review, was possible. Another recent LCA study found that the use of vaulted roofs can reduce embodied energy by over 40% relative to flat slabs (Huberman et al., 2015).

However, to the best of our knowledge, no study to date studied how life-cycle environmental performance(s) of roofing varies with materials choices. For WA's housing sector, roofs of three different types are common: sheet-metal, concrete-tile and clay-tiles; these alternatives are compared in this current study to determine the environmental implications of different specification options for West Australian climatic conditions.

The next section outlines the methodology to assess the alternative roofing specifications in terms of carbon footprint and embodied energy demand comparisons. Carbon footprints of roofing options are compared, both with and without recycling factored-in since many areas in WA have no available local recycling facilities.

Methodology

The LCA conducted here follows the guidelines outlined in ISO14040-44 (ISO 2006) which consists of four steps, namely: goal and scope; inventory analysis; impact assessment; and, interpretation.

Goal and scope

The goal of this study is to assess the environmental impact involved with the use of roof-covering materials in WA residential houses. Three roof-covering materials are considered: clay tile; concrete tile; and, sheet-metal.

The system boundary of the LCA study covers the entire life-cycle of the product. This is broken down into several stages including raw material acquisition, manufacturing and processing of construction materials, transportation of these materials to the construction site, construction phase, usage stage, and ultimately disposal/recycling residual considerations.

The functional unit of this study is $100m^2$ of roof-covering materials and the timber structure framework supporting it; the environmental impacts of respective (typically) timber framework(s) will be analysed with the roof-covering material options. The reason for choosing this functional unit was that approximately 50 % of average houses in Perth have this size of roof area (Department of Water and Environmental Regulation, 2017). Other dwelling superstructure elements are not analysed. This is a process-based LCA, where energy and chemical inputs of all stages during the life cycle of roof covering materials, have been utilised in assessing global warming impacts and embodied energy demand (Suh et al., 2014; Majeau-Bettez et al., 2011).

Quantities of the structural timber framework supporting the roof-covering materials are calculated in accordance with typical sections made available by local governments in Western Australia. Each item was classified according to its base material (treated pine, concrete, zinc, and aluminium). Natural gas and electrical energy are included where appropriate in consideration of the manufacture processing and installation of roof-coverings (Life Cycle Strategy, 2015; BPIC, 2014).

Construction locations are urban; local suppliers were contacted to determine respective manufacturers/ fabricators factory locations. Some industry representatives who provided materials and transportation related information will not be released in the paper due to requests for confidentiality. Where appropriate (raw) materials are deemed to have been shipped to (Fremantle) port and then road-transported to distributors/site. Timber/structural frameworks and roof-covering material installation is deemed by tradesman in-situ; (steel/ nail) fixings to install the roof-covering material have been included.

It is beyond the scope of this LCA to consider 100% data directly and indirectly associated with the production and use of these roofing materials. Therefore the GHG emissions and embodied energy demand values that have been calculated using available data are relative values and these results were used for comparison purposes (Sue et al., 2014; Majeau-Bettez et al., 2011).

Life-cycle inventory

LCIs were conducted for clay tiles, concrete tiles and sheet-metal on residential buildings to calculate energy and material consumption in all stages of roof life cycle.

Mining to material production

Composition and percentages of raw materials used in clay tiles, sheet-metal and concrete tiles respectively, were assessed (Table 1). For concrete and clay tiles roof, raw material quantities were calculated; the number of tiles per metre square multiplied by the mass per tile gives the total mass of tiles; the total mass then multiplied by relevant percentages finds raw materials required in 100m^2 (Whyte, 2015). The timber frame to support the clay tiles, concrete tiles and sheet-metal were sourced from typical sections and drawings from the City of Melville, Western Australia, alongside AS 1684.4 (Whyte, 2015). A sample calculation has been provided in Appendix A.

Table 2 shows the amount of natural gas and electricity that was required to produce 100 m^2 of clay tile, concrete tile and sheet-metal from raw materials (BPIC, 2014; Altas Steel, 2014).

Transportation

Construction sites for roof erections is Western Australian urban/metropolitan; shipping freight transportation is assumed from the (interstate) manufacturer/fabricator to WA (Fremantle) port. In order to estimate the tonnes-km (i.e. tkm) travelled by land, and sea Google Earth was used for calculating the distances in kilometres between origins and destinations. Local WA industry representatives (Boral and BlueScope Steel and others) noted that, typically clay tiles and sheet-metal are manufactured in New South Wales, with concrete tiles made in Victoria. Shipping distance between NSW and WA (Fremantle) has been calculated as 2,195 nautical miles (4065.14km), and between Victoria Melbourne and Fremantle – 1,681 nautical miles (3,113.2km). Upon arrival at (Fremantle) port, articulated trucked road transportation of materials from the port to distributor/site is calculated as 22.6km.

Construction

The construction stage involves the construction of the timber framework supporting the roof-covering materials, and the installing of the roof-covering materials, typically: marking-out (tape/ pencil/ chalk-line) the timber; cutting the timber (drop saws/ power saws/ hand saws); and, nailing members together (hammers/nail guns, with two galvanised steel nails per tile/length or alternatively, nails by mass of mild steel sheet).

The energy consumed in in-situ tradesman installation and tile/sheet connection is deemed nominal; effectively: positioning and installing the tile/sheet; and nailing the tile/sheet onto the battens is a manual process with nominal electrical equipment used.

Use

The usage stage quantifies the effects of varying solar reflectance of roofing materials (clay tile, concrete tile, sheet-metal). This research shows that an effective R factor (thermal resistance of roofing material) affects heat loss and heat gain of each roofing material. Physical data and assumptions are inputs in equation 1 (below) to calculate heat lost and heat gain.

$$q = U[(T_2 - T_1) + \frac{\partial G}{H}] \qquad (1)$$

q = rate of heat flow per square metre from roof to the inside

U = the overall heat transfer coefficient between the ambient and inside ($W/m^2.K$)

1/U = the thermal resistance

T_2 = Annual average ambient temperature °C

T_1 = Required level of temperature that needs to be maintained inside the house °C

H = Outside transfer coefficient between roof and ambient ($W/m^2.K$)

∂ = rate of absorption to solar radiation

G = Solar radiation per unit area (W/m^2)

Table 3 shows the cooling and heating loads of each roofing material in terms electricity consumption. Fossil and renewable energy account for 95.5% and 4.5% of the total primary energy sources for electricity generation (Grant, 2015). Appendix B shows a sample calculation for how the cooling load has been calculated for clay tiles. Since the thermal modelling software was unavailable during the time of the study, the heating and cooling load at hourly levels was not determined (for more accurate analysis) and hence it is considered as a limitation of this analysis (Robati et al. 2016; Robati et al. 2017). Also it should be noted that the usage stage has only been considered to capture variation in cooling and heating energy demand due to use of different roof covering materials over their life cycles. This variation was found very infinitesimal when comparing with impacts resulting from other life cycle stages. Therefore, the exclusion of the detailed thermal modelling analysis can be argued as not significantly affecting the overall outcomes of this LCA study.

The timeframe of use is deemed the life-cycle of such construction materials. According to multiple sources (Boral, 2014; Blue Scope Steel, 2014), clay tile has an average of lifetime of 65 years, compared to concrete tile and sheet-metal life-cycles of 50 years and 45 years respectively. For the purposes of this comparative assessment, the greatest value is adopted, assuming a total lifetime of 65 years which implies the need for 1.3 and 1.45 times more concrete roof tiles and sheet tiles than clay tiles during this period, respectively.

End of Life

A non-recycling approach is adopted *if* no local facilities exist, resultantly in such a scenario construction materials are disposed directly to landfill.

In the case of demolition of roofs and the transportation of demolition waste to landfill, two major activities were considered such as the use of tools and equipment used for demolition of roofs and then its transportation for disposal to landfill site (Lawania and Biswas 2017).

Alternatively, if recycling facilities do exist, values in Table 4 (below) are developed towards recycling databases for the 3 different roof types. Table 4 presents the construction & demolition (C&D) materials recovered and disposed in WA for the 2008-09 financial year (Hyder Consultant, 2009).

For recycling waste clay tiles, this study has determined that the tile will be crushed for aggregates towards potential replacement with limestone in road construction work. Therefore energy required to produce 3% of a clay tile has been reduced from the total raw material acquisition to calculate a net amount of energy.

In the case of concrete tiles, 45% of concrete tiles are typically recovered and recycled. Potentially all fines/sand waste-arisings from the concrete tile will be recovered and reused.

Metal is potentially 100% recyclable (Biswas 2014), however for this study a practicable local recycling rate of 78% is used (as Table 4); thus, energy consumed to produce 78% of metal has been taken away from a raw material acquisition stage to calculate the net energy for sheeting.

Impact assessment

Input and output life-cycle inventory data was entered into Simapro LCA software (Pre-consultant, 2015); application requires relevant materials to be linked to Australian libraries to ensure representative WA conditions. Where libraries did not exist, new libraries were developed from similar LCA studies. Table 5 (below) shows that most of the emission databases were sourced from Australian unit process libraries (Stephan and Stephan 2014) except for: silica and Iron-nickel-chromium alloy (where Eco-invent was used); and, natural gas (using Pré-Consultants 2015). Data concerning product residual uptake (cradle-to-cradle) was input to the software (i.e. chemicals, energy demand and heating and cooling loss) and linked to relevant libraries, towards the generation of associated impacts. The libraries are emission factor databases which include all upstream emissions and embodied energy demand of these inputs. The Intergovernmental Panel on Climate Change -IPCC2007- global warming potential (GWP)- method was used to calculate the associated environmental impact(s) of the product(s) (IPCC 2007). The cumulative energy demand method was also used to generate the embodied energy of the products.

Equation (2) shows the conversion of masses of different greenhouse gases associated with the production and use of material and energy inputs into global warming potential (GWP) (Fatimah and Biswas 2016), which is a single carbon dioxide-equivalent metric (CO_2 e-) (Stephan and Stephan 2014).

$$GWP\ (CO_2\ e-) = \sum_{i=1}^{i=N} \sum_{j=1}^{j=M} I_i EF_{ij} \text{ x } CF_j \qquad (2)$$

where, I is the amount of an input

i :1,2,…..N; type of inputs (e.g. cement, concrete, aluminium, electricity, natural gas)

EF_{ij} : Emission factor = Amount of emission of GHG type ‘j’ per kg of input of type ‘i’

CF_j : CF_1, CF_2, ……. CF_M; characterization factors of GHGs (e.g. CF is 1 for CO_2, 28 for CH_4, 265 for N_2O)

Following cumulative energy demand method (Fatimah and Biswas 2016), all inputs in the life-cycle inventory have been multiplied by the corresponding energy demand values to find out the total embodied energy demand of a roof cover

$$EE_{total} = \sum_{i=1}^{N} I_i \text{ x } EE_i \qquad (3)$$

where, EE_i is the embodied energy demand of an input i.

Results and discussions

Carbon footprint of roof cover materials

Respective carbon footprints of roof cover materials have been estimated for both traditional (residual landfill) and also recycling approaches to determine carbon saving benefits.

Traditional approach

As can been seen in the above Figures 1 a, b and c, the total carbon footprints of one hundred square metre of sheet-metals, concrete tiles and clay tiles are 9.85 t CO_2e-, 9.33 t CO_2e-and 4.39 t CO_2e-, respectively. Sheet-metal roofing is the most carbon intensive roofing material, because it is made of aluminium, which is 16 and 12 times more carbon intensive than concrete and clay blocks, respectively (NZAS, 2011; Dunlop, 2013; FISIS, 2013).

Raw material acquisition accounted for a significant portion (96%) of the total carbon footprint of one hundred metre square of sheet-metal roof, followed by manufacture and processing (2.6%), transportation (0.77%), construction (0.18%) usage (0.02%) and demolition and disposal stages (0.19%). Raw material acquisition for sheet-metal is very high due to aluminium production typically in Victoria State smelters using electricity generated from brown coal. This stage of the life-cycle is a significant source of carbon dioxide emissions and consequently the use of virgin sheet-metal is the least environmentally friendly roof material specification for residential buildings in WA, in locations where no recycling facilities exist. Whilst less timber structural framework is required to support a lightweight sheet-metal roof, this does not contribute to the overall reduction of GHG emissions. The use of carbon intensive sheet-metal roofs outweighs the benefit associated with use of light, structural roof carcassing materials. Like other studies (Stephan and Stephan 2014), this study also found that the demolition and disposal stage accounts for the very tiny portion ($\leq$1%) of the overall impact.

Followed by sheet-metal, concrete tile use ranked second in terms of output of carbon foot print 9.33 tonne of CO_2 e-. Acquiring the required materials alongside manufacturing to final product is deemed energy-intensive. Whilst raw material acquisition accounted for 51%, a significant portion of carbon footprint was produced during the manufacturing stage (43% of the overall carbon footprint). The is due to the use of large amounts of natural gas (1.5 times more than clay tiles and 4 times more than sheet-metal) to fire the kilns used to burn the limestone, clay shale and other materials.

Comparing these three options, clay tiles produced the lowest carbon footprint of 4.44 t of CO_2e-. A large proportion of which is linked to the manufacturing and processing stage(s) (76%) followed by raw material acquisition (10%), transportation (10%), construction (2%), the usage (0.03%) and demolition and disposal stage (1%). Figure 1c has identified that the combustion of natural gas in the furnace for clay tiles production contributed a large portion of the overall carbon footprint. In addition, the LCA analysis has also highlighted that transportation contributed 10% of the overall carbon footprint, which is significantly higher than the emissions from the transportation of sheet-metal and concrete roofs. This is due to the heavy mass of clay tiles and long travel distance from the manufacturing factory to the construction site (tonnes x km travelled).

Recycling approach

Where local residual processing-facilities exist, a recycling approach for roof material assessment is considered below, towards full environmental burden analysis of these materials.

Sheet-metal has the potential to be 100% recovered, reused and recycled. This study however considered a more practicable local WA recycling rate of ~78% (Hyder Consulting, 2009); subsequently this significant amount of carbon footprint offset can be attained. This

LCA confirms that there is much potential for reducing GHG emissions from sheet-metal roofing (73%) through a recycling approach that reduces emissions from mining and processing of such energy intensive metals. It is noted that the raw material acquisition stage of highly recyclable sheet metal materials such as aluminium and zinc is an environmental ‘hotspot’ for this roof type, and so recycling significantly reduces the carbon footprint of a sheet-metal roof covering.

Concrete and clay tiles after their respective end-of-life, are unlikely to be re-used again as roof materials specifically and therefore, recycling/crushing for alternative infrastructure applications can be considered. In the case of concrete tiles, 45% of the waste generated can be recycled/ recovered as fine aggregate-s (e.g. sand) through concrete-tile crushing, separation and grading for reuse as either sub-base file or as aggregate-fines in recycled concrete. Consideration of this recycling strategy offsets emissions from the acquisition of the raw material stage. Once this recycling strategy has been considered, the overall GHG emissions from the use of 100 m^2 of concrete tiles can be reduced to 8.44 t of CO_2e- (i.e. by 10%).

To recycle clay tiles, the waste-arising is crushed and graded into aggregates towards (localised) percentage replacement for virgin limestone in road construction. The amount of energy that could be avoided due to crushing clay tiles instead of limestone is only 3%. The material acquisition stage accounts for only 10% of the total GHG emission and so reducing (only) 3% of the total energy demand of raw material acquisition due to this recycling approach does not appear to decrease the overall GHG emission of clay tile roof.

For these three roof covering materials, GHG emissions associated with the demolition and disposal decreased due to decreases in the amount of demolition wastes going to landfill. The emissions from the transportation of construction materials have been decreased for the sheet metal roofs only, as recycled sheet metal is used for building roof application, which in turn would avoid the shipping of virgin materials from the eastern state. This is not the case for concrete and clay tiles, as recycled versions of these materials are used for different applications.

Embodied energy demand

When residual-processing facilities are not available and a recycling approach is not considered, it is not the sheet-metal roof, but rather the concrete roof that is found to have the highest embodied energy demand (83 GJ), followed by sheet-metal (58.6 GJ) and clay tiles (52.7 GJ). The embodied energy impact of a sheet-metal roof is not as great as its carbon footprint because GHG emissions are due to electricity generated from brown coal for aluminium production; on the other hand, as mentioned above the manufacturing energy for concrete is significantly higher than that for sheet-metal and clay tiles. Concrete manufacturing involves the use of energy for crushing aggregates and mixing concrete constituents in batching plants. Since higher percentages of sheet-metal can be recycled (than concrete tiles) with very high energy intensities (i.e. 240 MJ/kg for sheet-metal, as opposed to cement for concrete of 7.5 MJ/kg, and clay of 0.05 MJ/kg), the use of recycling approaches are argued to be able to significantly reduce the embodied energy demand of sheet-metal (i.e. 71%). Crushing and recycling of concrete and clay waste-arisings reduces insignificant amounts of the embodied energy (concrete by 7% and clay tiles by 0.04%) due to the fact that most of the energy was consumed in the manufacturing stage of these materials.

Conclusions

This paper discusses how Life-cycle Assessment (LCA) tool application can help inform the design process and specification choices of building materials in Western Australia, with particular regard to assessing key environmental impacts such as carbon footprint and embodied energy demand. This research compares three different roof alternatives which can be used as a guide for future study for a quick comparison, to guide choice of alternative specifications for (low carbon impact) roofing materials.

Where waste-processing facilities are not available and recycling strategies are not considered, this LCA analysis confirms that sheet-metal is the most carbon intensive roof cover material, whilst concrete roof tiling has the highest embodied energy demand. Where residual processing facilities do exist on the other hand, recycling strategies are found to be most effective for sheet-metal roof covering, as 73% of GHG emissions and 71% of embodied energy demand can be reduced by recycling. However, a similar recycling of waste arisings approach makes less significant environmental savings (i.e. ≤10%) for concrete-tile or clay-tiles; albeit respective energy conservation during manufacture (of concrete and clay tiles) can reduce overall environmental impacts where waste recycling facilities exist

The work here raises an awareness of the use of a simplified (off-the-peg software application) LCA approach, towards ongoing encouragement of designers and building materials specification stakeholders to incorporate environmental assessment into their decision-making process.

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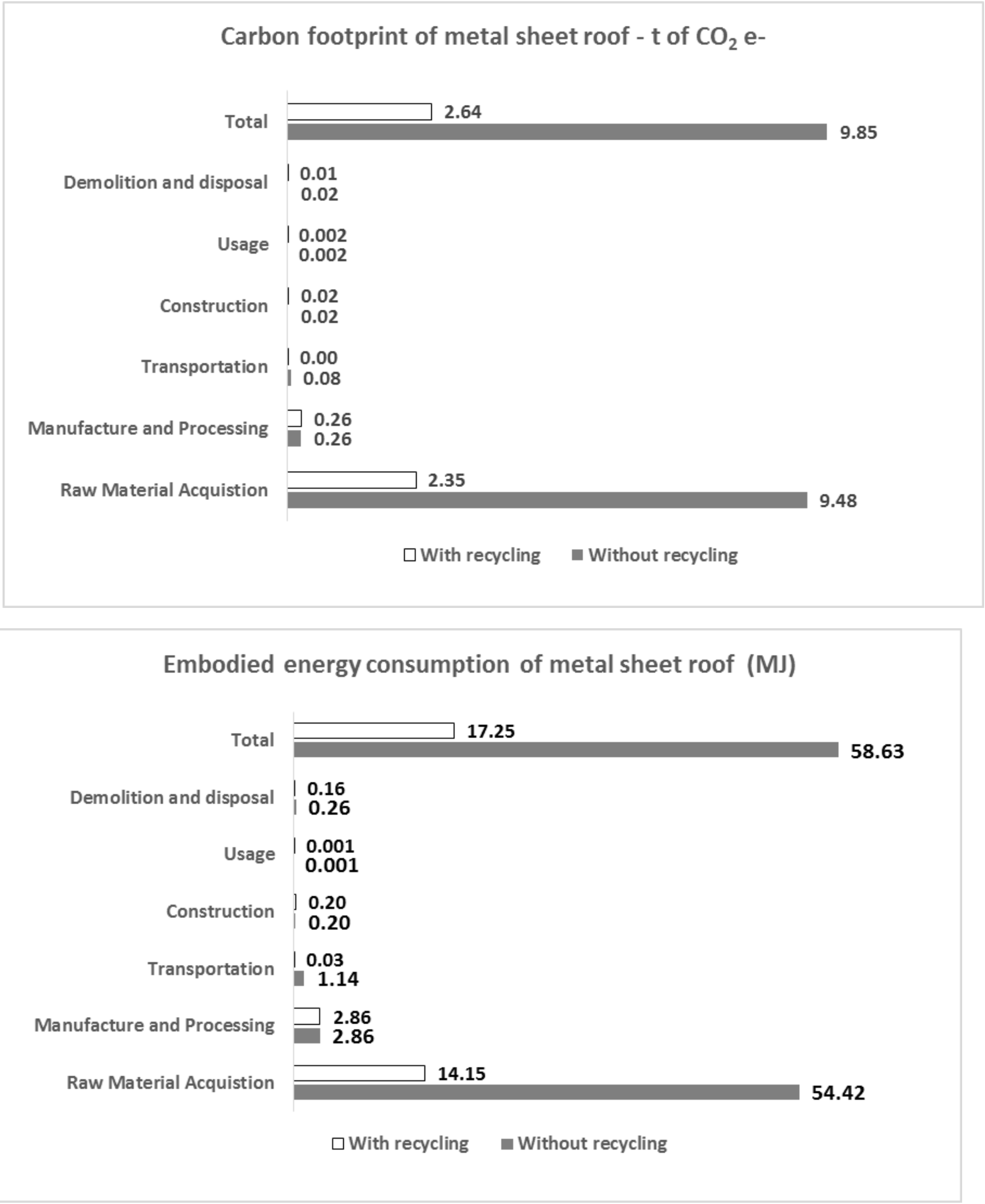
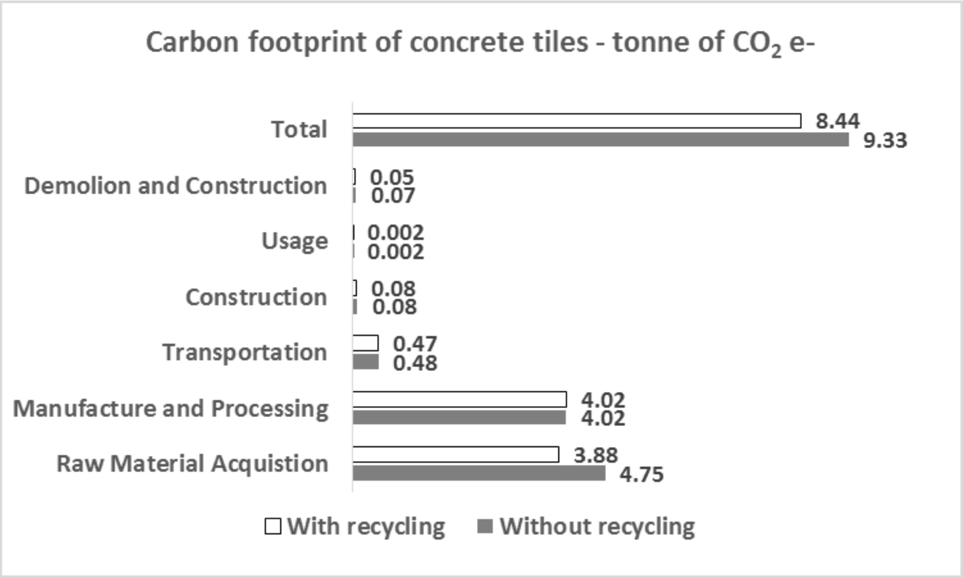
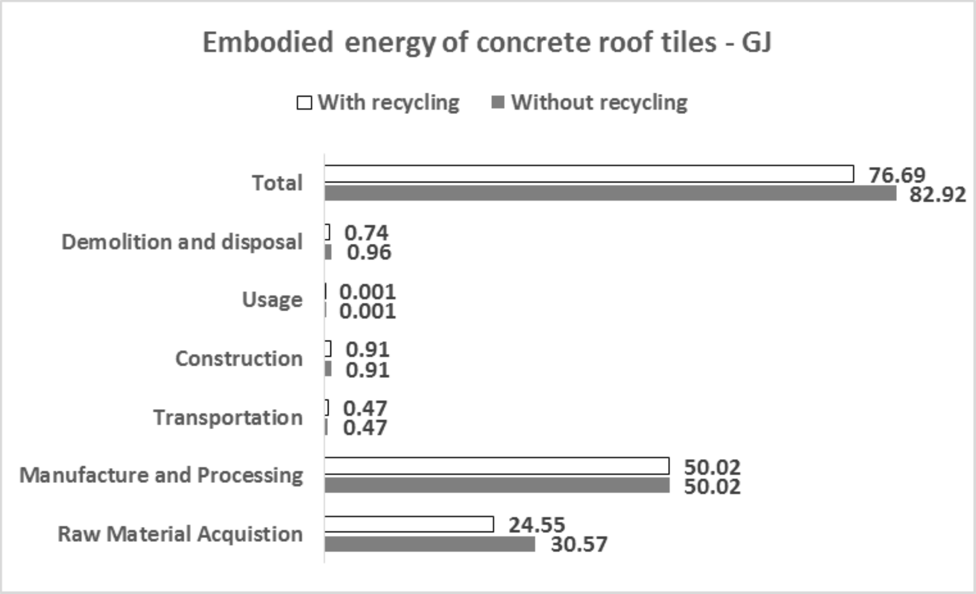
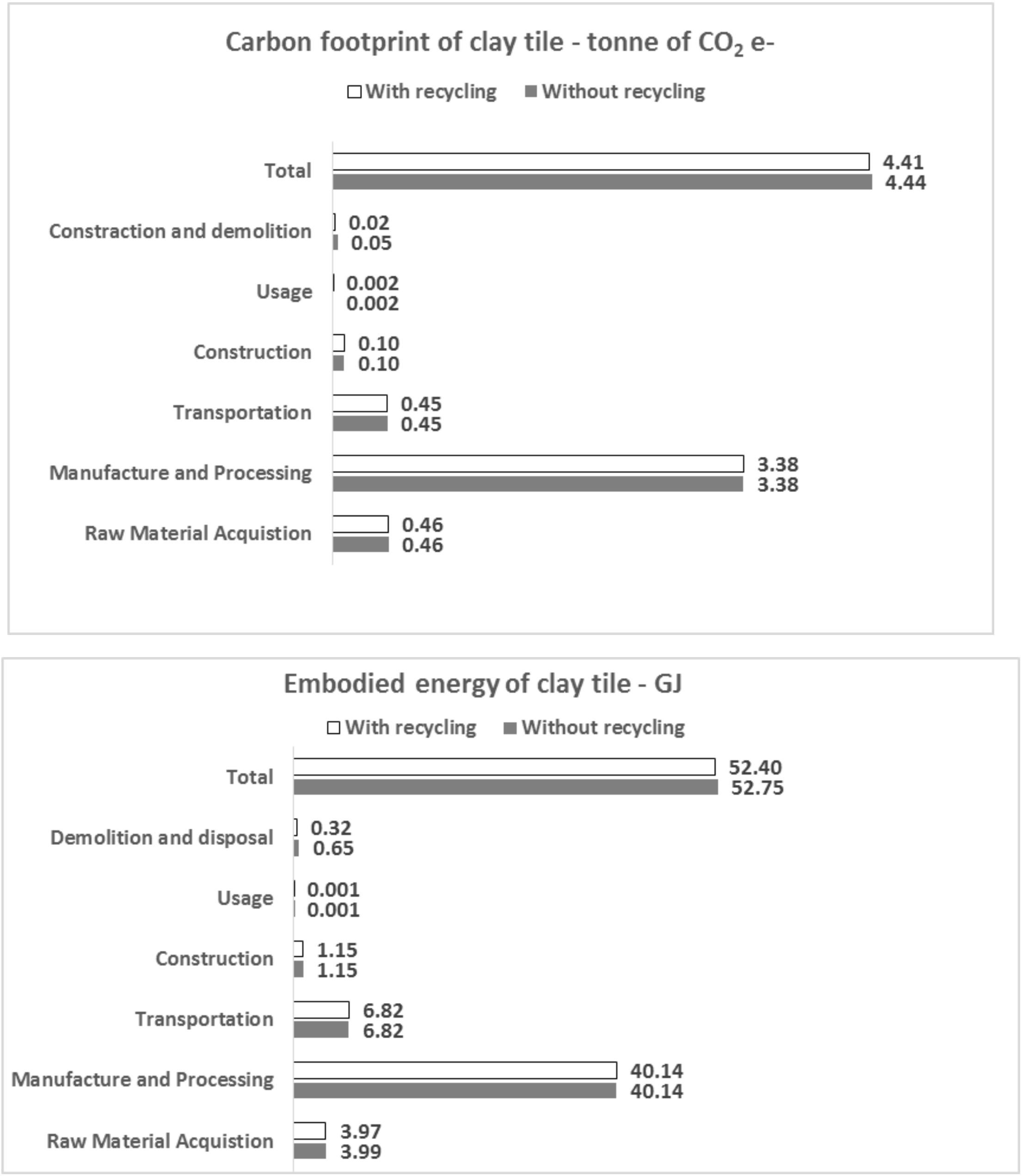


(a) Sheet-metal tiles





(b) Concrete tiles



(c) Clay tiles

Fig. 1. Carbon footprint and embodied energy demand of a) sheet-metal tiles b) concrete tiles and c) clay tiles

Table 1

Bill of materials for clay, concrete and sheet-metal tiles

Raw material	Amount of Material required in 100m^2
Clay tiles	
Quartz	2.21 t
Clay	1.48 t
Timber	1.65 t
Concrete tiles	
Quartz	3.65 t
Portland cement	1.50 t
Timber	1.65 t
Sheet-metal	
Aluminium	0.34 t
Zinc	0.27 t
Silicon	0.01 t
Timber	1.53 t

Table 2

Manufacturing and transportation information for clay, concrete and sheet-metal tiles

Materials	**Manufacturing Energy**	**GJ/100m^2**
Clay	Natural Gas	9.3
	Electricity	6.2
Concrete	Natural Gas	14.2
	Electricity	2.9
Metal	Natural Gas	3.5
	Electricity	1.2
Transportation Mode	**Distance (km)**	**tkm**
Clay tile		
Freight, shipping	4064.14	15,010
Freight, articulated truck	22.6	83.5
Concrete Tile		
Freight, shipping	3113.2	16,042
Freight, articulated truck	22.6	116.5
Metal		
Freight, shipping	4064.14	2,520
Freight, articulated truck	22.6	14
Construction	**Total weight of mild steel nail (**kg**)**	
Clay tiles	32	
Concrete tiles	25.3	
Sheet-metal	5.7	

Table 3

Heating and cooling load of 100m^2 clay, concrete and sheet-metal roof covers

Cooling	Output	Input, COP: 3.25	
Clay	215.86	66.42	GJ
Concrete	227.41	69.97	GJ
Sheet-metal	143.67	44.21	GJ
Heating			
Clay	127.29	36.37	GJ
Concrete	139.03	39.72	GJ
Sheet-metal	53.90	15.40	GJ

Note: COP = co-efficient of performance = It is a ratio of useful heating or cooling provided to work required.

Table 4

Recycling rate of materials in WA for the 2008-2009 financial year

Materials	Tiles	% of Recycling
Masonry materials	Clay Bricks/Tiles	3%
	Concrete	45%
Metals		78%

Table 5

Emission factors of inputs for this LCA analysis

	Carbon footprint (kg CO_2 e-)	Embodied energy consumption (MJ)
1 kg Clay, at mine/AU U (of project Australasian Unit Process LCI)	0.00313	0.0495
1 kg Silica sand, at plant/DE U (of project Ecoinvent unit processes)	0.021	0.323
1 kg Strutural pine, u=12%, at mill/AU S (of project Australasian System Process LCI)	0.25	8.98
1 MJ Electricity (natural gas) (of project LCA Food DK)	0.182	2.37
1 MJ Electricity, black coal NSW, sent out /AU U (of project Australasian Unit Process LCI)	0.273	0.294
1 tkm Articulated truck, 28 tonne load on 30 tonne truck, 90% rural operation, (freight task)/AU U (of project Australasian Unit Process LCI)	0.116	1.98
1 tkm Shipping, Domestic Freight/AU U (of project Australasian Unit Process LCI)	0.0292	0.0491
1 kg Iron-nickel-chromium alloy, at plant/RER U (of project Ecoinvent unit processes)	4.62E	0.821
1 kg Cement, Portland, at plant/AU U (of project Australasian Unit Process LCI)	0.905	7.47
1 MJ Electricity, high voltage, Western Australia/AU U (of project Australasian Unit Process LCI)	0.242	1.16
1 kg Aluminium, at plant/AU U (of project Australasian Unit Process LCI)	0.217	240
1 kg Zinc, primary, at regional storage/RER U/Adapted/AU U (of project Australasian Unit Process LCI)	6.50	78.2

1 kg Clay, at mine/AU U (of project Australasian Unit Process LCI)	0.003	0.05
1 kg Silica sand, at plant/DE U (of project Ecoinvent unit processes)	0.02	0.32
1 kg Strutural pine, u=12%, at mill/AU S (of project Australasian System Process LCI)	0.25	8.98
1 MJ Electricity (natural gas) (of project LCA Food DK)	0.18	2.37
1 MJ Electricity, black coal NSW, sent out /AU U (of project Australasian Unit Process LCI)	0.27	2.94
1 tkm Articulated truck, 28 tonne load on 30 tonne truck, 90% rural operation, (freight task)/AU U (of project Australasian Unit Process LCI)	0.12	1.98
1 tkm Shipping, Domestic Freight/AU U (of project Australasian Unit Process LCI)	0.03	0.46
1 kg Iron-nickel-chromium alloy, at plant/RER U (of project Ecoinvent unit processes)	4.62	82.10
1 kg Cement, Portland, at plant/AU U (of project Australasian Unit Process LCI)	0.91	7.47
1 MJ Electricity, high voltage, Western Australia/AU U (of project Australasian Unit Process LCI)	0.24	1.16
1 kg Aluminium, at plant/AU U (of project Australasian Unit Process LCI)	21.70	240.00
1 kg Zinc, primary, at regional storage/RER U/Adapted/AU U (of project Australasian Unit Process LCI)	6.50	78.2

Appendix A: A sample calculation of timber structure

Details and specification were provided by drawings and the Design Engineer from City of Melville.

General specification of a residential house:

Joist Spacing – 600mm

Rafter Spacing – 600mm

70/75mm frame

Pitch Angle – 20 degrees

Single Storey

Specification of material:

Top plates (AS 1684.4 Table A22)

Roof Type: sheet-metal roof

Rafter Span = 9,000mm

Timber size: MGP10 2/45x70

Roof Type: Clay and concrete Tile

Rafter Span = 9000mm

Timber size: MGP10 3/45x70

Ceiling Joists (AS 1684.4 Table A27)

Joist Span – 3,600mm

Timber size: MGP10 120x45

Hanging Beam (AS 1684.4 Table A28)

Ceiling Joist span – 3,600mm

Hanging Beam span – 3,600mm

Timber size: MGP10 240x35

Strutting Beams (AS 1684.4 Table A32)

Sheet Roof Strutting beam span – 4,800mm

Timber size: Sheet-metal– MGP10 2/190x35

Timber size: Clay and concrete Tile – MGP10 2/240x45 Underpurlins (AS 1684.4 TA33)

Strut Spacing – 2,400mm

Timber size: Sheet-metal– MGP10 2/90x45

Timber size: Clay and concrete Tile – MGP10 2/140x35 Rafters (HySPAN)

Timber size: sheet-metal - MGP10 120x35

Timber size: Clay and concrete Tile – MGP10 120x35 Ridge Beam (AS 1684.4 Table A36)

Beam Spacing – 2,400mm

Beam Span – 3,600mm

Timber size: sheet-metal – MGP10 2/190x45

Timber size: Clay and concrete Tile – MGP10 2/240x45 Batten (AS 1684.4 Table A37)

Rafter spacing – 600mm

Batten spacing – 900mm

Timber size: sheet-metal - MGP 45x70

Rafter spacing – 600 mm

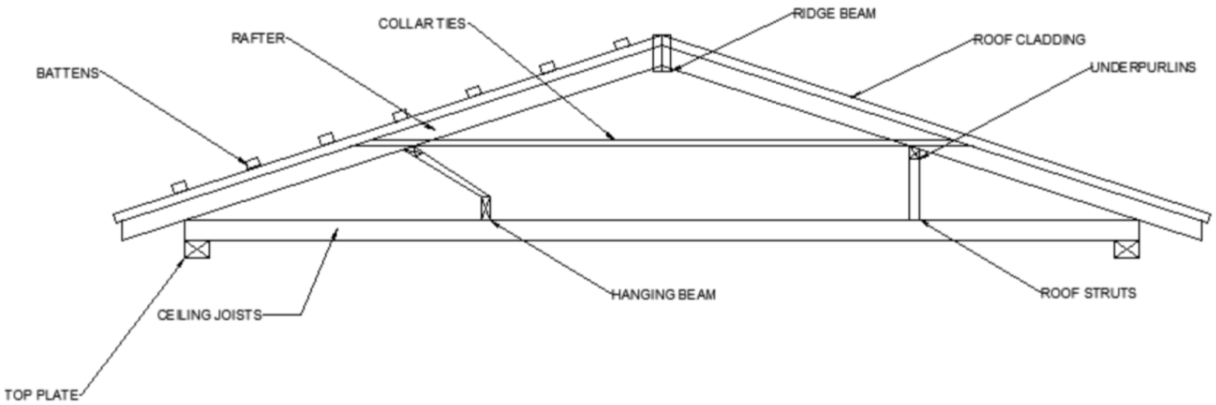
Batten spacing – 330mm

Timber size: Clay and concrete Tile -MGP10 35x42 Hip or Valley Rafters (HySPAN)

Timber size: sheet-metal – MGP10 190x45

Timber size: Clay and concrete Tile – MGP10 240x45 Roof Struts

Timber size: MGP10 90 x45



The timber frame required was calculated by measuring the drawings to calculate the length and then calculating the volume using the dimension of the timber frame in the above section.

Timber frame required (TILE – CONCRETE & CLAY):

Total length of Top Plate (MGP10 2/45x70) = 43.2m

Total volume of Top plate = 43.2 x 0.045 x 0.07 = 0.136m^3

Total length of Ceiling Joists (MGP10 120x45) = 204m

Total volume of Ceiling Joists = 204 x 0.12 x 0.045 = 1.1m^3

Total length of Hanging Beam (MGP10 240x35) = 44.6m

Total volume of Hanging Beam = 44.6 x 0.24 x 0.035 = 0.375m^3

Total length of Strutting Beam (240 x 45) = 13.45m

Total volume of Strutting Beam = 13.45 x 0.24 x 0.045 = 0.145 m^3

Total length of Underpurlin (MGP10 140 x 35) = 60.7m

Total volume of Underpurlin = 60.7 x 0.14 x 0.035 = 0.3 m^3

Total length of rafter (MGP10 120x 35) = 197 m

Total volume of rafter = 197 x 0.12 x 0.035 = 0.83 m^3

Total length of Ridge Beam (MGP10 240 x 45) = 3.22m

Total volume of Ridge Beam = 3.22 x 0.24 x 0.045 = 0.035 m^3

Total length of Batten (MGP10 35 x 42) = 317m

Total volume of Batten = 317 x 0.035 x 0.042 = 0.47 m^3

Total length of Valley Rafter (MGP10 240x45) = 26m

Total volume of Valley Rafter = 26 x 0.24 x 0.045 = 0.28 m^3

Total length of roof struts (MGP10 90 x 45) = 36m

Total volume of roof struts = 36 x 0.09 x 0.045 = 0.15 m^3

TOTAL TIMBER VOLUME = 3.821 m^3

Timber frame required (sheet-metal):

Total length of Top Plate (MGP10 3/45x70) = 43.2m

Roof Cladding required:

Clay Tiles:

No. of tiles per m^2: 11.9

No of tiles required: 11.9 x 150 = 1785 tiles

Mass per tile: 3.1kg

Total mass of tiles = 3.1 x 1785

Total mass of tiles = 5533.5 kg

Total mass of quartz (60%) = 5533.5 x 0.6

Total mass of quartz (60%) = 3320.1kg

Total mass of clay minerals (40%) = 5533.5 x 0.4 Total mass of clay minerals (40%) = 2213.4kg Concrete Tiles:

No. of tiles per m^2: 9.4

No of tiles required: 9.4 x 150 = 1410 tiles

Mass per tile: 5.55kg

Total mass of tiles = 5.55 x 1410

Total mass of tiles = 7825.5 kg

Total mass of quartz (70%) = 7825.5 x 0.7

Total mass of quartz (70%) = 5,477.85kg

Total mass of Portland cement (30%) = 7,825.5x 0.3 Total mass of Portland cement (30%) = 2347.65kg Steel Roofing:

Required steel roofing: 150m^2

Mass: 4.3 kg/m^2

Total mass of metal roofing: 150 x 4.3

Total mass of metal roofing: 645kg

Total mass of Aluminium (55%): 354.75kg

Total mass of Zinc (43.5%): 280.575kg

Total mass of Silicon (1.5%): 9.675kg

Appendix B: Calculation of the effects of varying solar reflectance of roofing materials

Physical Data: Physical data assumptions are detailed below for input into equation 1.

Temperature readings are taken from the (WA) Bureau of Meteorology (BOM). The temperature (T1) is the average temperature recorded at 3pm from 1994 – 2011 at Perth Metro WA each month. Industry representatives (thanks to TT Air-conditioning), the conformable temperature will vary individual to individual. However industry representatives note that many buildings are set at a room temperature of 24 degrees C.

Average radiation figures for areas in Perth metro WA have been derived from BOM. A figure of 625 W/m^2 for a 6 hour day is typical. BOM has also provided data that the heat flow transfer coefficient is 25 $W/m^2.K$.

The Building code of Australia, 2005 notes that roofing requires a total R Value (=1/U) of $2.2m^2. K/W$.

According to Selby (2006) the absorption rate for clay tile, concrete tile and sheet-metaling is 0.63, 0.67, and 0.38

Q = rate of heat flow per square metre from roof to the inside

U = the overall heat transfer coefficient between the ambient and inside ($W/m^2/K$) Note that 1/U = R (the thermal resistance)

H = Outside transfer coefficient between roof and ambient ($W/m^2/K$)

∂ = rate of absorption to solar radiation

G = Solar radiation per unit area

Calculation for January (Clay Tile):

Average temperature at 3pm: 29 degrees

Comfortable Temperature: 24 degrees

Change in temperature = 29 – 24 = 5 degrees (Cooling)

$\alpha = 0.63$ (Clay Tile)

h = 25 $W/m^2 .K$

G = 625 watts/m2

R = 1/U = 2.2 m^2 K/W (Building code of Australia, 2005)

Roof Area = $100m^2$

Heat Loss = (1/2)*((0.63*635/25)+5)

Heat Loss = 9.43 W

Heat Loss = 0.94 kW

Heat Loss over 6 hrs = -0.94 x 6 = 5.66 GJr

Heat Loss in a month = -5.66 * 31 days = 175.43 GJr

Heat Loss in 65 years = -175.43 x 65 years = 11403.07 GJr

Total Cooling in 65 years during the month that requires cooling = 59961.61 GJr

Calculation for applied energy

1 x Mitsubishi 4.2kW Air Conditioner

Energy Efficiency (Coolinsg) - 2 stars (Sourced from TT air-conditioning)

COP – 3.25 (Energy Aus)

Energy Efficiency (Heating) – 2.5 Stars (Sourced from TT air-conditioning)

COP – 3.5 (Energy Aus)

Cool Capacity – 4.2 kW

Heating Capacity – 5.4 kW

Total Output Energy for Clay (Cooling): 59961.61 GJr

COP = Output/Input

3.25 = 59961.61 GJr / Input

Input = 18449.73 GJr