

1 **Carbon footprint and embodied energy assessment of roof covering**
2 **materials**

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6 **Abstract** The residential building sector regularly satisfies a diverse range of housing needs
7 whilst addressing respective capital-cost considerations. Designers and builders must also be
8 aware of the environmental implications of their design specifications; the work here adds to a
9 body of knowledge concerned with carbon footprint and embodied energy demand, specifically
10 through an examination of alternative roof covering materials. A life-cycle assessment (LCA)
11 has been carried out, within a West Australian context, to compare impacts for the roof-
12 specification options of: clay-tile; concrete-tile; and, sheet-metal. In locations where recycling
13 facilities are unavailable and thus disregarded, it is found that clay tiles have the lowest carbon
14 footprint of 4.4 t of CO₂ equivalent (CO₂ e-) and embodied energy demand of 52.7 Mega Joule
15 (MJ) per 100 m², while sheet-metal roofing has the highest carbon-footprint (9.85 t of CO₂ e-
16), with concrete roof tiles having the highest embodied-energy demand (83 MJ). Findings
17 confirm that a sheet-metal roof can obtain significant carbon and embodied energy saving
18 benefits (i.e. 71-73%) compared to clay tile or concrete roof covers through ongoing
19 encouragement of recycling strategies and increased local recycling facilities able to embrace
20 residual cradle-to-cradle material re-use.

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22 **Keywords** Roof covering materials, carbon footprint, embodied energy demand

23

24 **Introduction**

25

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

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

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

49 Roofing accounts for 6% of a low-rise building's volume and, typically, 7% of a
50 residential building's GHG emissions (from mining to material production) (Lawania and
51 Biswas, 2018). Saiz conducted an LCA of a so-called 'green' roof in Madrid, finding that its
52 low solar absorbance resulted in a reduced level of energy demand for the building (Saiz et al.
53 2015). Chenani (2014) similarly determined the environmental performance of two lightweight
54 'green' roof systems and found that an environmental impact reduction, through layers'
55 configurations review, was possible. Another recent LCA study found that the use of vaulted
56 roofs can reduce embodied energy by over 40% relative to flat slabs (Huberman et al., 2015).

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

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

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67 **Methodology**

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

72 **Goal and scope**

73

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

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

81 The functional unit of this study is 100m² of roof-covering materials and the timber
82 structure framework supporting it; the environmental impacts of respective (typically) timber
83 framework(s) will be analysed with the roof-covering material options. The reason for choosing
84 this functional unit was that approximately 50 % of average houses in Perth have this size of
85 roof area (Department of Water and Environmental Regulation, 2017). Other dwelling
86 superstructure elements are not analysed. This is a process-based LCA, where energy and
87 chemical inputs of all stages during the life cycle of roof covering materials, have been utilised
88 in assessing global warming impacts and embodied energy demand (Suh et al., 2014; Majeau-
89 Bettez et al., 2011).

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

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

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

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Life-cycle inventory

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

Mining to material production

114 Composition and percentages of raw materials used in clay tiles, sheet-metal and concrete tiles
115 respectively, were assessed (Table 1). For concrete and clay tiles roof, raw material quantities
116 were calculated; the number of tiles per metre square multiplied by the mass per tile gives the
117 total mass of tiles; the total mass then multiplied by relevant percentages finds raw materials
118 required in 100m² (Whyte, 2015). The timber frame to support the clay tiles, concrete tiles and
119 sheet-metal were sourced from typical sections and drawings from the City of Melville,

120 Western Australia, alongside AS 1684.4 (Whyte, 2015). A sample calculation has been
121 provided in Appendix A.

122 Table 2 shows the amount of natural gas and electricity that was required to produce 100
123 m² of clay tile, concrete tile and sheet-metal from raw materials (BPIC, 2014; Atlas Steel,
124 2014).

125 *Transportation*

126 Construction sites for roof erections is Western Australian urban/metropolitan; shipping freight
127 transportation is assumed from the (interstate) manufacturer/fabricator to WA (Fremantle) port.
128 In order to estimate the tonnes-km (i.e. tkm) travelled by land, and sea Google Earth was used
129 for calculating the distances in kilometres between origins and destinations. Local WA industry
130 representatives (Boral and BlueScope Steel and others) noted that, typically clay tiles and
131 sheet-metal are manufactured in New South Wales, with concrete tiles made in Victoria.
132 Shipping distance between NSW and WA (Fremantle) has been calculated as 2,195 nautical
133 miles (4065.14km), and between Victoria Melbourne and Fremantle – 1,681 nautical miles
134 (3,113.2km). Upon arrival at (Fremantle) port, articulated trucked road transportation of
135 materials from the port to distributor/site is calculated as 22.6km.

136 *Construction*

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

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

145 *Use*

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

$$150 \quad q = U[(T_2 - T_1) + \frac{\partial G}{H}] \quad (1)$$

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

152 U = the overall heat transfer coefficient between the ambient and inside ($\text{W}/\text{m}^2\cdot\text{K}$)

153 $1/U$ = the thermal resistance

154 T_2 = Annual average ambient temperature $^{\circ}\text{C}$

155 T_1 = Required level of temperature that needs to be maintained inside the house $^{\circ}\text{C}$

156 H = Outside transfer coefficient between roof and ambient ($\text{W}/\text{m}^2\cdot\text{K}$)

157 ∂ = rate of absorption to solar radiation

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

159 Table 3 shows the cooling and heating loads of each roofing material in terms electricity
160 consumption. Fossil and renewable energy account for 95.5% and 4.5% of the total primary
161 energy sources for electricity generation (Grant, 2015). Appendix B shows a sample calculation
162 for how the cooling load has been calculated for clay tiles. Since the thermal modelling
163 software was unavailable during the time of the study, the heating and cooling load at hourly

164 levels was not determined (for more accurate analysis) and hence it is considered as a limitation
165 of this analysis (Robati et al. 2016; Robati et al. 2017). Also it should be noted that the usage
166 stage has only been considered to capture variation in cooling and heating energy demand due
167 to use of different roof covering materials over their life cycles. This variation was found very
168 infinitesimal when comparing with impacts resulting from other life cycle stages. Therefore,
169 the exclusion of the detailed thermal modelling analysis can be argued as not significantly
170 affecting the overall outcomes of this LCA study.

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

177 *End of Life*

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

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

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

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

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

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

197

198 **Impact assessment**

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

211 potential (GWP)- method was used to calculate the associated environmental impact(s) of the
212 product(s) (IPCC 2007). The cumulative energy demand method was also used to generate the
213 embodied energy of the products.

214 Equation (2) shows the conversion of masses of different greenhouse gases associated
215 with the production and use of material and energy inputs into global warming potential (GWP)
216 (Fatimah and Biswas 2016), which is a single carbon dioxide-equivalent metric (CO₂ e-)
217 (Stephan and Stephan 2014).

$$218 \quad GWP (CO_2 e -) = \sum_{i=1}^{i=N} \sum_{j=1}^{j=M} I_i EF_{ij} \times CF_j \quad (2)$$

219 where, I is the amount of an input

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

222 EF_{ij} : Emission factor = Amount of emission of GHG type 'j' per kg of input of
223 type 'i'

224 CF_j : CF_1, CF_2, \dots, CF_M ; characterization factors of GHGs (e.g. CF is 1 for CO₂, 28
225 for CH₄, 265 for N₂O)

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

$$229 \quad EE_{total} = \sum_{i=1}^N I_i \times EE_i \quad (3)$$

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

231

232 **Results and discussions**

233

234 **Carbon footprint of roof cover materials**

235

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

238 *Traditional approach*

239 As can be seen in the above Figures 1 a, b and c, the total carbon footprints of one hundred
240 square metre of sheet-metals, concrete tiles and clay tiles are 9.85 t CO₂e-, 9.33 t CO₂e-and
241 4.39 t CO₂e-, respectively. Sheet-metal roofing is the most carbon intensive roofing material,
242 because it is made of aluminium, which is 16 and 12 times more carbon intensive than concrete
243 and clay blocks, respectively (NZAS, 2011; Dunlop, 2013; FISIS, 2013).

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

257 Followed by sheet-metal, concrete tile use ranked second in terms of output of carbon
258 foot print 9.33 tonne of CO₂ e-. Acquiring the required materials alongside manufacturing to
259 final product is deemed energy-intensive. Whilst raw material acquisition accounted for 51%,
260 a significant portion of carbon footprint was produced during the manufacturing stage (43% of
261 the overall carbon footprint). This is due to the use of large amounts of natural gas (1.5 times
262 more than clay tiles and 4 times more than sheet-metal) to fire the kilns used to burn the
263 limestone, clay shale and other materials.

264 Comparing these three options, clay tiles produced the lowest carbon footprint of 4.44 t
265 of CO₂e-. A large proportion of which is linked to the manufacturing and processing stage(s)
266 (76%) followed by raw material acquisition (10%), transportation (10%), construction (2%),
267 the usage (0.03%) and demolition and disposal stage (1%). Figure 1c has identified that the
268 combustion of natural gas in the furnace for clay tiles production contributed a large portion of
269 the overall carbon footprint. In addition, the LCA analysis has also highlighted that
270 transportation contributed 10% of the overall carbon footprint, which is significantly higher
271 than the emissions from the transportation of sheet-metal and concrete roofs. This is due to the
272 heavy mass of clay tiles and long travel distance from the manufacturing factory to the
273 construction site (tonnes x km travelled).

274

275 *Recycling approach*

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

278 Sheet-metal has the potential to be 100% recovered, reused and recycled. This study
279 however considered a more practicable local WA recycling rate of ~78% (Hyder Consulting,
280 2009); subsequently this significant amount of carbon footprint offset can be attained. This

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

287 Concrete and clay tiles after their respective end-of-life, are unlikely to be re-used again
288 as roof materials specifically and therefore, recycling/crushing for alternative infrastructure
289 applications can be considered. In the case of concrete tiles, 45% of the waste generated can
290 be recycled/ recovered as fine aggregate-s (e.g. sand) through concrete-tile crushing, separation
291 and grading for reuse as either sub-base file or as aggregate-fines in recycled concrete.
292 Consideration of this recycling strategy offsets emissions from the acquisition of the raw
293 material stage. Once this recycling strategy has been considered, the overall GHG emissions
294 from the use of 100 m² of concrete tiles can be reduced to 8.44 t of CO₂e- (i.e. by 10%).

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

301 For these three roof covering materials, GHG emissions associated with the demolition
302 and disposal decreased due to decreases in the amount of demolition wastes going to landfill.
303 The emissions from the transportation of construction materials have been decreased for the
304 sheet metal roofs only, as recycled sheet metal is used for building roof application, which in

305 turn would avoid the shipping of virgin materials from the eastern state. This is not the case for
306 concrete and clay tiles, as recycled versions of these materials are used for different
307 applications.

308

309 **Embodied energy demand**

310

311 When residual-processing facilities are not available and a recycling approach is not
312 considered, it is not the sheet-metal roof, but rather the concrete roof that is found to have the
313 highest embodied energy demand (83 GJ), followed by sheet-metal (58.6 GJ) and clay tiles
314 (52.7 GJ). The embodied energy impact of a sheet-metal roof is not as great as its carbon
315 footprint because GHG emissions are due to electricity generated from brown coal for
316 aluminium production; on the other hand, as mentioned above the manufacturing energy for
317 concrete is significantly higher than that for sheet-metal and clay tiles. Concrete manufacturing
318 involves the use of energy for crushing aggregates and mixing concrete constituents in batching
319 plants. Since higher percentages of sheet-metal can be recycled (than concrete tiles) with very
320 high energy intensities (i.e. 240 MJ/kg for sheet-metal, as opposed to cement for concrete of
321 7.5 MJ/kg, and clay of 0.05 MJ/kg), the use of recycling approaches are argued to be able to
322 significantly reduce the embodied energy demand of sheet-metal (i.e. 71%). Crushing and
323 recycling of concrete and clay waste-arisings reduces insignificant amounts of the embodied
324 energy (concrete by 7% and clay tiles by 0.04%) due to the fact that most of the energy was
325 consumed in the manufacturing stage of these materials.

326

327

328 **Conclusions**

329

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

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

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

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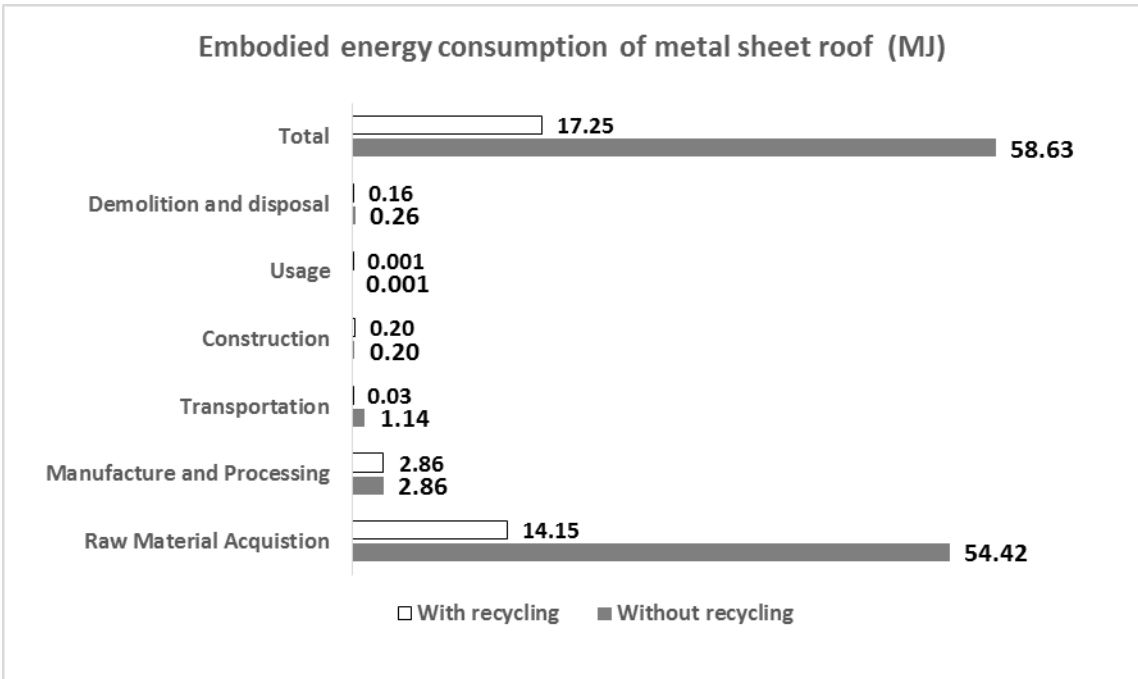
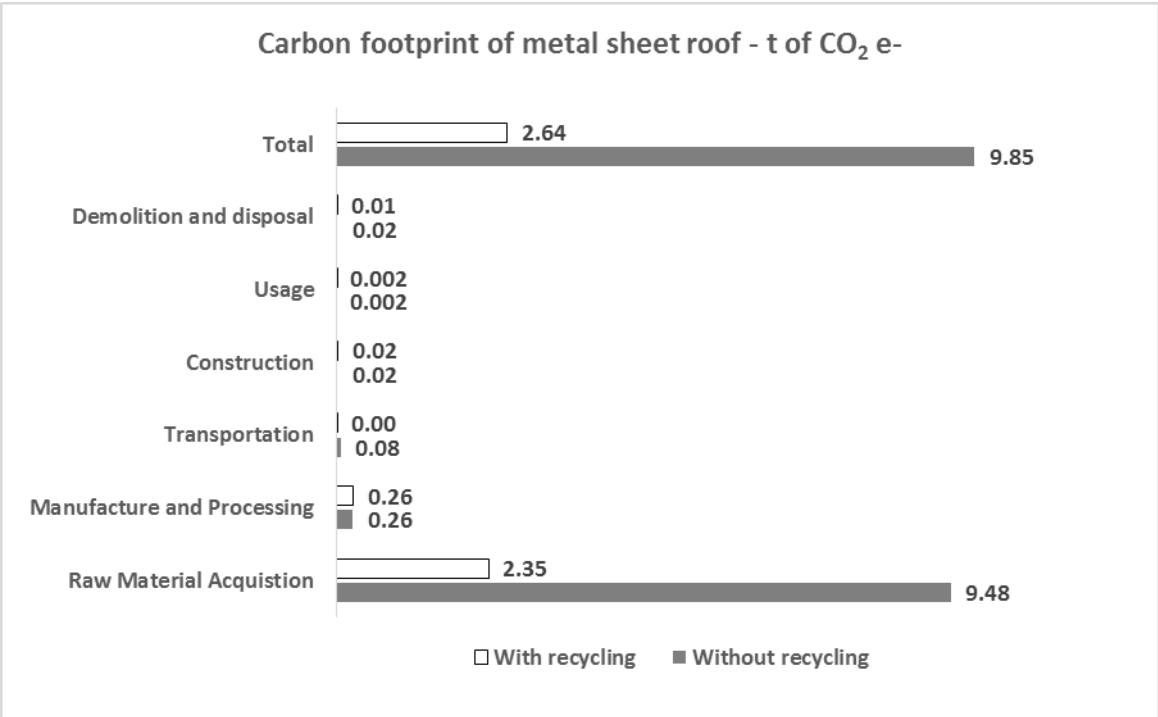
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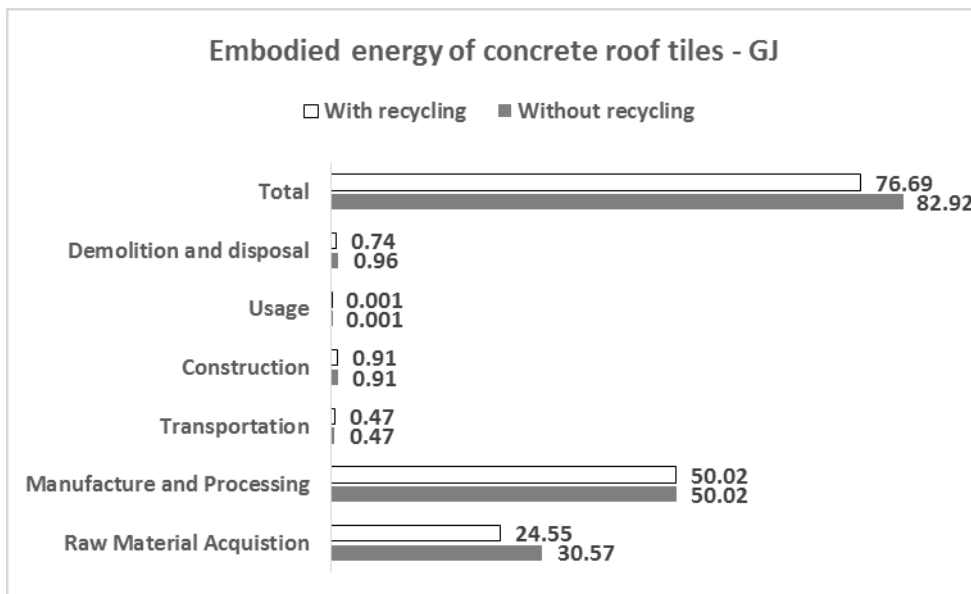
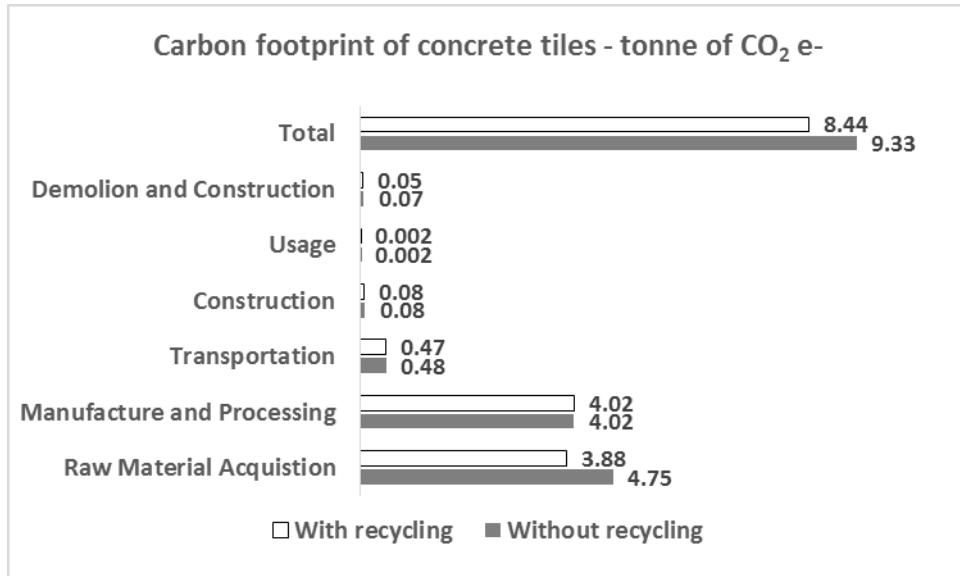
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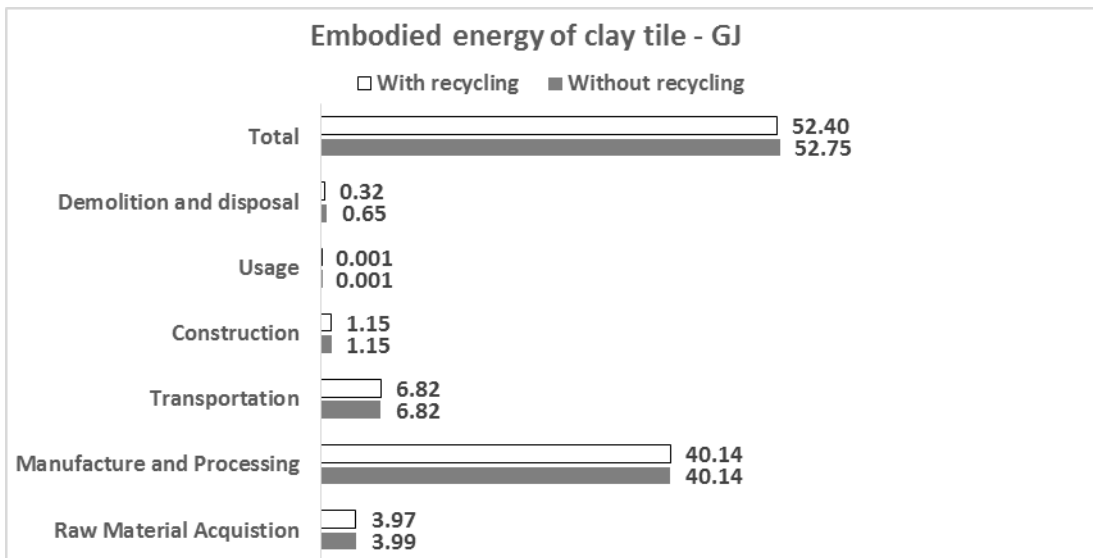
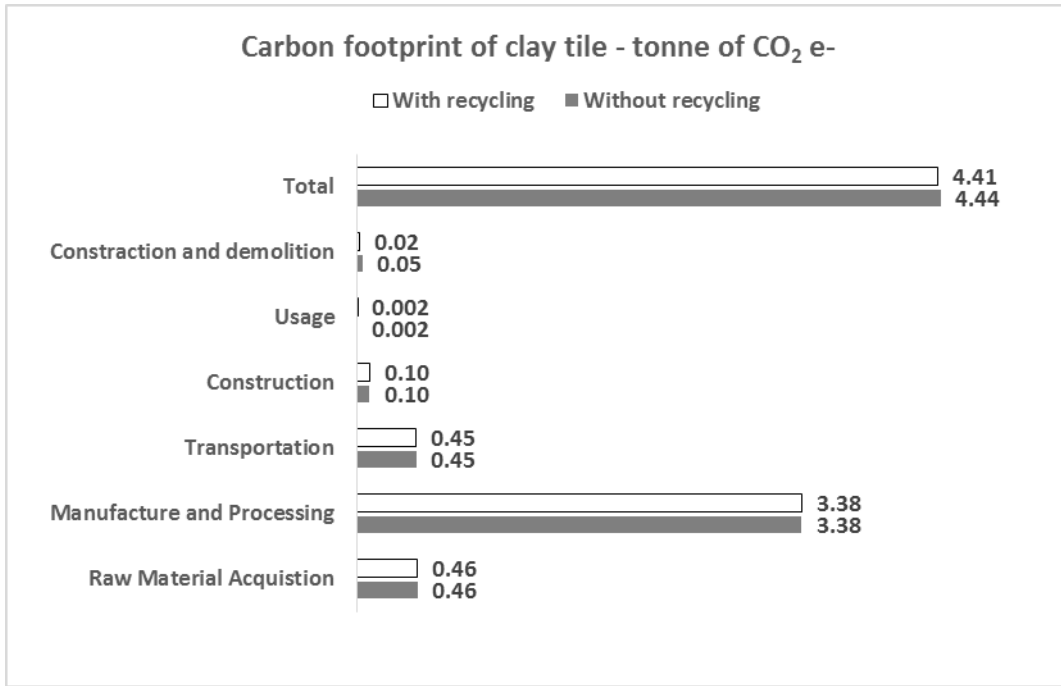
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(a) Sheet-metal tiles



(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 100m²
<i>Clay tiles</i>	
Quartz	2.21 t
Clay	1.48 t
Timber	1.65 t
<i>Concrete tiles</i>	
Quartz	3.65 t
Portland cement	1.50 t
Timber	1.65 t
<i>Sheet-metal</i>	
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/100m²
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 3Heating and cooling load of 100m² 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 Strutral 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 Structural 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

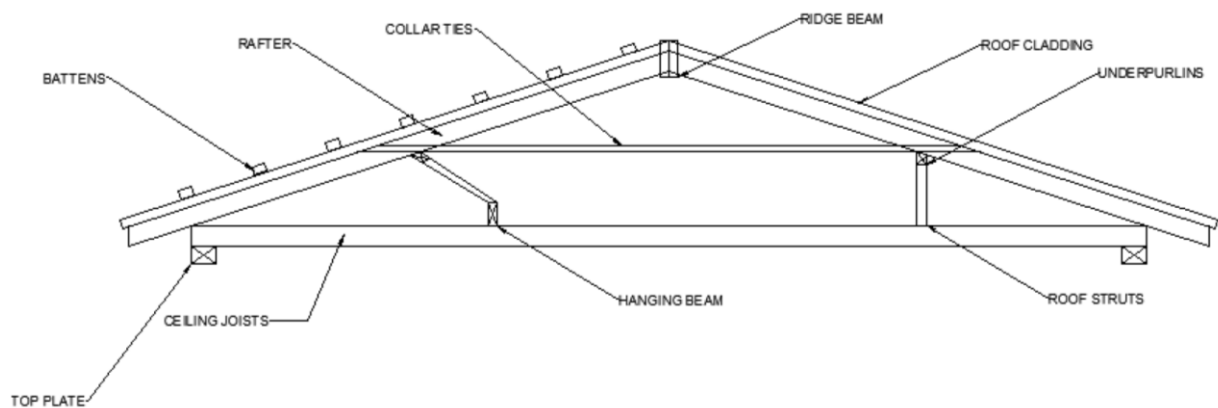
Batten spacing – 330mm

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 = $43.2 \times 0.045 \times 0.07 = 0.136\text{m}^3$

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

Total volume of Ceiling Joists = $204 \times 0.12 \times 0.045 = 1.1\text{m}^3$

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

Total volume of Hanging Beam = $44.6 \times 0.24 \times 0.035 = 0.375\text{m}^3$

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

Total volume of Strutting Beam = $13.45 \times 0.24 \times 0.045 = 0.145 \text{ m}^3$

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

Total volume of Underpurlin = $60.7 \times 0.14 \times 0.035 = 0.3 \text{ m}^3$

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

Total volume of rafter = $197 \times 0.12 \times 0.035 = 0.83 \text{ m}^3$

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

Total volume of Ridge Beam = $3.22 \times 0.24 \times 0.045 = 0.035 \text{ m}^3$

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

Total volume of Batten = $317 \times 0.035 \times 0.042 = 0.47 \text{ m}^3$

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

Total volume of Valley Rafter = $26 \times 0.24 \times 0.045 = 0.28 \text{ m}^3$

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

Total volume of roof struts = $36 \times 0.09 \times 0.045 = 0.15 \text{ m}^3$

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: $11.9 \times 150 = 1785$ tiles

Mass per tile: 3.1kg

Total mass of tiles = 3.1×1785

Total mass of tiles = 5533.5 kg

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

Total mass of quartz (60%) = 3320.1kg

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

No. of tiles per m^2 : 9.4

No of tiles required: $9.4 \times 150 = 1410$ tiles

Mass per tile: 5.55kg

Total mass of tiles = 5.55×1410

Total mass of tiles = 7825.5 kg

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

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

Total mass of Portland cement (30%) = $7,825.5 \times 0.3$ Total mass of Portland cement (30%) = 2347.65kg

Required steel roofing: 150m^2

Mass: 4.3 kg/m^2

Total mass of metal roofing: 150×4.3

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 comfortable 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/m² for a 6 hour day is typical. BOM has also provided data that the heat flow transfer coefficient is 25 W/m².K.

The Building code of Australia, 2005 notes that roofing requires a total R Value (=1/U) of 2.2m². 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/m²/K) Note that 1/U = R (the thermal resistance)

H = Outside transfer coefficient between roof and ambient (W/m²/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)

α = 0.63 (Clay Tile)

h = 25 W/m² .K

G = 625 watts/m²

R = 1/U = 2.2 m² K/W (Building code of Australia, 2005)

Roof Area = 100m²

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 = $-175.43 \times 65 \text{ years} = 11403.07 \text{ GJr}$

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 (Cooling) - 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

$\text{COP} = \text{Output/Input}$

$3.25 = 59961.61 \text{ GJr} / \text{Input}$

$\text{Input} = 18449.73 \text{ GJr}$