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A life cycle assessment of recycled polypropylene fibre in concrete footpaths

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Abstract

This study assesses the environmental impact of four alternatives for reinforcing 100 m^2 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 CO_2 equivalent, 65 % of PO_4 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 CO_2 equivalent, 97 % of PO_4 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.

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1. Introduction

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

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

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

In order to help decision makers choose reinforcing material that causes the lowest environmental impact, it is very important to carry out a comparative impact analysis. There are a variety of general and industry specific assessment methods, such as GMP-RAM (Jesus et al., 2006), INOVA Systems (Jesus-Hitzschky, 2007), and fuzzy logic environmental impact assessment method (Afrinaldi and Zhang, 2014). However, life cycle assessment (LCA) is the most comprehensive among the available tools and has been widely used (Sorensen and Wenzel, 2014). The LCA methodology is generally considered an excellent management tool for quantifying and comparing the eco-performance of alternative products.

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

Although these studies show promise, the literature on LCA of recycling plastic waste are actually very limited, and are strongly influenced by final product types, plastic sources, and by local characteristics of procedures for collecting and reprocessing plastic waste. Hence, these studies cannot be extrapolated to Australian conditions, where there is limited information on comparative LCA of recycling plastic waste. Moreover, recycling systems are typically multifunctional, which can constitute a challenge for LCA practitioners. LCAs of the same product can arrive at different conclusions when there are methodological differences or differences in life cycle inventory (LCI) data. It is therefore important to clearly define the scope, LCA methodology, inventory data sources, and functional unit (FU) involved. These issues are discussed in greater detail by Sandin et al. (2014).

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

The objective of this research is to quantify the life cycle environmental benefits brought about by using recycled PP fibres from domestic and industrial waste as compared to using typical materials for reinforcing concrete footpaths. Alternative reinforcing materials assessed include virgin PP fibre and SRM. This study is based on Australian conditions and quantifies the environmental impacts in terms of material consumption, water use, and emissions to the environment. The scope of this study is limited to the first stage of the fibre or SRM reinforced footpaths, namely, the production of PP fibres and SRM. The primary audience for this study is intended to be local governments, city councils, solid waste planners, and industries, such as plastic waste recycling and plastic fibre reinforced concrete industries, who are interested in pursuing not only positive economic outcomes but also environmental ones.

2. Methodology

2.1. Functional Unit and scenario formulations

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

The function of the systems under study is to reinforce an area of 10 m x 10 m (100 mm thick). According to AS 3600-2009 (AS, 2009) for 100 m^2 of concrete footpath reinforced with Class L SRM, seven sheets of SL82 SRM (6 m × 2.4 m) are needed. The SL82 SRM consists of 7.6 mm steel bars at 200 mm spacing in both directions (Fig. 1c). One SRM sheet weighs 52 kg. Alternatively, 0.45 % of PP fibres by volume (equivalent to 4 kg PP fibre per cubic meter of concrete) are found to be able to produce equivalent reinforcing effects to that of the SRM (Cengiz and Turanli, 2004). The PP fibres (Fig. 1a and 1b) have a thickness of 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 364 kg of SRM. The four scenarios, with equal reinforcing effects, are thus defined as follows:

Scenario a: Production of seven SL82 SRM (364 kg of total weight) using electric arc furnaces and basic oxygen furnace.

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

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

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

(Insert Fig. 1 here)

2.2. System boundaries and Life Cycle Inventory

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

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

2.2.1. Steel reinforcing mesh

Fig. 2, taken from Australian Building Products LCI (BPIC, 2010), shows the production process of SRM and its system boundary. According to Strezov and Herbertson (2006), around 93 % of SRM is produced by electric arc furnaces (EAF) and the remaining is produced by basic oxygen furnaces (BOF). The EAF process produces 9 % of slag and the BOF process produces 8 % of slag, according to Australian building products LCI (BPIC, 2010). The iron obtained from EAF and BOF is continuously casted, milled and cold rolled into steel bars. At this stage 20 % of steel scrap is reused in the BOF or EAF processes. The milled steel bars are then cut, bent and resistance welded into SRM. The cutting, bending and welding processes are mainly carried out by manual labour, and the electricity used in these processes is negligible compared to the BOF, EAF and casting processes. Hence the environmental impacts of these processes are not considered. GHG (such as CO_2), emissions causing eutrophication (such as NO_x), toxic gases (such as SO_2), particulate matter with 10 micrometers or less in diameter (PM10), and solid and liquid wastes are generated. The environmental impacts of BOF, EAF, casting and milling steel, and transportation are calculated using the SimaPro 8.0 databases (Associates and Sylvatica, 2004a, b; Grant and Grant, 2011a; Spielmann, 2012; Steiner, 2008).

(Insert Fig. 2 here)

2.2.2. Virgin PP fibre

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

(Insert Fig. 3 here)

2.2.3. Industrial recycled PP fibre

A diagram of the processes required in the production of industrial recycled PP fibre is shown in Fig. 4. The industrial PP waste are first compacted and then transported to a PP reprocessing plant by rigid trucks. The transport distance is on average 75 km. The collected industrial PP waste are shredded and recompounded in the PP reprocessing plant. The efficiency of both shredding and recompounding processes, as obtained directly from the reprocessing plant, is around 95 %. The machine generates about 800 kg of the recycled material per hour, and the energy consumption on the reclaim line is roughly 280 kWh. The processed PP granulates are then transported about 55 km to a collection centre, and finally transported a further 100 km to a fibre production plant. The processing and transportation data were collected from the manager of the PP reprocessing plant (Martogg Group, Australia).

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

(Insert Fig. 4 here)

2.2.4. Domestic recycled PP fibre

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

(Insert Fig. 5 here)

2.2.5. Life cycle inventory

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

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

(Insert Table 1 here)

2.3. Life Cycle Impact Assessment

The software SimaPro 8.0 has been used for the LCIA. All the LCIA data of the four scenarios, including all emissions released and all raw material requirements, are converted into environmental impact categories based on the Australian Indicator Set V3.00 (SimaPro, 2010). Impacts categories examined include CO_2 equivalent, PO_4 equivalent, water use and oil equivalent.

The processes of iron production, steel continuous casting and milling, virgin PP production, plastic waste collecting and recycling, and fibre production consume large amounts of primary energy and electricity. In Australia, the predominant primary energy sources for these processes are coal, oil and diesel, which lead to CO_2 emissions and associated global warming potential (GWP). Carbon dioxide equivalent (kg CO_2 eq) is a standard unit for measuring GWP, and the consumption of fossil fuels is used to assess the depletion of limited natural resources. Water use and water-based pollution are important issues in Australia, because of their scarcity. Water-based impacts can be significant in both steel production and also in domestic recycling, where washing is an important processing step. In this study both quantity and pollution are assessed. Eutrophication pollution impacts are aggregated into PO_4 equivalent. Water-based toxicity is not assessed because of a scarcity of data in this area.

The CO_2 equivalent (kg) was calculated based on the database of 100-year greenhouse impacts reported by Intergovernmental Panel on Climate Change method and data (Wang et al., 2015). PO_4 equivalent (kg) is based on the model of Climate Modelling Laboratory impact assessment (Camba et al., 2014). The consumption of fossil fuels (oil equivalent in kg) is based on Recipe database (Castanheira et al., 2015).

2.4. Uncertainty analysis

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

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

3. Results

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

To produce 40 kg of PP fibres, the industrial recycled fibre life cycle produces 81.7 kg of CO_2 equivalent. As explained in Fig. 5, processing of domestic PP waste into fibre needs more complex and energy intensive processes, such as PP waste collection and sorting, PP reprocessing, and fibre production. Hence, the production of domestic PP fibre consumes more energy and produces more CO_2 equivalent (109 kg). For the virgin PP fibre, 137 kg of CO_2 equivalent is predominately associated with the production of PP granulates and PP fibre, and also with propylene production (as Fig. 3).

The process used to produce the industrial recycled PP fibre generates a relatively lower eutrophication impact (0.033 kg of PO_4 equivalent). However, for the domestic recycled PP fibre, the waste washing process emits significantly more PO_4 equivalent (0.069 kg of PO_4 equivalent), and leads to higher eutrophication impacts in comparison to industrial recycled PP. It is also interesting to note that despite the comparatively high total volume of water used in producing domestic recycled PP, the eutrophication impact of the waste water is low compared to virgin PP production, mainly due to the catalytic cracking unit in the latter. Overall, the virgin PP fibre production process causes the highest eutrophication impact (0.085 kg of PO_4 equivalent).

When it comes to water consumption, manufacturing domestic recycled PP fibre consumes much more water (0.99 m^3) than producing either industrial recycled PP fibre or virgin PP fibre, which explains the differences in eutrophication impacts between domestic and industrial recycled PP. High water consumption occurs when reprocessing domestic PP waste, because the shredded PP fragments are washed in large volumes of sodium hydroxide solution. After washing, effluent is neutralised, then discharged to domestic sewage. Environmental benefits, including reduced water use and reduced eutrophication impact, could arise if the effluent was treated and recycled back to the washing process.

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

(Insert Fig. 6 here)

In Fig. 7 we compare the environmental impacts of industrial recycled PP fibre with SRM. Across all categories the environmental impacts of producing the industrial recycled PP fibre is negligible in comparison. As shown in Fig. 7, the production of 364 kg of SRM emits 15 times the CO_2 equivalent than production of 40 kg of industrial recycled PP fibre. The eutrophication impact of the SRM production is 33 times higher than that of industrial recycled PP fibre. 20.9 m^3 of water is needed for the production of 364 kg SRM, which is consistent with the research by Gu et al. (2015) about the water use in steel production. The water consumption is 20 times higher than that of even domestic recycled PP fibre. 245 kg of oil equivalent is also needed, which is 11.5 times more than that of industrial recycled PP fibre. Although any PP substitution leads to reduced impacts, comparing the best performing PP fibre process to the SRM, the production of industrial recycled PP fibre can save 93 % of CO_2 equivalent, 97 % of PO_4 equivalent, 99 % of water and 91 % of oil equivalent.

(Insert Fig. 7 here)

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

Fig. 8 shows contribution of major sub-stages to the overall impacts, for each PP production pathway. As can be seen, in the industrial recycled PP fibre production processes, the GWP, eutrophication impact, water use and fossil fuel consumption are dominated by the fibre production process. Reprocessing industrial PP waste into recycled PP granulates also gives rise to a substantial proportion of the burdens to environment. For the domestic recycled PP fibre processes, the fibre production process is again the dominant source of impact. However, the domestic waste collection, sorting and reprocessing stages are also significant, and emit considerably more CO_2 equivalent and PO_4 equivalent, as well as consuming substantially more fossil fuels than those in the transportation stage. Most notably, large amounts of water are needed to wash and separate plastic wastes. Improvements in processing and water recycling at this stage can make domestic recycling more competitive with industrial PP recycling in terms of environmental impacts. For the virgin PP fibre, the production of virgin PP granulates emits large amounts of CO_2 equivalent and PO_4 equivalent, and also consumes water in large amounts. Obviously, fossil fuels needed in this sub-stage are substantially higher than those in other sub-stages, because crude oil is used as raw material for production of virgin PP granulates. As shown in Fig. 8 (d), 83 % of crude oil use is for monomer production and the remaining 17 % is consumed for energy.

(Insert Fig. 8 here)

In the production of SRM, the EAF is the main process used to produce iron. In Fig. 9, which compares the SRM scenario impacts to the industrial recycled PP scenario, the EAF is energy intensive and emits large amounts of CO_2 equivalent and PO_4 equivalent, and also consumes fossil fuels in large amounts. Whether iron is produced by EAF or BOF processes, the iron will be continuously casted and roll milled, which also emits large amounts of CO_2 equivalent and PO_4 equivalent. 40 % of the total CO_2 equivalent contribution is from EAF, while 52 % of the total CO_2 is from continuous cast and rolling mill processes. 46 % of the total eutrophication impact originates during the EAF process and 49 % from the continuous cast and rolling mill. Casting and roll milling also require orders of magnitude larger amounts of water. Regarding the use of the fossil fuels, 9 % of total consumption is for producing heat in the BOF process, while 89 % of total consumption is within the EAF process.

(Insert Fig. 9 here)

4. Discussion

In common with other LCA's of plastic recycling processes, the boundaries of this LCA excluded the end-of-life impacts of the four products. These exclusions include disposal, landfilling, further recycling and reuse, which could provide a longer term view of the impacts. It is well known that in comparison to PP, steel has a lower impact in the disposal stage because of its easy recyclability (Guo et al., 2014). Thus it is reasonable to assume that if end-of-life options were considered, the conclusions of this study could be different. However in Australian context, we do not believe that including end-of-life impacts would alter the final conclusions. Firstly, based on a study of the long term durability of plastic fibres in alkaline environments (Roque et al., 2009), all four scenarios would require the same level of maintenance and have equal life spans. Furthermore, despite being easily recycled, end-of-life concrete footpaths in Australia are almost always landfilled, as sorting and recycling for the small volumes is considered uneconomical. In essence, the processes that would lead to different end-of-life impacts are, in practice, unlikely to occur. We would also argue that the extent of these end-of-life impacts would not be sufficient to make up for the substantial differences that arise during production. Furthermore, because the use of fibres in footpaths is a relatively new application, end-of-life impacts are not well defined. Including these estimates would introduce more uncertainty, and may not be useful for decision makers. However, we would recommend that the potential for water based pollution (i.e. toxicity) associated with PP leaching during the use phase, be more carefully considered.

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

Since this study is based on the Australian context and Australian inventory data, it is interesting to compare this work with the LCA by Shen et al. (2010), who assessed the impacts of recycled and virgin plastic fibres (PET) in a Western European context. Both studies used the same system boundaries, namely, starting from the point the plastic products become a waste and ending at the point that they become recycled plastic fibres. Although it was not clear if the PET fibres in Shen et al. (2010) were able to be used directly in concrete reinforcing, according to our judgement, the PET fibres would not require additional processing to be fit for purpose. Thus the comparative impacts remain valid and relevant to our study. Collection, sorting, washing, reprocessing, transportation and fibre production were included, but end-of-life impacts were not considered. The results in both studies are very similar, which gives us confidence in our methodology and sampled data. In comparison, the production of 40 kg domestic recycled plastic fibre in Australia has more global warming impact (109 kg CO_2 eq) and eutrophication impact (0.069 kg PO_4 eq) than those in Western Europe (81 kg CO_2 eq and 0.044 kg PO_4 eq). For the production of 40 kg virgin fibre, the two regions have a similar global warming impact (around 161 kg CO_2 eq), while Australian eutrophication impact (0.095 kg PO_4 eq) is much higher than in Western Europe (0.048 kg PO_4 eq), likely the result of more sophisticated water treatment and recycling initiatives in Western Europe. However, across all impact categories the comparisons between virgin and recycled fibres follow similar trends, and differences in absolute values arise because of local variations. These include differences in collection methods and frequency, transportation infrastructure and distances, as well as differences in the maturity of sorting, reprocessing and fibre production methods. Moreover, the different plastic types considered in these studies also contribute to differences in the calculated impacts.

5. Conclusion and recommendations

In this study, the environmental impacts of four alternative scenarios to reinforce 100 m^2 of concrete footpath were assessed using a LCA methodology based on the Australian context. The four scenarios considered were the use of industrial recycled PP fibre, domestic recycled PP fibre, virgin PP fibre and SRM.

The LCA results show that the industrial recycled PP fibre offers substantial environmental benefits over all other reinforcing options. The industrial recycled PP fibre can reduce CO_2 equivalent emission by 50 %, PO_4 equivalent by 65 %, use 29 % less water and use 78 % less oil equivalent natural resources compared to the virgin PP fibre. The domestic recycled PP fibre offers 32 % reduced CO_2 equivalent emissions, 27 % reduced PO_4 equivalent emissions, and 67 % reduction in oil equivalent resource consumption compared to virgin PP fibre. However, the production of domestic recycled PP fibre consumes 3.5 times more water than the virgin PP fibre due to washing. Improvements in water use can make domestic recycling a more attractive option for sourcing PP fibre. Compared to SRM, the production of industrial recycled PP fibre can save 93 % of CO_2 equivalent, 97 % of PO_4 equivalent, 99 % of water use and 91 % of oil equivalent resource use. Across all categories PP fibres show reduced impacts when compared to the use of SRM in concrete footpath applications.

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

6. Acknowledgements

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Captions for Figures and Tables

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

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

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

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

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

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

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

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

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

Table 1 Summary of data sources used for the LCI phase.

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Figure 1
Click here to download high resolution image

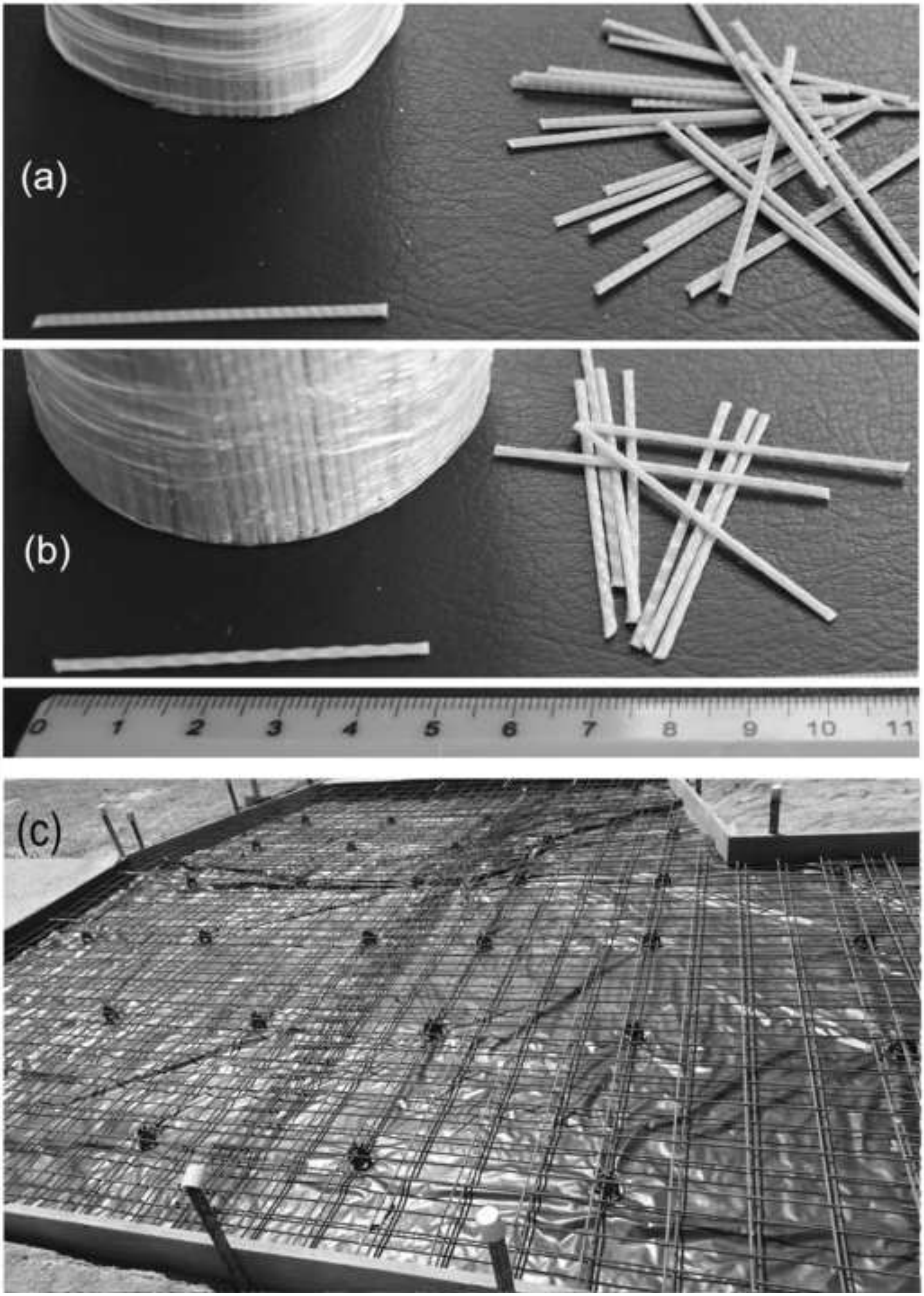
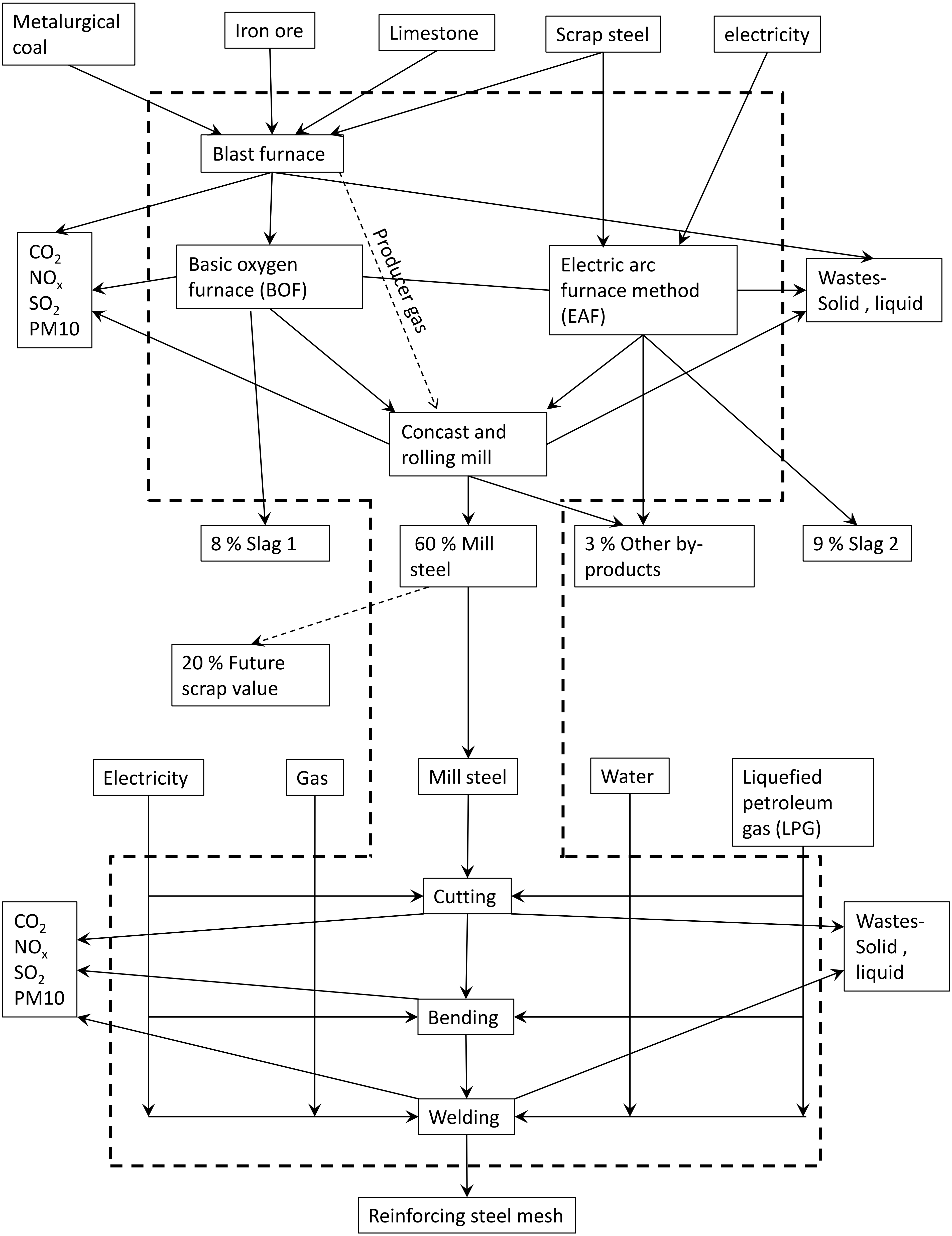
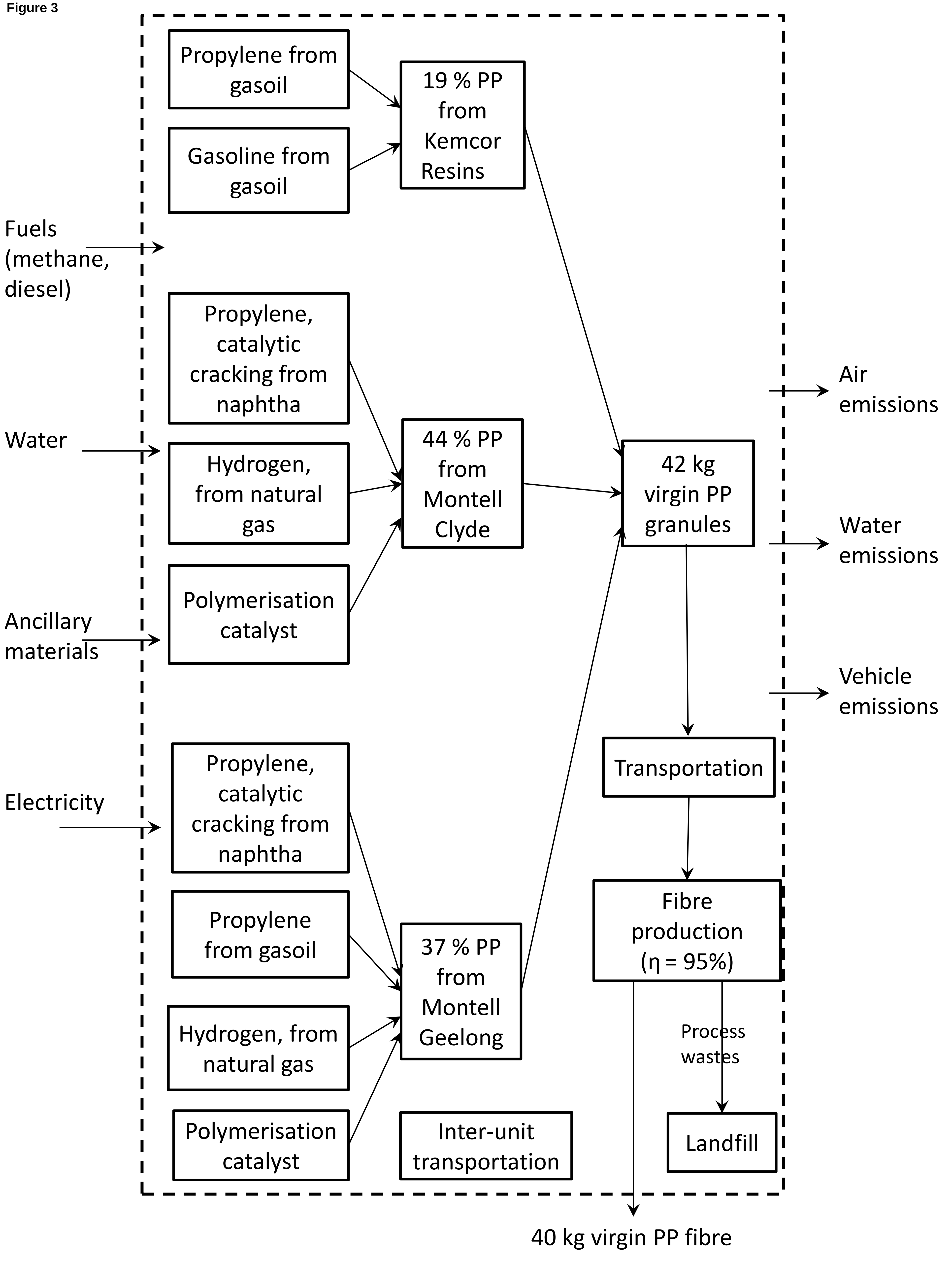


Figure 2



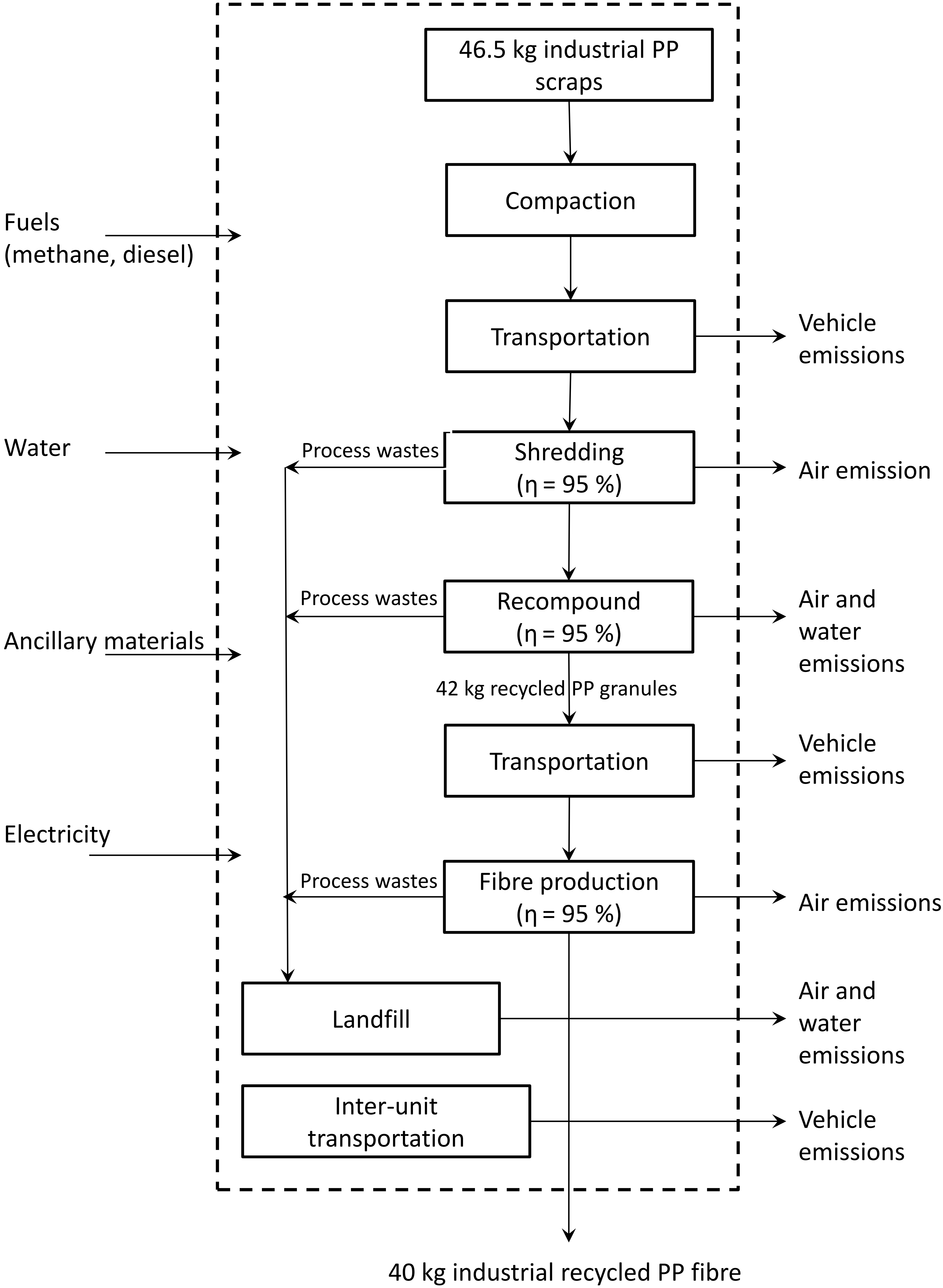
Metalurgical coal
Iron ore
Limestone
Scrap steel
electricity
Blast furnace
Producer gas
CO_2 NO_x SO_2 PM10
Basic oxygen furnace (BOF)
Electric arc furnace method (EAF)
Wastes- Solid , liquid
Concast and rolling mill
8 % Slag 1
60 % Mill steel
3 % Other by-products
9 % Slag 2
20 % Future scrap value
Electricity
Gas
Mill steel
Water
Liquefied petroleum gas (LPG)
Cutting
CO_2 NO_x SO_2 PM10
Wastes- Solid , liquid
Bending
Welding
Reinforcing steel mesh

Figure 3



Propylene from gasoil
Gasoline from gasoil
19 % PP from Kemcor Resins
Fuels (methane, diesel)
Propylene, catalytic cracking from naphtha
Water
Hydrogen, from natural gas
44 % PP from Montell Clyde
Polymerisation catalyst
Ancillary materials
42 kg virgin PP granules
Air emissions
Water emissions
Vehicle emissions
Transportation
Electricity
Propylene, catalytic cracking from naphtha
Propylene from gasoil
Hydrogen, from natural gas
37 % PP from Montell Geelong
Polymerisation catalyst
Inter-unit transportation
Fibre production (η = 95%)
Process wastes
Landfill
40 kg virgin PP fibre

Figure 4



46.5 kg industrial PP scraps
Compaction
Fuels (methane, diesel)
Transportation
Vehicle emissions
Water
Process wastes
Shredding (η = 95 %)
Air emission
Process wastes
Recompound (η = 95 %)
Air and water emissions
Ancillary materials
42 kg recycled PP granules
Transportation
Vehicle emissions
Electricity
Process wastes
Fibre production (η = 95 %)
Air emissions
Landfill
Air and water emissions
Inter-unit transportation
Vehicle emissions
40 kg industrial recycled PP fibre

Figure 5

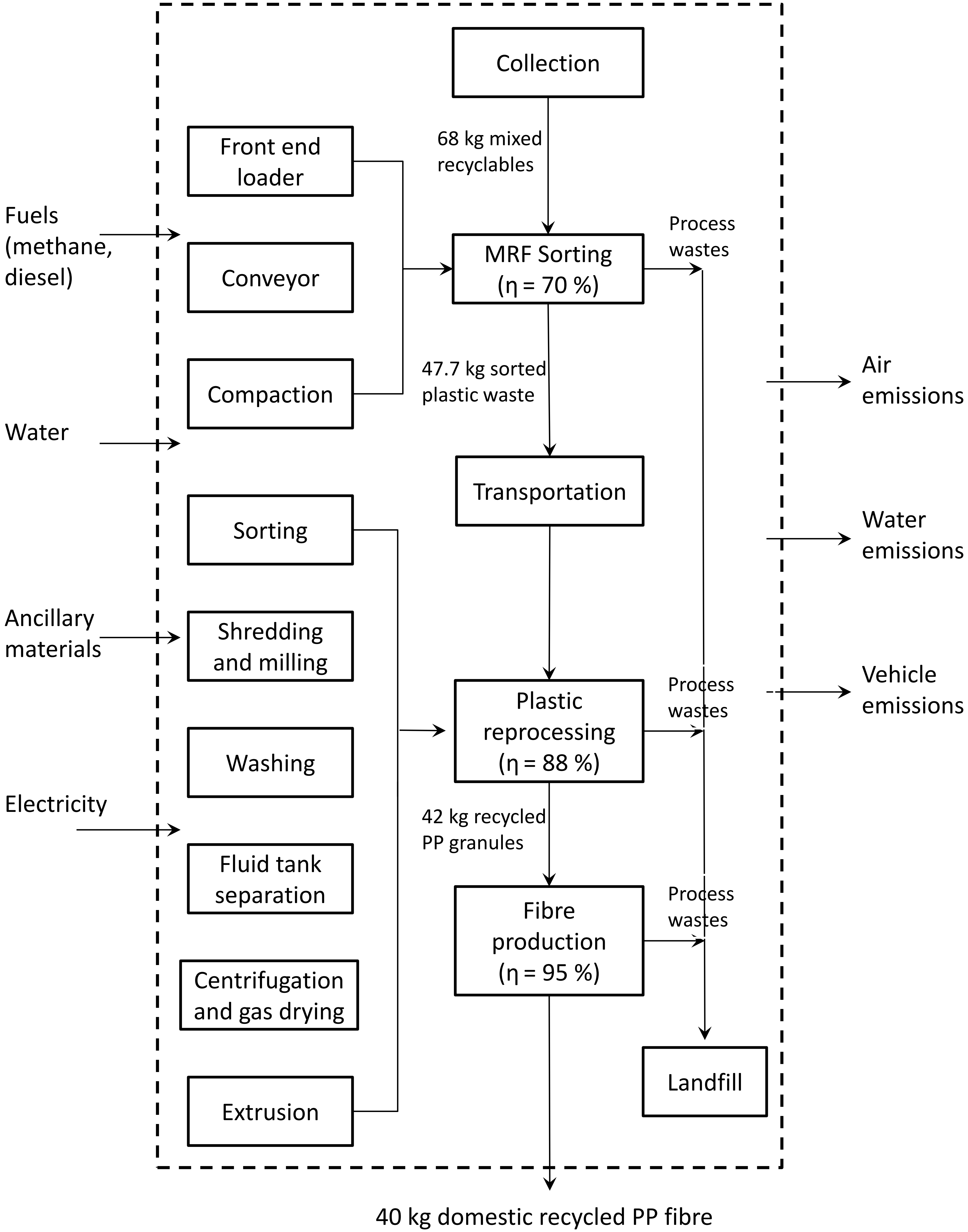

Collection
68 kg mixed recyclables
Front end loader
Conveyor
Compaction
MRF Sorting (η = 70 %)
Process wastes
Fuels (methane, diesel)
Water
47.7 kg sorted plastic waste
Transportation
Air emissions
Water emissions
Sorting
Ancillary materials
Shredding and milling
Washing
Fluid tank separation
Centrifugation and gas drying
Extrusion
Electricity
Plastic reprocessing (η = 88 %)
Process wastes
Vehicle emissions
42 kg recycled PP granules
Fibre production (η = 95 %)
Process wastes
Landfill
40 kg domestic recycled PP fibre

Figure 6
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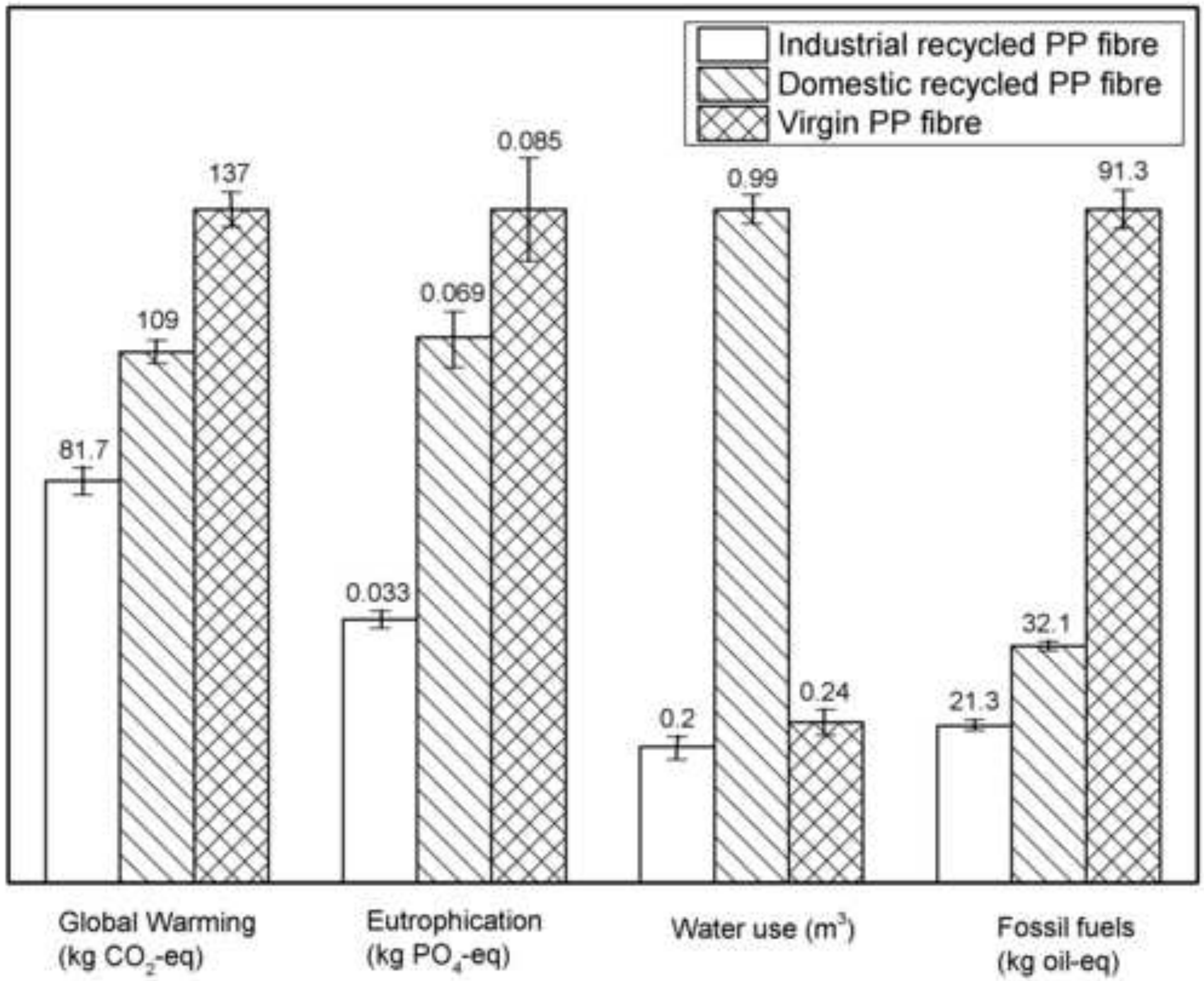

Figure 7
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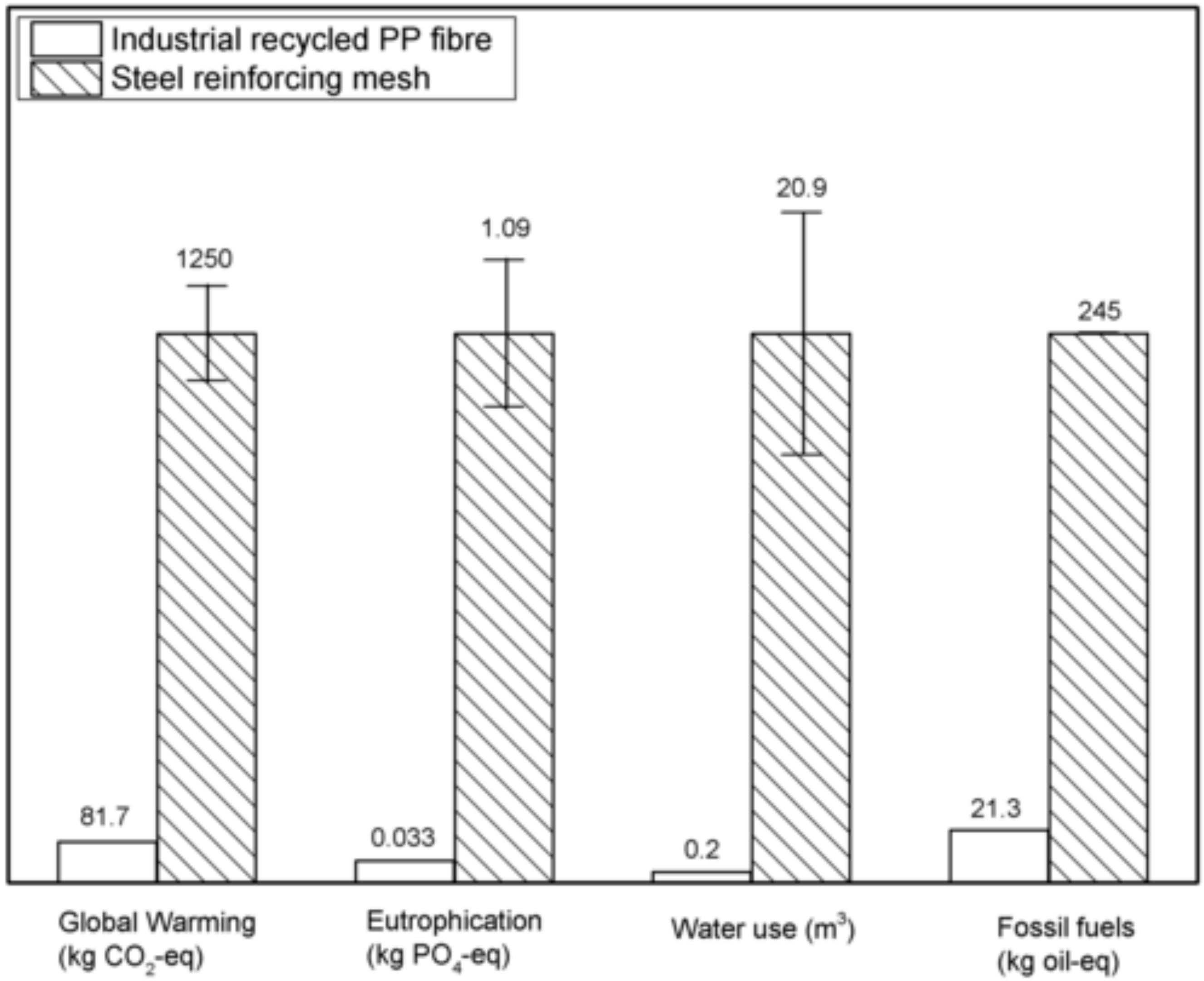

Figure 8
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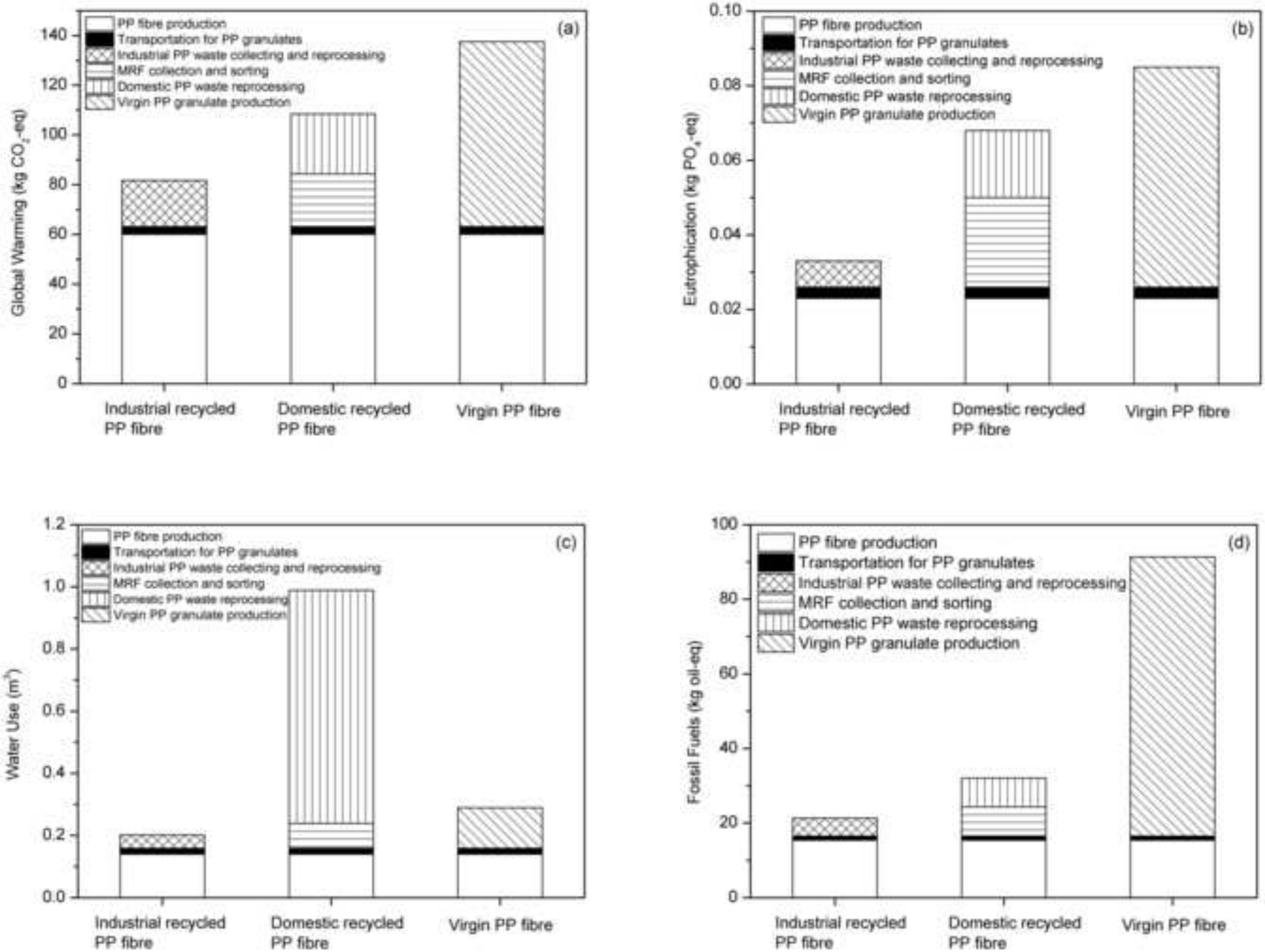

Figure 9
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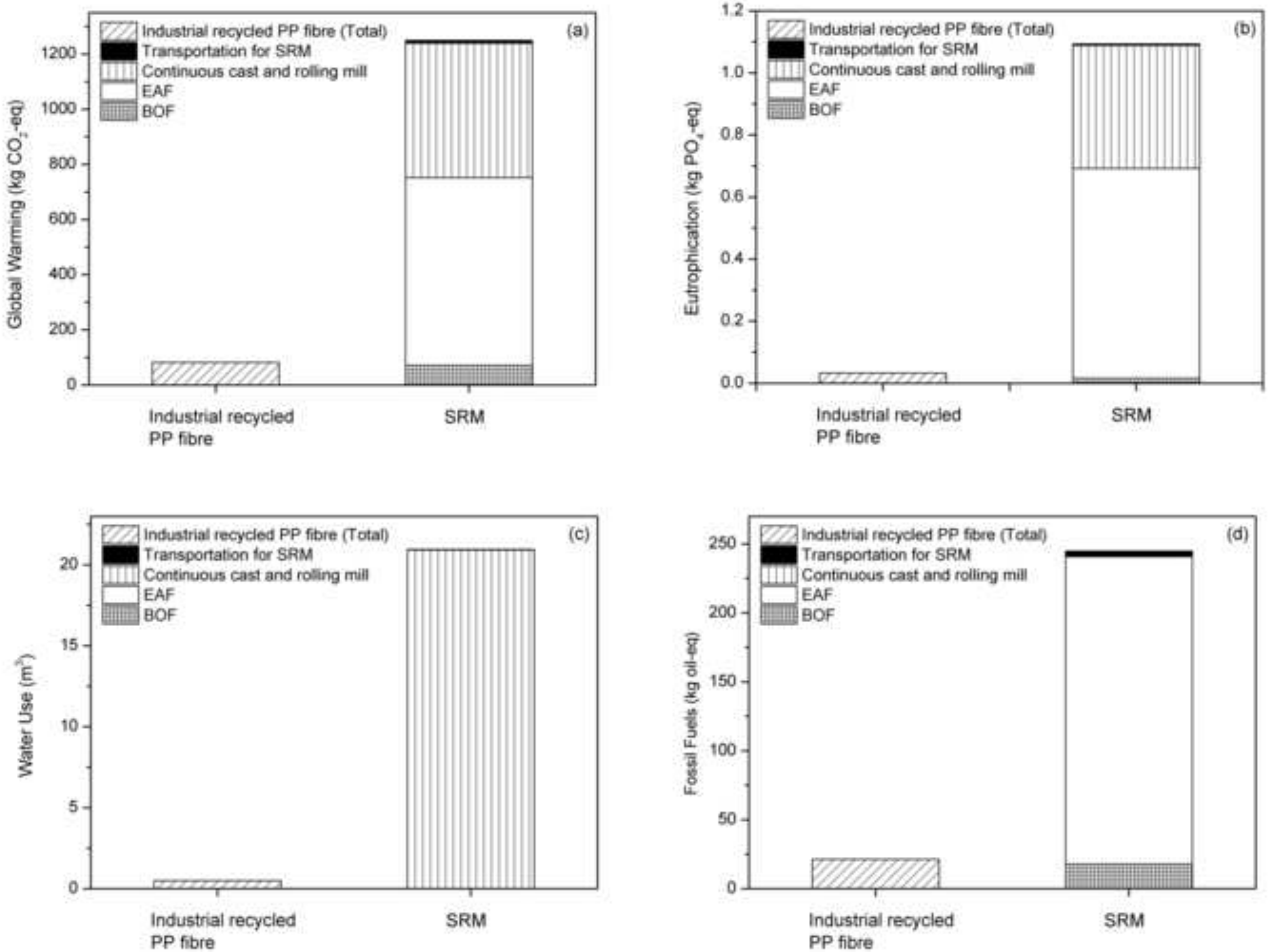

Table 1

Table 1 Summary of data sources used for the LCI phase

Data	Sources
Domestic PP waste collection	• 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	• 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	• 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	• Simapro 8.0 database, Australasian Unit Process LCI library, Polypropylene Production Australian Average (Grant and Grant, 2011d)
PP granulates transportation	• 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	• 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	• 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	• 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	• 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	• 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)

	• 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	• Communication with an executive director of SRIA • Building Products LCI form Australian Building Products Innovation Council, SRM (BPIC, 2010)