PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Exergy cost associated with polymers recycling in vehicles: from qualitative to quantitative indicators

***Sofia Russo*[a], *Alicia Valero*[b], *Marta Iglesias-Émbil*[c], *Ricardo Magdalena*[d] and *Abel Ortego*[e]**

[a] *CIRCE Institute, Universidad de Zaragoza, Spain, srusso047@gmail.com*
[b] *CIRCE Institute, Universidad de Zaragoza, Spain, aliciavd@unizar.es*
[c] *SEAT-SA, Martorell, Spain, marta-esther.iglesias@seat.es*
[d] *CIRCE Institute, Universidad de Zaragoza, Spain, rmagdalena@unizar.es*
[e] *CIRCE Institute, Universidad de Zaragoza, Spain, aortego@unizar.es*

Abstract

Implementing a recycling route for vehicle plastics surely represents a challenging mission for a company. In general, the recyclability of automotive plastic is influenced by the nature of the polymer (i.e. the material cannot be recycled or recycling would cause deterioration of its properties) or by the lack of an industrial recycling system. In general, there are several technological and economic barriers that must be overcome through design innovation and logistical measures. Based on these factors, an arbitrary scale has been first developed to translate the qualitative indicators into a numerical score that can be useful for comparing different plastic components in a vehicle. Then, the various indicators have been translated in exergy terms, for giving an idea of the order of magnitude of the resources invested in developing the recycling process. Therefore, a new methodology for including critical recycling factors in the total exergy recycling cost is here presented.

Keywords

Exergy, Resource assessment, Recycling, EoL vehicles, Eco-design

1. Introduction

The correct final disposal of End-of-Life Vehicles (ELVs) is still a crucial worldwide issue. At European level, many directives have been implemented in order to regulate the materials used in vehicles and the steps of their end of life (i.e. depollution, dismantling, shredding, and landfill). In particular, the EU Directive 2000/53/EC has set the recycling/recovery target for vehicle to 85% by 2006 and 95% by 2015. This means that from 2015, recovery requirements should achieve the target of at least 95% (with a maximum energy recovery of 10%) and a minimum of 85% of the total material must be reusable and recyclable. The compliance of the EU Directive has been accompanied by a changing in the material composition of cars. According to the EU 2000/53/EC definitions, reuse means "any operation by which components of ELVs are used for the same purpose for which they were conceived", while recycling means "the reprocessing in a production process of the waste materials for the original purpose or for other purposes but excluding energy recovery". In this view, plastic materials comply with this standard, since they are theoretically reusable and recyclable. Moreover, their low cost and weight make them even more appealing for cars manufacturers. As a consequence, in the last 10 years, the percentage of plastic in vehicle increased, being the reduction in weight also justified by a decrease in fuel consumption [1]. The current amount of plastic is between 15-17% of the car total weight and 50% of its volume [2]. Currently, the 10% of the global European demand of plastic is for the automotive sector [3][4]. In the last 15 years, an impressive enhancement of End of Life Vehicles (ELVs) occurred, due to the shortening of the cars average life, estimated in 10-12 years [5]. According to a survey delivered by the EU commission [6], the ELVs legally deregistered produce every year between 7 and 8 million tonnes of wastes; anyway, considering also the number of estimated 'unknown whereabouts' vehicles, the total increase to 13-15 million tonnes of wastes. Apart from sporadic cases, plastics in ELVs are not recycled. During the pre-shredding phases of depollution and dismantling, the amount of plastic that can be 'incidentally' reused (e.g. tyres, bumpers, tanks) does not exceed 25% of the total [7]. Considering an average weight of vehicle of 1250 kg, it means that 150 kg of mixed plastics per

https://doi.org/10.52202/069564-0278

vehicle are discarded, shredded and ultimately landfilled. Therefore, only in EU about 2 millions of tonnes of plastic are dispersed every year due to the automotive sector, approximately 4 kg per person. For comparison, the average production of plastic packaging per year in EU is 31 kg per person [8]. The fact that plastics in vehicle are merely reused or recycled leads to ah huge dispersion of resources. An estimation of the resources embodied in the polymeric content of the ELVs has already be presented in Russo et al. [9], where the concept of Embodied Exergy (EE) is used for assessing the material and energy consumption in each step of polymers production and recycling routes. It resulted that, for the analysed vehicle, about 18.3 GJ of exergy are embodied in the plastic content, only considering the polymers processing and feedstock contribution.

1.1 Recycling practices

The inclusion of recycling in the automotive sector can follow various paths, which can be eventually linked in a closed-loop vision: (i) recycling of plastics to be used in non-automotive applications (i.e. open-loop recycling); (ii) recycling of plastics to be re-integrate in vehicle components (i.e. closed-loop recycling); (iii) integration of recycled plastic from other waste sources, e.g. municipal solid waste (i.e. reverse open-loop recycling. The more diffused practice is the integration of recycled plastic from external sources [10]. However, between the recycling schemes, the closed-loop might assure a predictable and secure source of material, overcoming the problem of scarcity in recycled plastic supply. The recycled material can be used for the same component fabrication or for lower mechanical performance applications. In fact, since mechanical recycling always leads to partial degradation of polymer mechanical properties, solutions have to be adopted. The options are the blending with virgin plastics or the incorporation of additives.

1.2. Recycling issues

Implementing a recycling path for vehicle plastics surely represents a challenging mission for a company. In general, the recyclability of automotive plastic is influenced by the nature of the polymer (i.e. the material cannot be recycled or the recycling would lead to deterioration in its properties) or by the lack of an industrial recycling system. Therefore, there are a series of technological and economic barriers that must be overcome by design innovation and logistic measures**.** A list of the main limits and issues of recycling is reported below.

- ***Compatibility of polymers.*** Nowadays, vehicles contain from 20 to 40 types of polymers [11]. Different polymeric materials are often incompatible at the time of recycling. Mixing of incompatible plastics leads to a recycled material with degraded properties, that cannot be re-used for the same noble application; the tolerance rarely exceeds 2% of contaminants in a mixture; compatibility can change according to the types of polymers [12]. Vehicle parts are practically always made of more than one plastic, but many times this is due to aesthetic reasons. This is the case of the polymer-based surface coatings, films or paint, which are included for obtaining the textile or leather appearance to plastics. Even if the use of compatibility additives is lately gaining attention in recycling practice [], they still represent an extra cost for recyclers and are generally not used, aside from antioxidants.

- ***Use of additives and fillers.*** Additives and fillers are incorporated into the polymers for enhancing mechanical characteristics, strength, fire resistance and for colouring. Additives can hinder the recycling for several reasons: health hazards due to presence of heavy metals and halogens (Br, Cl, F) or incompatibility of different flame retardants; impossible separation of fibres (glass or natural) from the polymer; lack of information on additive composition, which makes impossible the plastic sorting. It is not easy to find information on the degree of tolerance of additives in the recycling process. The fact that many of them are not declared means that the resulting polymer composition is unclear. In addition, given the wide use of additives, the combinations can be multiple and the final composition very varied. For each case, experimental studies must be carried out to quantify the degradation of the material and its possible re-use for different applications. In general, many types of additives migrate from one polymer to another during recycling []. For the purposes of this paper, we will focus on the declared additives found in large quantities in vehicle components: glass fibres, talc, titanium and carbon oxides. The objective is to find out the tolerance range of these additives in the recycling process. The benchmark studies used are as follows. In [13], Pegoretti et al. describe the various recycling alternatives (i.e. mechanical recycling, use of recycled matrices, use of recycled fibres, use of waste composites, chemical recycling) and provide a literature review on various recycling processes of reinforced polymers. It is highlighted that in mechanical recycling processes the percentage of glass fibres never exceeds 40% of the total polymer matrix, while for talc we report examples with samples up to 20%; data on mechanical characteristics of recycled materials are also reported. The study of Scaffaro et al. [14] focuses more on a review of the various recycling processes of carbon and glass-fibre reinforced polymers and the modification of the mechanical characteristics of the material that affect the field of reuse. Among the results, it is highlighted that recycled composites can be reused for the same applications, when the properties do not change much after recycling, or recycled to applications that require less performance. The main disadvantage lies in the loss of fibre structure and length due to fibre size reduction. The need for milling and grinding steps before the remanufacturing process can also increase the operational cost (even non-standard equipment may be required, able to withstand the wear caused by the fibre during milling). Still, the authors were able to obtain compression-moulded panels with good tensile strength and the same flexural properties as virgin composites by adopting a 'sandwich', multilayer configuration in which virgin material was used as the outer layers and recycled material was used as the core layer. By doing so, 50% of the volume of the virgin material could be replaced by recycled material while maintaining good mechanical properties. An experimental estimation of the additional energy required for the recycling process of PET with 30% glass fibres is given in [15]. In [16], the authors analyse the effect of titanium oxide on the plastic matrix up to concentrations of 12%. A general resume of the allowed additives, in the hypothesis of excellent quality of the recycled products is given in [..]; according to this review, flame-retardants, high concentrations of glass fibres (> 10%), vegetable fibres, nano-particles, pigments with heavy metals are totally not tolerated; small fibres concentrations (< 5%) are partially tolerated, while talc, calcium carbonate, barytes and TiO_2 are admitted for recycling. In general, in order to have noble outlets, i.e. with a property loss <5%, the impurity rate during the sorting process must be <3%. As for carbon, no studies have been found that analyse the criticalities in the recycling phase (apart from the problems of optical separation due to the black colour), so a good tolerance is assumed.

- ***Recycling volumes and dismantling time***. In order to make the recycling process economically viable, consistent recycling volumes of the same polymer have to be achieved. In fact, the investment in dismantling operations must be offset or exceeded by revenues from the sale or reuse of dismantled plastics. Polymer recovery for recycling can take place both upstream and downstream of shredding phase. The degree of precision in polymer recovery at the 'pre-shredding' stage determines the extent and therefore the cost of the dismantling stage. The number of different polymers and vehicle subcomponents, the compatibility of polymers in recycling and the presence of mechanical or adhesive connections between parts of different materials are the influencing factors of the dismantling time. For evaluating the dismantling cost, it would be necessary to have empirical data on dismantling operation and to know the type of dismantling methodology (e.g. manual, mechanized). The energy and monetary cost of the labour could then be accounted with various methodology. As an example, Sciubba et al. [17] have included labour and capital in the exergy assessment.
- ***Supply stability and lack of market demand.*** One of the major limits of plastic recycling is the lack of an industrial and well-assessed market for recycled materials. The relative low-cost of virgin plastic material is still a barrier to the development of a circular economy of plastics, since the costs of installing a new recycling plant is not compensated by the revenues. As consequence, often the companies have doubts about including recycled plastics, because of the concerning of not having stable supply.

1.3. Aim of the analysis

The aim of the present work is to assess methodologies for evaluating the recyclability of polymers in vehicles, including all the factors that influence the process and giving an order of magnitude of the exergy cost associated to recycling of EoL vehicle components. In order to do that, a first qualitative analysis is developed for assessing all the recyclability crucial factors, followed by a translation of some of them into exergy terms.

https://doi.org/10.52202/069564-0278

2. Methodology

2.1. Recyclability table

First, based on the critical factors expressed above, an arbitrary scale (Table 1) has been developed to translate the qualitative indicators into a numerical score that can be useful to compare different polymeric vehicle components. The number of polymers and subcomponents and the compatibility of polymers in recycling influence the dismantling time; the compatibility of additives and fillers in recycling and the presence of adhesives or coatings influence the effective recycling of the polymers, while the compatibility in density separation has an effect on the post-shredding recovering. The scale is arbitrary, decided after empirical attempts in comparing resulting scores for different components. In fact, the main goal is to quantify the qualitative characteristics influencing recyclability and to compare different vehicle parts. For this work, data on vehicle plastic composition have been provided by Seat-SA for a 350 Seat Leon. Four components have been chosen for the analysis: rear bumper, dashboard, floor covering and rear seats. The analysis of vehicle components starts with the identification of the main polymeric materials (present in quantities higher than 1 g) and the main subcomponents containing them. If the same polymer is present but containing different additives, it counts as a different polymer. Resins, adhesives and not-declared additives are not included in the computation of polymers. Then, the recyclability table factors have been identified and a total score from 0 to 5 is assigned to each category. For the compatibility indicators, the main polymers (i.e. the polymers that embodied the majority of the weight) are taken as reference; a weighted average is calculated for assigning the final score, considering that the presence of recycling technologies has a relatively higher importance than the other factor (weight percentages are reported in Table 1). Obviously, this procedure is not based on an absolute criterion, but it is based on common practice and empirical considerations.

Table 1 – Recyclability table for score assigning according to critical factors

	Score	0	1	2	3	4	5
A	**Number of main polymers:** polymeric materials present in quantities higher than 1 g are identified [10%]	≥8	7	6	5	4	≤3
B	**Number of main subcomponents**: only subcomponents containing polymers are considered [10%]	≥16	13-15	10-12	7-9	4-6	≤3
C	**Compatibility of polymers in recycling:** mean value based on the main polymer compatibility with each of the others [10%]	If not compatible		2.5 If limited compatibility for moderate quantities			If 100% compatible
D	**Compatibility of additives and fillers in recycling:** mean value based on the main polymer compatibility with their additives [10%]	Prohibited additive	>60%wg	40-60%wg	20-40%wg	≤20%wg	No additive
E	**Compatibility in density separation:** mean value based on the main polymer compatibility [10%]	Overlapping densities					No overlapping densities
F	**Presence of coatings:** paint and skin can be present and should be chemically removed [10%]	Prohibited coatings	On the main polymer (main part)	On the main polymer (secondary parts)	On the other polymers (main part)	On the other polymers (secondary parts)	No coatings
G	**Presence of adhesives:** adhesives in high quantities can hinder the recycling [10%]	Prohibited adhesives	On the main polymer (main part)	On the main polymer (secondary parts)	On the other polymers (main part)	On the other polymers (secondary parts)	No adhesives
H	**Presence of recycling technologies** for the main polymer for the same application (closed loop) [30%]	No recycling technologies		2.5 If limited technologies are present			Well developed recycling technologies

2.2. Exergy cost of recyclability

The score may be important for a first comparison, but it does not give an idea of the order of magnitude of the energy and resources invested to develop the recycling process. For this reason, the attempt has been trying to translate some indicators using exergy. The initial idea is that all indicators express characteristics that make recycling more difficult and consequently more expensive in terms of resources and money. The recycling routes assessed in [10] referred to 'standard' recycling process, namely they refer to basic polymers (those generally used for packaging), without additives or in percentages compatible with recycling. Due to the lack of information on the effective additional energy burden associated to vehicle dismantling, polymer separation and recovering and coatings and adhesives removal, the analysis has been focused on the recycling of polymers with additives and fillers. According to the review presented in Section 1.2., a set of rules has been chosen as reference for evaluating additives presence in vehicle components and hypothesis of recycling, as presented in Table 2. No declared additives in plastic components are generally lower than 5%, even if it is not possible to know their composition. Concentrations higher than the ones reported in Table are supposed to be not allowed. Therefore, three recycling scenarios are analyzed; every scenario is analyzed in terms of Embodied Exergy in the operations of dismantling of the old vehicle polymeric component and making of the new one, as follows.

Table 2 – Admitted additives and recycling options

Additive		Recycling
Talc <20%	Admitted	Polymer 100% recycled
Titanium Dioxide <15%	Admitted	Polymer 100% recycled
Glass fibers <5%	Admitted	Polymer 100% recycled
Glass fibers 5%<GF<40%	Partially admitted	Multilayer - Polymer 50% recycled 50% virgin
No declared additives >5%	Partially admitted	Multilayer - Polymer 50% recycled 50% virgin

- **1st scenario: No recycling.** In case of no recycling all the EE of the polymers in the vehicle component is lost and it is necessary the same amount of EE for remanufacturing them
- **2nd scenario: Recycling only the main polymers in closed-loop,** according to the limitations and the recycling options reported in Table 2. The other polymers are reintroduced as new, so their EE is lost; in case of multilayer configuration, also the EE of the 50% of polymer is lost. The same amount of EE is necessary for remanufacturing them.
- **3rd scenario: Recycling the main polymers in closed-loop and inclusion of recycled polymers from open loops,** according to established markets**.** The EE of the replaced polymers is lost but less exergy is required for their new production, since they come from recycling routes.

In all three cases, the total EE (EE_{tot}) is taken as comparison indicator, being the sum of the EE lost (EE_{lost}) within the old vehicle component and the EE necessary for its new production ($EE_{new\ prod}$), Equation 1.

$$EE_{tot} = EE_{lost} + EE_{new\ prod} \tag{1}$$

In order to perform the calculation the values of EE associated to polymers production and recycling reported in Table 3 are considered [10]. The EE values of production refer to the process only (i.e. from naphtha steam cracking to polymerization), without including the feedstock part or the exergy replacement cost of fuel in the environment. The EE values of recycling refer to standard recycling processes found in literature. The values of EE_{lost} and $EE_{new\ prod}$ were then calculated as the sum of the products of the EE of polymers for the respective quantity in the vehicle part

Table 3 – Production and recycling Embodied Exergy

Polymer	EE of production (MJ/kg)	EE of recycling (MJ/kg)
PP	39	3
PE	24.3	3
EPM	32.3	11.4
PVC	25.5	1.1
PU	41	5.3
PA	59.3	10.3
PET/PES	51.2	4
SBR	73	11.4
EPDM	55.9	11.4
ABS	69.8	2.3
PC	48.8	3
PMMA	48.8	3

https://doi.org/10.52202/069564-0278

3. Results

3.1. Qualitative indicators

First, the material composition of the four plastic components have been analyzed, mapping the distribution of polymers among the subcomponents. Results are reported in Tables 3-6. If the same polymer is present with different additives, it counts as a different polymer.

Table 3 – Plastic composition and distribution in rear bumper

Rear bumper					
Sub-component	**Material**	**g**	**Additive**	**g**	**TOT**
Main bumper part	PP	2627.3	ND 5%	175.2	2802.5
Diffuser	EPM	725.6	Talc 12%	83.5	809
Mobil guides	EPM	212	Talc 12%	24.4	236.4
Hook cover	EPM	7.5	Talc 12%	0.86	8.4
Screws	PA66	1.9	ND 1.5%	0.03	1.93
Soundproofing	PET	39.6	Titan Dioxide 1%	0.3	39.9
Plaque cover	EPM	464	Talc 5%	53.4	517.4
	PE foam	18.9			18.9
LED housing	PC	12	ND 1.5%	0.2	12.2
Lens	PMMA	4	ND 0.25%	0.1	4.1
Catadioptric lampshade	PMMA	36.4	ND 2%	0.7	37.1
Catadioptric housing	PC+ABS	26.8	ND 1%	0.3	27.1
TOTAL		**4175.9**		**339**	**4514.9**

	PP	**EPM+Talc**	**PMMA**	**PET**	**PC+ABS**	**PE**	**PC**	**PA66**
Tot (g)	2802.5	1571.2	41.2	39.9	27.1	18.9	12.2	1.93
% on total plastic wg	**62.1**	**34.8**	**0.9**	**0.8**	**0.6**	**0.4**	**0.3**	**0.1**

Table 4 – Plastic composition and distribution in dashboard

Dashboard					
Sub-component	**Material**	**g**	**Additive**	**g**	**TOT**
IP Carrier	PP	1106	GF 60%	1843.2	2949.2
	PVC flexible	511.6	ND 6%	62.1	573.7
	PU foam	604.8	ND 1%	6.1	610.9
	PET fibre	6.6			6.6
Airbag bracket	PP	170.4	GF 36%	284	454.4
Central defrost	PP	480.5	Talc 25%	166.9	647.4
IP upper defrost cover	EPM	699.8	GF 25%	243	942.8
Double DIN carrier	PP	257.7	GF 60%	429.5	687.2
Panel drivers lower	EPM	178.2	Talc 15%	32.6	210.8
Panel passenger lower	EPM	144.8	Talc 15%	26.5	171.3
Light switch support	PP	38.4	Talc 25%	13.35	51.75
Kombi support	PP	65.7	GF 60%	65.7	131.4
Manifold Air Distribution	PP	155	Talc 25%	53.8	208.8
Air canal	PE	380.6	ND 1%	2.4	383
Defrost canal	PE	237.6	ND 1%	1.7	239.3
Gasket	PU	1.2	ND 3%	0.03	1.23
Side defrost	EPM	18.2	Talc 15%	3.45	21.65
TOTAL		5057.1		3234.3	**8291.4**

	PP+GF	**PP+Talc**	**EPM+GF**	**PE**	**PU**	**PVC**	**EPM+Talc**	**PET fibre**
Tot (g)	4222.2	907.95	942.8	622.3	612.1	573.7	403.75	6.6
% on total plastic wg	**50.9**	**10.9**	**11.4**	**7.5**	**7.4**	**6.9**	**4.8**	**0.2**

Table 5 – Plastic composition and distribution in floor covering

Floor covering					
Sub-component	**Material**	**g**	**Additive**	**g**	**TOT**
Floor carpet	SBR	48.6	GF 65%	105.2	161.9
			ND	8.1	
	PET fibre	1391	ND 1%	14.05	1405.1
	PE powder	161.1	ND 0.5%	0.8	161.9
Propylat support	PP fibre	575.5	ND 1%	5.8	581.3
	PET fibre	362.7	ND 1%	3.7	366.4
Plastic film	PE	57.2			57.2
Fixing floor carpet	PA66	7.4	GF 30%	3.2	10.76
			ND	0.16	
Cover floor carpet	PA66	8.1	ND 1%	0.12	8.22
TOTAL		**2611.6**		**141.3**	**2752.7**

	PET fibre	**PP fibre**	**PE powder**	**SBR+GF**	**PE**	**PA66+GF**	**PA66**
Tot (g)	1771.5	581.3	161.9	161.9	57.2	10.8	8.2
% on total plastic wg	**64.3**	**21.1**	**5.9**	**5.9**	**2.1**	**0.4**	**0.3**

Table 6 – Plastic composition and distribution in rear seats

Rear seats					
Sub-component	**Material**	**g**	**Additive**	**g**	**TOT**
PU foam	PU foam	2990.46	ND 1.5%	45.4	3036.1
Seats cover	PU foam	63.4	ND 1.5%	1	64.41
	PET fibre	174.1	ND 2.5%	4.6	178.7
	PES fibre	35.96	ND 0.5%	0.2	36.14
	PU	12,77	ND 1.5%	0.2	12.97
	PES fibre	62,01	ND 0.5%	0.3	62.3
	PU	43.3	ND 1.5%	0.7	43.98
	PES fibre	29.4	ND 3%	0.9	30.3
	PU	29.68	ND 5.2%	1.6	31.3
	PU	7.36	ND 1.5%	0.1	7.5
	PET	35.5	ND 4.5%	1.7	37.2
	PU	20.37	ND 3%	0.6	20.97
	PAN fibre	1.01	ND 0.5%	0.05	1.1
	PES fibre	6.77	ND 0.35%	0.02	6.8
	PET fibre	40.18	ND 0.5%	0.02	40.2
	PU	13.3	ND 1.5%	0.2	13.5
	PES	16.77	ND 0.3%	0.04	16.8
	SBR	3.15			3.15
	PU	13.35	ND 1.5%	0.2	13.55
	PES	6.2			6.2
TOTAL		3605.1		57.95	**3663.1**

	PU foam	**PET fiber**	**PES fiber**	**PAN fiber**	**SBR**
Tot (g)	3244.3	256.1	158.5	1,1	3.15
% on total plastic wg	**88.5**	**6.9**	**4.3**	**0.1**	**0.2**

Then, a score is assigned to each component according to the recyclability table. Results are shown in Table 7, where details on the presence of each indicator are reported. An average value is also calculated. According to this scoring, the best component in terms of recyclability is the rear bumper. More detailed comments are reported below.

https://doi.org/10.52202/069564-0278

Table 7 – Results of application of recyclability table

	Rear bumper		Dashboard		Floor covering		Rear seats	
		Score		**Score**		**Score**		**Score**
A	7	2/5	8	0/5	7	1/5	5	3/5
B	11	1/5	14	0/5	5	4/5	2	5/5
C	PP has a limited compatibility with PC+ABS, PA, PMMA and PET and is not compatible with EPM and PE fiber.	1.7/5	PP has a limited compatibility with PVC and PU. PP compatible with PE and not compatible with EPM and PET fiber.	2/5	PET not compatible with any polymer	0/5	PU foam is not compatible with any polymer	0/5
D	Talc, TiO_2 and not declared additives.	4.5/5	Talc admitted and GF not allowed in this percentage.	2.5/5	GF not compatible in this percentage	4.7/5	Only not declared additives in small percentage are present	4/5
E	PP and EPM not compatible	4/5	PP only compatible with PU, PET fiber and PVC	2.5/5	PET not compatible with PA66	4/5	PP has no overlapping densities with other polymers	5/5
F	TiO_2, PU and acrylic resin	1.5/5	No	5/5	PE powder	1/5	Yes	2/5
G	Soundproofing and cover plate	4/5	PU basket	3/5	Plastic film	4/5	Yes	2/5
H	Limited recycling options for EPM+GF	3.75/5	No options for PP+60GF, limited options for EPM+25GF	3.1/5	No closed loop recycling options	0/5	No closed loop recycling options	0/5
	Average value	**3**		**2.4**		**1.9**		**2.1**

3.1.1. Comments

- **Rear bumper.** The main polymer is PP, even if EPM is present in a consistent amount. These two polymers have overlapping densities, so they should be separated before shredding. This means that the diffuser, the mobile guides, the hook cover and the plaque cover should be removed and processed separately. PP has a limited compatibility with the other polymers, even if the level of impurity in recycling should not exceed 2%. For reducing the impurities, some parts should be removed, such as the lens and the catadioptric or the soundproofing. The possibility of dismantling the various parts of the bumper depends on the facility of removing the adhesives and the mechanical junctions. Coatings are present on the surface of the main PP bumper part in a weight percentage of 3.9%; they should be chemically removed before shredding and recycling.
- **Dashboard.** The main recyclable polymer is PP filled with GF or talc, followed by EPM with GF. Since these two polymers have overlapping densities, they should be separated before shredding. Glass fibres content in these percentages hinders the recycling. Even if PP has a limited compatibility with low volumes of PVC and PU, the quantities of PVC and PU are in the same order of magnitude. Flexible PVC and PU foam are all concentrated in the IP carrier subcomponent and they should be separated and recycled separately, as well as PVC and PET fibre contained in the airbag hinge. PU of the gasket could be eventually processed with PP, since they represent an impurity lower than 2%.
- **Floor covering.** This is a component where polymeric materials are mainly used as textiles. The main burdens are represented by the scarce compatibility of PET and PP fibres, the poor practice in polymer fibres recycling and the presence of PE coatings and films. The main material is PET fibre, which is present in the floor carpet and the propylat support. PET is not compatible with PP fibre so these materials should be separated. PE powder used for coating should be removed. Moreover, SBR and PA filled with these percentages of glass fibres are not compatible for recycling and have to be separated and processed separately. Recycling of PET and PP fibres is scarcely diffused, even if the process is possible and some technologies are available; however, many times these materials are reemployed in secondary application (e.g. filling, insulation). For all these reasons, the recoverable volume for this component is pretty low.

- **Rear seats**
  This is a component where polymeric materials are mainly used as fillers (i.e. foam). The main burdens are represented by the absence of closed loop recycling options for PU foam and the scarce compatibility in recycling PU with other polymers. The only advantages are the few number of polymers and sub-components that facilitates the dismantling and the not overlapping density of PU with the other polymers, for an eventually separation after shredding. PU foam can be reused for secondary applications of filling, even if closed loop practices for vehicle applications are not documented.

3.2 Quantitative indicators

The methodology described in Section 2.2 is then applied to the four components, analyzing the three scenarios. Table 8 reports the results of calculation of the lost and new production EE and the total value with an explication for each component. Values of EE are given in MJ.

Table 8 – Results of calculation of EE for the three scenarios

	1st scenario No recycling			**2nd scenario Recycling only the main polymers in closed loop**			**3rd scenario Recycling the main polymers in closed loop and inclusion of recycled polymers from open loops**		
	EE_{lost}	$EE_{new\ prod}$	EE_{tot}	EE_{lost}	$EE_{new\ prod}$	EE_{tot}	EE_{lost}	$EE_{new\ prod}$	EE_{tot}
Rear bumper	154.5	154.5	**309**	42.9	54	**96.9**	42.9	52.1	**95**
	All the EE of the component is lost, and it is necessary the same amount of EE for reproducing it			PP and EPM are recycled in closed loop; PP is totally recycled since 5% of additives are allowed, while recycled EPM is included in percentage of 20/80 ratio; other polymers are reintegrated as new			PP and EPM are recycled in closed loop as in the 2nd scenario; PET is included as recycled material, so their 'first' EE is lost but less exergy is required for their new production		
Dashboard	175.7	175.7	**351.4**	147.2	150	**297.2**	147.2	57.8	**205**
	All the EE of the component is lost, and it is necessary the same amount of EE for reproducing it			PP and EPM cannot be recycled in closed loop with these percentage of GF. Talc is admitted so PP+talc is totally recycled and EPM+talc is included in 20/80 ratio.			PP with GF is included as recycled material (only PP part). EPM is included as recycled in 20%. PET and PE are included as recycled, but not PU and PVC		
Floor covering	122	122	**244**	-	-	-	122	13.3	**135.3**
	All the EE of the component is lost, and it is necessary the same amount of EE for reproducing it			Closed loop recycling is not assessed for the main polymers (PET fiber); SBR cannot be recycled with this percentage of GF			SBR is partially introduced as recycled material (20/80 ratio), while PET and PP fibers and PE are 100% substituted. PA is always included as new material		
Rear seats	152.2	152.2	**304.3**	-	-	-	152.2	132.9	**285.1**
	All the EE of the component is lost, and it is necessary the same amount of EE for reproducing it			Closed loop recycling is not assessed for the main polymers (PU foam)			PU foam is not reccyled in general; only recycled PET/PES can be included		

A graphical representation of the results is shown in Figure 1, while a comparison between the scenarios is presented in Figure 2. The four components have been chosen because they are examples of different cases that can occur when recycling vehicle parts. As expected, there is always a saving in performing some type of recycling; the amount of saving depends on the polymeric composition. In the rear bumper the difference is evident (- 68.6% in the 2nd scenario), since it is composed mainly of PP, which could be completely recycled, and of EPM which can be included in multilayer configuration. ncluding PET from recycled material in the 3rd scenario leads to a further saving of 2%. The step is less evident for the dashboard; here the main polymers, PP and EPM, are present both with talc and GF. Polymers with GF in these percentages cannot be recycled for closed loop application, so only the polymers with talc can be substituted in the second scenario (-16.8% of EE). PET, PE and the polymeric matrix of PP and EPM with GF can be introduced as recycled material in the 3rd scenario, being the saving more evident (-41.6%). The floor covering is an example of component made mainly of textile; in this case the majority of fibers are of PET and PP. Closed loop fiber recycling is not industrially well assessed, so the second scenario is not analyzed. On the other hand, recycling from plastic to fiber is very common, so recycled fibers can be 100%

substituted leading to a saving in 44.5% in the exergy of new production. Finally, rear seats are an example of component made of filler material (i.e. foam) and fibers. Since PU foam is generally not recycled, 2nd scenario is not analyzed; in the 3rd scenario PU is included as new polymer, so that the savings are not so consistent (-6.3%).

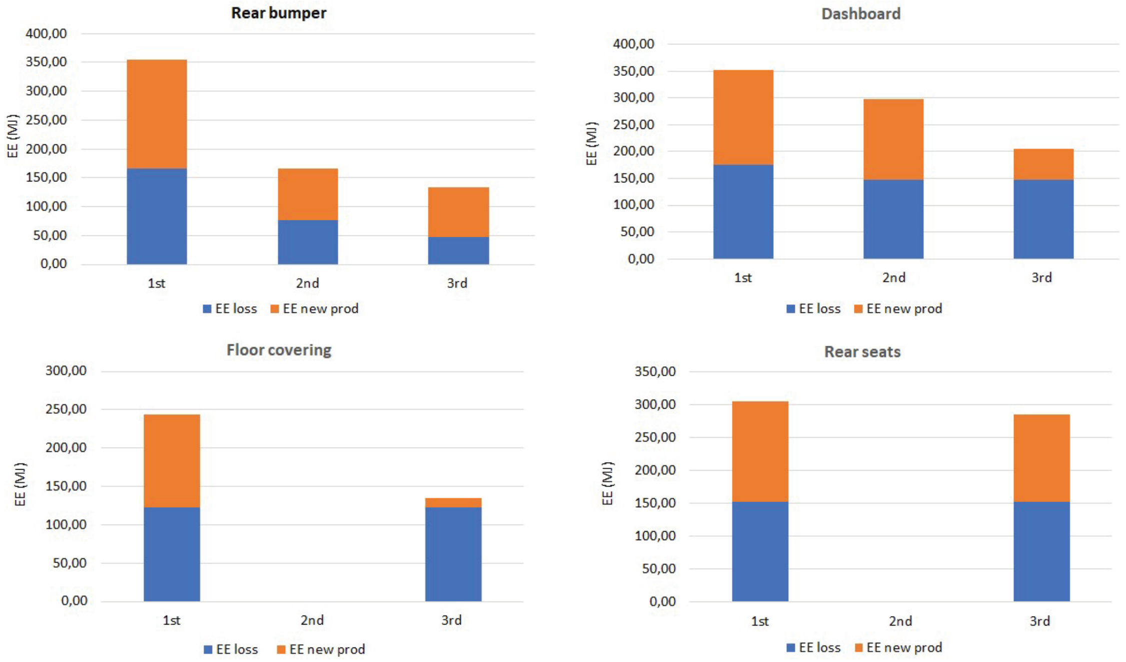

Figure 1 – EE values for the four components in the three scenarios

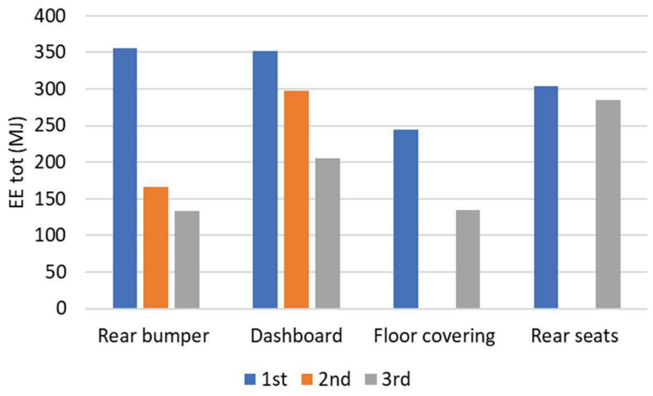

Figure 2 – Comparison between the total EE for the three scenarios

4. Conclusions

The aim of the present work was to assessing methodologies for evaluating the recyclability of polymers in vehicles, including all the factors that influence the process and giving an order of magnitude of the exergy cost associated to recycling of EoL vehicle components. In order to do that, a first qualitative analysis is developed for assessing all the recyclability crucial factors, followed by a translation of some of them into exergy terms. In order to do so, first, based on the critical factors, an arbitrary scale has been developed to translate the qualitative indicators into a numerical score that can be useful to compare different polymeric vehicle components. Then, some of these indicators have been translated using exergy and the values of total EE have been calculated for three recycling scenarios. Results show that, according to the scoring, the best component in terms of recyclability is the rear bumper, due to the high percentage of PP with no additives, while the worst is the floor covering, mainly due to the absence of recycling process for PET fibers. The analysis of the recycling scenarios underlines that savings between 1st and 2nd scenarios are more evident for the rear bumper and floor covering.

[1] Wen Zhang, Jun Xu, Advanced lightweight materials for Automobiles: A review, Materials & Design, Volume 221,2022,110994,ISSN 0264-1275,https://doi.org/10.1016/j.matdes.2022.110994.

[2] Miller, L.; Soulliere, K.; Sawyer-beaulieu, S.; Tseng, S.; Tam, E. Challenges and Alternatives to Plastics Recycling in the Automotive Sector. Materials 2014, 7, 5883–5902.

[3] PlasticEurope. Plastics—The Facts 2020. 2020. Available online: https://www.plasticseurope.org/en/resources/publications/43 12-plastics-facts-2020

[4] CBI Market Intelligence. CBI Product Factsheet: Plastics for Vehicles in the European Union; CBI Market Intelligence: Dutch, The Netherlands, 2016; p. 10

[5] EU Parliament. End of Life Vehicles (ELV) Directive. An Assessment of the Current State of Implementation by Member States; Policy Department: Brussels, Belgium, 2007; p. 69

[6] European Commission. Assessment of the Implementation of Directive 2000/53/EU on End-of-Life Vehicles (the ELV Directive) with Emphasis on the End of Life Vehicles of Unknown Whereabouts; European Commission: Brussels, Belgium, 2017; p. 105.

[7] Santini, A.; Morselli, L.; Passarini, F.; Vassura, I.; Di, S.; Bonino, F. End-of-Life Vehicles management: Italian material and energy recovery efficiency. Waste Manag. 2011, 31, 489–494.

[8] Eurostat. Packaging Waste Statistics. 2018. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/ Packaging_waste_statistics

[9] Russo, S.; Valero, A.; Valero, A.; Iglesias-Émbil, M. Exergy-Based Assessment of Polymers Production and Recycling: An Application to the Automotive Sector. Energies 2021, 14, 363. https://doi.org/10.3390/ en1402036

[10] Elias Hallack, Nestor Mario Peris, Mattias Lindahl, Erik Sundin, Systematic Design for Recycling Approach – Automotive Exterior Plastics, Procedia CIRP,Volume 105, 2022, Pages 204-209, ISSN 2212-8271, https://doi.org/10.1016/j.procir.2022.02.034

[11] “New Trends In Plastics Consumption In The Automotive Industry – Which Materials Will Be The Winners And Losers?” Adapt Plastics website, accessed in 25/03/2023

[12] Régis Kovacs Scalice , Daniela Beckera, Ramon Cesconetto Silveira, Developing a new compatibility table for design for recycling, Product: Management & Development, Vol. 7 nº 2 December 2009

[13] Alessandro Pegoretti, Recycling concepts for short-fiber-reinforced and particle-filled thermoplastic composites: A review, Advanced Industrial and Engineering Polymer Research, Volume 4, Issue 2, 2021, Pages 93-104, ISSN 2542-5048, https://doi.org/10.1016/j.aiepr.2021.03.004

[14] Scaffaro R, Di Bartolo A, Dintcheva NT. Matrix and Filler Recycling of Carbon and Glass Fiber-Reinforced Polymer Composites: A Review. *Polymers*. 2021; 13(21):3817. https://doi.org/10.3390/polym13213817

[15] Norshah Aizat Shuaib, Paul Tarisai Mativenga, Energy demand in mechanical recycling of glass fibre reinforced thermoset plastic composites, Journal of Cleaner Production, Volume 120, 2016, Pages 198-206, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2016.01.070.

[16] Matxinandiarena E, Múgica A, Zubitur M, Yus C, Sebastián V, Irusta S, Loaeza AD, Santana O, Maspoch ML, Puig C, Müller AJ. The Effect of Titanium Dioxide Surface Modification on the Dispersion, Morphology, and Mechanical Properties of Recycled PP/PET/TiO2 PBNANOs. Polymers (Basel). 2019 Oct 16;11(10):1692. doi: 10.3390/polym11101692. PMID: 31623120; PMCID: PMC6835408.

[17] Enrico Sciubba, Exergy-based ecological indicators: From Thermo-Economics to cumulative exergy consumption to Thermo-Ecological Cost and Extended Exergy Accounting, Energy, Volume 168, 2019, Pages 462-476, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2018.11.101.