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Life cycle energy and carbon analysis of a road-safety barrier produced using recycled tire rubber

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Abstract

Increasing end-of-life material recovery and its application in new products is essential to reduce resource consumption. This paper assesses the cradle-to-gate life cycle energy and carbon dioxide (CO_2) emissions of a new road safety barrier product to be installed around guardrails' poles. To analyze the potential life cycle benefit of incorporating recycled materials, a base case product A, produced with conventional virgin synthetic rubber and polypropylene (PP), was compared with two equivalent alternatives under study: B (using recycled end-of-life tire rubber granulate (TRG) and PP), and C (using TRG and recycled polypropylene). The results show that the incorporation of recycled TRG has a positive effect in primary energy and carbon emissions. Product B presents less 38% CO_2 emissions and 47% non-renewable primary energy than product A. The combination of TRG and recycled polypropylene (C), presents even more benefits: less 69% CO_2 and 86% non-renewable primary energy than A. Supply chain processes and material production have much higher impacts than the product manufacturing (e.g. product molding only represents 5% of the primary energy of product A). To conclude, recycled materials incorporation should be strongly encouraged since it has a great potential to reduce current carbon emissions and primary energy of products.

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Keywords: Circular economy; LCA; Primary energy; Recycling; Secondary material; Tire rubber

Abbreviations: EoL, End-of-Life; LCA, Life Cycle Assessment; PP, Polypropylene; RPP, Recycled Polypropylene; SR, Synthetic Rubber; TRG, Tire Rubber Granulate

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1. Introduction

Promoting a circular economy requires to re-think current industrial production systems and take consistent actions to increase products reuse, repair, remanufacture, material and energy recovery, recycling, waste minimization and, ultimately, to reduce overall raw materials extraction and resource consumption. In 2005, only 6% of all material processed globally were recovered and re-used [8]. To increase material recovery, current wastes should be appropriately sorted and managed to allow new circular business models to grow. At the same time, products should be designed with the goal of retaining their material value at their End-of-Life (EoL). EoL products ought to be considered as material feedstocks. Simultaneously, new products should be designed to incorporate recycled materials and to avoid the overexploitation of resources.

With the worldwide rise of road transport, it is estimated that, yearly, a billion of tires reach their EoL and require appropriate disposal [12]. Managing safely the EoL of tires is currently a global challenge, which has been addressed by initiatives supported by local authorities, tire industry producers, and researchers. According to the World Business Council for Sustainable Development [12], the EoL of tires can be managed and valued though different recovery routes, such as: (i) energy recovery, as an alternative energy source for cement kilns, paper and pulp mills, high power industrial boilers, and; (ii) material recovery, of crumb rubber or Tire Rubber Granulate (TRG), textile fibers, steels and oils, which can be used to replace valuable raw materials in construction industry (through incorporation in asphaltic pavements, filling layers, playgrounds) and in new molded products when mixed with thermoplastics (some of which under study). The avoidance of sending EoL tires to landfill and (endangering) stockpiles is therefore imperative.

In Europe, landfill deposition of tires has been already banned, which encourages energy and material recovery routes. Nevertheless, material recovery businesses and secondary material applications still need to grow to reduce natural resource consumption and carbon emissions more effectively, while contributing to the development of circular economy and better solve the EoL of the tires used by the European transport sector.

In the past years, Life Cycle Assessment (LCA) has been used to assess and compare the potential environmental life cycle impact of alternative EoL scenarios for tires. Comparing material recycling through TRG incorporation in asphalt pavements with energy recovery in cement kilns, material recovery presented lower environmental impact than the energy recovery route [5,9].

Other studies also compared and evaluated the potential environmental benefits of material recovery of TRG to be incorporated in asphaltic pavements [2,10] as well as to replace traditional materials in various other applications. For instance, Clauzade et al. [3] studied synthetic turf, molded objects, equestrian floors, retention and infiltration basins, cement works, and energy recovery for urban heating, steelworks and foundries. Additionally, Fiksel et al. [6] studied synthetic turf, asphalt, tire rethreading, and molded product (TRG with polyethylene or with other rubbers), lightweight backfill, and energy recovery (for incineration, industrial boiler and cement kiln). Generally, material recovery from EoL tires offered a better environmental performance than the use of conventional alternatives. Synthetic turf was identified as having the best environmental performance. Simões et al. [11] studied the environmental benefit of substituting aluminum for a polymer composite of TRG, PP and ethylene propylene diene monomer for the manufacturing of solar panel structure. The results showed that the best life cycle performance is dependent on composite structure at the EoL stage. If the considered frame is landfilled, the aluminum shows globally better performance, while if the frame was assumed to be incinerated or recycled, the composite structure shows greater benefits.

Anchustegui and Pasakopoulos [1] used a LCA to assess the environmental impact of the four most common EoL tire routes in Sweden (from cradle-to-grave): where 40% (mass-based) is incinerated in cement industry (clinker production), 32% is incinerated in coal furnaces (metallurgical coke production), 12% processed to recover materials (e.g. secondary rubber, steels and textiles), and 5% undergoes pyrolysis. The authors observed that despite the current low scale of pyrolysis, it is a promising route since it allows to produce secondary products and therefore avoid the use of conventional materials. The mechanical material recovery was also identified to have low environmental impact, but the secondary rubber is mainly used in artificial turf infill and asphalt pavements. The authors highlighted that further LCA research is needed on other products incorporating TRG, prior to increase the share of material recovery Tire-EoL route.

The LCA studies of molded products incorporating TRG are still scarce and the uptake of tire secondary material by molding industry is still low. Therefore, the goal of this paper is to assess the potential life cycle primary energy and carbon dioxide (CO_2) emissions associated with a new road-safety barrier product, using LCA. The road-safety barrier was developed to be installed around metallic poles of guardrails, to cushion the clash in case of an accident, thus mitigating motorcyclists' harmful and fatal injuries. Following circular economy principles, this product, requiring elastomeric properties, has been designed to be produced from a blend of recycled EoL Tire Rubber Granulate (TRG) and a thermoplastic matrix of polypropylene (PP). The study also aims to assess the potential life cycle benefit of incorporating recycled materials (TRG and recycled polypropylene, RPP) when compared with a blend of conventional materials (synthetic rubber and PP) and identify preliminary hotspots for improvement.

2. Materials and methods

LCA is an internationally accepted and standardized methodology (ISO 14040/14044) to evaluate the potential environmental impacts of a product or service along its life cycle, or part of it. With the goal of assessing the potential life cycle energy and CO_2 emissions associated to a new road-safety barrier product, in a preliminary stage of its development, a cradle-to-gate LCA approach was followed. To assess the influence of incorporating recycled materials three equivalent product alternatives, produced with different blends, were compared:

(A) A base case conventional, using a blend of non-recycled materials: synthetic rubber (SR) and PP;

(B) A blend with recycled TRG and conventional PP;

(C) A blend using TRG and recycled polypropylene (RPP).

To allow the comparison among alternatives the functional unit considered was to produce one road-safety barrier product with a volume of 0.0189 m^3 and a height of 0.395 m. The alveolar geometry and specific design of the product was optimized for an extrusion process assuming the blend B (with 55% recycled tire rubber granulate, and a 45% thermoplastic matrix of polypropylene, mass-based). The product geometry is not disclosed since it will be protected under intellectual property rights. Nevertheless, a rough scheme of the product is shown in Fig. 1 and a comparison of alternative blends was made assuming identical densities among conventional and recycled materials.

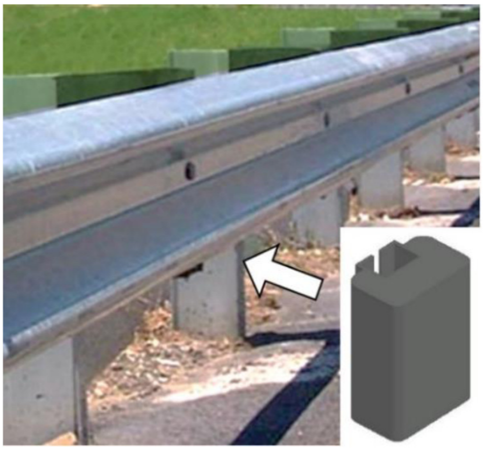


Fig. 1. Road-safety barrier product (insert) application.

Fig. 2 presents the unit processes included in the LCA study and the system boundaries (cradle-to-gate) for which the main inputs and outputs were collected. Depending on the alternative blend of materials considered, the life cycle impact of material production or/and material recycling were accounted. The product installation, use, removal and EoL was not included in this study since these processes incorporate high uncertainty and the goal of the study is to inform the manufacturer's decision in a preliminary stage.

The LCA results were calculated for two life cycle impact assessment methods: (i) CED Cumulative Energy Demand v1.11, which estimates the direct and upstream primary energy use (MJ), identifying renewable and non-renewable content; (ii) IPCC - Inter Panel on Climate Change (2013, v1.03) for 100 years, which estimated the global warming potential (GWP) in kg of CO_2-equivalent emissions.

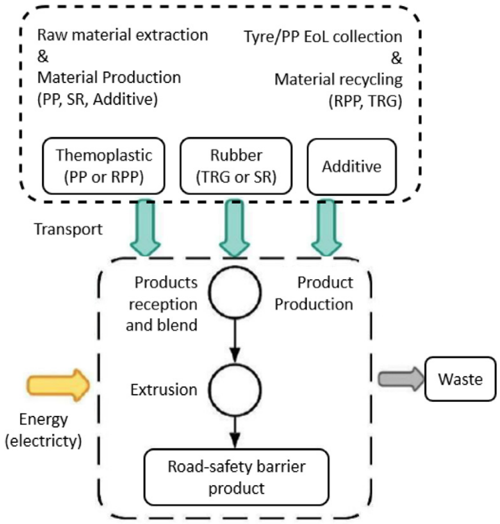


Fig. 2. System boundaries of the LCA study (cradle-to-gate).

2.1. Life cycle inventory (LCI)

For the system boundaries previously presented the main inputs, outputs of the processes were inventoried (Table 1) based on data gathered at different levels: foreground data from the product development; background data from literature (regarding material recovery and recycling of TRG and PPR) and background data from an accepted and robust environmental database *ecoinvent* 3.6. Whenever possible, the local Portuguese suppliers (and transport distances) were considered and the electricity mix of material and product production was adopted. Background data for the medium voltage Portuguese electricity mix (market for) available in *ecoinvent* 3.6 (documenting the year 2014) was considered for material production, recycling and in plant manufacturing. Packing of rubber, thermoplastic and additive granulated materials were also considered using the following *ecoinvent* 3.6 activity as a proxy: "Packing, lime product | processing". Regarding the tire recycling and TRG production, it was assumed that EoL tires were transported from a Portuguese EoL tire managing facility to a processing facility located 45 km away. The main inventory data for that process was modeled based on data from the study by Corti and Lombardi. (2004) and it is presented in Table 2, for the functional unit of this study.

In this study, a cut-off or recycled content approach was assumed. EoL tires had no impact from primary rubber production. Still, the full impact of tire recycling was attributable to the TRG, despite according to Corti and Lombardi [4] other two by-products can be recovered (metal scrap and textile fibers). Thus, the energy and emissions of tire recycling could be allocated (for instance on a mass-basis) to the three secondary products, which would result in lower inputs and outputs for TRG (as can be seen in the third column of Table 2).

Table 3 presents the inventory data used to model the Polypropylene recycling, which was gathered based on a recent Report on Plastic recycling in the United States [7]. Electricity environmental data of the recycling facility was adapted for the medium voltage Portuguese electricity mix.

3. Results and discussion

In this section, the life cycle primary energy and carbon emissions of the three product alternatives are presented and discussed. Fig. 3(a) presents the global warming potential and Fig. 3(b) presents the life cycle renewable and non-renewable primary energy. Results show that the primary energy associated with this product development is mostly non-renewable, this is mainly because the materials used (PP and SR) are primarily derived from petroleum hydrocarbons, thus, being fossil-fuel based. In the conventional alternative (A) the rubber (SR) and the thermoplastic material (PP) together are accountable for more than 90% of the non-renewable embodied energy of the product and for more than 80% of life cycle carbon emissions.

Table 1. Road-safety barrier, product production inventory.

	Product production inventory		Amount	Transport Distance [km]	Alternative		
					A	B	C
Inputs:	Rubber	SR [kg]	10.01	200	•		
		TRG [kg]		165		•	•
	Thermoplastic	PP [kg]	8.19	2600	•	•	
		RPP [kg]		16			•
	Additive, Maleic anhydride, RER [kg]		0.96	1900	•	•	•
	Extrusion, [kWh]		9.73	–	•	•	•
Outputs:	Wastes, blended [kg]		0.08	–	•	•	•
	1 Product [kg]		19.08	–	•	•	•

Synthetic rubber (SR). Tire rubber granulate (TRG); Polypropylene (PP); Recycled PP (RPP).

Table 2. Tire recycling inventory, TRG production. FU: one road-safety barrier product.

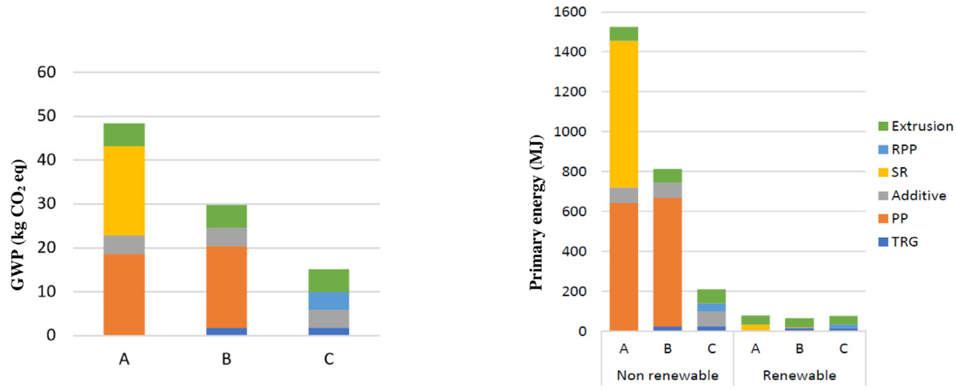
	TRG inventory	Amount	Amount per FU	TRG Mass allocation per FU
Inputs:	EoL Tires [kg]	1000	14.70	10.01
	Primary Grinding [kWh]	47.2	0.69	0.43
	Water [kg]	150	2.20	1.50
	Secondary Grinding [kWh]	153.8	2.26	1.54
	Granulation [kWh]	103.4	1.52	1.03
	Packing of TRG [kg]			10.01
Outputs:	TRG [kg]	681	10.01	10.01
	Metal scrap [kg]	275.5	4.05	–
	Textile fibers [kg]	43.5	0.64	–
	Particulates [g]	0.19	0.003	0.002

Table 3. Polypropylene recycling inventory, RPP production for one road-safety barrier (FU).

	RPP inventory	Amount	Amount per FU
Inputs:	Treatment/sorting of waste, for recycling [kg]	1058	14.7
	Transport, lorry (>32 mton) Euro 4 [ton km]	16.3	0.13
	Water [kg]	394.8	3.23
	Chemical inorganics [kg]	2.9	0.02
	Electricity [kWh]	530.0	4.34
	Heat, district or industrial, natural gas [MJ]	957.5	7.84
	Sodium hydroxide, without water, in 50% solution state [kg]	15.5	0.13
	Waste preparation facility [unit]	0.69	0.01
Outputs:	RPP [kg]	1000	8.19
	Particulates, < 2.5 µm [g]	15.0	0.12
	Particulates, > 2.5 µm, and < 10 µm [g]	23.0	0.19

Regarding the comparison among product alternatives, a significant non-renewable primary energy reduction (over 46%) is achieved with the incorporation of recycled TRG (in B) when compared with the conventional product (A), and an impressive reduction of around 82% can be achieved if both conventional materials are replaced by recycled materials TRG and RPP (C). In the alternative C the processes with highest primary energy are the material production of the additive and the molding process (extrusion).

The CO_2 emissions trend among scenarios is strongly related to their non-renewable energy consumption. Whereas the conventional product alternative (A) was responsible for around 48 kg CO_2 eq. emissions, alternative B reduced potential emissions by 38%, and the alternative C reduce emissions by 68.5%. The processes with the highest CO_2 emissions in C are extrusion, TRG production and the additive's material production. Given that the tire recycling impact was not allocated to the different secondary materials that can be recovered to re-use from tire recycling, it is likely that the embodied impact of tire rubber granulates is lower than the one considered.



a) b)

Fig. 3. Life cycle results for one road-safety barrier: (a) global warming potential (kg CO_2 eq.); (b) Cumulative primary energy demand (MJ).

4. Conclusion

This study used LCA to analyze the life cycle primary energy and carbon emissions associated with a new road-safety barrier product in a preliminary stage of product development. The goal was to inform decision regarding the environmental benefits of incorporating recycled materials such as TRG and recycled PP in comparison to a conventional material blend of synthetic rubber and PP. The study showed that from a life cycle primary energy and CO_2 emission point of view, the use of TRG is preferable when compared to synthetic rubbers' use, allowing to reduce the non-renewable primary energy of the product by over 46% and its carbon emission by 38%. The combined use of two recycled materials (TRG and RPP) achieved a substantially higher reduction (-82% of primary energy and -68% of CO_2 emissions) than the product with conventional virgin materials. Thus, the use of recycled materials should be urgently encouraged, for instance in molded products like this, where aesthetic requirements are not as stringent as in other products and with the proper geometric optimization to achieve the functional requirements. In this sense research projects and initiatives that promote eco-design and secondary material incorporation are of paramount importance to support new circular business models.

CRediT authorship contribution statement

H. Monteiro: Investigation, Supervision, Validation, Writing – original draft preparation, Writing – review & editing. **I. Ribeiro:** Investigation, Formal analysis, Writing – original draft. **M. Gonçalves:** Writing – review & editing. **M. Iten:** Writing – review & editing. **N.S. Caetano:** Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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