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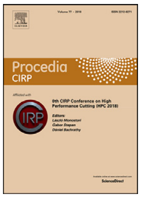

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Analysing the contribution of automotive remanufacturing to the circularity of materials

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ABSTRACT

Remanufacturing can boost resource efficiency, circularity of raw materials and reduce environmental impacts. Material Flow Analysis and Life Cycle Assessment tools are integrated to assess the contribution of remanufacturing in reducing both consumption and impacts of primary resources for passenger cars. Results show that remanufacturing allows keeping within EU about 150,000 tonnes of materials, which is particularly relevant for Critical Raw Materials, such as rare-earth elements. Also, remanufacturing contributes in decreasing environmental impacts of vehicle's key components, as combustion engines (up to 79% of Global Warming Potential reduction). Further work will address data gaps and it will include current/innovative mobility.

1. Introduction

Remanufacturing is a type of reuse belonging to the resource efficient strategies boosting circularity of products and improving their environmental performance in a life-cycle perspective. Transport has a significant potential in terms of decarbonization of the EU, but also to the transition towards a more EU circular economy (EC, 2019).

The average stock of vehicle in EU is around 0.5 vehicles per person, which represents between 450 and 750 kg of materials per person (Huisman et al., 2017). End-of-life vehicles (ELVs) generate 7–8 million tonnes of waste every year, which should be managed correctly to avoid massive quantities of residual waste and environmental pollution (EC, 2018). Thus, vehicles represent an important industry sector in terms of demand of primary raw materials and potential recovery of secondary raw materials (SRMs).

The ELVs Directive (2000/53/EC) contributed and contributes to reduce residual waste from ELVs, by ensuring that their constituent parts can be reused, recycled or recovered. Accordingly, reuse and recycling shall be set to a minimum of 85% by an average weight per vehicle and year. However, reuse is only contributing to less than 10% to this target (EC, 2019a); it is underlined that details of statistics on reused flows are not available, therefore, it is still not clear the contribution of automotive reuse, and in particular, remanufacturing to the overall circularity of materials in EU.

1.1. (Critical raw) materials in vehicles and potential of remanufacturing

Although all materials are important, some of them are of more concern than others in terms of economic importance for the EU and vulnerable to supply disruption, i.e. Critical Raw Materials (CRMs) (EC, 2019a). Some examples of CRMs embedded in vehicle are: cobalt (in lithium-ion batteries especially for electric vehicles), platinum group metals (palladium, platinum and rhodium in catalytic converters and particulate filters), and rare earth elements (REEs) (in permanent magnets, auto-catalysts, filters and additives) (Huisman et al., 2017; Cullbrand and Magnusson, 2012; Bresser et al., 2018; Knobloch et al., 2018; Mathieux et al., 2017).

Not only CRMs are key for the current automotive sector, but also more and more important for future vehicles as they provide key functions (related to connectivity, efficiency, and lightweight). The rapid growth of electric vehicles (EVs) sales bears important implications for the increasing demand of CRMs, amongst which REEs (Cullbrand and Magnusson, 2012; Wallington et al., 2013; Field et al., 2017). According to Cullbrand and Magnusson (Cullbrand and Magnusson, 2012), electrification and higher equipment level are the factors that mainly influence the quantities of CRMs in vehicles (especially concerning neodymium, REEs, niobium and platinum group metals); the same study states that the

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size of car seems to be less relevant (Cullbrand and Magnusson, 2012).

Although CRMs are necessary for several applications in the automotive sector, their functional recycling[1] is very limited, e.g. for REEs. Typically only around 1% of the REEs are recycled from end-products, with the rest deporting to waste and being removed from the materials cycle (Jowitt et al., 2018; Binnemans et al., 2013). This is mainly due to inefficient collection, technological problems and, especially, a lack of incentives (Binnemans et al., 2013), even though the supply difficulties enforced the downstream users of REEs to invest in developing recycling technologies and reuse options (Binnemans et al., 2013; Yang et al., 2017). It is estimated that in the coming 10–15 years, recycled REEs from permanent magnets will play a significant role in the total REEs supply for magnets, provided the development and the implementation of efficient technologies (Yang et al., 2017).

While it is recognized that recycling will contribute to overcome some of the criticality issues with these materials (Jowitt et al., 2018), the authors believe that more efficient strategies can help in boosting resource efficiency in the road transport system. Extending the lifetime of products embedding CRMs, e.g. through their reuse, is an interesting option to keep them longer within the economic system. An example is the second-use of tractions batteries, which also deals with some environmental benefits (Bobba et al., 2018). Remanufacturing is another option, even though not yet developed in EU (Bobba et al., 2019).

In addition, remanufacturing can maintain the value of products (and not only materials) in the economy. Colledani et al. (2014) estimated that the cost of remanufacturing can be between 45% and 65% lower than the manufacturing cost, because remanufacturing processes use 20–25% of the energy needed to manufacture the same product. At the same time, remanufacturing preserves more or less 85% of the initial value, while recycling preserves only almost 7.5% of initial value.

Finally, precise considerations about future mobility are key elements to address the issue of materials' use intensity and circularity of resources, e.g. taking into account the development of connected and autonomous vehicles and the consequent need of new/more components (Gawron et al., 2018).

1.2. Aim of the study

This paper reports the approach used to assess the contribution of resource-efficient strategies (especially remanufacturing) in terms of both materials and environmental impacts in the automotive sector. The study focuses on the EU passenger cars value-chain and it aims at better understanding their life-cycle value chain, the mass of (critical raw) materials embedded and potentially part of different circular flows (e.g. through recycling, remanufacturing, etc.) and the environmental benefits/burdens of remanufacturing core components of vehicles.

Also, it is highlighted the relevance of integrating different assessment tools to provide a more complete figure of the environmental impacts of vehicles (and their components).

2. Environmental assessment

The effects of extending the lifetime of products through different strategies can be captured through the estimation of increase/decrease of in-stocks of products (Mayer et al., 2018). Therefore, the Material Flow Analysis (MFA) approach is adopted and coupled with Life Cycle Assessment (LCA).

The scales adopted for the analysis range from the macro-scale (i.e. the whole EU fleet of passenger vehicles) to the micro-scale (i.e. the analysis on the specific vehicle part).

Within this work, the above-mentioned assessment tools are applied, and three examples are provided in the following sections: (1) MFA to estimate the contribution of remanufacturing in reducing the need for primary raw materials in the EU automotive sector (Section 2.1); (2) LCA to assess the environmental burdens/benefit of remanufacturing a used part instead of producing a new one (Section 2.2); (3) MFA to understand the potential flows of SRMs thanks to improved reusability/recyclability of CRMs (Section 2.3).

2.1. Material flow analysis (MFA) of the EU fleet

The effects of extending the lifetime of products were assessed through the estimation of the stocks and flows of vehicles in the EU (Fig. 1). To the authors' knowledge, MFA models describing the value-chain of EU vehicles, including all the possible EoL strategies, are not available in the scientific literature. Thus, available literature data were complemented by experts' consultation to identify the stocks and flows of the system and to model the MFA. The creation of the MFA model allowed to identify knowledge gaps and opportunities to better collect information.

Literature (EC, 2018; ProSUM, 2018; Oeko-Institut 2017; Weiland, 2012; Weiland, 2016; ACEA, 2018) was used to estimate the amount of materials entering the EU market, the stock of vehicles in use, the flow of materials leaving the stock, the flows of materials exported (both legally and illegally), the amount of registered ELVs, the flows of reused/recycled/recovered materials and residual waste, and the contribution of remanufacturing. According to the goal of the analysis, i.e. remanufacturing, the reference year 2012 was considered as a baseline. The reason behind the choice is that the most detailed information about remanufacturing refer to 2012 (Weiland, 2012; Weiland, 2016).

MFA results

In 2012, approximately 14.6 million new vehicles were put in the market (99% of which are Internal Combustion Engine Vehicles - ICEVs) (ProSUM, 2018); we estimated a corresponding flow of materials entering into the market being equal to 18.2 million tonnes. Concerning the stock, year 2012 accounted about 260.5 million vehicles (ProSUM, 2018), i.e. about 325 million tonnes of materials. Almost 11 million vehicles left the stock (ProSUM, 2018) (i.e. about 13.7 million tonnes of materials). We estimated that about 1.6 million vehicles were legally exported and between 3 and 4 million vehicles per year were deregistered without a Certificate of Destruction (likely to be illegally treated or exported) (based on Oeko Institut (Oeko-Institut, 2017)). As a results, a net amount of about 6.2 million tonnes units of materials were treated by ELV operators, as reported by Eurostat (EUROSTAT, 2019). The operations performed by ELV operators on the ELV materials can be classified as follows: 8% reuse, 77% recycling and 5% energy recovery (own elaboration based on Eurostat (EUROSTAT, 2019)). The share of reuse is about 480,000 tonnes of materials (Fig. 1). Note that based on the available data it was not possible to estimate a breakdown into more detailed processes, such as directly reused, repaired, reconditioned or remanufactured parts. Likewise, it was not possible to estimate how many parts are collected by garages during the maintenance of the vehicle, and are then repaired, reconditioned or remanufactured.

Weiland (Weiland, 2012; Weiland, 2016) provided an evaluation on the number of remanufactured spare parts put on the market, as well as the overall aftermarket need (supplied by new and remanufactured parts). With a number of remanufactured spare

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[1] Functional recycling, in which metal is returned to raw material production. Non-functional recycling could be beneficial for the environmental but not from a metal perspective

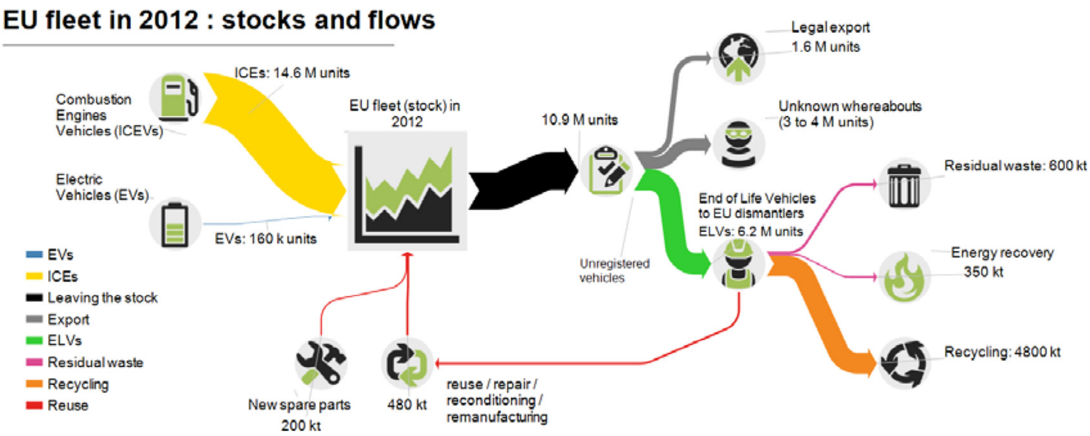

Fig. 1. Stocks and flows of vehicles and materials in EU, year 2012. Own elaborations based on available literature.

Table 1
Assumptions concerning the use of materials, energy and water during remanufacturing (scenarios min, dep, max), compared to the manufacturing process of a new ICE (base-case).

Remanufactured parts	Base-case [new/rem]	Scenario min [new/rem]		Scenario max [new/rem]	
Aluminium [kg]	30.0	2.1	27.9	10.0	20.0
Bronze [kg]	0.2	0.2	0.0	0.2	0.0
EPDM [kg]	0.2	0.0	0.2	0.2	0.0
Iron[kg]	68.6	1.6	67.0	10.8	57.8
PA66 [kg]	0.5	0.1	0.4	0.5	0.0
PP [kg]	0.5	0.4	0.1	0.5	0.0
Rubber [kg]	0.7	0.6	0.1	0.7	0.0
Steel [kg]	50.0	7.1	42.9	28.3	21.7
Tin [kg]	0.1	0.1	0.0	0.1	0.0

parts reaching 22.5 million units and meeting about 55% of the aftermarket demand (Weiland, 2016), we estimated a remanufacturing flow of about 150,000 tonnes of materials. Main contributors are two product groups: internal combustion engines (ICEs) (26%), and starters and alternators (28%). The new spare parts put on the market in 2012, instead, were supposed to require about 200 thousand tonnes of materials.

2.2. Life cycle assessment (LCA)

The LCA methodology was adopted to assess the environmental burden/benefit from-cradle-to-grave in remanufacturing a core component, such as an engine of a conventional vehicle. A simplified study was conducted to compare the environmental performance of a new ICE (base-case manufacturing) in which all components are newly manufactured (Ardente et al., 2018), with a remanufactured one. The functional unit of the LCA is 1 ICE (average weight of 245 kg). No credits from SRMs are considered. The elaborations were performed based on the SimaPro software and the Ecoinvent 3.1 database.

The Global Warming Potential (GWP) impact category was considered, with characterization factors retrieved from the International Reference Life Cycle Data System (EC, 2010) and following integrations.

Based on Smith and Keoleian (Smith and Keoleian, 2008), three scenarios were considered (Table 1):

- “Base-case” Scenario, the ICE is manufactured by using only new parts;
- “Scenario min”, the ICE is remanufactured by using a minimum number of new parts (i.e. maximising reused components);
- “Scenario max”, all the ICE parts are replaced with new parts with exception of the 3 major castings (aluminium, iron, steel) since they are generally remanufactured.

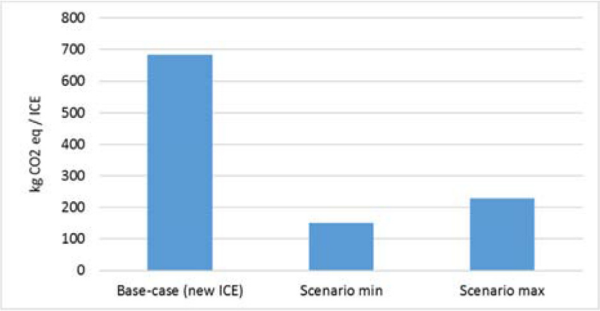

Fig. 2. Global Warming Potential: results for the three considered scenarios.

For the analysis, it is considered that the remanufacturing parts save 80% energy; 88% water; 92% chemical products and 70% waste production (Ellen MacArthur Foundation, 2013) (Table 1).

LCA results

The LCA results show that the average GWP per ICE is 0.7 tonnes of $CO_{2\ eq}$. Main contributors are materials (69%), energy used during the manufacturing process (24%) and mechanical shredding at the EoL (7%).

Fig. 2 reports the comparison between the GWP of the assessed scenarios. Note that in all scenarios, the same assumptions for EoL operations are considered. On average, the GWP reduction ranges between 77.9% (scenario min) and 66.4% (scenario max). Therefore, the higher is the percentage of remanufactured parts, the higher is the GWP saving.

2.3. MFA and critical raw materials

As mentioned in previous sections, MFA is used to assess the potential of CRMs. Due to the fast increase of the EVs demand and the consequent increasing demand of CRMs (Mathieux et al., 2017), the analysis focused on a key component for EVs: the high voltage electric motors (EMs). The main technologies currently on the market are relying on the use of permanent magnets, which are made of metal alloys, embedding REEs. REEs are amongst the most important and vulnerable metals to ensure a sustainable manufacture of specific assemblies of different propulsion systems of passenger cars (Knobloch et al., 2018). Thus, recycling of REEs contained in permanent magnets from ELVs will play an important and complementary role in the total supply of REEs in the future (Yang et al., 2017).

The material composition of EMs was derived by an Ecoinvent Life cycle Inventory (LCI), representing an average EM used in EVs. The full drivetrain considered has about 100 kW maximal power. The EM weights approximately 53 kg, and its material composition is mainly made of steel (75%), aluminium (16%) and copper (9%). Information about permanent magnets and use of REEs were deduced by the scientific literature (Nordelöf et al., 2018). Yang et al. estimated an average amount of 1.2 kg of permanent magnets in EVs, and where the permanent magnets contain about 31–32% of REEs (Yang et al., 2017). This results in 0.46 kg per EM on average.

Concerning EoL, 99 wt% of after shredding REEs is not functionally recovered, and can be considered either down-cycled (i.e. a non-functional recycling process) or lost (Jowitt et al., 2018; Binnemans et al., 2013). According to Binnemans et al. (2013), we assumed that the efficiency rate of recycling REEs can increase up to 55%.

To the knowledge of the authors, there is no consolidated literature and data on EMs' remanufacturing. However, thanks to interviews with stakeholders (in particular with car-sharing companies focused on EVs), we estimated that the maintenance of EMs during the lifetime of EVs is very limited since their lifetime is longer than the EV lifetime. As an assumption, EMs entering in the waste flow are considered as potentially extracted from ELVs (and EVs after accidents), remanufactured and recirculated again in new vehicles, and not only as spare parts for the aftermarket.

For the assessment, different scenarios were established:

0) Baseline scenario, in which the current REE recycling is set to 1%;
1) Scenario 1, considering a pessimistic collection rate (i.e. 30%) and an average recycling process efficiency of 55%. This results in a functional recycling of 16.5%;
2) Scenario 2, considering an optimistic collection rate (i.e. 60%) and an average recycling process efficiency of 55%. This results in a functional recycling of 33%;
3) Scenario 3, considering a pessimistic collection rate (i.e. 30%) and a reuse of 100%;
4) Scenario 4, considering an optimistic collection rate (i.e. 60%) and a reuse of 100%.

Note that in the Scenario 3 and Scenario 4, we assumed that collected magnets are reused for the same application.

CRMs results

Assuming that from 2000 to 2020 about 5 million EVs are put on the EU market (own elaboration based on (Bobba et al., 2019; ProSUM, 2018)), EU risks a potential loss of 2000–2500 tonnes of REEs when such EVs will reach their EoL, unless technological innovations occur. In 2020, about 0.9 million EVs are expected to be sold in EU, of which more than 25% being BEVs (own elaboration based on (Bobba et al., 2019; ProSUM, 2018)). The recycling/reuse scenarios previously illustrated are applied to this volume of BEVs, at the moment they leave the stock to become ELVs. Fig. 3 shows the distribution of results. The min and max values for each scenario refer to the min and max REEs' content (Yang et al., 2017).

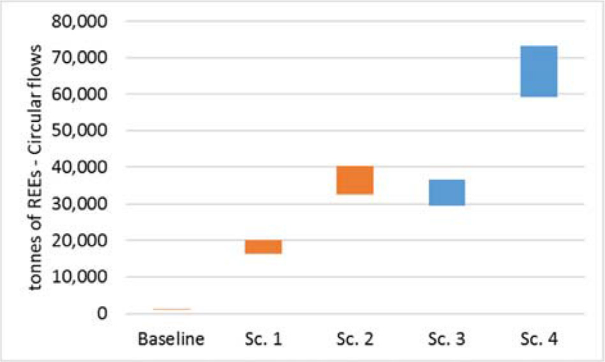

Fig. 3. Circular flows of CRMs from resource efficient recovery of permanent magnets in electric motors: distribution of results for the flows of rare earth elements (as SRMs) in recycling (orange bars) and reuse (blue bars) scenarios. Bars refer to minimum and maximum values (uncertainty depends on the mass of REEs in magnets and on the mass of magnets in cars).

Less than 1 ton of REEs is recycled in Scenario 1, which can be even considered an optimistic scenario for the current ELV recycling practices, where most of CRMs resulting from post-shredding treatments are indeed downcycled. Higher amounts of recycled REEs can be achieved assuming that 30%–60% of the permanent magnets are collected before shredding. In this case, with a recycling efficiency of 55%, the flow of SRMs range from 16,000 to 20,000 tonnes in Scenario a, and from 32,000 to 40,000 tonnes in Scenario 2. The circular flow of CRMs is of course even higher when permanent magnets are supposed to be reused for the same application (as spare parts or for new vehicles). In this case, the estimated circular flows or CRMs range from 29,000 to 36,000 tonnes in Scenario 3, and from 59,000 to 73,000 tonnes in Scenario 4. Results show the relevance of increasing the collection rate (Scenarios 2 and 4) to maximise the benefits of recycling and reuse practices.

3. Discussion

The MFA results highlighted how remanufacturing can contribute to the circularity of passenger cars, with about 150,000 tonnes of materials kept into the economy. We can assume that the saving of raw materials for the production of new parts is even higher, if we consider that each manufacturing process involves a certain amount of production scraps, on top of the resources used to extract, transport, refine and convert raw materials. Note that a drastic reduction of the unknown whereabouts can potentially increase the amount of available cores (used automotive parts, input of the remanufacturing process); also, the flow of new spare parts represents a significant mass of materials compared to the flow of remanufactured materials (about 1.3 times higher). A more robust and comprehensive monitoring framework would help to understand both the collection rates of cores (from ELVs or from vehicle under repair/maintenance) and the specific amount (volume, but also mass of materials) of remanufactured spare parts put on the market.

The results of the LCA highlight the environmental benefits brought by remanufacturing a core part instead of producing a new one: remanufactured ICEs carry on an environmental burden that is 22%–33% the environmental burden associated with the manufacturing of new ICEs. This is mainly due to the reduced amount of energy for the processing, and thanks to the savings of primary resources. Remanufactured parts are mainly used to replace worn out or defective components. A LCI populated with primary data, collected at the remanufacturing facility, would definitively improve the LCA model and thus the reliability of the obtained results.

The results of the analysis on the flows of CRMs (focused on REEs) from permanent magnets, as a potential source of SRMs, showed the importance of resource efficient practices in keeping the real value of materials into the economy. At the time of Yang's publication (2017) (Yang et al., 2017), no commercial operations have been identified for recycling permanent magnets and recovering the embedded REE. The recycling efficiency can be estimated only when permanent magnets are removed from ELVs for tailored processing (Binnemans et al., 2013), but most of the processing methods were still at various research and development stages (Yang et al., 2017). The results of the analysis are still largely uncertain and aim to raise awareness about the potential benefits that could be achieved by circular flows of REEs thanks to resource-efficient practices. This could be achieved only if these components can be easily disassembled form vehicles. A sustainable flow of SRMs from ELVs will be indeed key for the growing market of new electric car sales. Future technological innovations could modify the demand of raw materials, but is difficult to be assessed at the moment[2] (Deloitte Sustainability, 2017). The developed MFA model, together with the LCA of specific components/materials provides the base for the ongoing research work of the current and future EU fleet and the potential of remanufacturing to the circularity of materials.

4. Conclusions

The evaluation of the contribution of automotive remanufacturing to a more efficient circularity of materials is a complex exercise: it requires a deep knowledge of the automotive sector, of automotive components and their material compositions, other than the skills required to perform such assessments. To evaluate the potential environmental benefits deriving from remanufacturing automotive components in a holistic perspective, the MFA and LCA tools have been integrated; hence both environmental impacts and resource efficiency can be assessed. Results of the developed analysis provided an MFA model based on 2012 data that represents the baseline for modelling the current and future situation of the automotive system (ongoing research work). Also, the MFA model developed thanks to both literature data and experts' consultation allowed to identify the knowledge gap in order to have a more in-depth knowledge of the stocks and flows of the system. Finally, results of the LCA showed the potential benefits that remanufacturing in the automotive sector, in particular some components and materials. This approach will be further extended to different vehicles' components and embedded (critical raw) materials to also consider the evolution of the automotive market in the EU up to 2050.

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[2] For example, neodymium in permanent magnets may be replaced by praseodymium (listed as CRM). Permanent magnets may be replaced by ferrite magnets, but these are currently not suitable for high tech applications.

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