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Abstract: This study assesses the environmental impact of four alternatives for reinforcing 100 m² of concrete footpath (Functional Unit, FU) by using cradle to gate life cycle assessment (LCA), based on the Australian context. Specifically, the four options considered are a) producing steel reinforcing mesh (SRM), b) producing virgin polypropylene (PP) fibre, c) recycling industrial PP waste and d) recycling domestic PP waste. The FU yields 364 kg of SRM (in a) and 40 kg of PP fibres (in b, c and d), necessary to achieve the same degree of reinforcing in concrete. All the activities required to produce these materials are considered in the study, namely manufacturing and transportation, and also recycling and reprocessing in the case of industrial and domestic recycled PP waste fibres. These processes are individually analysed and quantified in terms of material consumption, water use, and emissions into the environment. This allows for the impacts from producing recycled fibres to be compared with those from producing virgin PP fibre and SRM, which are traditionally used. The LCA results show that industrial recycled PP fibre offers important environmental benefits over virgin PP fibre. Specifically, the industrial recycled PP fibre can save 50 % of CO₂ equivalent, 65 % of PO₄ equivalent, 29 % of water and 78 % of oil equivalent, compared to the virgin PP fibre. When compared to the SRM, the industrial recycled PP fibre can save 93 % of CO₂ equivalent, 97 % of PO₄ equivalent, 99 % of water and 91 % of oil equivalent. The domestic recycled PP fibre also generates reduced environmental impacts compared to virgin PP fibre, except for higher consumption of water associated with the washing processes.

1 **A life cycle assessment of recycled polypropylene fibre in concrete**

2 **footpaths**

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6 **Abstract**

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8 concrete footpath (Functional Unit, FU) by using cradle to gate life cycle assessment (LCA),
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27

28 **1. Introduction**

29 The last few decades have seen huge production and consumption of plastics, due to low
30 cost and their suitability for a wide variety of applications. They have been widely used to
31 replace traditional materials, such as wood (Qiang et al., 2014), glass (Han et al., 2015) and
32 metal (Liu et al., 2015). Polypropylene (PP), one of the most widely used plastics (Campion
33 et al., 2015), has various applications including packaging, textiles, stationery, laboratory
34 equipment and automotive components. According to the Annual National Plastics
35 Recycling Survey (A'Vard and Allan, 2013) in Australia, the total consumption of PP from
36 2012 to 2013 was around 220,000 t. However, the recycling rate of PP waste was only 21 %,
37 including 21,000 t of domestic PP waste, and 20,000 t of industrial PP waste. As a result of
38 the high PP consumption and the low recycling rate, plastic waste has led to increasingly
39 serious pollution issues (Tonn et al., 2014). This includes emissions of powerful greenhouse
40 gases (GHG) such as methane during landfilling (Zhou et al., 2014), emissions of toxic
41 chemicals (e.g. bisphenol A and polystyrene) (Trinkel et al., 2015), and poisoning of marine
42 species (La Vedrine et al., 2015). One of the ways to address this problem is to develop
43 various reusing and recycling techniques for these materials, such as material recycling
44 (Castro et al., 2014), feedstock recycling (Zeng et al., 2015) and energy recovery (Gallardo et

45 al., 2014). Improving the quality of recycled PP products and extending their applications are
46 also effective ways to promote the recycling rate (Ravi, 2015).

47 In recent years macro plastic fibres have been widely used in construction industries to
48 improve the performance of concrete. Examples include controlling cracks, reducing drying
49 shrinkage and improving post-crack behaviour of concrete elements (Yin et al., 2015a). The
50 plastic fibres in these applications are normally produced by melting and extruding plastic
51 granulates into filaments and hot stretching the monofilament into fibres, before cutting to
52 a length of around 30-70 mm. This drawing process orients the molecular chains and
53 improves crystallinity, thus significantly increasing the Young modulus and tensile strength
54 of the fibres, as reported by Yin et al. (2015b). Among various plastic fibres, virgin PP fibre
55 shows good stability and performance, and has been widely used in concrete for tunnel
56 lining, footpaths, and precast elements.

57 Drying shrinkage occurs in the hardened concrete due to the loss of water from the
58 hardened concrete, and can be significant in footpaths in hot and dry environments such as
59 North Queensland, Australia. Steel reinforcing mesh (SRM) is traditionally used to prevent
60 drying shrinkage cracks, but is now being replaced by PP fibres because of ease of
61 construction, and associated savings in labour and cost (Yin et al., 2015c). Using recycled PP
62 fibre has the potential to significantly reduce environmental impacts and extend the
63 applications of recycled plastic products.

64 In order to help decision makers choose reinforcing material that causes the lowest
65 environmental impact, it is very important to carry out a comparative impact analysis. There
66 are a variety of general and industry specific assessment methods, such as GMP-RAM (Jesus
67 et al., 2006), INOVA Systems (Jesus-Hitzschky, 2007), and fuzzy logic environmental impact

68 assessment method (Afrinaldi and Zhang, 2014). However, life cycle assessment (LCA) is the
69 most comprehensive among the available tools and has been widely used (Sorensen and
70 Wenzel, 2014). The LCA methodology is generally considered an excellent management tool
71 for quantifying and comparing the eco-performance of alternative products.

72 Perugini et al. (2005) undertook LCA of recycled Italian household plastic packaging waste
73 and compared environmental performance with conventional options. Their results
74 confirmed that recycling scenarios were always preferable to those of non-recycling. Arena
75 et al. (2003) studied the collection and mechanical recycling of post-consumer polyethylene
76 (PE) and polyethylene terephthalate (PET) containers. They found that the recycled PET can
77 reduce energy by between 29 % and 45 %, compared to virgin PET production. Similar
78 reductions in energy use were observed for recycled PE compared to virgin PE. Shen et al.
79 (2010) also assessed the environmental impact of PET bottle-to-fibre recycling, and LCA
80 results showed that recycled PET fibres offered important environmental benefits over
81 virgin PET fibre.

82 Although these studies show promise, the literature on LCA of recycling plastic waste are
83 actually very limited, and are strongly influenced by final product types, plastic sources, and
84 by local characteristics of procedures for collecting and reprocessing plastic waste. Hence,
85 these studies cannot be extrapolated to Australian conditions, where there is limited
86 information on comparative LCA of recycling plastic waste. Moreover, recycling systems are
87 typically multifunctional, which can constitute a challenge for LCA practitioners. LCAs of the
88 same product can arrive at different conclusions when there are methodological differences
89 or differences in life cycle inventory (LCI) data. It is therefore important to clearly define the

90 scope, LCA methodology, inventory data sources, and functional unit (FU) involved. These
91 issues are discussed in greater detail by Sandin et al. (2014).

92 This study focuses on the use of PP fibres in reinforcing footpaths where currently SRM is
93 used. Virgin PP fibre normally has a tensile strength of above 550 MPa (Victoria Road
94 Technical Specification (VicRoads, 2009)), and recycled PP fibre has reduced tensile strength
95 (300-450 MPa) (Yin et al., 2013). However, Zhou and Xiang (2011) has shown that both
96 recycled and virgin PP fibre have sufficient strength to be used as a replacement for SRM,
97 and both have already been used in footpath applications. The recycled PP fibre considered
98 in this study is sourced from industrial PP wastes, which are scrap off-cuts and off-
99 specification items from the nappy manufacturing industry. An alternative source of
100 recycled plastic fibre is domestic PP waste, consisting mostly of packaging materials from
101 kerbside recycling collections. Recycled PP fibre from domestic waste has not been used in
102 the footpath applications, mainly because of higher reprocessing cost and lower fibre
103 strength. However, it is still worth considering the life cycle impact of using domestic
104 recycled PP fibre in footpath applications.

105 The objective of this research is to quantify the life cycle environmental benefits brought
106 about by using recycled PP fibres from domestic and industrial waste as compared to using
107 typical materials for reinforcing concrete footpaths. Alternative reinforcing materials
108 assessed include virgin PP fibre and SRM. This study is based on Australian conditions and
109 quantifies the environmental impacts in terms of material consumption, water use, and
110 emissions to the environment. The scope of this study is limited to the first stage of the fibre
111 or SRM reinforced footpaths, namely, the production of PP fibres and SRM. The primary
112 audience for this study is intended to be local governments, city councils, solid waste

113 planners, and industries, such as plastic waste recycling and plastic fibre reinforced concrete
114 industries, who are interested in pursuing not only positive economic outcomes but also
115 environmental ones.

116 **2. Methodology**

117 **2.1. Functional Unit and scenario formulations**

118 Following the international standards, including ISO 14040: 2006 - Principles and framework
119 (ISO14040, 2006), and ISO 14044: 2006 - Requirements and guidelines (ISO14044, 2006),
120 LCA addresses the environmental aspects and potential environmental impacts throughout
121 a product's life cycle from raw material acquisition through production, use, end-of-life
122 treatment, recycling and final disposal.

123 The function of the systems under study is to reinforce an area of 10 m x 10 m (100 mm
124 thick). According to AS 3600-2009 (AS, 2009) for 100 m² of concrete footpath reinforced
125 with Class L SRM, seven sheets of SL82 SRM (6 m x 2.4 m) are needed. The SL82 SRM
126 consists of 7.6 mm steel bars at 200 mm spacing in both directions (Fig. 1c). One SRM sheet
127 weighs 52 kg. Alternatively, 0.45 % of PP fibres by volume (equivalent to 4 kg PP fibre per
128 cubic meter of concrete) are found to be able to produce equivalent reinforcing effects to
129 that of the SRM (Cengiz and Turanli, 2004). The PP fibres (Fig. 1a and 1b) have a thickness of
130 0.7 mm, a width of 1.5 mm and a length of 47 mm. This yields a FU of 40 kg of PP fibres and
131 364 kg of SRM. The four scenarios, with equal reinforcing effects, are thus defined as follows:
132 Scenario a: Production of seven SL82 SRM (364 kg of total weight) using electric arc furnaces
133 and basic oxygen furnace.

134 Scenario b: Virgin PP fibre production. 40 kg of virgin PP fibre produced from 42 kg of virgin
135 raw materials using traditional extrusion process. 2 kg of waste produced during the fibre
136 production is landfilled.

137 Scenario c: Industrial recycled PP fibre, which refers to mechanically recycling industrial PP
138 waste into recycled PP fibre. In order to get 40 kg of recycled PP fibre, 46.5 kg of industrial
139 PP waste is collected (taking into account manufacturing efficiency provided by Martogg
140 Group and Danbar Plastic). During the processing of 46.5 kg of industrial waste, 6.5 kg of
141 processing waste is landfilled.

142 Scenario d: Domestic recycled PP fibre, which is produced from mechanically recycling
143 domestic PP waste into PP fibre. Taking into account manufacturing efficiency according to
144 the research of Chilton et al. (2010), Perugini et al. (2005), Arena et al. (2003), SimaPro 8.0
145 Australian LCA databases (Grant and Grant, 2011b, e) and on-site investigation, 68 kg of
146 domestic plastic waste needs to be collected to obtain 40 kg of recycled PP fibre, 28 kg of
147 waste produced during processing is considered to be landfilled.

148 *(Insert Fig. 1 here)*

149 **2.2. System boundaries and Life Cycle Inventory**

150 The scope of this cradle to gate LCA study is limited to the production of SRM, virgin fibre,
151 and recycled fibres (industrial and domestic), and does not include environmental impact of
152 end-of-life disposal of the concrete footpaths. The scope is limited to the first stages since it
153 is assumed that the four scenarios have similar disposal procedures and lifespans in the
154 Australian context.

155 For scenarios a and b (SRM and virgin PP fibre), system boundaries include all steps from the
156 extraction and transportation of raw materials and fuels, followed by all conversion steps
157 until the products are delivered at the factory gate. The system boundaries of scenarios b
158 and c in this study begin with industrial and domestic PP waste products, and end at the
159 point that they become fit for purpose recycled PP fibres. The upstream processes leading
160 to the production of the PP waste are not included in order to avoid allocations. Labour and
161 capital goods required in the process are not considered, because the analysis is focussed
162 on environmental rather than economic impacts.

163 2.2.1. Steel reinforcing mesh

164 Fig. 2, taken from Australian Building Products LCI (BPIC, 2010), shows the production
165 process of SRM and its system boundary. According to Strezov and Herbertson (2006),
166 around 93 % of SRM is produced by electric arc furnaces (EAF) and the remaining is
167 produced by basic oxygen furnaces (BOF). The EAF process produces 9 % of slag and the BOF
168 process produces 8 % of slag, according to Australian building products LCI (BPIC, 2010). The
169 iron obtained from EAF and BOF is continuously casted, milled and cold rolled into steel bars.
170 At this stage 20 % of steel scrap is reused in the BOF or EAF processes. The milled steel bars
171 are then cut, bent and resistance welded into SRM. The cutting, bending and welding
172 processes are mainly carried out by manual labour, and the electricity used in these
173 processes is negligible compared to the BOF, EAF and casting processes. Hence the
174 environmental impacts of these processes are not considered. GHG (such as CO₂), emissions
175 causing eutrophication (such as NO_x), toxic gases (such as SO₂), particulate matter with 10
176 micrometers or less in diameter (PM₁₀), and solid and liquid wastes are generated. The
177 environmental impacts of BOF, EAF, casting and milling steel, and transportation are

178 calculated using the SimaPro 8.0 databases (Associates and Sylvatica, 2004a, b; Grant and
179 Grant, 2011a; Spielmann, 2012; Steiner, 2008).

180 *(Insert Fig. 2 here)*

181 2.2.2. Virgin PP fibre

182 The virgin PP is produced commercially from olefin monomers (propylene). Two techniques
183 (liquid propylene pool process and gas phase polymerisation) are normally used for the
184 production of PP in Australia (Hou et al., 2014). Three main virgin PP granulate
185 manufacturers (Kemcor Resins, Montell Clyde and Montell Geelong) form the basis of the
186 Australasian Unit Process LCI data available in the SimaPro 8.0 database (Grant and Grant,
187 2011d). As shown in Fig. 3, Kemcor Resins extracts propylene from gasoil, while Montell
188 Clyde extracts propylene through catalytic cracking from naphtha. Montell Geelong
189 extrudes propylene from both gasoil and naphtha. The mass allocation splitting PP
190 production across these three plants is 19 %, 44 % and 37 %, respectively. The virgin fibre
191 production process from virgin PP granulates is assumed to be the same as the production
192 of recycled PP fibres.

193 *(Insert Fig. 3 here)*

194 2.2.3. Industrial recycled PP fibre

195 A diagram of the processes required in the production of industrial recycled PP fibre is
196 shown in Fig. 4. The industrial PP waste are first compacted and then transported to a PP
197 reprocessing plant by rigid trucks. The transport distance is on average 75 km. The collected
198 industrial PP waste are shredded and recompounded in the PP reprocessing plant. The
199 efficiency of both shredding and recompounding processes, as obtained directly from the

200 reprocessing plant, is around 95 %. The machine generates about 800 kg of the recycled
201 material per hour, and the energy consumption on the reclaim line is roughly 280 kWh. The
202 processed PP granulates are then transported about 55 km to a collection centre, and finally
203 transported a further 100 km to a fibre production plant. The processing and transportation
204 data were collected from the manager of the PP reprocessing plant (Martogg Group,
205 Australia).

206 For the plastic fibre manufacturing process, an on-site investigation was carried out. The
207 manufacturing process considered in this study includes PP granulates extrusion, PP fibre
208 drawing and stabilisation, and fibre cutting and packing. In this process, the plastic
209 granulates are vacuumed into an extruder, and then stretched and stabilised in ovens at
210 110-170 °C. The fibres are then cut into a length of 30-70 mm and packed. The majority of
211 waste is generated during the cutting process (approximately 5 %). The electricity
212 consumption in the PP fibre manufacturing process is obtained through actual electricity
213 bills from the plastic processing plant data. According to the data, 1445 kWh are used to
214 produce one tonne of PP fibres. Fig. 4 also shows the system boundary of the LCA study for
215 the recycled PP fibre. Information was collected from on-site investigation of Danbar Plastic,
216 and communication with the managers of Martogg Group and Danbar Plastic. The
217 environmental impacts of production of industrial recycled PP fibre were obtained by
218 including this collected data within SimaPro 8.0 (LCS, 2014). The calculations are based on
219 Australian databases (Grant, 2011a, b, 2012; Grant and Grant, 2011c) and Australian
220 Indicator Set V3.00 method (SimaPro, 2010).

221 *(Insert Fig. 4 here)*

222 2.2.4. Domestic recycled PP fibre

223 Fig. 5 shows the flow of production of recycled PP fibre from domestic PP waste and its
224 system boundary. The domestic recyclables are collected from kerbside bins every fortnight
225 by local materials recovery facility (MRF) workers. Mixed recyclables are sorted in the MRF.
226 The sorted plastic wastes are sent to plastic reprocessing plants, where manual and
227 mechanical sorting is undertaken to separate out plastic bottles. Plastics are then shredded
228 and milled into flakes, before being washed in sodium hydroxide solution at 60 °C. The PP
229 fragments are then separated from other plastics (e.g. PET) based on density differences in a
230 water tank. After centrifugation and drying, the PP fragments are extruded and
231 recompounded into small granulates for future fibre production. The processing steps
232 described here for domestic plastic waste are taken from the SimaPro databases for
233 Australian PP reprocessing and recycling (Grant and Grant, 2011b, e), and relevant scientific
234 publications (Arena et al., 2003; Shen et al., 2010). The MRF sorting efficiency is taken as
235 70 %, based on a Townsville MRF plant and Perugini et al. (2005). The PP reprocessing
236 efficiency is based on Perugini et al. (2005). The transportation and fibre production process
237 are assumed to be same as those used for industrial recycled PP fibre.

238 *(Insert Fig. 5 here)*

239 2.2.5. Life cycle inventory

240 The LCI data used in this study was obtained through cooperation with many companies,
241 including Materials Recovery Facility, plastic waste reprocessing plants, the fibre production
242 factory, and inventory databases such as SimaPro 8.0 Australian LCA databases (Associates
243 and Sylvatica, 2004a, b; Grant, 2011a, b, 2012; Grant and Grant, 2011a, b, c, d, e; Spielmann,
244 2012; Steiner, 2008), Building Products LCI databases (BPIC, 2010) and scientific publications

245 (Arena et al., 2003; Chilton et al., 2010; Perugini et al., 2005; Shen et al., 2010; Strezov and
246 Herbertson, 2006). These details are specifically outlined in Table 1.

247 *(Insert Table 1 here)*

248 **2.3. Life Cycle Impact Assessment**

249 The software SimaPro 8.0 has been used for the LCIA. All the LCIA data of the four scenarios,
250 including all emissions released and all raw material requirements, are converted into
251 environmental impact categories based on the Australian Indicator Set V3.00 (SimaPro,
252 2010). Impacts categories examined include CO₂ equivalent, PO₄ equivalent, water use and
253 oil equivalent.

254 The processes of iron production, steel continuous casting and milling, virgin PP production,
255 plastic waste collecting and recycling, and fibre production consume large amounts of
256 primary energy and electricity. In Australia, the predominant primary energy sources for
257 these processes are coal, oil and diesel, which lead to CO₂ emissions and associated global
258 warming potential (GWP). Carbon dioxide equivalent (kg CO₂ eq) is a standard unit for
259 measuring GWP, and the consumption of fossil fuels is used to assess the depletion of
260 limited natural resources. Water use and water-based pollution are important issues in
261 Australia, because of their scarcity. Water-based impacts can be significant in both steel
262 production and also in domestic recycling, where washing is an important processing step.
263 In this study both quantity and pollution are assessed. Eutrophication pollution impacts are
264 aggregated into PO₄ equivalent. Water-based toxicity is not assessed because of a scarcity of
265 data in this area.

266 The CO₂ equivalent (kg) was calculated based on the database of 100-year greenhouse
267 impacts reported by Intergovernmental Panel on Climate Change method and data (Wang
268 et al., 2015). PO₄ equivalent (kg) is based on the model of Climate Modelling Laboratory
269 impact assessment (Camba et al., 2014). The consumption of fossil fuels (oil equivalent in kg)
270 is based on Recipe database (Castanheira et al., 2015).

271 **2.4. Uncertainty analysis**

272 Uncertainty due to methodological choices (e.g. when defining the system boundaries,
273 allocation vs. system expansion) has not been addressed in this study, because it is
274 considered to be beyond the scope. However, the uncertainty in the estimation of
275 environmental impacts associated with LCI raw input data variances was assessed.

276 In the SimaPro LCI databases, the quantities of required raw materials are stated for each
277 basic process. Paired with each data entry is an estimate of the standard deviation in these
278 raw material quantities. These standard deviations are used to define the range of
279 uncertainty in each quantity. Monte-Carlo simulation, which is a function built into SimaPro
280 8.0 (LCS, 2014), is used to propagate data base value uncertainty to overall uncertainty
281 across each environmental impact category. In the Monte-Carlo approach, 10,000 runs
282 using random LCI data, generated within 95 % confidence interval for each raw material
283 input quantity, are calculated. Uncertainty distributions for each overall impact category are
284 derived from these results. The uncertainty analysis performed is just a first approximation
285 to a more robust analysis (i.e. using primary data) that would more substantially improve
286 the assessment reliability. However, preliminary analysis demonstrates that the uncertainty
287 in the comparative assessment is negligible.

288 3. Results

289 Fig. 6 shows the aggregated environmental impact comparison between recycled and virgin
290 PP fibres across all impact categories. Because the fibre-based scenarios all have similar
291 impact magnitudes, we cluster all fibre-based scenarios together in Fig. 6. Since there are
292 orders of magnitude differences between use of any fibre and steel, we have selected the
293 best performing fibre to compare to SRM in Fig. 7. As can be seen in Fig. 6, the production of
294 industrial recycled PP fibre has minimum impacts on the environment under all categories
295 considered. Generally, virgin PP fibre has higher environmental impacts than either of the
296 recycled fibres, especially in terms of resource consumption.

297 To produce 40 kg of PP fibres, the industrial recycled fibre life cycle produces 81.7 kg of CO₂
298 equivalent. As explained in Fig. 5, processing of domestic PP waste into fibre needs more
299 complex and energy intensive processes, such as PP waste collection and sorting, PP
300 reprocessing, and fibre production. Hence, the production of domestic PP fibre consumes
301 more energy and produces more CO₂ equivalent (109 kg). For the virgin PP fibre, 137 kg of
302 CO₂ equivalent is predominately associated with the production of PP granulates and PP
303 fibre, and also with propylene production (as Fig. 3).

304 The process used to produce the industrial recycled PP fibre generates a relatively lower
305 eutrophication impact (0.033 kg of PO₄ equivalent). However, for the domestic recycled PP
306 fibre, the waste washing process emits significantly more PO₄ equivalent (0.069 kg of PO₄
307 equivalent), and leads to higher eutrophication impacts in comparison to industrial recycled
308 PP. It is also interesting to note that despite the comparatively high total volume of water
309 used in producing domestic recycled PP, the eutrophication impact of the waste water is

310 low compared to virgin PP production, mainly due to the catalytic cracking unit in the latter.
311 Overall, the virgin PP fibre production process causes the highest eutrophication impact
312 (0.085 kg of PO₄ equivalent).

313 When it comes to water consumption, manufacturing domestic recycled PP fibre consumes
314 much more water (0.99 m³) than producing either industrial recycled PP fibre or virgin PP
315 fibre, which explains the differences in eutrophication impacts between domestic and
316 industrial recycled PP. High water consumption occurs when reprocessing domestic PP
317 waste, because the shredded PP fragments are washed in large volumes of sodium
318 hydroxide solution. After washing, effluent is neutralised, then discharged to domestic
319 sewage. Environmental benefits, including reduced water use and reduced eutrophication
320 impact, could arise if the effluent was treated and recycled back to the washing process.

321 In terms of natural resource consumption (in this case fossil fuel), virgin PP fibre production
322 consumes three times more fossil fuel (91.3 kg) than the production of either recycled PP
323 fibres. As well as oil/coal consumed for electricity production, the propylene monomer is
324 extracted through the catalytic cracking of crude oil.

325 *(Insert Fig. 6 here)*

326 In Fig. 7 we compare the environmental impacts of industrial recycled PP fibre with SRM.
327 Across all categories the environmental impacts of producing the industrial recycled PP fibre
328 is negligible in comparison. As shown in Fig. 7, the production of 364 kg of SRM emits 15
329 times the CO₂ equivalent than production of 40 kg of industrial recycled PP fibre. The
330 eutrophication impact of the SRM production is 33 times higher than that of industrial
331 recycled PP fibre. 20.9 m³ of water is needed for the production of 364 kg SRM, which is

332 consistent with the research by Gu et al. (2015) about the water use in steel production. The
333 water consumption is 20 times higher than that of even domestic recycled PP fibre. 245 kg
334 of oil equivalent is also needed, which is 11.5 times more than that of industrial recycled PP
335 fibre. Although any PP substitution leads to reduced impacts, comparing the best
336 performing PP fibre process to the SRM, the production of industrial recycled PP fibre can
337 save 93 % of CO₂ equivalent, 97 % of PO₄ equivalent, 99 % of water and 91 % of oil
338 equivalent.

339 *(Insert Fig. 7 here)*

340 Uncertainty is an inherent feature of LCA, and it can be caused by multiple reasons: missing
341 inventory data or inventory data inaccuracy; model uncertainty; uncertainty due to choices
342 of allocation rules; impact factors and system boundaries; spatial and temporal variabilities;
343 and epistemological uncertainty. In Figs. 6 and 7 the uncertainty range per impact category
344 is shown, and expresses the 95 % confidence interval. Across all categories except fossil fuel
345 use, SRM shows much greater uncertainties than all other product alternatives, primarily as
346 a result of the larger raw material quantities associated with SRM. This is particularly
347 evident in water use, where uncertainty is very large. For global warming potential and
348 water use, the recycled and virgin PP fibres show similar levels of uncertainty. For
349 eutrophication potential, only industrial recycled PP fibre shows a small level of uncertainty,
350 whilst the other fibres are subject to greater uncertainty. This may be the result of limited
351 data describing the variance in input raw materials and output flows associated with
352 industrial recycled PP processing inventory data. However, the impact of uncertainty on the
353 project conclusions is negligible. For the comparative assessment, the impacts of industrial

354 recycled PP fibre are clearly smaller than all other scenarios considered, particularly in
355 comparison to SRM.

356 Fig. 8 shows contribution of major sub-stages to the overall impacts, for each PP production
357 pathway. As can be seen, in the industrial recycled PP fibre production processes, the GWP,
358 eutrophication impact, water use and fossil fuel consumption are dominated by the fibre
359 production process. Reprocessing industrial PP waste into recycled PP granulates also gives
360 rise to a substantial proportion of the burdens to environment. For the domestic recycled PP
361 fibre processes, the fibre production process is again the dominant source of impact.
362 However, the domestic waste collection, sorting and reprocessing stages are also significant,
363 and emit considerably more CO₂ equivalent and PO₄ equivalent, as well as consuming
364 substantially more fossil fuels than those in the transportation stage. Most notably, large
365 amounts of water are needed to wash and separate plastic wastes. Improvements in
366 processing and water recycling at this stage can make domestic recycling more competitive
367 with industrial PP recycling in terms of environmental impacts. For the virgin PP fibre, the
368 production of virgin PP granulates emits large amounts of CO₂ equivalent and PO₄
369 equivalent, and also consumes water in large amounts. Obviously, fossil fuels needed in this
370 sub-stage are substantially higher than those in other sub-stages, because crude oil is used
371 as raw material for production of virgin PP granulates. As shown in Fig. 8 (d), 83 % of crude
372 oil use is for monomer production and the remaining 17 % is consumed for energy.

373 *(Insert Fig. 8 here)*

374 In the production of SRM, the EAF is the main process used to produce iron. In Fig. 9, which
375 compares the SRM scenario impacts to the industrial recycled PP scenario, the EAF is energy
376 intensive and emits large amounts of CO₂ equivalent and PO₄ equivalent, and also consumes

377 fossil fuels in large amounts. Whether iron is produced by EAF or BOF processes, the iron
378 will be continuously casted and roll milled, which also emits large amounts of CO₂
379 equivalent and PO₄ equivalent. 40 % of the total CO₂ equivalent contribution is from EAF,
380 while 52 % of the total CO₂ is from continuous cast and rolling mill processes. 46 % of the
381 total eutrophication impact originates during the EAF process and 49 % from the continuous
382 cast and rolling mill. Casting and roll milling also require orders of magnitude larger amounts
383 of water. Regarding the use of the fossil fuels, 9 % of total consumption is for producing
384 heat in the BOF process, while 89 % of total consumption is within the EAF process.

385 *(Insert Fig. 9 here)*

386 **4. Discussion**

387 In common with other LCA's of plastic recycling processes, the boundaries of this LCA
388 excluded the end-of-life impacts of the four products. These exclusions include disposal,
389 landfilling, further recycling and reuse, which could provide a longer term view of the
390 impacts. It is well known that in comparison to PP, steel has a lower impact in the disposal
391 stage because of its easy recyclability (Guo et al., 2014). Thus it is reasonable to assume that
392 if end-of-life options were considered, the conclusions of this study could be different.
393 However in Australian context, we do not believe that including end-of-life impacts would
394 alter the final conclusions. Firstly, based on a study of the long term durability of plastic
395 fibres in alkaline environments (Roque et al., 2009), all four scenarios would require the
396 same level of maintenance and have equal life spans. Furthermore, despite being easily
397 recycled, end-of-life concrete footpaths in Australia are almost always landfilled, as sorting
398 and recycling for the small volumes is considered uneconomical. In essence, the processes

399 that would lead to different end-of-life impacts are, in practice, unlikely to occur. We would
400 also argue that the extent of these end-of-life impacts would not be sufficient to make up
401 for the substantial differences that arise during production. Furthermore, because the use
402 of fibres in footpaths is a relatively new application, end-of-life impacts are not well defined.
403 Including these estimates would introduce more uncertainty, and may not be useful for
404 decision makers. However, we would recommend that the potential for water based
405 pollution (i.e. toxicity) associated with PP leaching during the use phase, be more carefully
406 considered.

407 From a pragmatic point of view, the main objective of this research is to provide decision
408 makers with accurate information on environmental impacts from plastic waste collection
409 stage to the production of recycled PP fibre. This LCA study only considers the
410 environmental impacts of the four products, and it is worth noting that other factors such as
411 costs, markets for recovered products and national and international policy and regulations
412 are not taken into account. Uncertainties regarding the quantities of required raw materials
413 were considered in this study. However, uncertainty accuracy of data and data inventory
414 has not been considered here, thus a more thorough uncertainty analysis using primary data
415 is recommended for future studies.

416 Since this study is based on the Australian context and Australian inventory data, it is
417 interesting to compare this work with the LCA by Shen et al. (2010), who assessed the
418 impacts of recycled and virgin plastic fibres (PET) in a Western European context. Both
419 studies used the same system boundaries, namely, starting from the point the plastic
420 products become a waste and ending at the point that they become recycled plastic fibres.
421 Although it was not clear if the PET fibres in Shen et al. (2010) were able to be used directly

422 in concrete reinforcing, according to our judgement, the PET fibres would not require
423 additional processing to be fit for purpose. Thus the comparative impacts remain valid and
424 relevant to our study. Collection, sorting, washing, reprocessing, transportation and fibre
425 production were included, but end-of-life impacts were not considered. The results in both
426 studies are very similar, which gives us confidence in our methodology and sampled data. In
427 comparison, the production of 40 kg domestic recycled plastic fibre in Australia has more
428 global warming impact (109 kg CO₂ eq) and eutrophication impact (0.069 kg PO₄ eq) than
429 those in Western Europe (81 kg CO₂ eq and 0.044 kg PO₄ eq). For the production of 40 kg
430 virgin fibre, the two regions have a similar global warming impact (around 161 kg CO₂ eq),
431 while Australian eutrophication impact (0.095 kg PO₄ eq) is much higher than in Western
432 Europe (0.048 kg PO₄ eq), likely the result of more sophisticated water treatment and
433 recycling initiatives in Western Europe. However, across all impact categories the
434 comparisons between virgin and recycled fibres follow similar trends, and differences in
435 absolute values arise because of local variations. These include differences in collection
436 methods and frequency, transportation infrastructure and distances, as well as differences
437 in the maturity of sorting, reprocessing and fibre production methods. Moreover, the
438 different plastic types considered in these studies also contribute to differences in the
439 calculated impacts.

440 **5. Conclusion and recommendations**

441 In this study, the environmental impacts of four alternative scenarios to reinforce 100 m² of
442 concrete footpath were assessed using a LCA methodology based on the Australian context.
443 The four scenarios considered were the use of industrial recycled PP fibre, domestic
444 recycled PP fibre, virgin PP fibre and SRM.

445 The LCA results show that the industrial recycled PP fibre offers substantial environmental
446 benefits over all other reinforcing options. The industrial recycled PP fibre can reduce CO₂
447 equivalent emission by 50 %, PO₄ equivalent by 65 %, use 29 % less water and use 78 % less
448 oil equivalent natural resources compared to the virgin PP fibre. The domestic recycled PP
449 fibre offers 32 % reduced CO₂ equivalent emissions, 27 % reduced PO₄ equivalent emissions,
450 and 67 % reduction in oil equivalent resource consumption compared to virgin PP fibre.
451 However, the production of domestic recycled PP fibre consumes 3.5 times more water than
452 the virgin PP fibre due to washing. Improvements in water use can make domestic recycling
453 a more attractive option for sourcing PP fibre. Compared to SRM, the production of
454 industrial recycled PP fibre can save 93 % of CO₂ equivalent, 97 % of PO₄ equivalent, 99 % of
455 water use and 91 % of oil equivalent resource use. Across all categories PP fibres show
456 reduced impacts when compared to the use of SRM in concrete footpath applications.

457 Based on the findings of this study and the methodological choices made, we would
458 recommend expanding the scope of analysis to include both use and end-of-life phases. This
459 would be important when end-of-life recycling is a more widely adopted practice. To truly
460 characterise the sustainability of using recycled PP fibre in footpath applications, a
461 comparative economic analysis should be undertaken.

462 **6. Acknowledgements**

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588 Captions for Figures and Tables

589 Fig. 1 Virgin PP fibre (a), recycled PP fibre (b), and SL 82 SRM (c).

590 Fig. 2 Flow sheet of the production of SRM in traditional methods and the system boundary
591 (BPIC, 2010).

592 Fig. 3 Flow sheet of the production of virgin PP fibre in traditional methods and the system
593 boundary.

594 Fig. 4 Flow sheet of the production of recycled PP fibre from pre-consumer industrial PP
595 wastes and the system boundary.

596 Fig. 5 Flow sheet of the production of recycled PP fibre from municipal PP wastes and the
597 system boundary.

598 Fig. 6 LCIA results from the three scenarios producing 40 kg of PP fibre.

599 Fig. 7 LCIA results of the industrial recycled PP scenario (40 kg of PP fibre) vs. the reinforcing
600 steel scenario (364 kg of SRM).

601 Fig. 8 Contribution of major sub-stages for three PP fibre scenarios to the overall impacts
602 within each impact category.

603 Fig. 9 Contribution of major sub-stages for the SRM scenario within each impact category,
604 compared to the total impacts for the industrial recycled PP scenario.

605

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Figure 1
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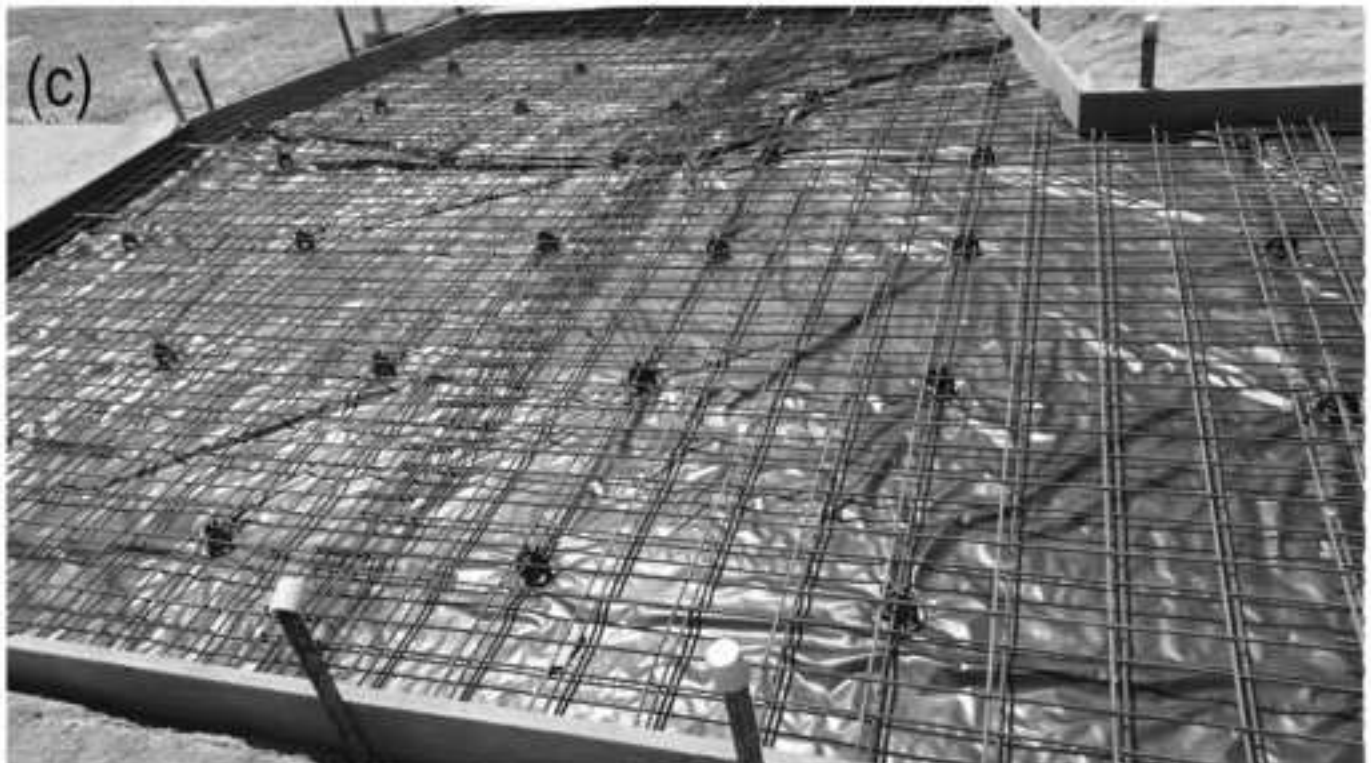
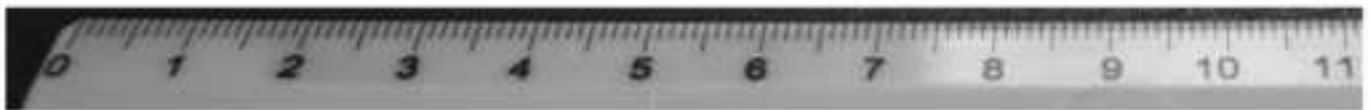
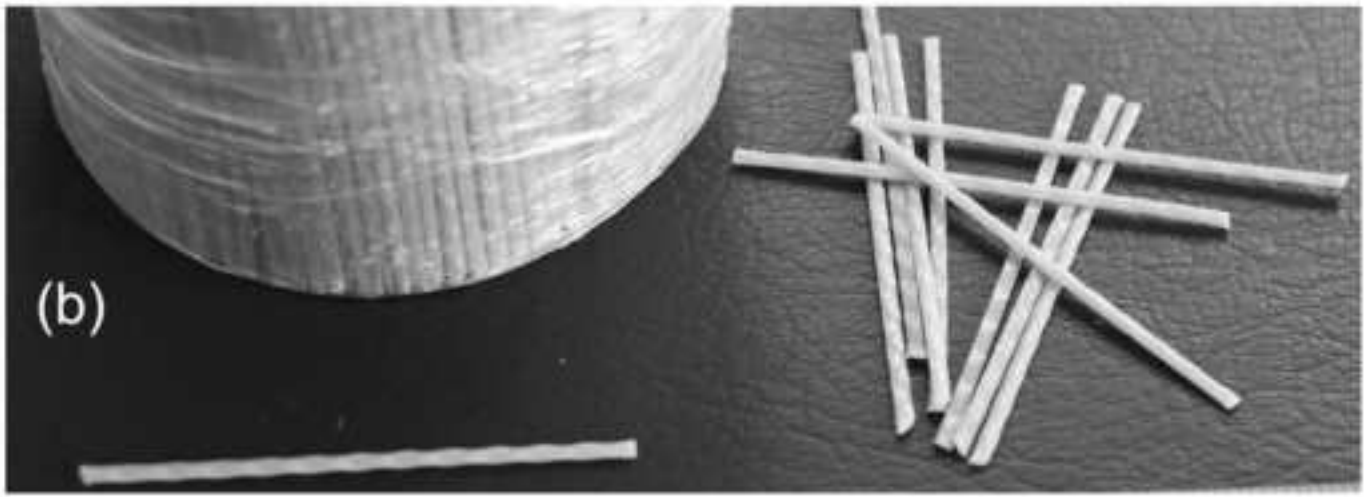
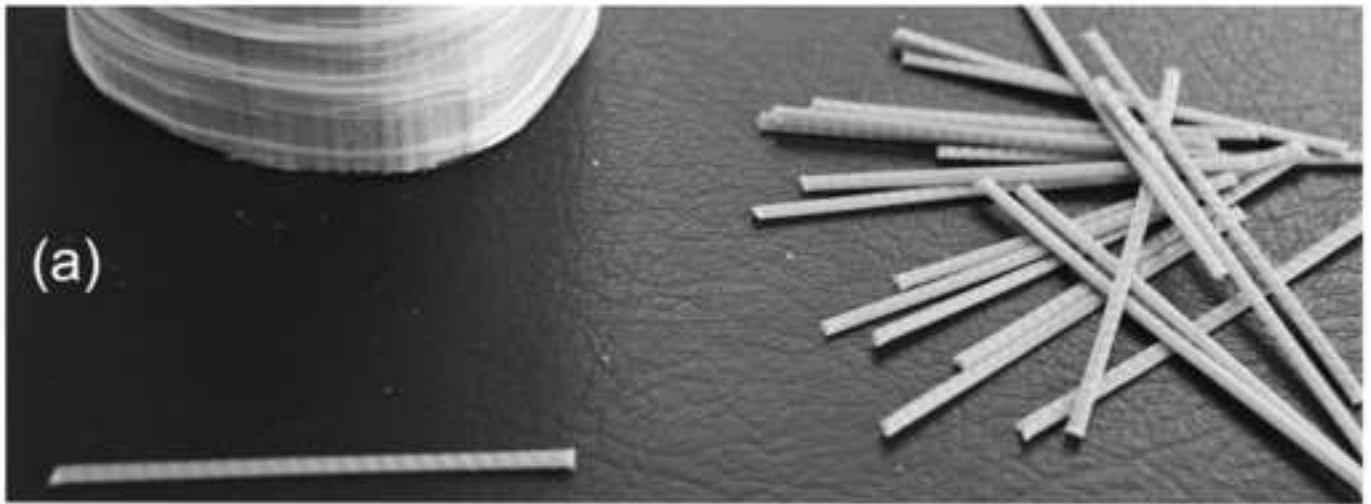


Figure 2

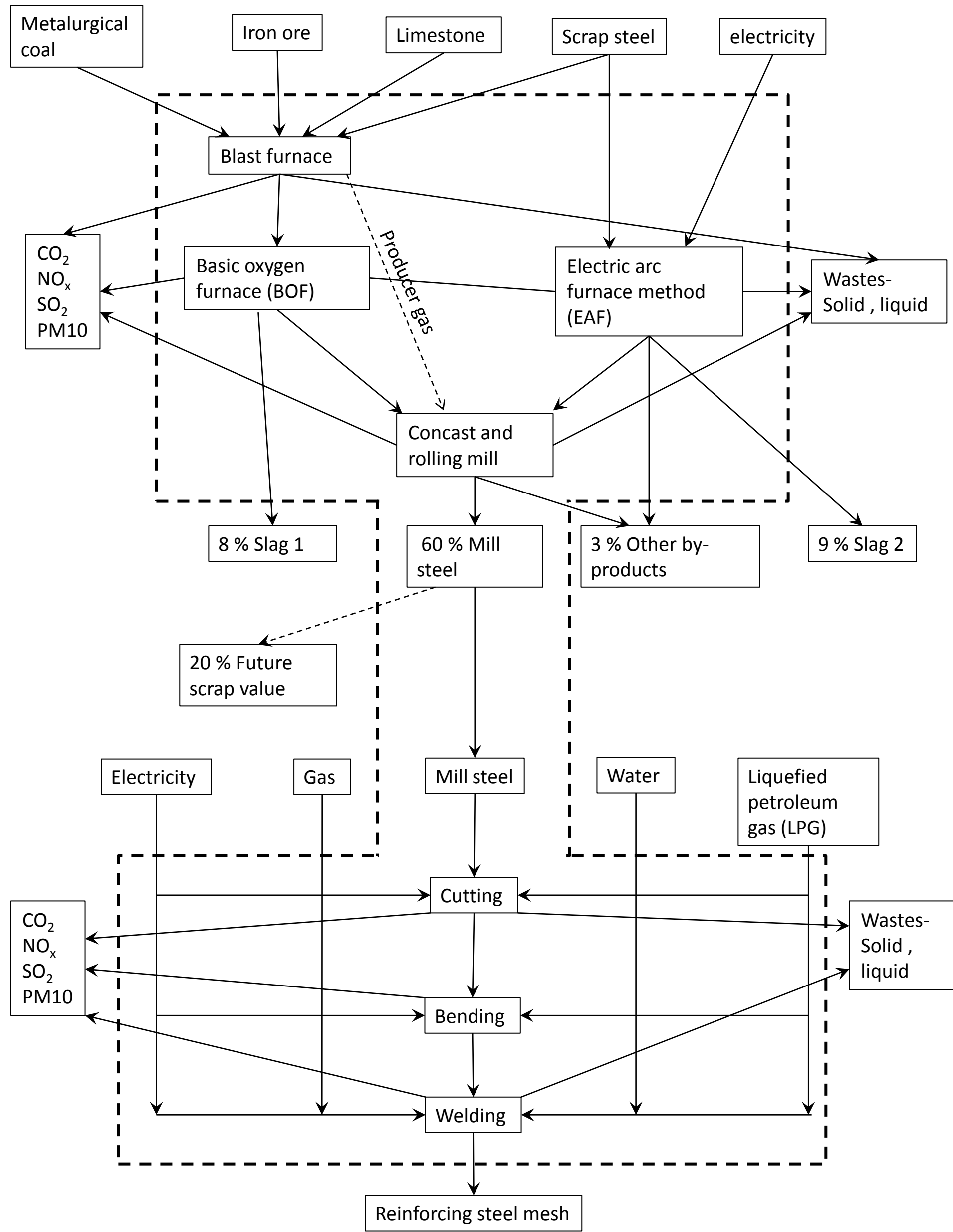


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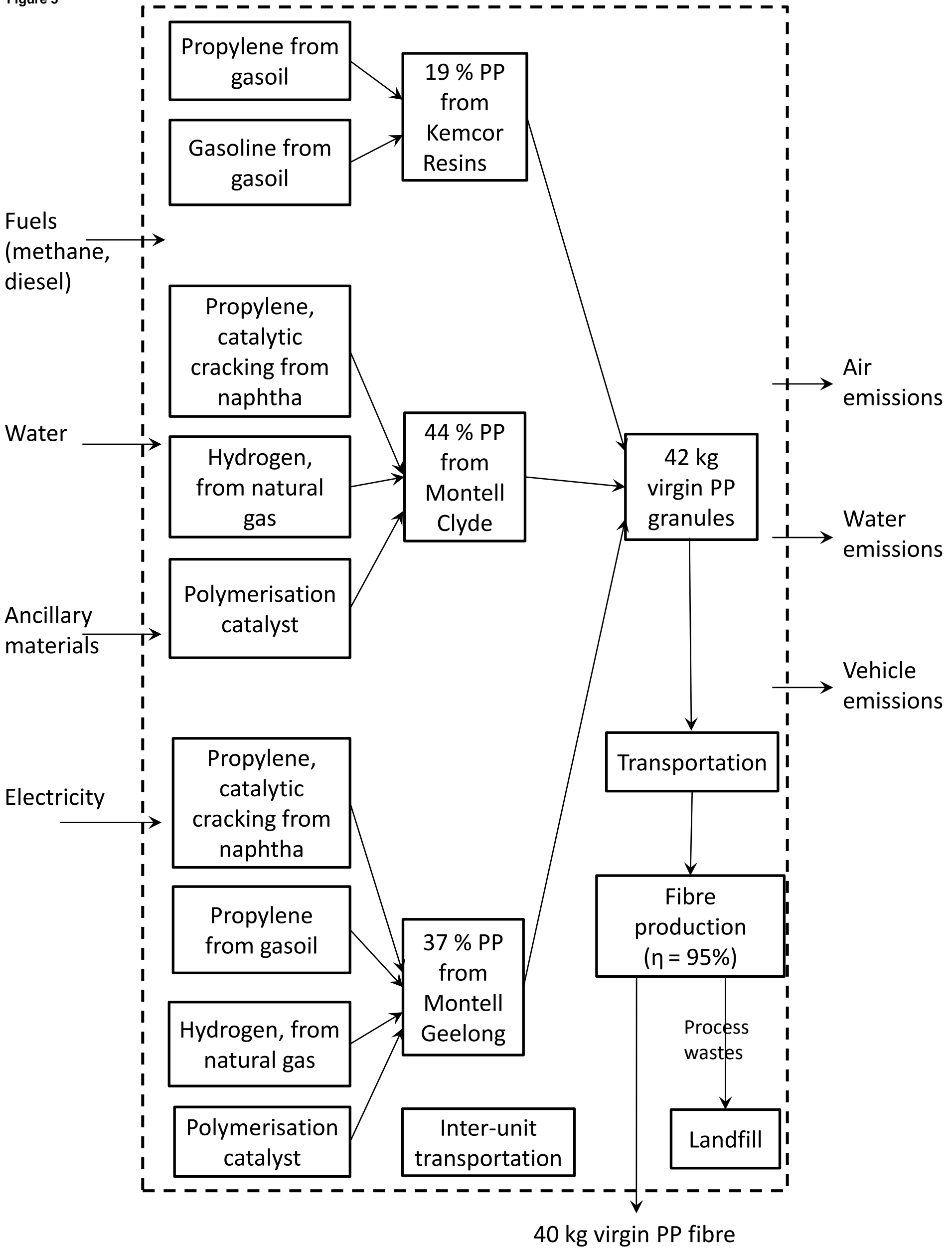


Figure 5

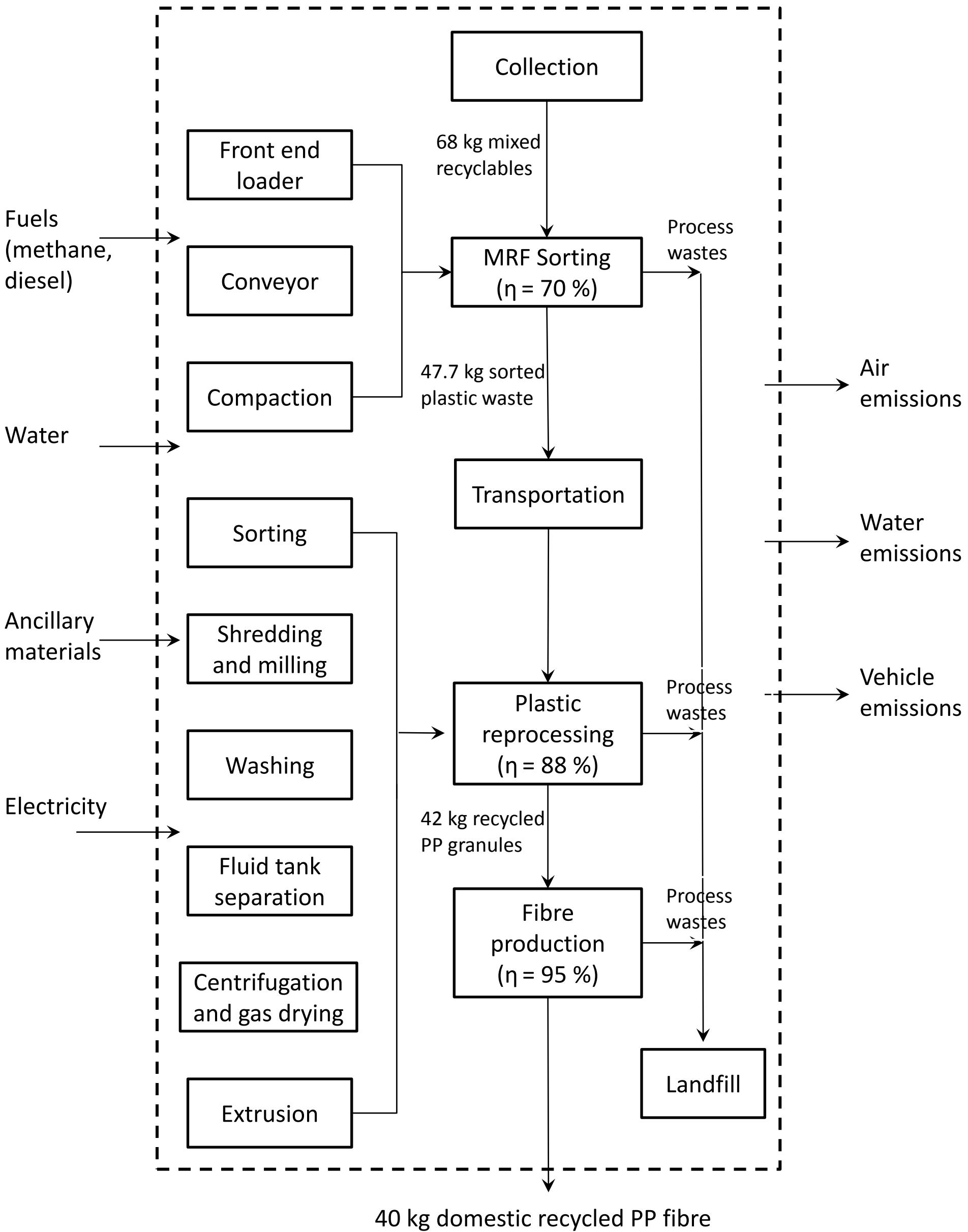


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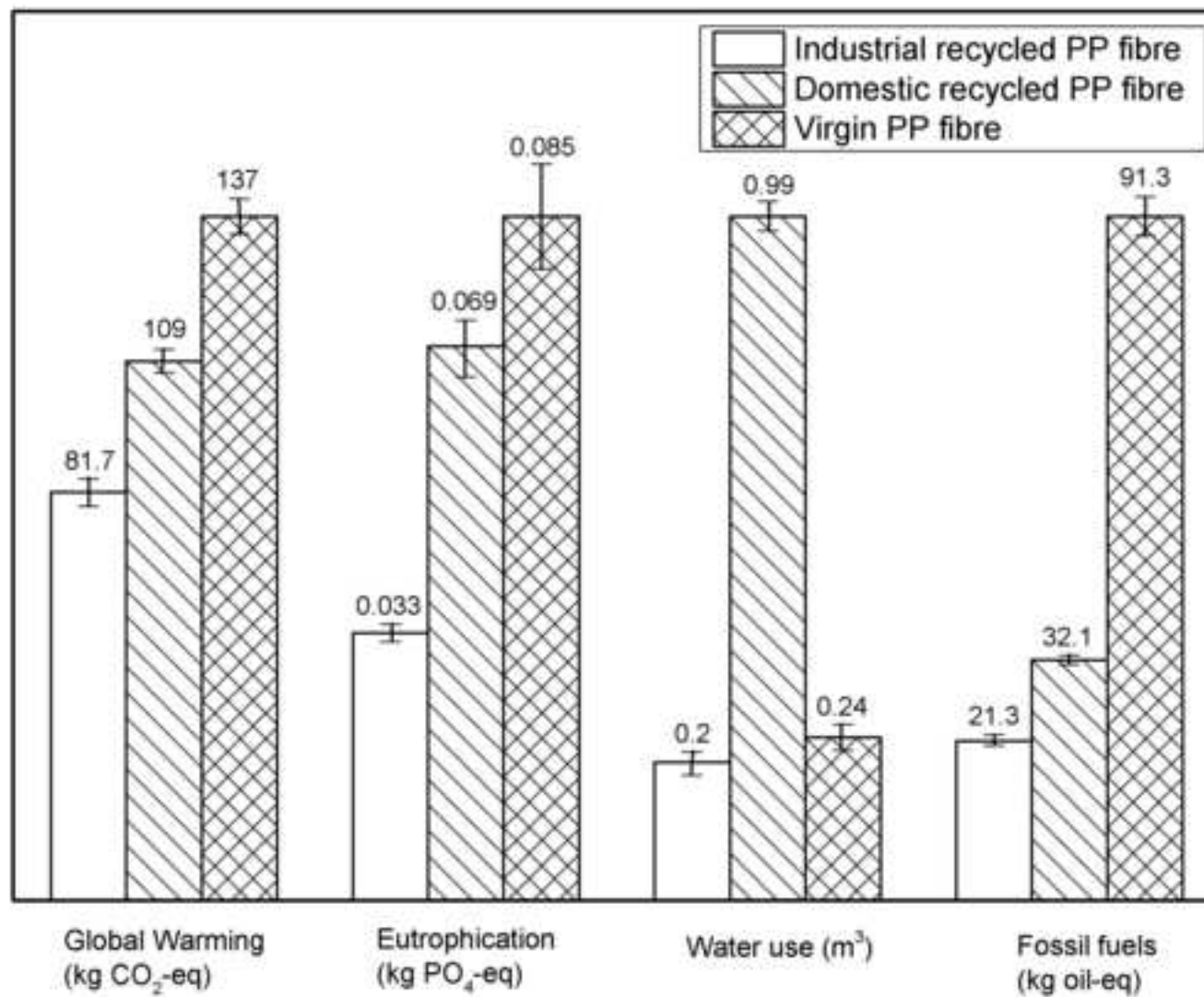


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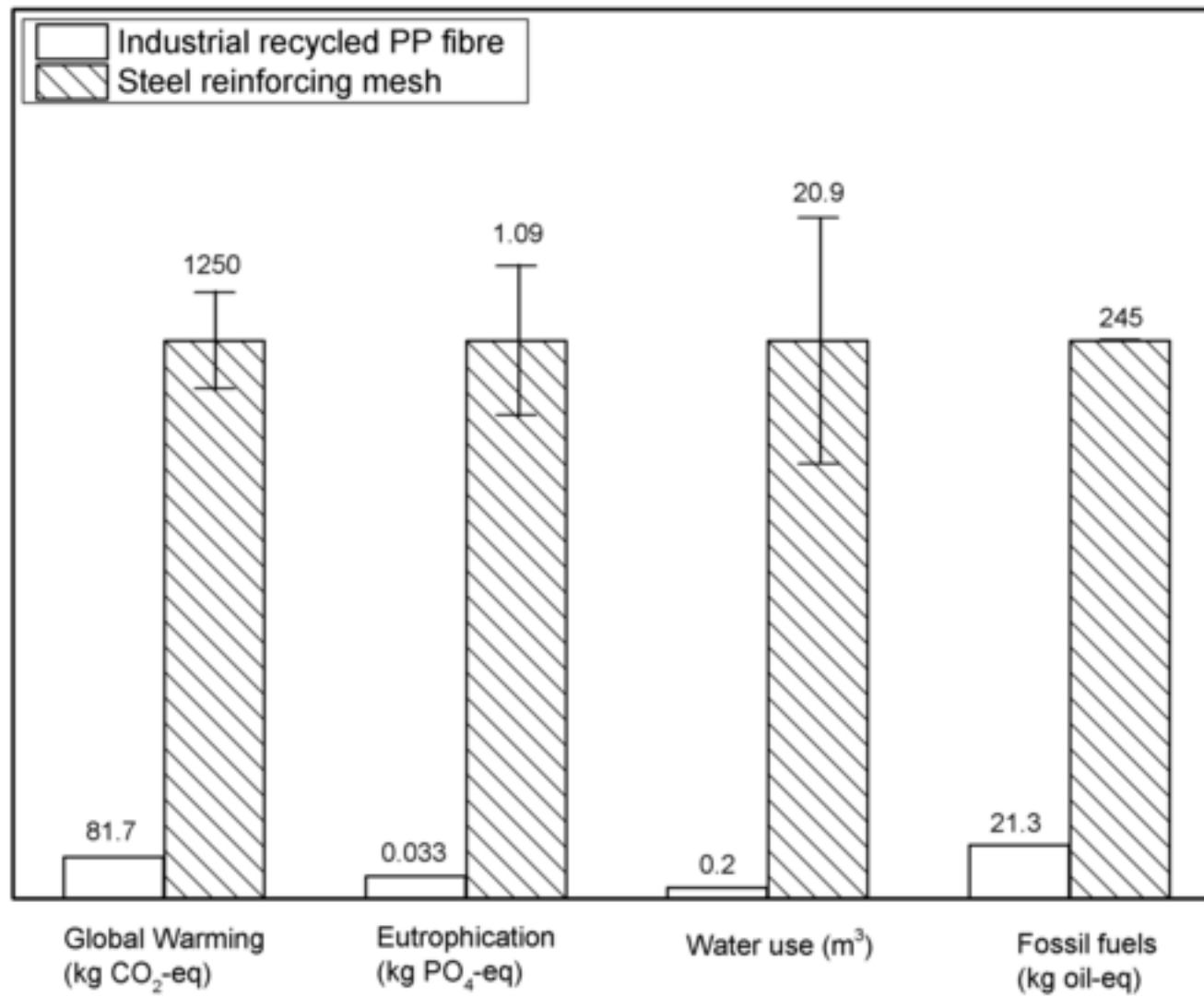


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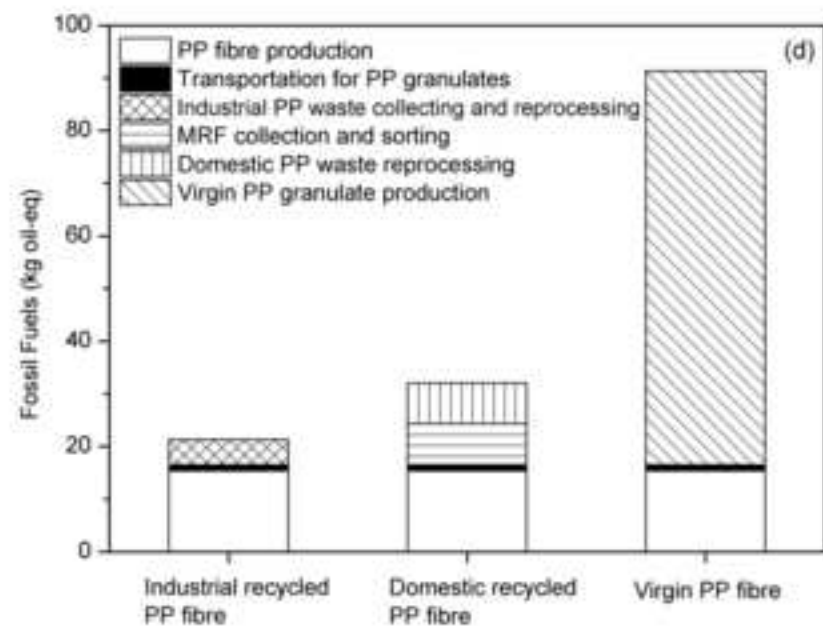
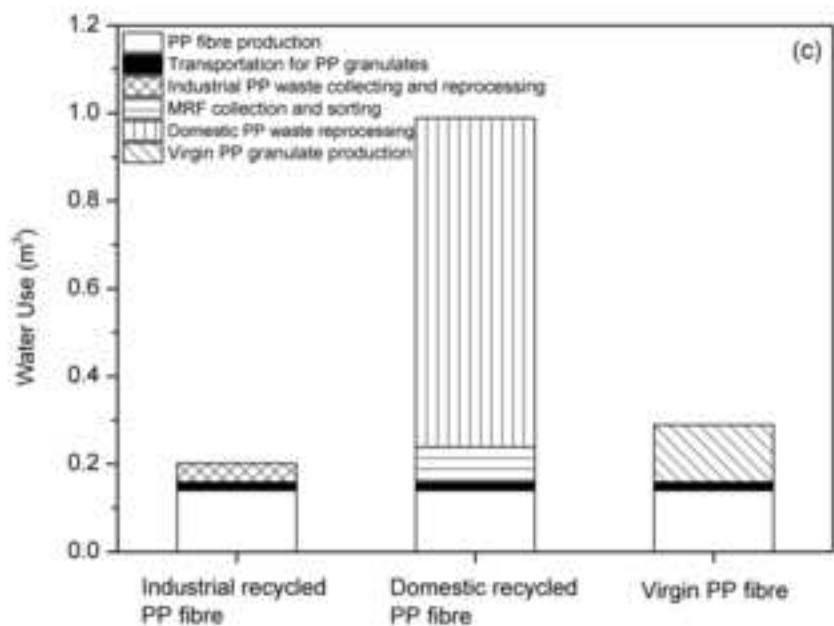
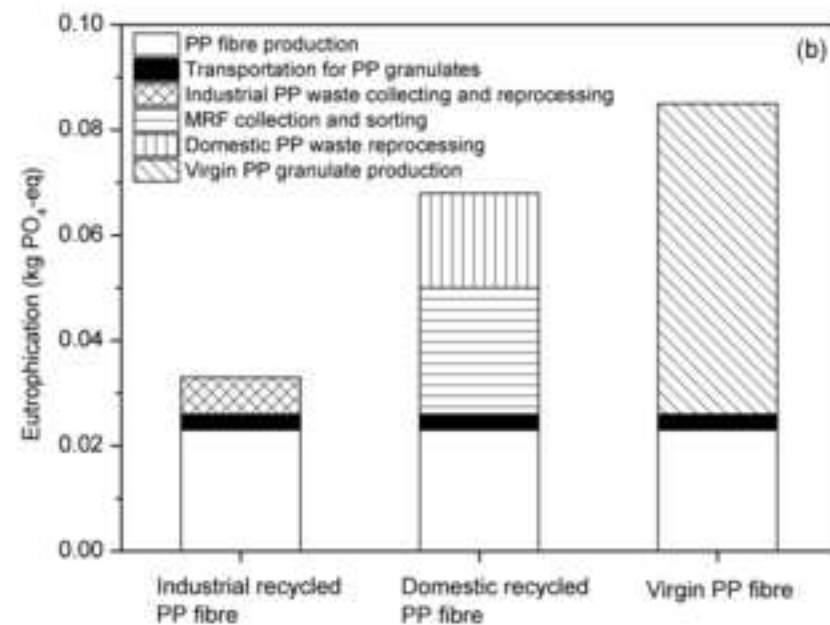
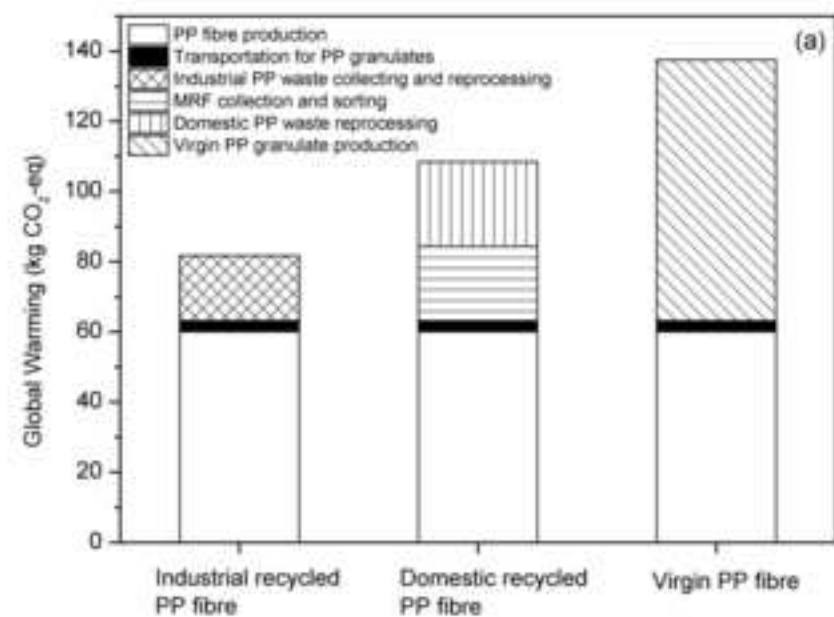


Figure 9

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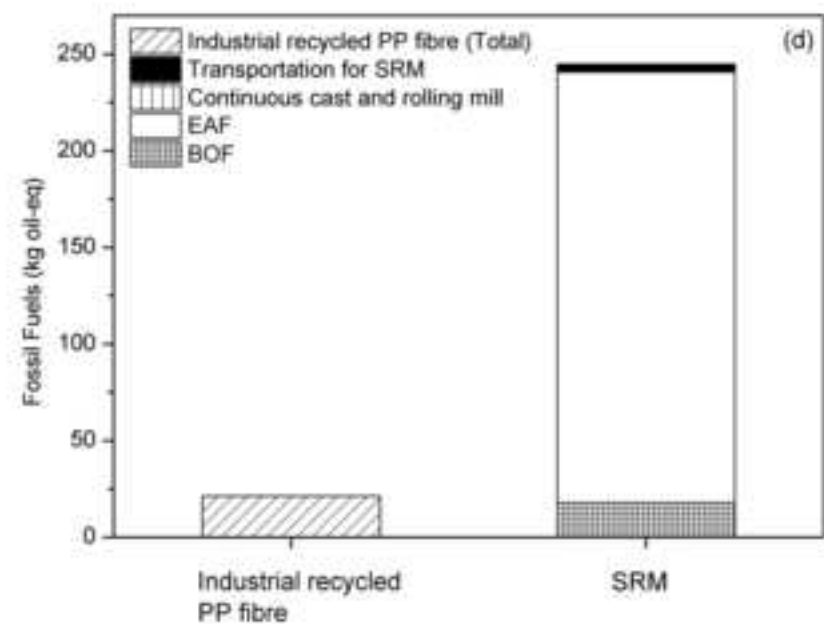
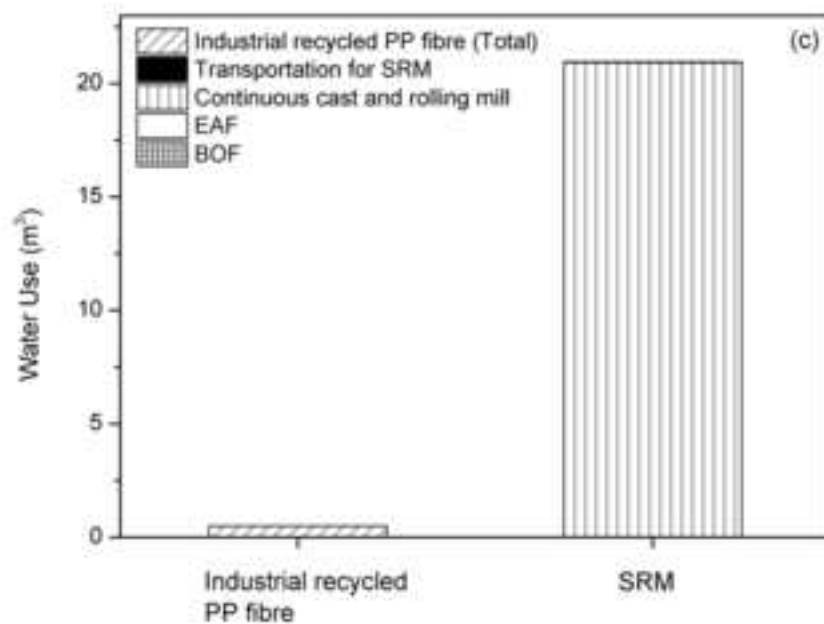
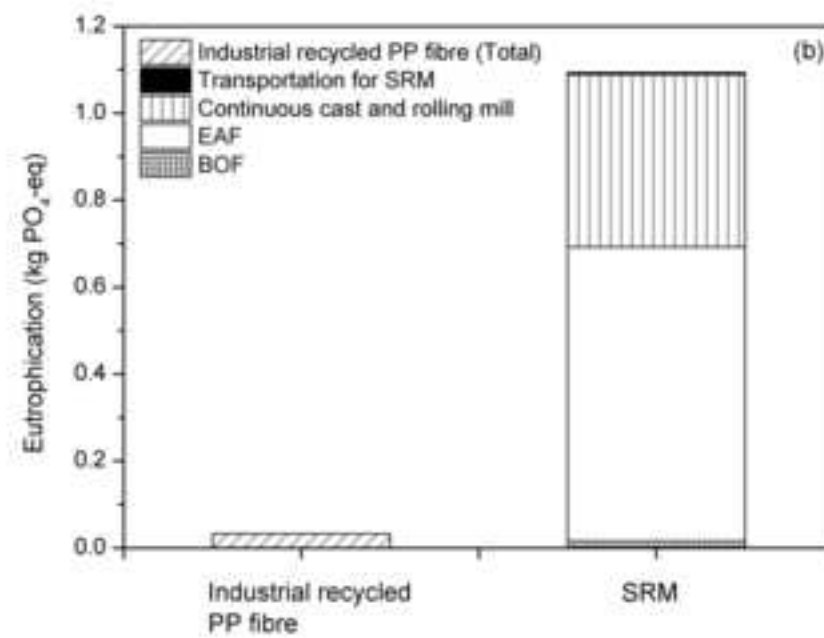
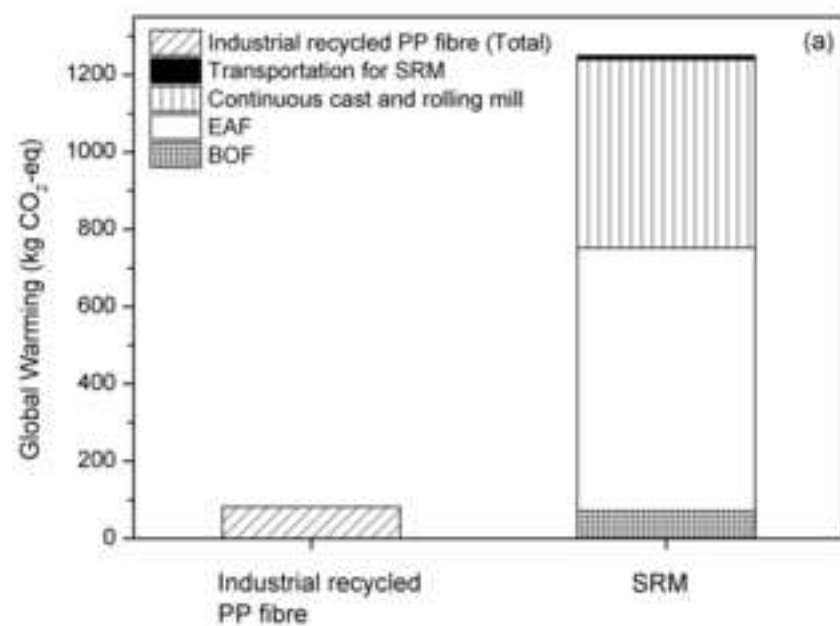


Table 1 Summary of data sources used for the LCI phase

Data	Sources
Domestic PP waste collection	<ul style="list-style-type: none"> On-site investigation and communication with a manager in Visy recycling-Townsville MRF (2012) Scientific publications: Chilton et al. (2010) Simapro 8.0 database, Australasian Unit Process LCI library, Kerbside collection of mixed recyclables (Grant and Grant, 2011b)
Domestic PP waste reprocessing	<ul style="list-style-type: none"> Scientific publications: Perugini et al. (2005) and Arena et al. (2003) Simapro 8.0 database, Australasian Unit Process LCI library, Reprocessing PP from MRF's for use in as Recycled Granulate (Grant and Grant, 2011e)
Industrial PP reprocessing	<ul style="list-style-type: none"> Communication with a manager of Martogg Group (2013) Simapro 8.0 database, AusLCI unit process library, Low voltage electricity (Grant, 2012)
Virgin PP granulates production	<ul style="list-style-type: none"> Simapro 8.0 database, Australasian Unit Process LCI library, Polypropylene Production Australian Average (Grant and Grant, 2011d)
PP granulates transportation	<ul style="list-style-type: none"> Scientific publications: Shen et al. (2010) Communication with the manager of Martogg Group to get actual transportation distances and vehicle types (2013) Simapro 8.0 database, Australasian Unit Process LCI library, Rigid Truck Transport in Australia (Grant, 2011b), Articulated Truck Transport (Grant, 2011a)
PP fibre production	<ul style="list-style-type: none"> On-site investigation, checking real electricity bills to get electricity consumption, and communication with a manager in Danbar Plastic (2013) Simapro 8.0 database, AusLCI unit process library, Low voltage electricity (Grant, 2012)
Plastic waste landfilling	<ul style="list-style-type: none"> Scientific publications: Perugini et al. (2005) and Arena et al. (2003) Simapro 8.0 database, Australasian Unit Process LCI library, LCI of 1000kg Plastic in Landfill (Grant and Grant, 2011c)
Steel production	<ul style="list-style-type: none"> Communication with an executive director of Steel Reinforcement Institution of Australia (SRIA) Scientific publications: Strezov and Herbertson (2006) Building Products LCI from Australian Building Products Innovation Council, SRM (BPIC, 2010) LCA databases Simapro 8.0 database, Franklin USA 98 library, Steel from Basic Oxygen Furnace (Associates and Sylvatica, 2004b), Cold-rolled steel sheet from Electric Arc Furnace (Associates and Sylvatica, 2004a)
Concast and rolling mill	<ul style="list-style-type: none"> Communication with an executive director of SRIA Building Products LCI form Australian Building Products Innovation Council, SRM (BPIC, 2010) Simapro 8.0 database, Ecoinvent unit processes library, Milling steel (Steiner, 2008)
Mill steel transportation	<ul style="list-style-type: none"> Communication with an executive director of SRIA Scientific publications: Strezov and Herbertson (2006) Building Products LCI form Australian Building Products Innovation Council, SRM (BPIC, 2010)

	<ul style="list-style-type: none"> • LCA databases Simapro 8.0 database, Australasian Unit Process LCI library, Domestic Shipping in Australia (Grant and Grant, 2011a); AusLCI unit process library, lorry >32t (Spielmann, 2012)
SRM production	<ul style="list-style-type: none"> • Communication with an executive director of SRIA • Building Products LCI form Australian Building Products Innovation Council, SRM (BPIC, 2010)