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Life cycle assessment and potential of remanufacturing of vehicle components

Mats Zackrisson and Jutta Hildenbrand

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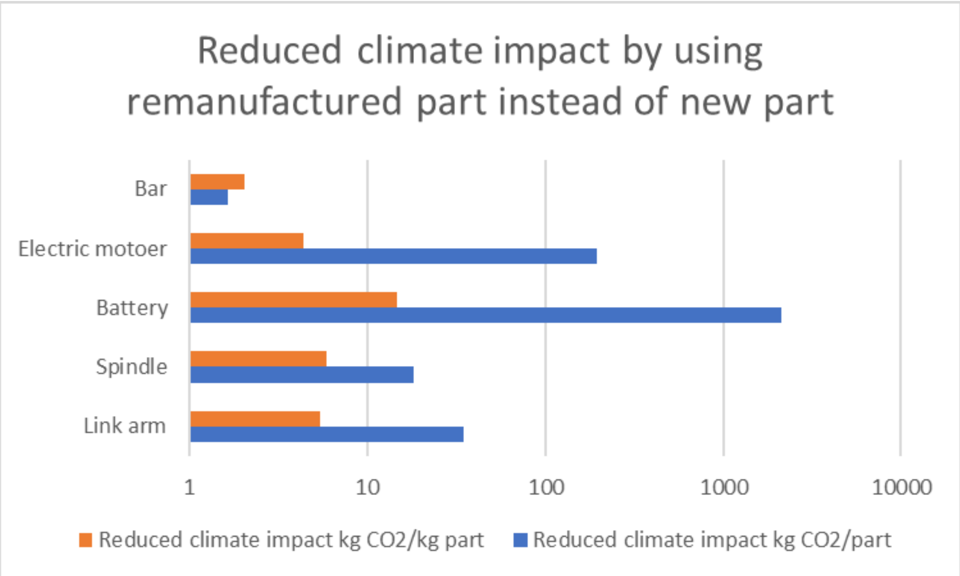
Abstract

Life cycle assessment of remanufacturing of vehicle components

Life cycle assessment, LCA, has been used to compare the environmental impact of new vehicle components with remanufactured vehicle components. The aim was to develop simplified guidelines for decisions when a component, for environmental reasons, should be remanufactured, or scrapped and recycled. The study focuses on a stay, wheel spindle, link arm and electric motor from the rear trailer on a Volvo XC90 Hybrid, a traction battery from the plug-in Volvo V60 and various seats cover constructions.

The figure below shows how much climate impact is avoided if a damaged component is replaced with a remanufactured component, instead of a new component. The reduced climate impact per component or part (blue bars) varies greatly between different parts, while the climate gain per kilogram part (orange bars) is between 2-14 kg CO2 per kg part or component.



Also with regard to resource depletion, all examined parts provide resource savings in remanufacturing compared with new production.

The results are so unequivocally positive and the components so different that one should be able to assume that, if it is economically advantageous to remanufacture a car component, it is in all probability also environmentally beneficial. The difference between the bar in steel and the aluminium components (link arm, wheel spindle) indicates that one can count on more environmental benefits the more precious metal is used. Both the battery and the electric motor indicate potentially very large environmental benefits from remanufacturing. However, it is important that driveline components do not lose efficiency due to remanufacturing, as the use phase dominates the life cycle environmental impact of driveline components.

Seat covers were investigated with an alternative focus. Remanufacturing of seat covers as an isolated component is not practiced and also not foreseen with the current construction, since they are an integrated part of a seat. Investigations therefore focused on proposed design changes and on changes of material choice. For the seat covers as they are currently used, remanufacturing assumes that they remain on the seat and are transferred to another vehicle. This requires removal of the airbag and addition of a new one in all cases. For remanufacturing of seats, economic barriers have been identified due to the relatively high demand for storage space and transport volume of car seats, and the large number of variations in seat design with covers in textile and leather in several colours.

Regarding the simplified LCA methodology used in the project, the following can be concluded:

- New manufacturing is often complex and thus resource-intensive to model. An alternative is then to instead compare with existing LCA studies on similar components. This strategy was applied, in this study, regarding battery and electric motor.
- The seat cover manufacturing is modelled based on existing models for textile processes intended for apparel and fashion evaluation (Mistra future fashion and several studies related to environmental product declarations, EPD). With the perspective of a supplier who explores options in design that reduce the climate impact of a future seat cover, the focus for this case was on the cradle to gate stages of seat cover manufacturing. Remanufacturing of seat covers is not well established and based on assumptions and thus not modelled as completely as the other parts of the life cycle.
- The sub-components that are replaced in the remanufacturing need not be included in the remanufacturing model if they are included in the new manufacturing model, since they even out. However, this simplification presupposes a separate, or sufficiently detailed LCA model of the new production, so that replaced sub-components can be removed there.
- Large uncertainty about how material recycling gains should be calculated. The rule of crediting with the same material data set used for the new manufacture provides a degree of certainty, but further guidelines would be desirable. Use of cut-off methodology is a possibility.

Key words: Life cycle assessment, remanufacturing, vehicle

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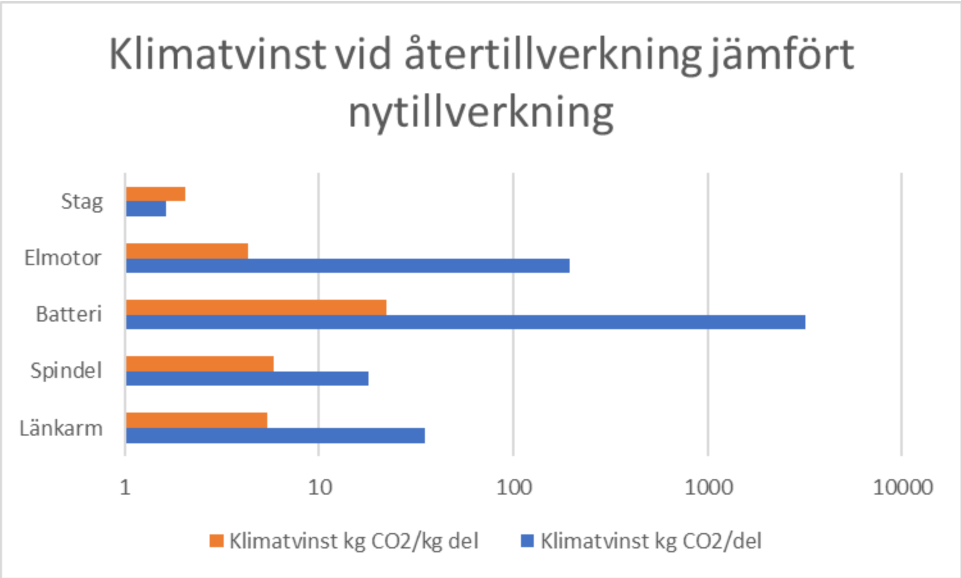
Sammanfattning

Livscykelanalys, LCA, har använts för att jämföra miljöpåverkan av nytillverkade fordonskomponenter med återtillverkade fordonskomponenter. Målet var att utarbeta förenklade riktlinjer för beslut när komponent, av miljöskäl, bör återtillverkas, eller skrotas och materialåtervinnas. Studien fokuserar på stag, hjulspindel, länkarm, elmotor och batteri från en bakvagn på en Volvo XC90 Hybrid ett batteri från Volvo V60 plug-in hybrid och bilstolsöverdrag.

I figuren nedan visas hur stor klimatvinst som görs om en skadad komponent ersätts med en återtillverkade komponent, i stället för en ny komponent. Klimatvinsten per komponent eller del (blåa staplar) varierar mycket mellan olika delar, medan klimatvinsten per kilogram del (brandgula staplar) ligger mellan 2–14 kg CO_2/kg del eller komponent.



Även avseende resursutarmning, så ger samtliga undersökta delar resursbesparing vid återtillverkning jämfört med nytillverkning.

Resultatet är så pass entydigt positiva och komponenterna så pass olika att man borde kunna anta att, om det är ekonomiskt fördelaktigt att återtillverka en bilkomponent, så är det med stor sannolikhet också miljömässigt fördelaktigt. Skillnaden mellan staget i stål och aluminiumkomponenterna (länkarm, hjulspindel) indikerar att man kan räkna med mer miljöfördel ju ädlare metall som används. Såväl batteri som elmotor indikerar potentiellt mycket stora miljöfördelar med återtillverkning. Det är dock viktigt att drivlinekomponenter inte förlorar i effektivitet på grund av återtillverkningen, eftersom användningsfasen dominerar miljöpåverkan för drivlinekomponenter över hela livscykeln.

Sätesöverdrag undersöktes med ett alternativt fokus. Återtillverkning av stolsöverdrag som en isolerad komponent praktiseras inte och förutses inte heller med den nuvarande konstruktionen, eftersom de är en integrerad del av ett säte. Undersökningarna fokuserade därför på ändringar av design och material för överdragen. För stolsöverdragen som de används för närvarande förutsätter återtillverkning att de sitter kvar på sätet och överförs till ett annat fordon. Detta kräver borttagning av krockkudden och ersättning med en nytillverkad. För återtillverkning av stolar har ekonomiska barriärer identifierats på grund av den relativt höga efterfrågan på förvaringsutrymme och transportvolym för bilstolar samt det stora antalet variationer i stolsdesign med överdrag i textil och läder i flera färger.

Avseende den förenklade LCA-metodik som använts i projektet kan följande konstateras:

- Nytillverkning är ofta komplext och därmed resurskrävande att modellera. Ett alternativ är då att istället jämföra med existerande LCA-studier på liknande komponenter. Denna strategi tillämpades, i denna studie, avseende batteri och elmotor.
- Tillverkningen av stolsöverdragen är modellerad utifrån befintliga modeller för textila processer avsedda för utvärdering av kläder och mode (Mistra future fashion och flera miljöpåverkansdeklarationer). Med perspektivet av en leverantör som undersöker designalternativ som minskar klimatpåverkan från ett framtida stolsöverdrag, var fokus för detta fall på vagga till grindstadier av tillverkning av sätesöverdrag. Återtillverkning är inte väl etablerad och baserad på antaganden och därför inte modellerad så komplett som de andra komponenterna.
- De detaljer som byts i återtillverkningen, kan kvittas mot samma detaljer i nytillverkningen. Denna förenkling förutsätter dock en egen, eller så detaljerad LCA-modell av nytillverkningen, att utbytesdetaljerna kan plockas bort där.
- Stor osäkerhet om hur materialåtervinningsvinster bör kalkyleras. Regeln om att kreditera med samma materialdataset som används för nytillverkningen, ger en viss säkerhet, men ytterligare riktlinjer vore önskvärt. Användning av cut-offmetodik är en möjlighet.

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Preface

This report examines remanufactured vehicle components with life cycle assessment. The analysis was made by Mats Zackrisson (metal parts) and Jutta Hildenbrand (seats and covers) at RISE, within the framework of the project SE:Kond2LIFE. Hanna Linden at RISE, project leader of the SE:Kond2LIFE project, has reviewed the report from a project leader perspective. Individual vehicle components are studied in order to develop simplified guidelines for decisions when a component, for environmental reasons, should be remanufactured, or scrapped and recycled. The climate impact avoidance of individual components is extrapolated to European level.

1 Introduction

Life cycle assessment, LCA, has been used to compare the environmental impact of remanufactured vehicle components with new vehicle components. The main goal was to develop simplified guidelines for decisions when a component, for environmental reasons, should be remanufactured, or scrapped and recycled. The study includes several different vehicle components from a Volvo XC90 Hybrid. Comparisons are also made with other studies. It should be mentioned that reuse, repair and reconditioning of vehicle components are also common and similar to remanufacturing, but not the same. Remanufacturing implies industrial processes and active sourcing of cores. For a precise definition of remanufacturing, see Figure 3.

The methodology for developing simplified guidelines for decisions when a component, for environmental reasons, should be remanufactured, was developed in the feasibility study *Analys av hinder för återtillverkning och återanvändning samt avvägd miljönytta av fordonskomponenter - SE:kond2LIFE*, (Zackrisson 2019), and is described below. Both the current project and the feasibility study assume that in the future more people will buy transport services instead of physical cars and that this provides benefits (environmentally as well as economically) for long-lasting components that can be remanufactured.

1.1 Method

The life cycle assessment, LCA, is performed in accordance with ISO 14044 (ISO, 2006) and the ILCD Handbook (Wolf & Pant, 2012). The various case studies in this report were started successively in the spring of 2021. The report has been referred to the project group and also to a larger group including product owners at Volvo Cars.

Simplified LCA has been widely used, which in principle means that upstream data for the raw materials for the production of newly manufactured components are taken from generally available data and generally represent global or European averages. Material specifications from Volvo Cars were the starting point for the LCA modelling of link arm, spindle, electric motor and stay. Borgstena provided a bill of materials for seat covers including eco-design ideas. System boundaries were adjusted to highlight what is different between new and remanufactured parts and components, and thus excluded the use phase, which is assumed to be similar for both. The battery was modelled on the basis of the remanufacturing methodology developed by Volvo Cars and ECRIS as well as data from other battery studies and database data. Above all, data has been retrieved from RISE's own database and the commercial database Ecoinvent. SimaPro 9.2.0.2 was used for the calculations. The calculations can be found in project SE:Kond2LIFE.

The extrapolation of potential future climate gains at the European level by, not only remanufacturing, but also reuse, repair and reconditioning is based on a literature study. Here the EU Joint Research Centre, JRC, Technical Report *Sustainable use of Materials through Automotive Remanufacturing to boost resource efficiency in the road transport system SMART*, in itself containing a literature survey, should be mentioned as an important part.

1.2 Functional unit

With the functional unit defined as a vehicle part for the remaining life of a vehicle, it is possible to compare the environmental impact, EI, of the newly manufactured part, with the remanufactured part with the formulas (Zackrisson 2019):

EI new part = EI end-of-life damaged part + EI new manufacturing

EI remanufactured part = EI checking + EI remanufacturing

With the functional unit vehicle km, it should be the same basic formulas, you only divide by the number of km until the vehicle is scrapped, i.e. the service life of the vehicle. The unit vehicle km is reflected in the more simplistic functional unit: vehicle part for the remaining life of a vehicle. Remanufacturing also includes some new production of wear parts. These wear parts are also included in the new production, so in theory they can be subtracted from both systems in a comparison.

1.3 System boundary

Principal system boundary for the study is shown in the figure below. Note that only the part of the life cycle that is within the yellow system boundary is studied. The remaining processes are assumed the same regardless of whether you choose new manufacturing or remanufacturing.

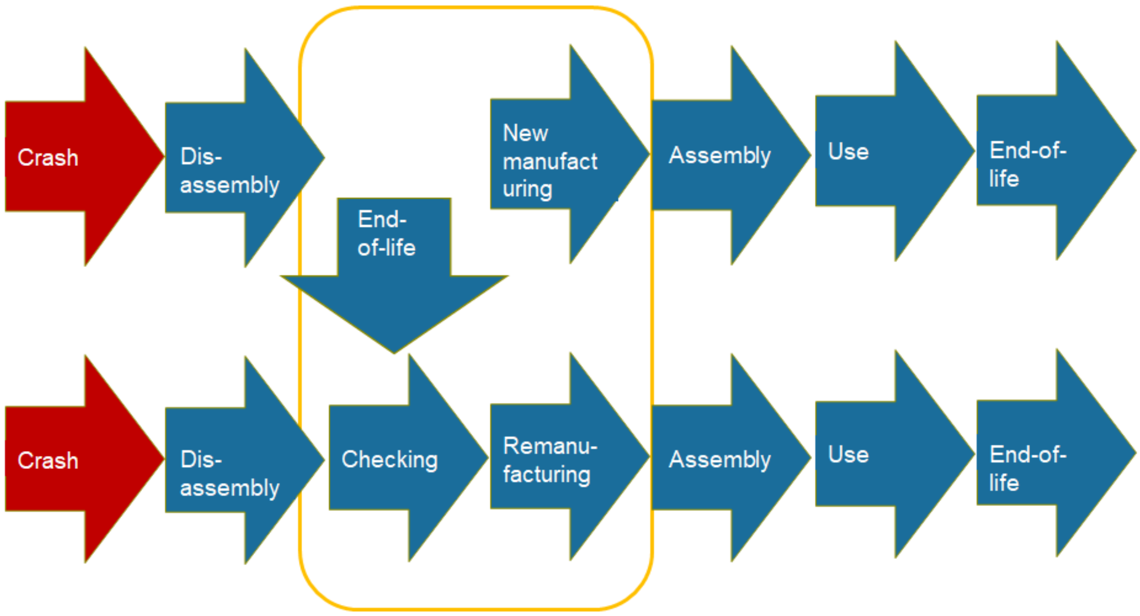


Figure 1 Principal system boundary for the study

Note that material recycling (at end-of-life) of the scrapped component is included in the system studied. In general, cut-off rules are applied to recyclable waste that arises from new manufacturing, checking and remanufacturing, which means that environmental benefits and burdens are, in general, not credited to the studied system in any other way than that raw materials used by inflows have a normal content of recycled material.

1.4 Environmental impact categories

Environmental impacts in the form of the following environmental impact categories are taken into account:

- Climate impact
- Resource depletion, minerals and metals

Resource depletion is studied with two indicators to reflect both long-term and short-term resource depletion. The reason is that the (more long-term) method recommended in reputable LCA guidelines (EC 2017) does not reflect the current scarcity of typical battery metals such as cobalt, nickel and lithium (Zackrisson 2021). For calculations of the environmental impact categories, the method CML-IA Baseline 3.06, were used for climate impact (implementation of method IPCC 2013) and long-term resource depletion, while the Non-baseline CML method were used for the short-term resource depletion; both methods as implemented in SimaPro 9.2.0.2.

2 Modelling

2.1 Electricity

The study makes use of several different electricity mixes. How they are used and the climate impact from each mix are described in the table below.

Table 1 Electricity

Name of dataset	Climate impact (gram CO_2-eq/kWh)	Use
Electricity, medium voltage {SE}| market for | Cut-off, S	37	Used for remanufacturing at ECRIS.
Electricity, medium voltage {ENTSO-E[1]}| market group for | Cut-off, S	398	Used for die casting of aluminium in Europe.
Electricity, medium voltage {CN}| market group for | Cut-off, S	1010	Used for die casting of aluminium in China.
Electricity, low voltage {SE}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, S	94	Used for remanufacturing at ECRIS. Note that solar electricity generated in Sweden has more than double the climate impact compared to Swedish average electricity. The environmental benefit of producing and using solar in Sweden should not, however, be assessed in comparison with the Swedish average, but rather with the European average.
Several electricity datasets for suppliers to seat cover production, southern and western Europe, both with conventional and renewable fuels. Locations not disclosed due to confidentiality.	10 (renewable)…200 (grid mix)	Used for comparing impacts of design choices for Borgstena seat covers, analysis of material and process related impacts.

2.2 Transports

Remanufacturing should involve changed transports compared to new manufacturing. The project has not studied this in detail but used data from Lundberg et al (2020), which states transport between warehouse (storage) and workshop to 500 km for newly manufactured parts, compared with 1600 km for remanufactured parts. For the newly manufactured part, the actual transport distance from the place of manufacture to the warehouse is added, while the remanufactured part is assumed to be stored at the same place as it is remanufactured.

[1] ENTSO-E means European Network of Transmission System Operators and represents 43 Transmission Systems companies in 36 European countries.

For electric motor and battery, where data from other LCA studies have been used, these studies are assumed to include transports from the place of manufacture to the warehouse. Transports of materials to the place of manufacture are included in the market datasets used or are included in the LCA studies used. It can be added that Lundberg et al (2020) mapped in detail all transports in connection with the repair of a typical damage to a Volvo V60 (with a new, used or repaired component), and concludes that "the transports have a generally quite low impact". One can also conclude that in total there are approximately equal lengths of transports in the various cases being investigated.

For the seat covers, transports from suppliers to the original equipment manufacturer, OEM, and from there to the assembly location are considered. Means of transport are sea transport for long distances and road transport for shorter distances.

2.3 Link arm and wheel spindle

Modelling of link arm and wheel spindle is based on actual data from material specifications and product owners on weight and material for the two parts, combined with specific data for remanufacturing at a remanufacturing company and for disassembly, inspection, cleaning, storage and sale at a company selling used vehicle components. The two different companies share the same facilities. Database data were combined to simulate new production of the parts in Italy or China. The link arm weighs approximatively 6400 gram and the wheel spindle half of that. Both components are made in die-cast aluminium. Remanufacturing includes cleaning, blasting, checking for cracks, and changing three bushings made in rubber and steel, or, rubber and aluminium.

2.4 Battery

The battery study began with an LCA scoping meeting on January 2020 with representatives from the remanufacturing company and the LCA practitioner from RISE. The focus of the study is the newest version of the Volvo V60 battery, which has the following specification:

- 11.8 kWh nominal energy (10.4 kWh first version)
- 10.89 kg per module with 20 cells, 10 modules per pack, becomes 200 cells per pack. 144 kg per complete pack of which 109 kg cells/modules. 10.89/20=0.54 kg/cell, but a small part of this is module. The ratio of cells or modules to pack thus 109/144 = 75%.
- 11.8/109 = 0.11 kWh/kg cell-in-module; 110 Wh/kg cell-in-module
- 11.8/144=82 Wh/kg battery
- Pouch or bag cells
- LMO-NMC chemistry

To enable comparisons with other studies, the functional unit 1 kWh battery storage was used.

2.4.1 Remanufacturing of battery

Volvo Cars and the remanufacturing company have jointly developed the method for remanufacturing the driveline battery for the plug-in hybrid V60. The method requires an effort of 32 man-hours of work, which includes inspection, disassembly, replacement of defective parts for used parts from scrapped V60 batteries, replacement of 20 O-rings and test driving which requires 0.5 litres of diesel. According to Lundberg et al (2020), a transport from warehouse to workshop of 1600 km is also required. Parts that are replaced are mainly modules, fuses, circuit boards and other components, all of which are already used, except the 20 O-rings.

2.4.2 End-of-life and new production of battery

LCA modelling of a lithium-ion battery is demanding in many ways, including access to detailed data on battery chemistry and component and raw material supply. Instead of modelling end-of-life and new production of the V60 battery, comparisons are made instead, partly with a similar battery in size and chemistry, partly with the battery in Volvo's latest electric car C40, for which data was available. By comparing per kWh of battery storage, reliable comparisons can be made.

2.4.2.1 Volvo C40 Recharge and ReLion

According to Volvo Cars (2021), the production of the lithium-ion cells and modules in the C40 battery pack of 74.5 kWh involves emissions of 7 tonnes of CO_2. This corresponds to 94 kg CO_2/kWh battery cell-in-module. The study uses cut-off in recycling so no "recycling credits" are included in the carbon dioxide footprint of 94 kg CO_2/kWh. It should also be emphasized that 7 tonnes do not include the rest of the battery pack, but only the cells in the modular pack. Battery box, cooling system and electronics are thus not included.

Recycling credits can be added via data from the ReLion project (Zackrisson 2019), which indicates that 1.6 kg CO_2/kg NMC cell can be avoided by recycling nickel, cobalt and manganese (the main constituents of an NMC cell) and lithium. NMC cells can have an energy content of 0.155 kWh/kg cell (Zackrisson 2018). The recycling credit would then correspond to approximately 1.6/0.155=10 kg CO_2/kWh (compared to 94 kg CO_2/kWh for production.)

According to (Zackrisson 2018), the cells' climate impact compared to the rest of the battery pack is, for manufacturing, about 75% cell and 25% rest-of-pack, while recycling credits are 26% cell and 64% rest-of-pack (Zackrisson 2019). Adjustment of the values for the C40 cell, to pack level, should therefore mean: 94/0.75 = 125 kg CO_2/kWh battery for production, of which 10/0.26=38 kg CO_2/kWh battery can be recovered at recycling.

2.4.2.2 A la Cusenza et al

Cusenza et al (2019) examine an 11.4 kWh LMO[2]-NMC battery, which is very similar, but not the same as the V60 battery. Among other things, Cusenza's battery has prismatic cells and fewer cells (80), while the V60 has pouch cells and more cells (200). The V60 pack is also lighter, 114 kg, compared to 175 kg for Cusenza's pack. However, both packs

[2] lithium manganese oxide

are intended for plug-in hybrids, have almost the same nominal power of 11.4 compared to 11.8 kWh and have the same chemistry, LMO-NMC.

The climate impact of the production of the LMO-MNC battery in Cusenza et al (2019) amounts to 312 kg CO_2/kWh. Of this, it is estimated that about 5% or 16 kg/kWh can be recovered in the recycling.

2.5 Electric motor

The climate impact of new production and remanufacturing of electric motors has been estimated using data from Tillman et al (2020) in which life cycle assessment, LCA, of three different electric motors are performed, in combination with extensive studies of today's and tomorrow's end-of-life handling of electric motors.

Using Figure 12.3 on page 121 in Tillman et al (2020), (Figure 12.3 on page 121), it can be determined that the climate impact of producing their reference engine is (23-3 mm)/8 mm/g CO_2eq/km*200000 km=500 kg CO_2eq, while material recycling can give back between (12-1)/8*200000=275 and (14-1.5)/8*200000=312 kg CO_2eq.

The table below compares some characteristic data concerning the electric motor SPA1 ERAD EM (hereinafter referred to as SPA1) in the SE:Kond2LIFE project, with the reference motor in (Tillman et al 2020) and an LCI model (Nordelöf 2018) of SPA1 in the middle column. The reference motor is described as a radial flow motor with distributed copper wire winding and inserted neodymium magnets often referred to as Nd(Dy)FeB magnets. Nd(Dy)FeB stands for neodymium, dysprosium, iron and boron

Regarding remanufacturing Tillman et al (2020) estimates that remanufacturing by replacing the motor shaft and ball bearings could provide an additional 100,000 km mileage. Note that weights and specifications in Table 2 agree relatively well between the models and SPA1, except for bearings and axles. The climate impact of new production of bearings and shaft has therefore been assumed proportional to the mass share (4.4%) for bearings and shaft (in Scalable PMSM LCI Model of SPA1) and the climate impact for production of the entire electric motor according to (Tillman et al 2020), i.e. 0.044*500=22 kg CO_2eq.

Table 2 Electric motors - characteristics

Characteristic	SPA1	Scalable PMSM LCI[3] Model of SPA1	Reference motor
Max power (kW)	65	108	100
Weight (kg)	48	48	44,9
Max torque (Nm)	240	258	239
Number of bearings	3	2	?
Weight of bearings (kg)	1 (for 3)	0,178 (for 2)	?
Weight of magnet (kg)	1,12	1,35	1,26
Material in magnet	Neodymium, Dysprosium, Terbium	Nd(Dy)FeB	Nd(Dy)FeB
Weight of shaft (kg)		1,95	8,5 (rotor chore)

[3] (Nordelöf 2018)

2.6 Stay

The stay was approximated to an elongated box measuring 350 mm long, 30 mm high, 40 mm wide. Material thickness 2 mm. Such a box has the area: 2*3*35+2*4*35+2*3*4= = 514 cm^2 and weighs 514*0.2*0.0078 kg/cm^3=0.8 kg. Any bushings and any surface treatment can be offset, (see chapter 1.2) and are therefore not included in the LCA model. Remanufacturing assumed to include disassembly, visual inspection, cleaning, blasting, checking for cracks, changing bushings and surface treatment, while LCA model excludes changing bushings and surface treatment as mentioned above.

2.7 Seats and seat covers

The investigation of seat covers explored options to reduce the environmental impacts from the perspective of a supplier and considering design choices. Due to this perspective, detailed cradle to gate models for the seat cover were created.

Seat covers are the top layers on the seat over a metal frame structure and padding, for example a polyester, PES, weave material as top layer with a polyurethane foam (PU) with a laminated polyester backing that supports assembly underneath. The weight of a front seat with metal structure is approximately 25 kg and includes the cover material (less than 10% of the seat weight), padding, metal structure and support components, depending on the customer's choices also electronics for seat heating and other extras.

A common treatment scheme for end-of-life vehicles, ELV, includes depollution or "detoxification", removal of fluids and known hazards, dismantling (including removal of components that are used as spare parts) and shredding of the remaining vehicle including components. Only few seats are removed as spare parts. Seats from older vehicles, seats that have stains or seats that come from a vehicle involved in a crash are not considered as spare parts, but even seats that could be available are rarely used, for several less visible reasons. Further treatment includes separation as automotive shredder reject, ASR, fraction, which contains foams and textiles in a light fraction. According to an older study (1998) that is cited by Tasala Gradin (2012), the polymer fraction in vehicles at that time consisted on average of 66% polypropylene, PP, 15% polyethylene, PE, 10% polyurethane, PUR, 4% polymethyl methacrylate, PMMA, 3% acrylonitrile butadiene styrene, ABS, and 2% polyethylene terephthalate, PET. The polymer fraction is not recycled at all after shredding, since the polymers become contaminated, which distorts their melting indexes. With manual disassembly, polymers can be removed unaltered. PUR, which is not easily recycled, is in all cases still separated and incinerated (Tasala Gradin 2012).

Remanufacturing is implemented to some extent but not as regular as for technical parts. The modelled remanufacturing process includes cleaning and visual testing, but not storage. Transport to second use phases is explored in the model to be consistent with transportation of other parts. All processes that include removal of a seat and transfer to another vehicle are considered as remanufacturing and not as reuse due to the required level of processing.

For the seat cover, a simplified material list for the top layer and base layer has been provided and used for the modelling together with knowledge on typical textile processes such as melt spinning of fibres, weaving and knitting, non-woven fabric making, and laminating. Note that no data were available for the inner metal structure of a seat, and not for any dyeing and finishing processes for the textile part.

Textile processes are usually organized in a way that individual process stages are performed by sub-suppliers, for example melt-spinning of fibres and yarn processing is performed in location A whereas fabric making is performed in location B. This was considered for the current design and process by using locations (countries) of the factories to determine transport distances and national/regional datasets for electricity and heat. Moreover, the models considered use of renewable sources for generating electricity and heat and recycled raw materials or virgin raw materials where this was confirmed by the OEM. This information had been used to model different scenarios to identify contributions from raw material and processing to the environmental impact. An innovative design was suggested to replace the current base layer (PU foam) and provide a seat cover that is made from polyethylene terephthalate (PET) based polyester only. This would allow recycling of a single material, which potentially leads to higher value capturing through a secondary material.

An important aspect of the investigation into seat covers was to explore which contributions design choices for material and construction, as well as choices of energy sources in production, provide to the environmental impact. The following options were modelled for comparison:

1. Benchmark construction with polyester weave as top-layer, polyurethane foam with polyester scrim as base layer; electricity at OEM from renewables, electricity and heat at sub-suppliers from grid (location in Southern and Western Europe). Heat from natural gas and share of fossil energy carriers for electricity. All materials primary from fossil raw materials.
2. Benchmark construction as in 1. All electricity and heat inputs from renewable sources, Materials from primary sources/fossil.
3. Benchmark construction as in 1, All electricity and heat inputs from renewable sources, polyester from recycled material.
4. New construction with top-layer and base layer polyester based (different fabric constructions considered). Electricity at OEM from renewables, electricity and heat at sub-suppliers from grid with share of fossil energy carriers. Recycled raw materials as input.
5. New construction as in 4, with renewable energy sources for electricity and heat at suppliers and recycled material.

The calculations are performed per square meter of seat cover and normalized with the current design and suppliers (option 1) set to 1 (or 100%) to compare all other options in relation to that. .

For remanufacturing of the seat (cover) it is assumed that seats are removed from the vehicles and cleaned by using vacuum cleaners and steam cleaners with 0.1 litre of water and 20 grams of soap. The duration of inspecting and cleaning is estimated to take 15 minutes, no further testing of the structure has been investigated so far, this could be used to further investigate whether a seat that comes from a crashed car is damaged and should not be remanufactured for safety reasons. Currently only a small number of seats are removed before shredding, and this is limited to seats that look as new (no comments in the disassembly protocol). An increased number of remanufacturing could be reached by applying a testing and cleaning routine. For transport to second life applications, similar assumptions as for other components in this study are considered. This is however not based on a larger set of empirical data. Stakeholders mentioned the large variety of seats and the heavy weight and large storage volume as barriers for implementing seat remanufacturing.

Material recycling after dismantling and separation (avoiding a shredder) would be restricted to the polyester layer. Polyurethane (together with the laminated polyester scrim) would most likely be sent to energy recovery even after dismantling.

Note that all seats that are removed from a vehicle need to be equipped with new airbags and control units for safety reasons.

3 Remanufacturing and reuse of vehicles at societal level

This section explores remanufacturing in a European and circular economy context. Barriers and incentives to remanufacturing are discussed and an attempt is made to explore the size of the remanufacturing market, in order to grasp how much environmental improvement is possible.

3.1 The European fleet of cars

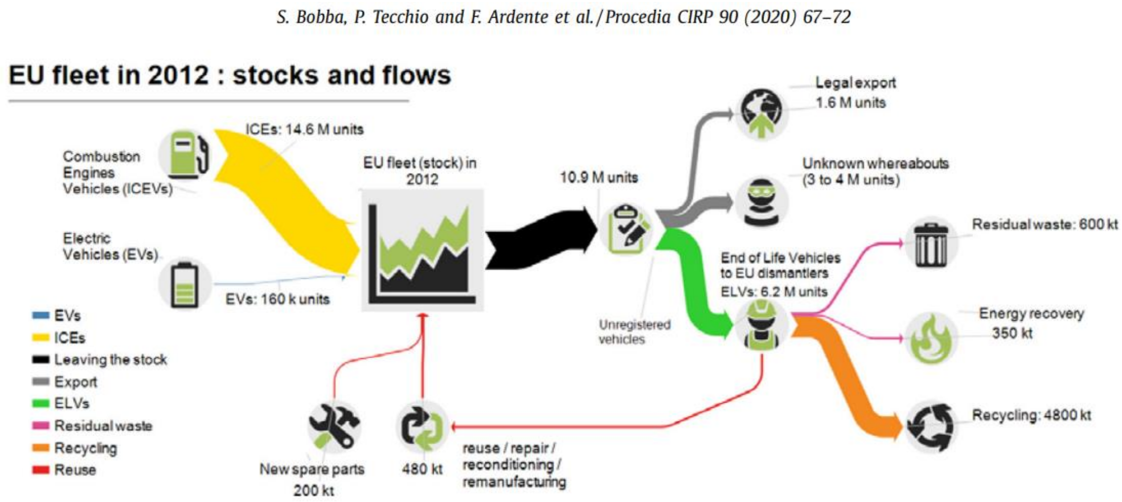


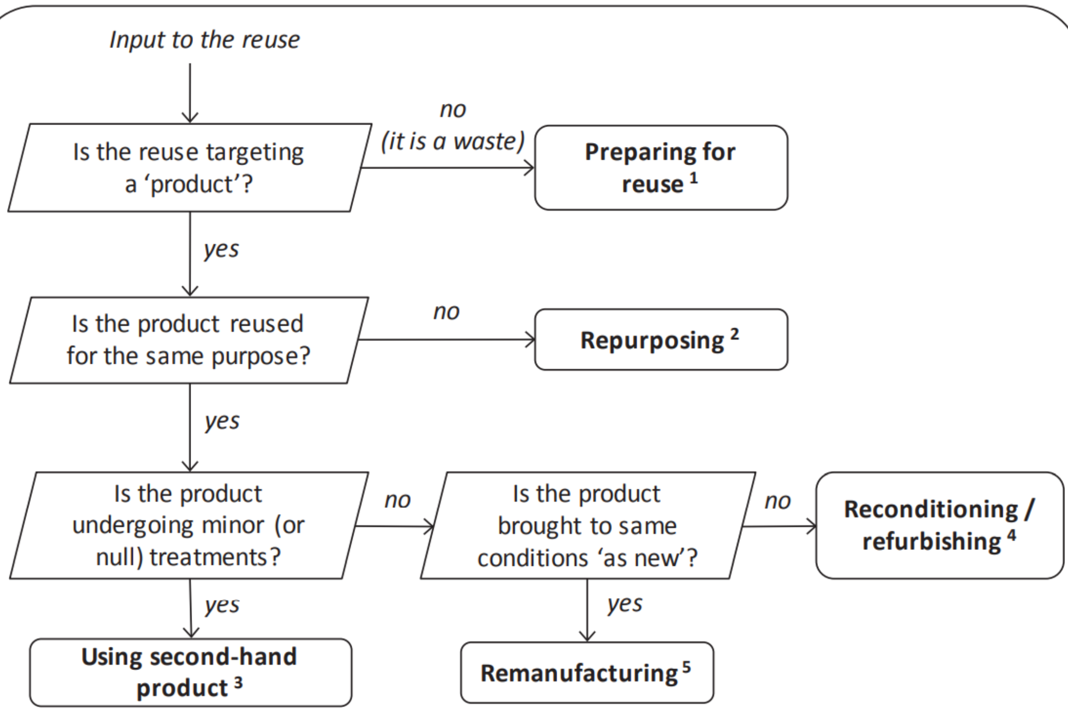
Figure 2 Stocks and flows of vehicles and materials in EU in year 2012 (Bobba et al 2020)

The diagram above from an article by Bobba et al (2020) shows the flow of light-duty vehicles, in the EU 2012. Almost 15 million new vehicles were added to the total stock, most of them with combustion engines, yellow flow. The total stock was 260 million units. Almost 11 million units unregistered, that is left the stock, black flow, so the stock grew with 3,9 million.

6,2 million units were classified as end-of-life vehicles, ELV, and sent to EU dismantlers, green flow, but note the high export flow in grey, most of it illegal. Most of the ELV vehicle flow is material recycled, around 90%, in orange, although this preserves only 7,5% of the initial value (Bobba et al 2021). Smaller portions of the green ELV flow become residual waste or is incinerated with energy recovery.

Reuse/repair/reconditioning/remanufacturing, preserves 85% of the initial value, and use only 25% of the manufacturing energy (Bobba et al 2021). This small red flow is only 480 kilo ton (kt), which is less than 10% of the total ELV flow. Of these 480 kt, 150 kt are classified as remanufactured. See Figure 3 for a definition of remanufacturing versus reuse.

One reason the subject of circular materials is receiving so much attention today is that electric vehicles contain more critical raw materials, e.g. rare earth elements in electric motors, cobalt in batteries etc, than combustion engines, and the small blue flow[4] of new EVs will gradually grow and eventually replace the large yellow flow of internal combustion engine vehicles, ICEs. But **only 1% of Rare Earth Elements, REEs, are recycled as REEs** with their very specific and highly sought-after functions today. Which means that **99% of REEs are lost** as impurity in steel and similar large flows, maybe forever, mixed with other materials. Losing all this value of the materials and the extra energy needed for new manufacturing, with related climate impact, is a main driver for increasing reuse, repair, reconditioning and remanufacturing.



Definitions:

[1] **Preparing for reuse** "means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused [...]" (EU, 2008).

[2] **Repurposing** means to "utilize a product or its components in a role that it was not originally designed to perform" (as the definition of "repurpose" by BSI (2009)).

[3] **Second-hand product** "shall mean tangible movable property that is suitable for further use as it is or after repair [...]" (as the definition of "second-hand good" by European Council (2006)).

[4] **Reconditioning (or refurbishing)** means to "return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components" (as the definition of "recondition" by BSI (2009)).

[5] **Remanufacturing** means to "return a used product [or component] to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product" (modified from the definition of "remanufacture" by BSI (2009), with the addition of the term within brackets).

Figure 3 Reuse, repair, reconditioning and remanufacturing according to Ardente et al (2018)

An attractive way of reducing the large, orange, recycling stream (which only preserves 7,5% of the initial value), is to increase the service life of vehicles, i.e. less green flow (unregistered vehicles) would give less vehicles reaching end-of-life vehicle, ELV, and more material kept in use.

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[4] Already in beginning of 2022, in Sweden, more EVs than ICEs were sold (29% battery electric vehicles and 23% plug-in hybrid electric vehicles (Dagens Nyheter 21 May 2022)).

Note that new spare parts only involve 200 kt of materials, so this could not really absorb the enormous, orange, flow of 4800 kt of recycled material, if some of it, could be remanufactured rather than recycled. In this context, Bobba et al (2021), claims that only 20% of remanufacturable units are actually remanufactured in the EU. If 20% means 150 kt, then remanufacturing the remaining 80% means an additional flow of 600 kt. So much spare parts are not needed, but **use of remanufactured parts in new vehicles**: 15 million units*1,25 ton=19 million ton materials, **could easily absorb such an enlarged flow of remanufactured parts**; maybe it will become possible in the future. Business models that use remanufactured cores for manufacturing are very rare today and limited to heavy duty vehicles.

In a report from the EU Joint Research Center, JRC, Bobba et al (2021), also mentions several barriers and incentives for remanufacturing. The table below lists barriers and incentives without implying any significance or weight, though OEM acceptance is stressed as main barrier in the JRC report. Note that several barriers, like customers attitudes and competition from low-cost new production, are seen as both barriers and drivers.

Table 3 Barriers and incentives for remanufacturing of vehicle components. Adapted from Bobba et al (2021)

Barrier	Incentive	Comment
OEM acceptance	Asset and brand protection	
	Higher profit margins	
Customer recognition/acceptance	Customer pressure	
Volume/availability and quality of 'cores' (used parts intended to become remanufactured)	Securing spare parts supply	
	Reduced resource security risks	
High labour costs	Potential to lower product prices	
Legal ambiguity over remanufacturing in different jurisdictions (e.g. Russia and Turkey not allowing remanufactured parts as spare parts)	Environmental responsibility	
	Strategic advantage and increasing market share	
Lack of sales channels (linked to customer recognition)	Enabling and designing alternative business models	
	Product warranties	
	Digitalization opportunities for brokers in the remanufacturing value-chain	

Barrier	Incentive	Comment
No design for remanufacturing	Design for remanufacturing including prognostics, electronic life assessment and component restoration	Highlighted in external project webinar 22 May 2022
Rapid evolution of the technology (energy efficiency, light weighting)		
Competition from low-cost new production	Ease competition from low-cost new production	
Lack of product knowledge, including third-party product technical information		
Lack of technology		
Skills shortages		
Variation of interior details like seats, creates high demand for storage to meet demand		

A webinar on barriers and incentives for increased use of remanufactured vehicle parts in May 2022 brought together both vehicle manufacturers, insurance companies, remanufacturers and researchers. Among other it was concluded that there is no general barrier for using remanufactured parts in insurance repairs, but repair protocols/instructions that allows such parts are sometimes not yet developed. Furthermore, when the insurance is involved, there is today no direct economic incentive for the car owner to push for using cheaper parts. **The lack of design for remanufacturing in product planning** was also highlighted as a key ingredient that **is still largely missing.** Design for remanufacturing and circular business systems need to move from single isolated projects to full implementation in all product planning.

3.2 The case of the electric motor

This chapter examines what increased remanufacturing would mean for the case of the electric motor. The electric motor contains a lot of rare earth elements, REEs, in the permanent magnet, 2-3% of motor weight, which are very difficult to recycle. One way of using the REEs better would be to remanufacture the motor by changing bearings and maybe the axle. Two different LCA studies, one by Bobba et al (2021) commissioned by the EU Joint Research Center, one in the SE:Kond2LIFE project, using data from Tillman et al (2020) in combination with data from Volvo Cars, all find quite large climate gain by such remanufacturing compared to new production: Bobba et al: 2,9 kg CO_2/kg motor, SE:Kond2LIFE found 4,3 kg CO_2/kg motor.

Bobba et al (2021) makes a calculation of future climate impact from electric motors in the EU fleet of cars, considering that all motors are new, see Figure 4 , and compares this to a scenario where an increasing number of motors are remanufactured, reaching 30% in 2050, see Figure 5.

Figure 46: GWP (Global Warming Potential) of electric motors in the EU fleet for different years considering all motors newly manufactured

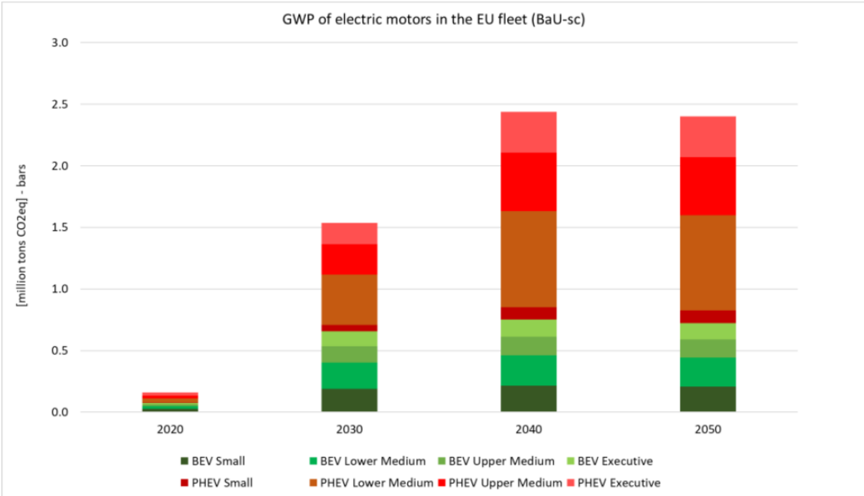

Figure 4 Climate impact of electric motors in the EU fleet considering all motors newly manufactured, Figure 46 in Bobba et al 2021

Figure 47: GWP (Global Warming Potential) of electric motors in the EU fleet for different years considering an increasing share of remanufactured electric motors over time

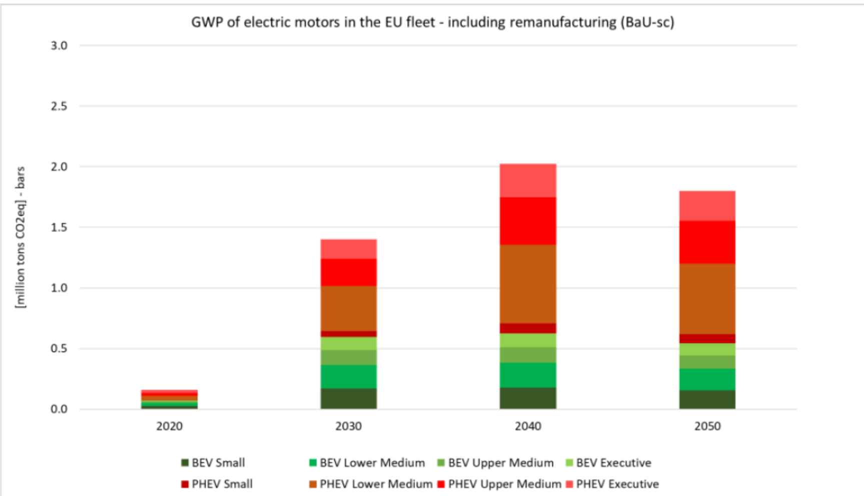

Figure 5 Climate impact of electric motors in the EU fleet considering an increasing share remanufactured (reaching 30% in 2050), Figure 47 in Bobba et al 2021

The different colours are different electric vehicles, battery electric vehicles, BEV, (greenish), plug-in hybrid electric vehicles, PHEV, (red/brown), of different sizes gradually increasing their share of the EU fleet of electric cars up to 2050. Figure 4 considers all motors newly manufactured in a Business-as-Usual scenario, BaU-sc. This scenario, BaU-sc, largely represents the current situation and takes a pessimistic view of improvements in both production systems and future mobility. As mentioned above, Figure 5 assumes an increasing share of electric motors being remanufactured, reaching 30% in 2050. Comparing Figure 4 with Figure 5, shows that the climate impact of electric motors in the EU by 2050, if 30% are remanufactured compared to no remanufacturing, will decrease with 0,6 million ton, from 2,4 to 1,8 million ton, that is 25%, compared to no remanufacturing. It should be remembered that the main motivation to remanufacture electric motors is to save/use the REEs in the magnet, so the CO_2 decrease is an added benefit.

To use this result, 0,6 million tons less CO_2, or 25% decrease of CO_2 emissions for remanufacturing of the electric motor, as a basis to make a prognosis for what remanufacturing vehicle components would mean for the whole EU future electric vehicle fleet, is difficult for several reasons. One is of course the electrification of the vehicle fleet; we do not how long it will take, for example. Figure 6 shows that the bulk of remanufactured and spare parts for 2012 belong to internal combustion engine, ICE, vehicles. Some studies predict 30% less gross demand for parts on the aftermarket for BEVs than for ICEs (Berger 2022). Typical prime candidates for remanufacturing among electrical vehicle components are batteries and electric motors as shown by the examples in this report. Batteries make up 5-25% of EV curb weight and electric motors maybe 2,5 % of EV curb weight, so there is future potential. Power electronics are other candidates for remanufacturing, that should be investigated. Berger (2022) values BEV-specific aftermarket components to around 7 billion Euro in Europe 2040, see Figure 7. Seats and interior details have also been studied in the SE:Kond2LIFE project and this category could be interesting to remanufacture with an adjusted design and if and when vehicle service life increases. The model developed by Bobba et al (2021), which can make EU vehicle fleet projections in combination with both remanufacturing rates and demand for remanufactured parts and resulting environmental impacts, could potentially be used to analyse and optimize such future remanufacturing flows.

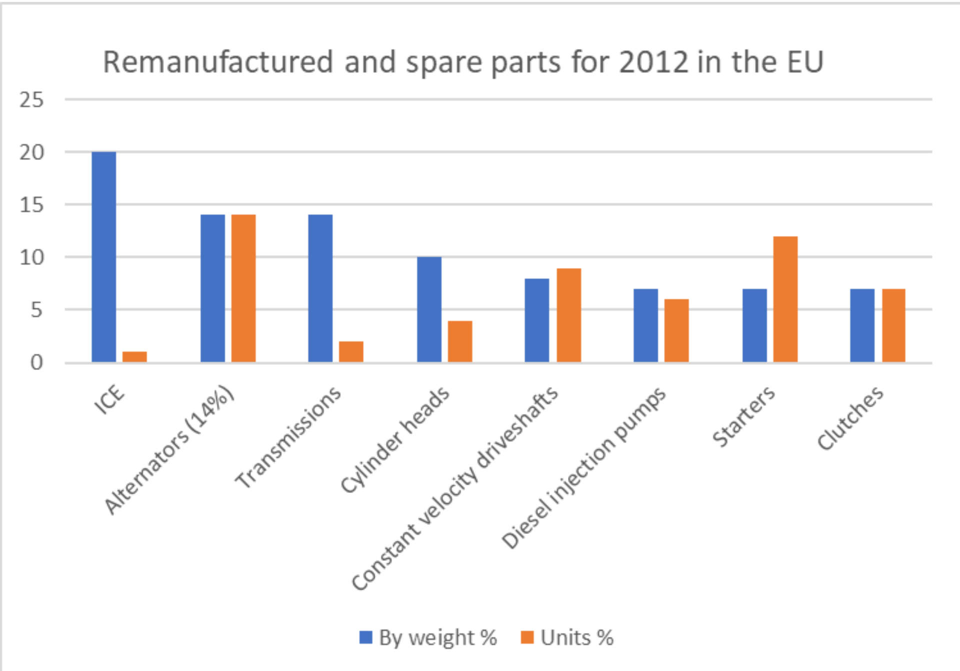

Figure 6 Remanufactured and spare parts for 2012 in the EU

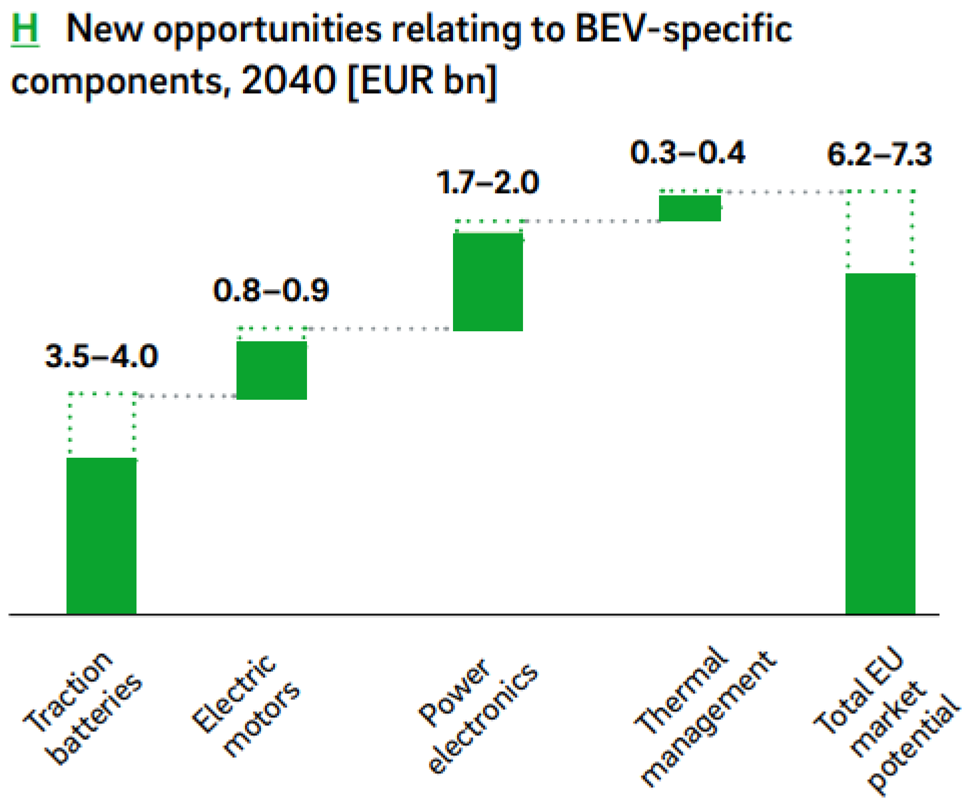

Figure 7 Market value of BEV-specific aftermarket components in EU 2040 (Berger 2022)

4 Results, individual components

4.1 Link arm

In the Sankey diagrams below, the environmental impact is proportional to the thickness of the arrows. The quantity is at the top of each box (p means piece and is understood together with the name of the box: for example, *1 p Kontroll och återtillverkning länkarm*, means 1 piece checked and remanufactured link arm). The environmental impact is in the lower left corner of the box, i.e., 10.3 kg CO_2-eq for a checked and remanufactured link arm.

Checking and remanufacturing, on the right, is compared with End-of-life and new manufacturing on the left. The least environmental impact is best environmentally. Cut-off 0.5% in Figure 8, means that only processes that contribute more than 0.5% to the total are shown in the image. However, all processes are included in the calculations.

4.1.1 Climate impact

Since the climate impact, 10.3 kg CO_2-eq, for a checked and remanufactured link arm is less than 45.2 kg CO_2-eq for End-of-life and new production (difference 35 kg), it is from a climate change perspective better to remanufacture, see Figure 8. Furthermore, it can be concluded that:

- To credit recycling profits from the scrapped part is of great importance for the result. Therefore, how to do such crediting becomes very significant. The assumption here is that 90% of the material is recycled, that the remelting is done as at Stena in Älmhult and that the remelted material replaces the original material, in this case, virgin aluminium made in EU27 and EFTA.
- The production of aluminium for the link arm accounts for the largest climate impact, followed by the die casting, which is assumed to take place in Italy using European electricity mix. Die casting with Swedish electricity mix means just under 4 kg CO_2 per link arm, compared with 16 kg CO_2 per link arm for European electricity mix.
- The bushings, which must be replaced during remanufacturing, are also included in the newly manufactured part and therefore do not need to be included in the model at all; they can be off-set. This is a general lesson for calculations of the usefulness (or uselessness) of remanufacturing: parts that must be replaced with new parts during remanufacturing do not have to be included in the model, as they can be off-set against the same parts in the newly manufactured part. The bushings can therefore be removed from the calculations (off-set) with the parameter option Kvitta=0 in the software model. The difference between *Resthantering och nytillverkning*, and, *Kontroll och återtillverkning*, is still 35 kg, the same as when the bushings were included in the calculations, compare Figure 8 with Figure 9.
- The longer transport for the remanufactured link arm from warehousing to the workshop (Lundberg et al 2020) makes a small but not decisive contribution in terms of climate (1.8 kg CO_2eq for the remanufactured link arm compared with 0.6 CO_2eq for the newly manufactured one).

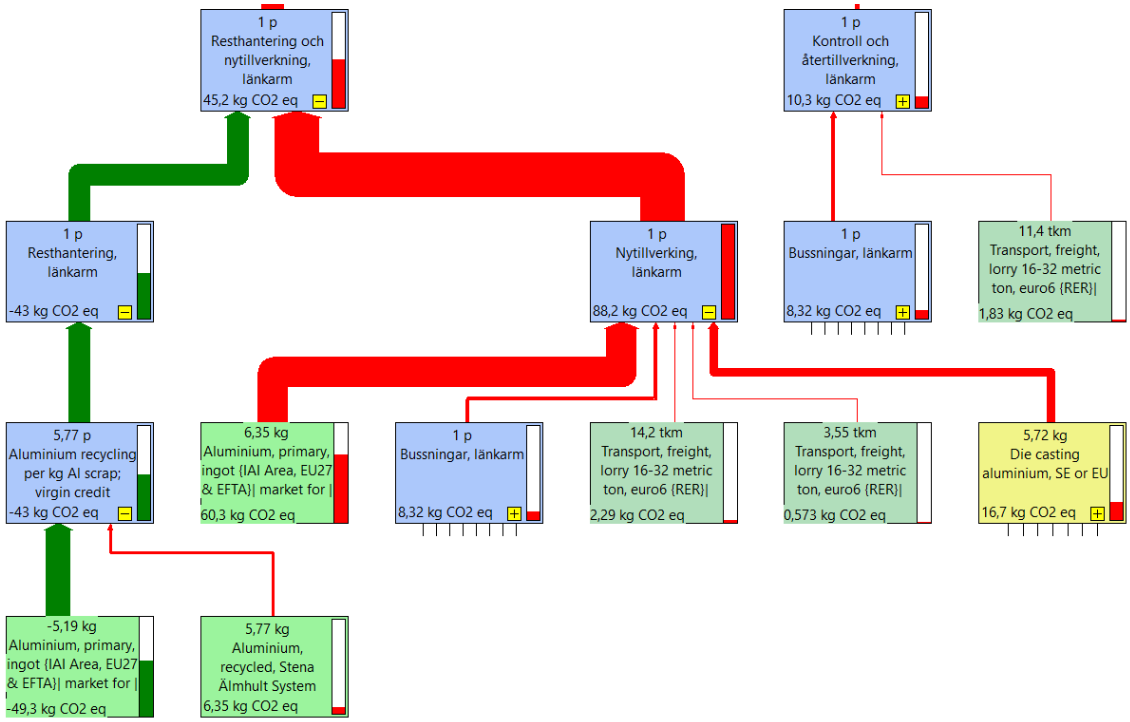

Figure 8 Climate impact for end-of-life and new production of link arm in Italy, left, compared with checking and remanufacturing, right, cut-off 0.5%

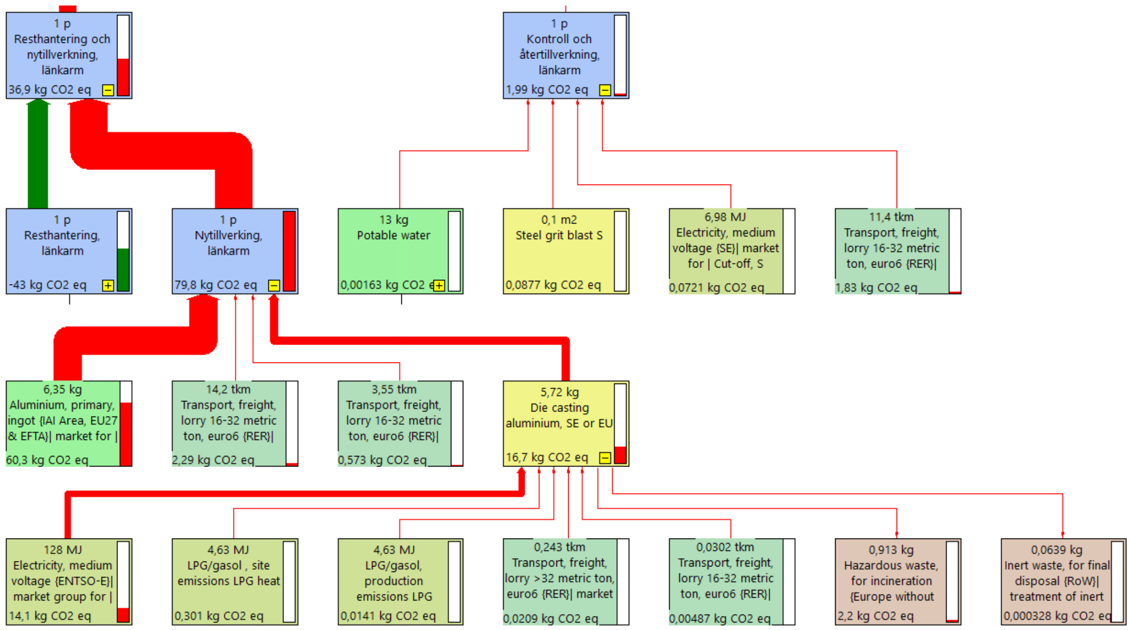

Figure 9 Climate impact for end-of-life and new production of link arm in Italy, left, compared with checking and remanufacturing, right, bushings excluded.

Figure 10 below simulates manufacturing in China. The aluminium raw material and die casting contribute to a significantly greater climate impact. Sea transport from China contributes less than truck transport from Italy, compare with Figure 8. However, primary aluminium production in China is much more climate heavy. Instead of 9.6 kg CO_2/kg aluminium during production in Europe, 22 kg CO_2/kg aluminium is generated during production in China. The climate impact from aluminium in the new part then rises from 60 kg to 137 kg CO2 per part. The die casting, calculated below with a Chinese electricity mix, more than doubles the climate impact.

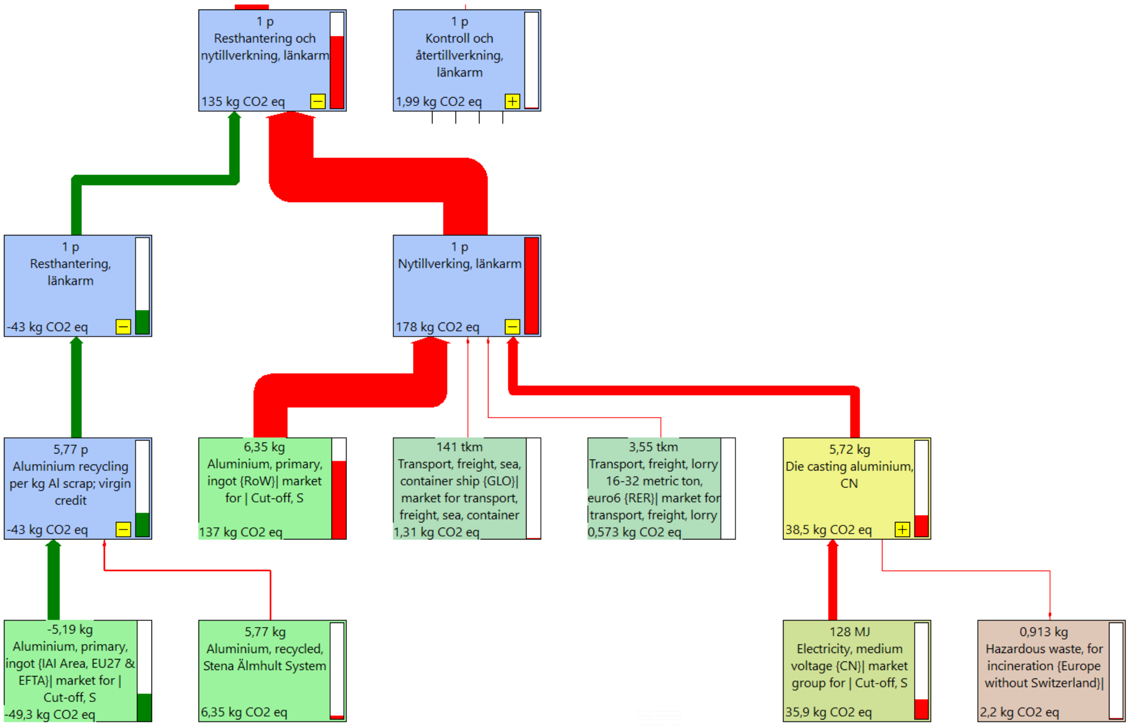

Figure 10 Climate impact for end-of-life and new production of link arms in China compared with checking and remanufacturing. Bushings subtracted. Cut-off 0.23%

4.1.2 Solar electricity

As previously mentioned, the remanufacturing company produces its own electricity through solar panels on the roof and a battery storage built from used battery packs. However, the climate impact for remanufacturing with solar electricity will be somewhat higher compared with the Swedish average, compare Figure 11 where solar electricity contributes with 0.18 kg CO2, with Figure 8 where the same amount of Swedish average electricity accounts for 0.07 kg CO2. This can be explained by the contribution of the PV cells (production and mounting). Since it is more or less a practice within LCA that production equipment is excluded, it can also be argued that including it for self-produced electricity causes an asymmetry in the model for the environmental impact of remanufacturing. See also reasoning in Table 1 that self-produced solar electricity in Sweden should rather be compared with European average electricity (because it can replace European average electricity) than with Swedish average electricity. In this study, however, **Swedish average electricity is henceforth assumed for the remanufacturing company in order to represent general conditions in Sweden.**

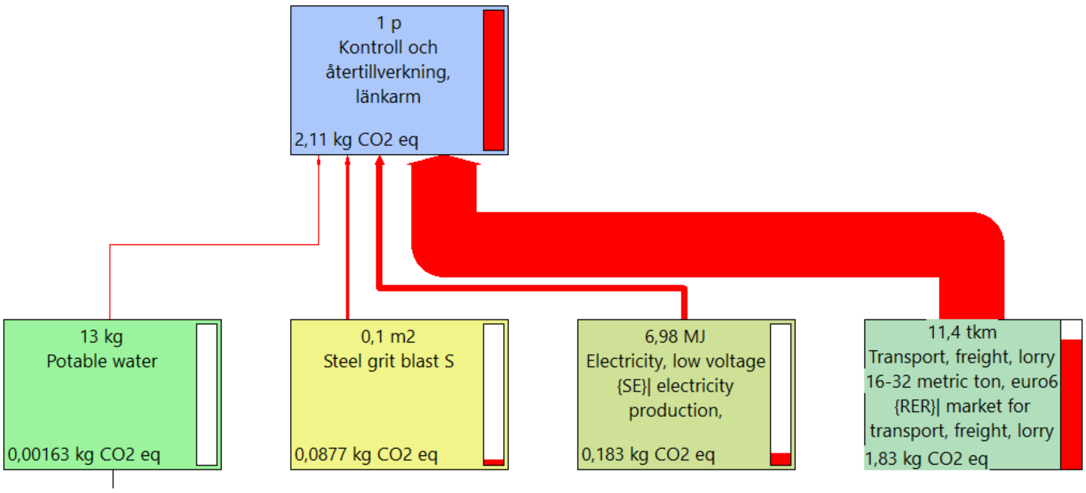

Figure 11 Climate impact for checking and remanufacturing of link arm, with own generation of solar electricity

The transport (on average 1600 km from storage to repair shop for remanufactured parts) is dominating climate impacts for checking and remanufacturing of the link arm. This is very visible in Figure 11 but not all visible in Figure 9 although numerically the same.

4.1.3 Resource depletion

Resource depletion is measured with two indicators to reflect both long-term and short-term resource depletion, see Figure 12 and Figure 13 below. The reason, as mentioned earlier, is that the (more long-term) method recommended in reputable LCA guidelines (EC 2017) does not reflect the current scarcity of typical battery metals such as cobalt, nickel and lithium (Zackrisson 2021). For long-term resource depletion, checking and remanufacturing of the link arm is 16 times smaller than end-of-life and new manufacturing. For short-term resource depletion, checking and remanufacturing of the link arm is 10 times less than end-of-life and new manufacturing. Since both resource depletion indicators show the same tendency for the link arm, only the long-term one is used for the wheel spindle and for the stay.

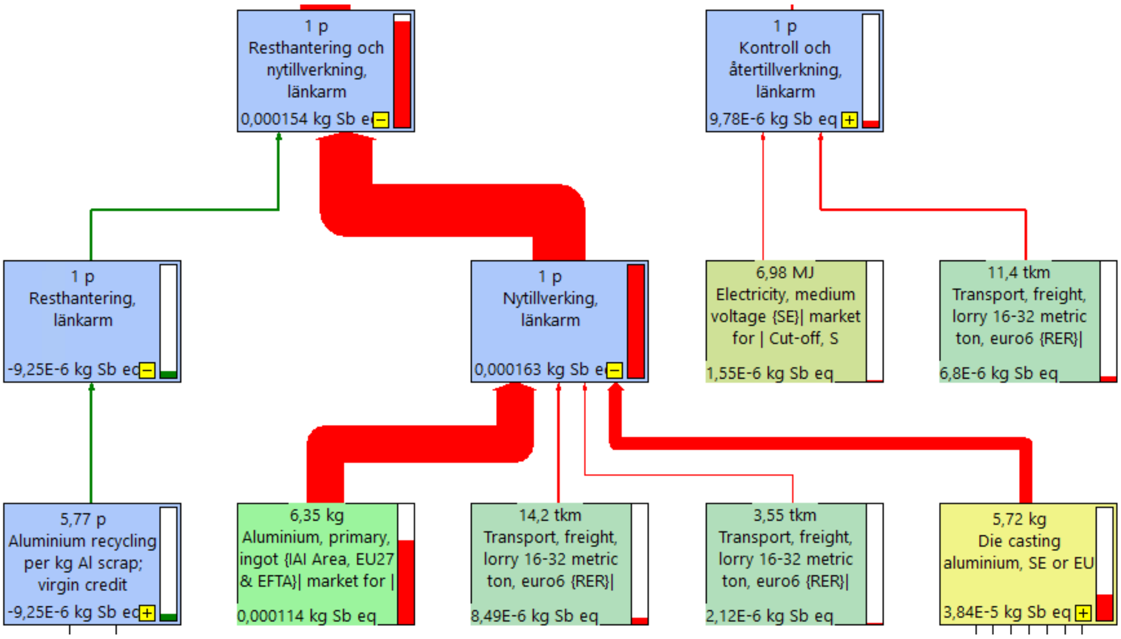

Figure 12 Long-term resource depletion for end-of-life and new manufacturing of link arm compared with checking and remanufacturing, bushings subtracted, new manufacturing in Italy, Swedish average for remanufacturing, cut-off 0.91%

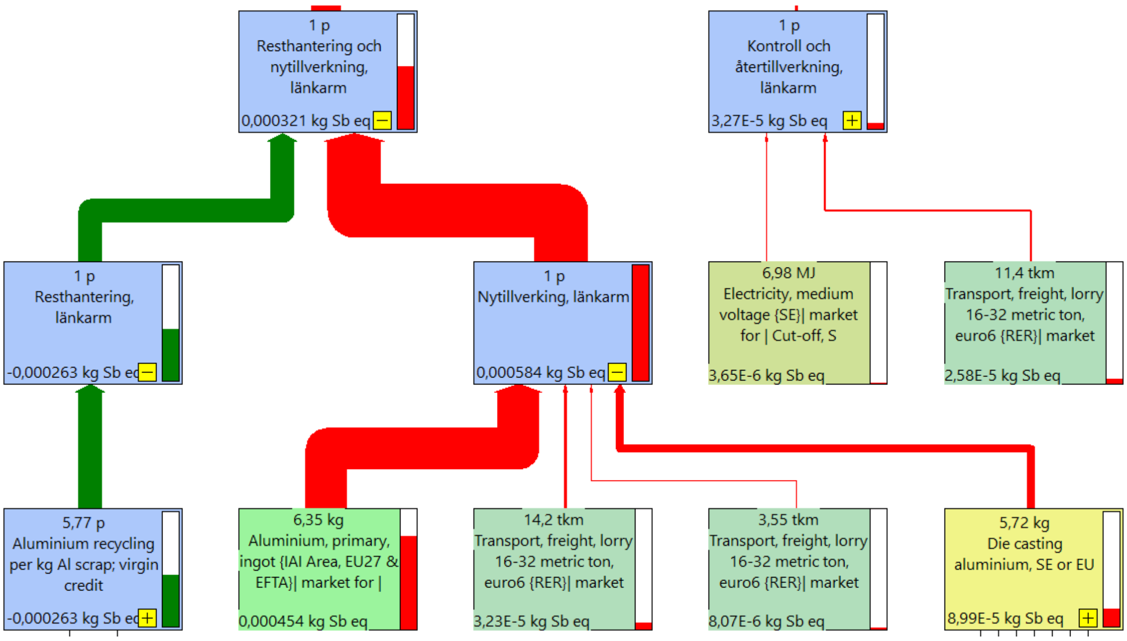

Figure 13 Short-term resource depletion for end-of-life and new manufacturing of link arm compared with checking and remanufacturing, bushings subtracted, new manufacturing in Italy, Swedish average for remanufacturing, cut-off 0,6%

4.2 Wheel spindle

4.2.1 Climate impact

The climate impact, 1 kg CO2-eq, for a piece of checked and remanufactured wheel spindle is less than 19.1 kg CO2-eq for end-of-life and new production (difference 18.1 kg). So it is from a climate change perspective better to remanufacture the wheel spindle. See Figure 14 below. However, the difference and weight are halved compared to the link arm.

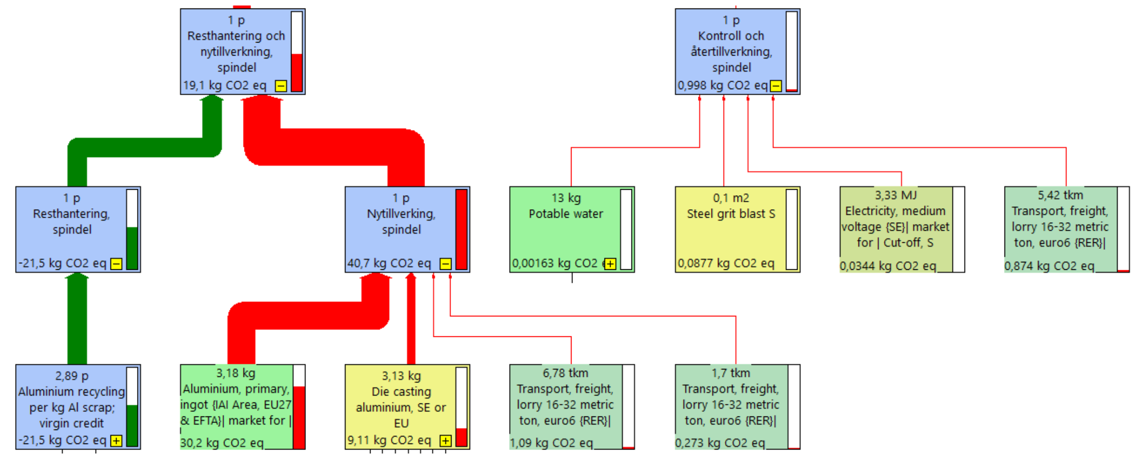

Figure 14 Climate impact for end-of-life and new production of wheel spindle compared to checking and remanufacturing, bushings subtracted

4.2.2 Resource depletion

For long-term resource depletion of wheel spindle, end-of-life and new manufacturing means 15 times more resource depletion compared to remanufacturing, see Figure 15. That is about the same condition that applied to the link arm.

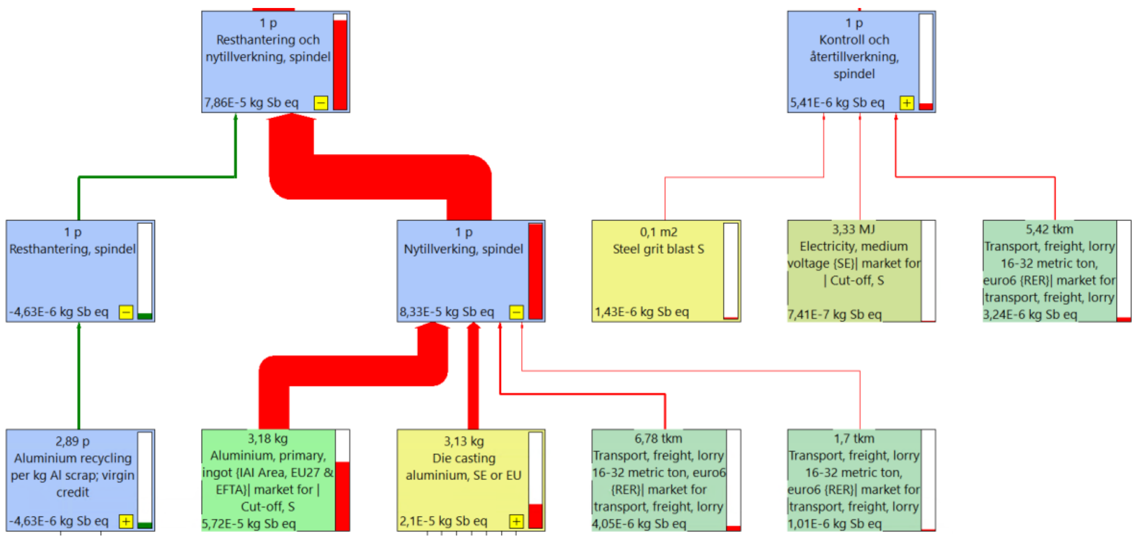

Figure 15 Resource depletion for end-of-life and new production of wheel spindle compared to checking and remanufacturing, bushings subtracted, cut-off 0,87%

4.3 Battery

4.3.1 Climate impact

As can be seen from Figure 16 and Figure 17 below, it is very advantageous from a climate point of view to swap to a remanufactured battery, compared with swapping to a new battery. The climate benefit of remanufacturing compared to end-of-life and new manufacturing is between 290 and 81 kg CO_2eq per kWh battery. Most climate benefit can be achieved compared to the older LMO-NMC battery; considerably less in comparison with the new C40 battery. The fact that Cusenza's battery is significantly older may be an explanation for the differences. Since the V60 battery has a nominal energy content of 11.4 kWh, the total saving will be somewhere between 11.4*290= 3306 and 11.4*81=923 kg CO_2eq, compared to, for example, the recycled link arm saving of 22 kg CO_2eq. For the sake of simplicity, the average of 290 and 81, i.e. 185 kg CO_2eq /kWh, is used in comparison with the other components. Emilsson and Dahllöf (2019) investigated the climate impact of lithium-ion batteries with NMC chemistry and then found that these were in the range 61-106 kg CO_2eq/kWh battery. In comparison, 185 kg CO_2eq/kWh is high, but in the same order of magnitude and a different chemistry.

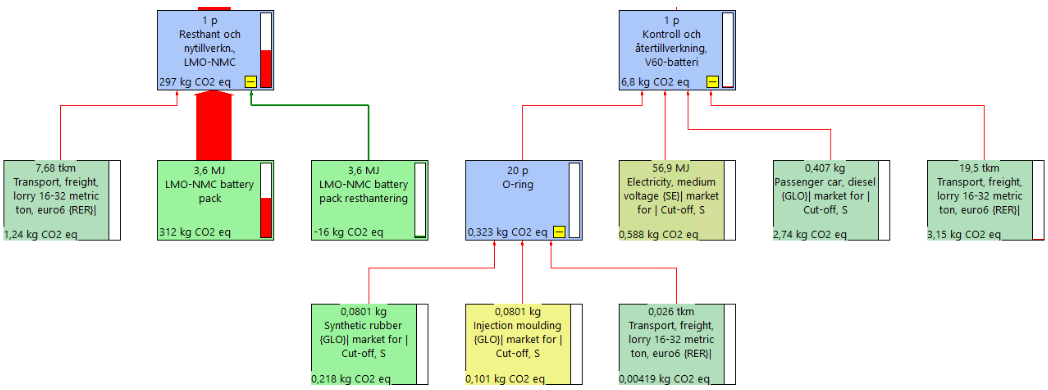

Figure 16 Climate impact of swapping to a new LMO-NMC battery (Cusenza et al 2019) compared to swapping to a remanufactured battery, kg CO_2eq per kWh battery

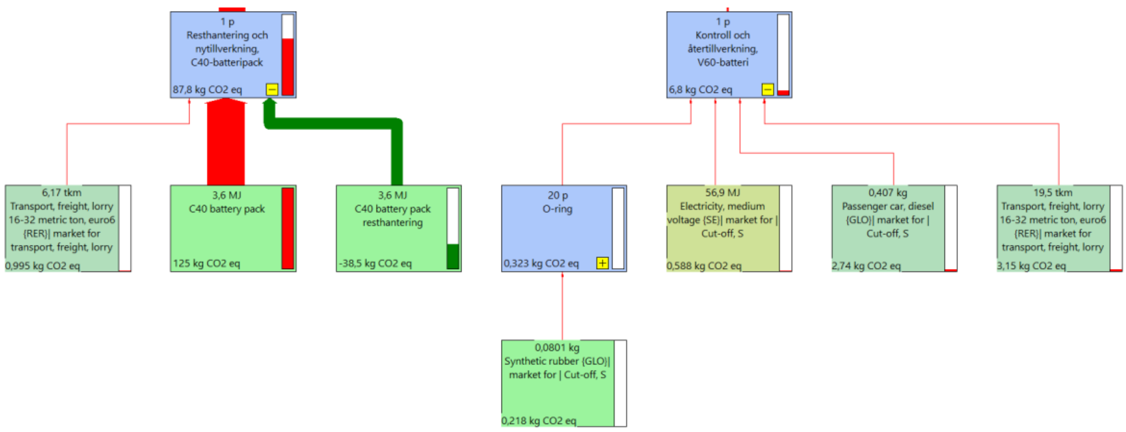

Figure 17 Climate impact of swapping to a new battery similar to a C40 battery, compared to swapping to a remanufactured battery, kg CO_2eq per kWh battery

Checking and remanufacturing of the V60 battery gives, in comparison with new manufacturing, very little climate impact, 6.8 kg CO_2eq per kWh. Note that the O-rings that are replaced cannot be subtracted, as they are not clearly visible in the datasets being compared. The largest climate impact in the remanufacturing is the transport from storage of remanufactured battery to workshop.

4.3.2 Resource depletion

The C40 battery has no available information on resource depletion (Volvo Cars 2021), only about climate impact. So resource depletion can only be assessed based on Cusenza et al (2019). Cusenza et al (2019) use the long-term perspective and finds that remanufacturing means 25 times less resource depletion, see Figure 18.

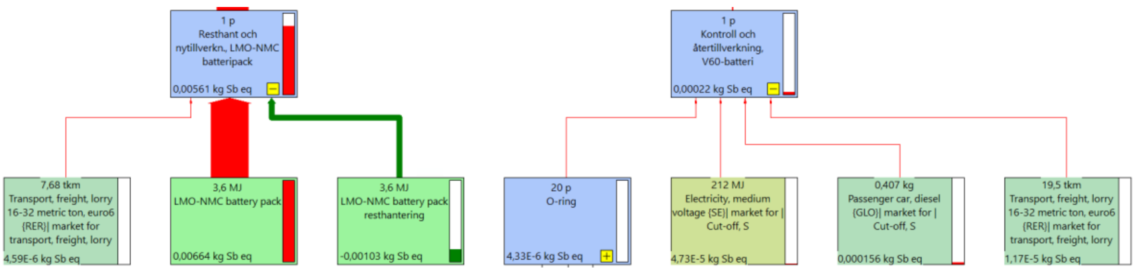

Figure 18 Long-term resource depletion for end-of-life and new production of battery compared to checking and remanufacturing, kg Sb_{eq} per kWh battery

4.4 Electric motor

4.4.1 Climate impact

As can be seen in Figure 19, it is from a climate change perspective advantageous to swap to a remanufactured electric motor, compared to swapping to a new electric motor. The climate benefit of remanufacturing compared to end-of-life and new manufacturing is 229-34.2 = 195 kg kg CO2eq per electric motor of about 100 kW.

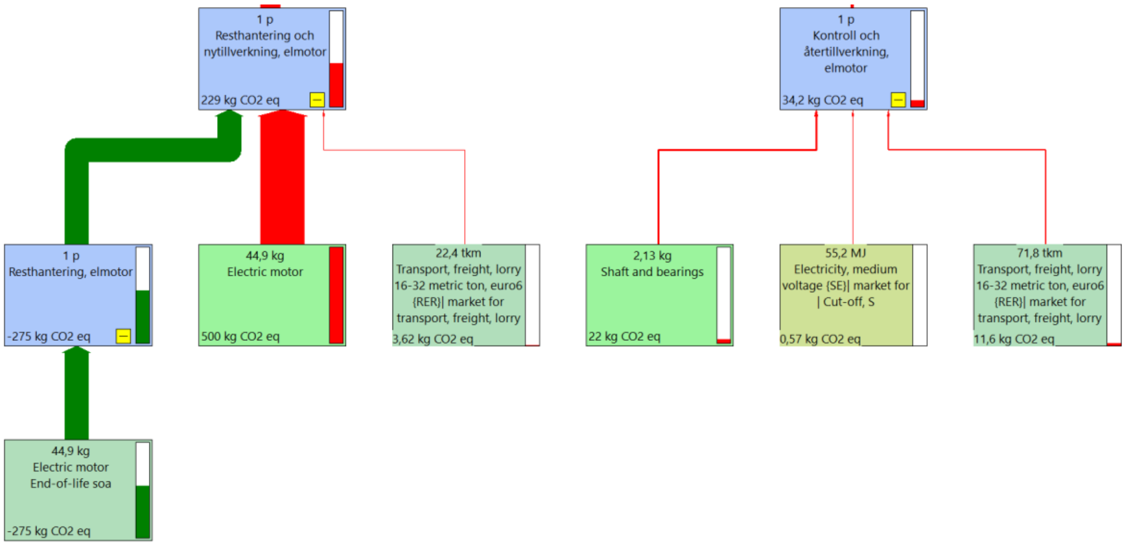

Figure 19 Climate impact for switching to a new electric motor, compared to switching to a remanufactured electric motor, kg CO_2eq per 100 kW electric motor

It should be added that end-of-life credits contribute to an unusually large amount of avoided climate impact in the case of end-of-life and new production (green flow in Figure 19). That one can "get back" well over 50% of the production's climate impact via end-of-life credits is very unusual and is explained (Tillman et al 2020) by a large proportion of aluminium in the investigated electric motor. This could be compared to the link arm in Figure 7, which consists of 89% aluminium, but where the recycling "only" gives 43/88 = 49% avoided climate impact compared to new production. The region of production and its specific electricity mix is a relevant parameter in that case. It needs to be observed never to give higher recycling credits on the output side than corresponding production debits on the input side.

4.4.2 Resource depletion

For the electric motor, it is difficult to assess the resource depletion due to asymmetric data, i.e. we have different data sources for the different parts of the calculations. It is not possible to triangulate the same way as for climate impact. Tillman et al (2020) note, however, that resource depletion shows the same pattern as climate impact in terms of the ratio of resource depletion in new production and avoided resource depletion in end-of-life. Considering that the link arm, the wheel spindle and the battery all show advantages in remanufacturing from both a climate and a resource perspective, we probably dare to believe that this also applies to the electric motor. Especially since one of the main drivers to remanufacture electric motors is to use the critical raw materials in the permanent magnet, for which separation and recycling is very difficult (Tillman et al 2020).

4.5 Stay

4.5.1 Climate impact

The climate impact, 0.13 kg CO_2eq, for one piece of checked and remanufactured stay is less than the 1.77 kg CO_2eq calculated for end-of-life and new production (difference 1.64 kg). So, it is from a climate change perspective better to remanufacture the stay, but you only save 1.6 kg CO_2eq per stay. See Figure 20. See Figure 21 for details about the remanufacturing.

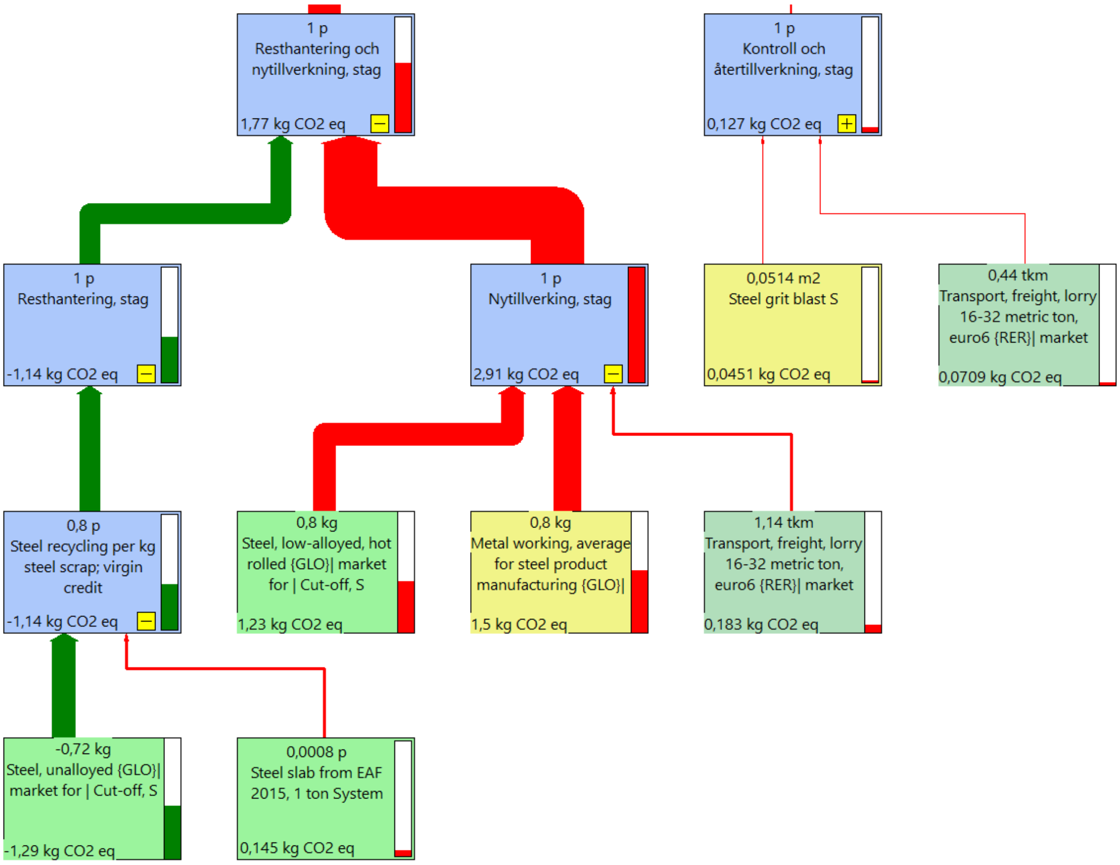

Figure 20 Climate impact of swapping to a new stay, to the left, compared to swapping to remanufactured stay, right, kg CO_2eq per stay, cut-off 1,5%

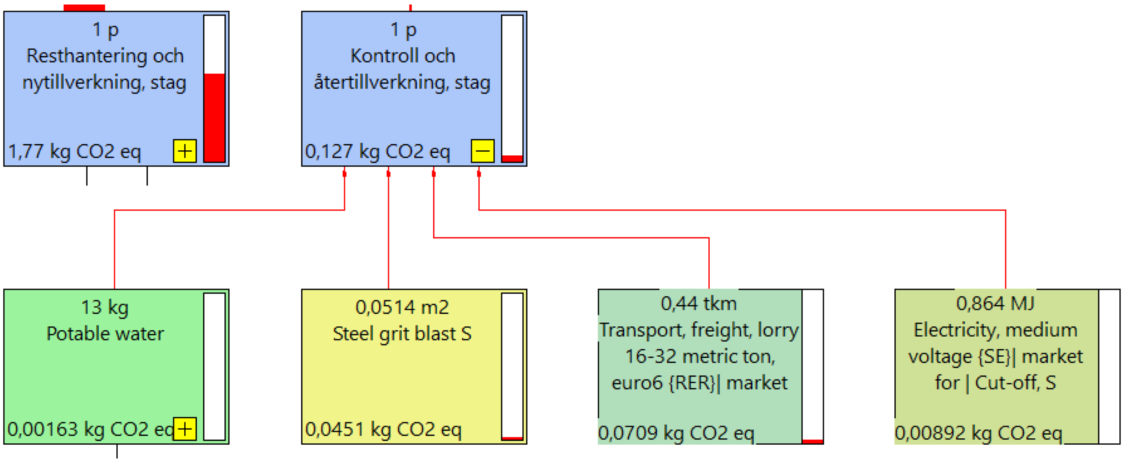

Figure 21 Climate impact of swapping to a new stay, compared to swapping to remanufactured stay, kg CO_2eq per stay. Focus on checking and remanufacturing.

4.5.2 Resource depletion

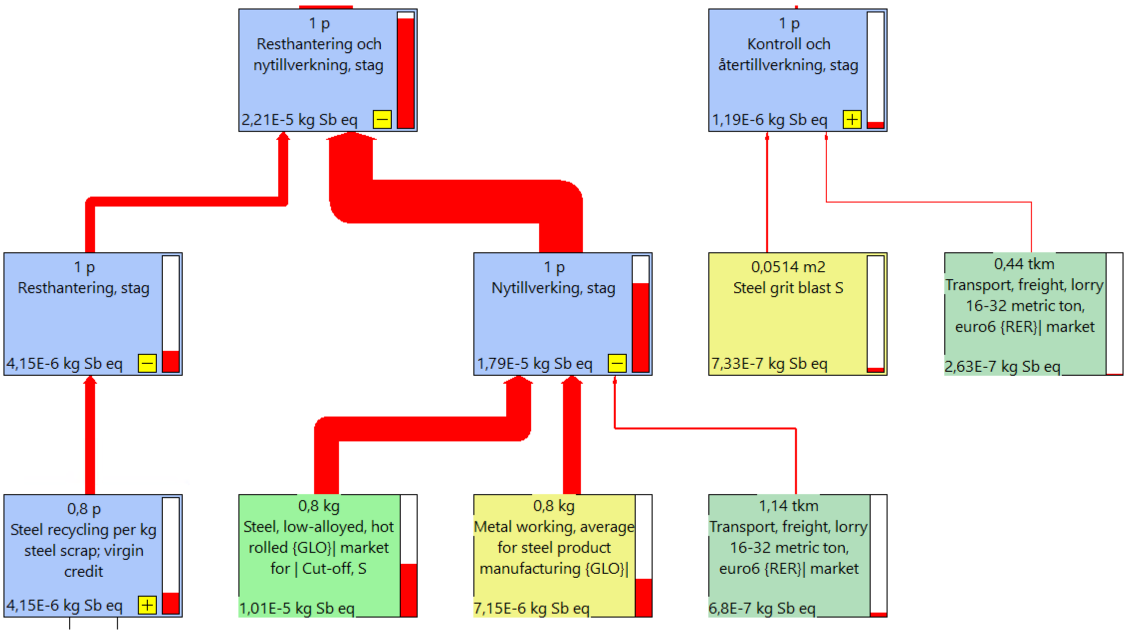

Figure 22 Long-term resource depletion for end-of-life and new production of stay compared to checking and remanufacturing of stay, kg Sb_{eq}

For long-term resource depletion of the stay, end-of-life and new production involves 19 times more resource depletion compared to remanufacturing, so about the same order that applied to the link arm, see Figure 22.

4.6 Eco-design of seat covers

The calculated climate impact for all five modelled scenarios (see also section 2.7) is set to one for the current benchmark construction. The new design with input of recycled materials and renewable energy carriers is estimated to be 0.34, indicating that a reduction of approximately two thirds of the emissions can be achieved.. An overview is provided in Table 4.

Table 4 Climate impact for the production of seat cover, relative climate impact based on results in kg CO_2eq per square meter; PES polyester (polyethylene terephthalate based), PU: Polyurethane

	Design	Top layer	Base Layer	Raw material PET	Energy sources	Climate impact (relative)
1	Existing, benchmark	PES	PU foam/PES scrim	Primary	Conventional (at suppliers)	1
2	Existing, benchmark	PES	PU foam/PES scrim	Primary	Renewable (at suppliers)	0,76
3	Existing, benchmark	PES	PU foam/PES scrim	Recycled	Renewable (at suppliers)	0,59
4	New design	PES	PES	Recycled	Conventional (at suppliers)	0,72
5	New design	PES	PES	Recycled	Renewable (at suppliers)	0,34

Selected results for the design options are shown as Sankey diagrams to highlight contributions from materials and processes. Note that the manufacturing of PU foam is included as a market process, which offers less details.

All results were converted to 1 kg of seat cover material (base layer and top layer combined). The results are provided as contribution in % to the estimated impact. The total amount of PET needed as input material (visible at the top of process boxes in Sankey diagrams) is higher than the weight of the fabric, as losses during spinning, texturing and fabric making are considered. Not all processes are visible in the diagrams.

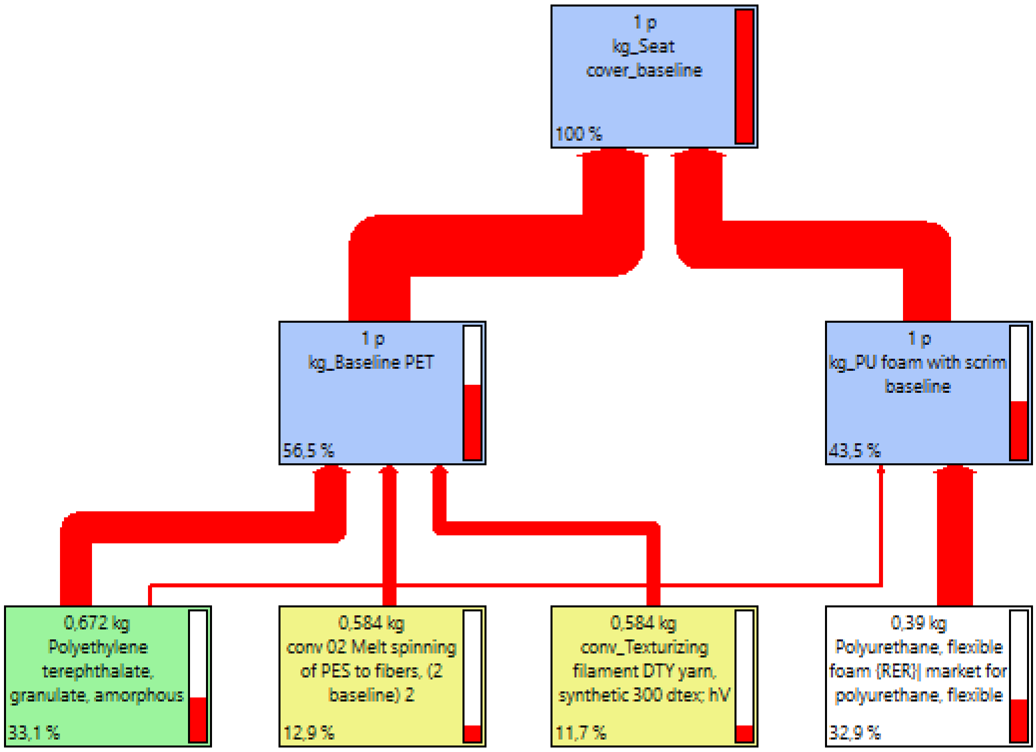

Figure 23 Contributions of materials and processes to the climate impact of 1 kg of seat cover, existing process (benchmark, option 1)

For the polyester part contributions from material (in green, PET granulate) and processing to yarn (in yellow, melt spinning and texturizing) can be seen separately. For a reduction of the climate impact there are several options.

Replacing primary raw material with recycled raw material leads to changes of the environmental impact of the green box; larger potential compared to processing. Increasing process efficiency of melt spinning and texturizing, using renewable fuels for heat and electricity required for melt spinning and texturizing are options to reduce the environmental impacts of the yellow boxes.

Polyurethane foam is based on a market process, which includes materials, processing, and transports.

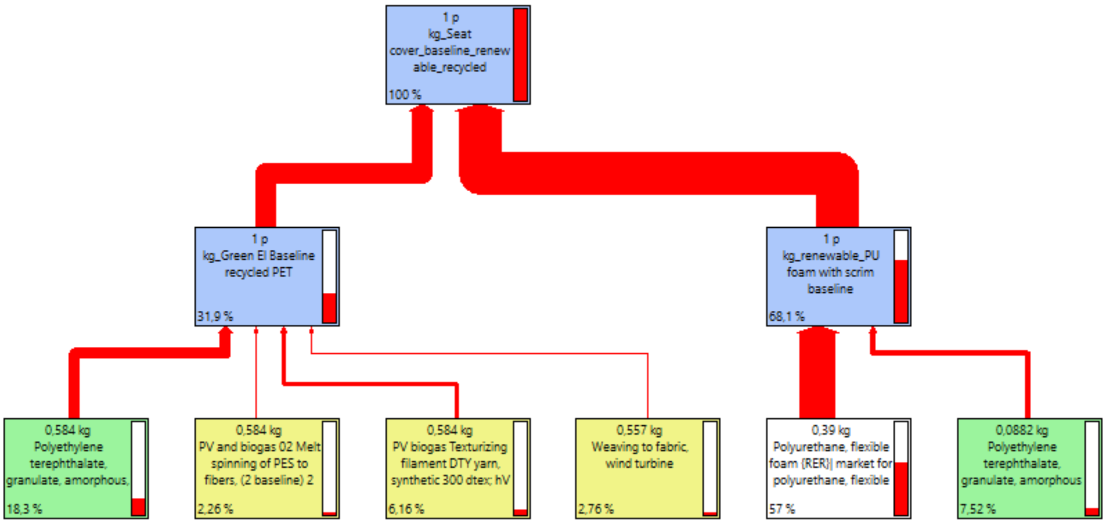

Figure 24 Contributions of materials and processes to the climate impact of 1 kg of seat cover, existing design with recycled PET and renewable energy carriers (benchmark, 3)

Figure 24 shows climate impacts if options for reduction are implemented. Changing the raw material to recycled PET and the energy carriers to renewable/fossil free options where possible, the results for the benchmark system can be reduced to approximately 60% of the contribution calculated for the benchmark 1. Processes and materials have different shares as illustrated in the Sankey diagram in Figure 24.

The absolute contributions from PU foam remains unchanged, the contribution from the polyester backing (scrim) was not visible in the previous diagram in Figure 23, but it was included in the calculation, as well as weaving.

The new design is based on PET as a raw material source for both layers with different fabric constructions for top layer and base layer. The contributions of environmental impacts of material and production are illustrated in Figure 25.

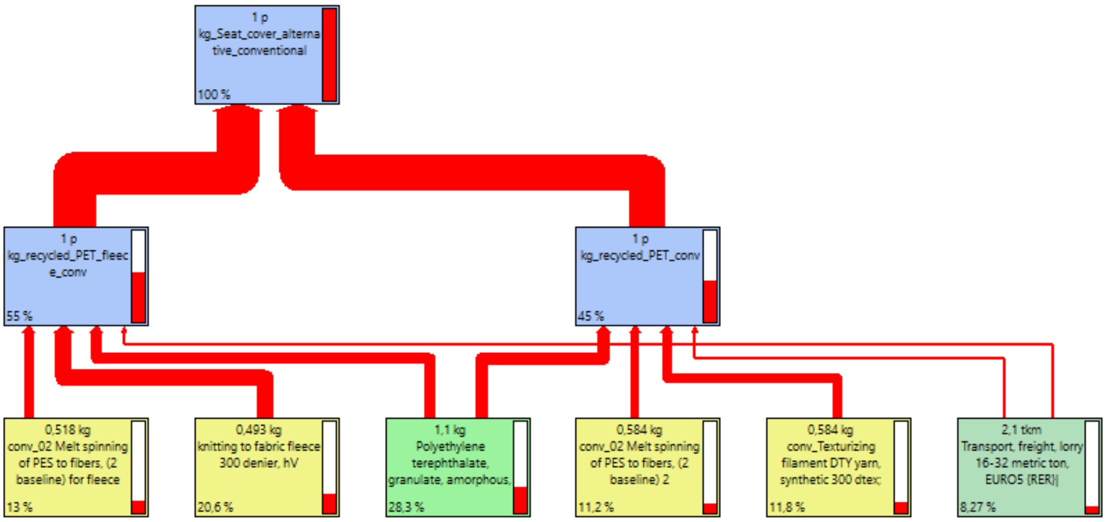

Figure 25 Contributions of materials and processes to the climate impact of 1 kg of seat cover, new design process (new design, 4)

Both top layer and base layer are made of a polyethylene terephthalate (PET) based polyester, which is processed in different ways. The top layer is a weave, as in the benchmark processes. The base layer is a fleece, for which PET yarn is knitted and mechanically treated. These processes are not implemented in practice and other options to produce fleece can be investigated. The green box shows the contribution of (recycled) material to both layers, whereas all yellow boxes show contributions of processes with renewable fuels to provide heat and electricity.

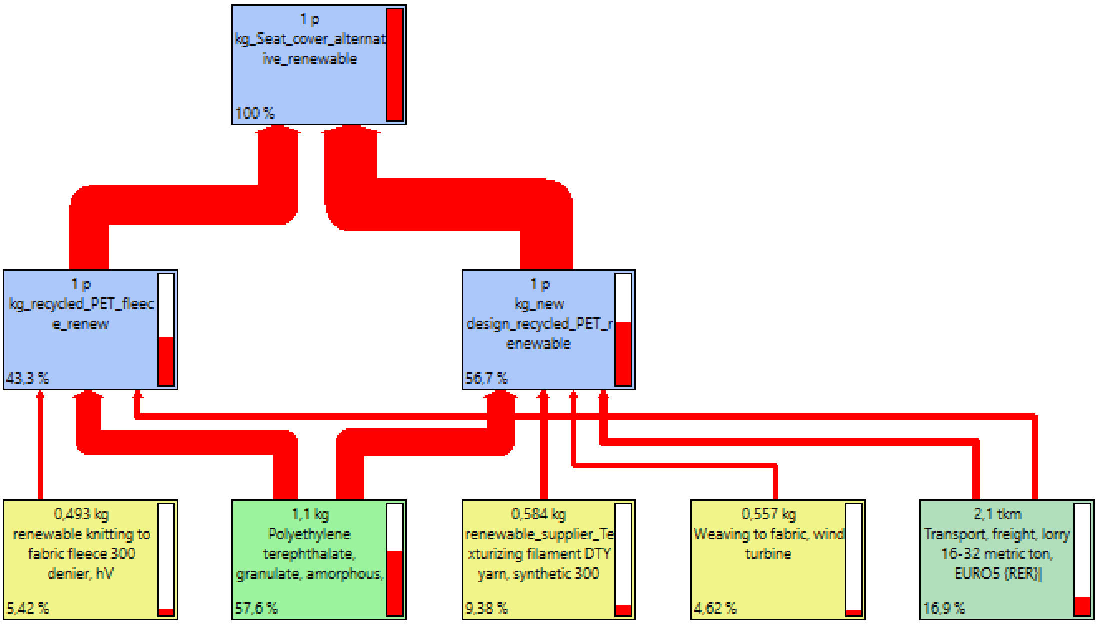

Figure 26 Contributions of materials and processes to the climate impact of 1 kg of seat cover, new design process and renewable energy carriers (new design, 5)

Figure 26 shows materials and processes and their contributions to the climate impact if renewable energy carriers are selected to provide heat and electricity required for processing (all yellow boxes) and the material is also selected as recycled.

Both material choice and process energy carriers contribute to the reduction of climate impact. The new design has additional benefits as it facilitates material recycling, while the multi material mix of PET and PU used today for the existing design is potentially treated as waste without recovering value. If any recovery can be established, the mix is used as an energy carrier and not recycled as material.

The remanufacturing process that is available and performed at this stage is done for few seats that are in condition “as new” and for which a demand is expected. At the time of this investigation, this was done for seats with a leather cover for which production was not included in the study. For textile covers it is assumed that a future procedure needs to include (steam) cleaning and inspection, which is estimated to require electricity and steam as well as water and soap/surfactant. The estimated effort for cleaning stands for 0.06 kg CO_2eq, mostly due to the use of soap. More sophisticated inspection routines and repair steps might be required to increase the number of remanufactured seats and seat covers, and storage and transport also contribute to the environmental impact. However, even with an optimised design and renewable energy carriers the impact for manufacturing a front seat cover is estimated to be far higher than the 0.06 kg CO_2eq for remanufacturing.

To be consistent with other parts, a transport process to a workshop is included in the model with the assumption that the distance for a remanufactured part is longer than the distance for a newly produced part. Transport processes are done for complete seats (without airbag) as there is no disassembly foreseen.

A front seat with 25 kg weight is assumed. The additional shipping distance for remanufactured components suggested by Lundberg is 900 km (1500 km compared to 600 km from warehouse; transport from manufacturing to warehouse not included), which would dominate the impacts modelled for remanufacturing. For a transport distance of 900 km, the climate impact is estimated to 3.7 kg CO2eq.

With the model largely based on assumptions and no similar investigations available in literature, this result can only be seen as tentative. However, due to the weight of a seat and effort to handle it, long shipping distances can outweigh benefits of remanufacturing.

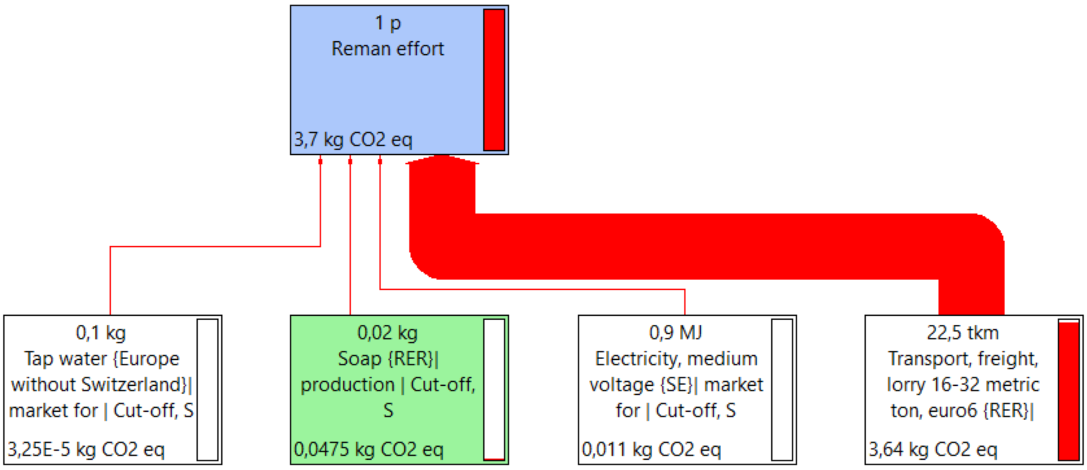

Figure 27 Remanufacturing effort for a front seat including cleaning, inspection, and transport to a workshop (900 km distance assumed)

This part of the investigation focuses on climate impacts as the investigated materials are made from fossil raw materials with energy for processing. No resource depletion results are provided.

4.7 All parts

The figure below shows how much climate gain is made if a damaged component is replaced with a remanufactured component, instead of a new component. The climate gain per component or part (blue bars) varies greatly between different parts, while the climate gain per kilogram part (orange bars) is between 2–14 kg CO_2/kg part or component. Note logarithmic scale. However, it is surprising that such a complex and expensive part as the electric motor gives less climate gain per unit weight than the simpler parts give. However, this may be because the recycling gains have been overestimated, as discussed in section 2.5.

Seat cover remanufacturing is not included in this comparison.

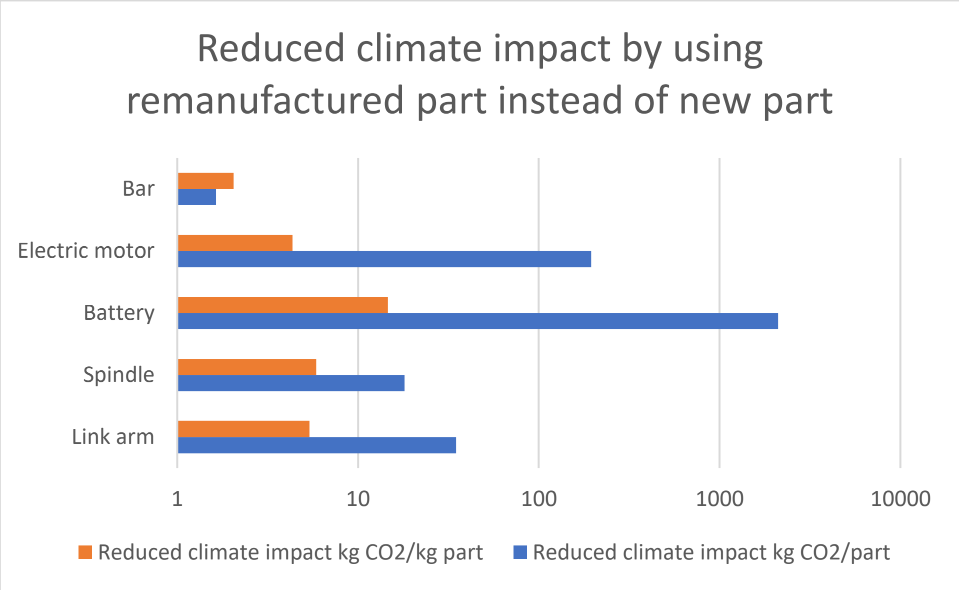

Figure 28 Reduced climate impact from remanufacturing of damaged part instead of new production. Note logarithmic scale.

Regarding resource depletion, all assessed parts provide resource savings in remanufacturing compared with new manufacturing. For the electric motor no data were available to assess resource depletion.

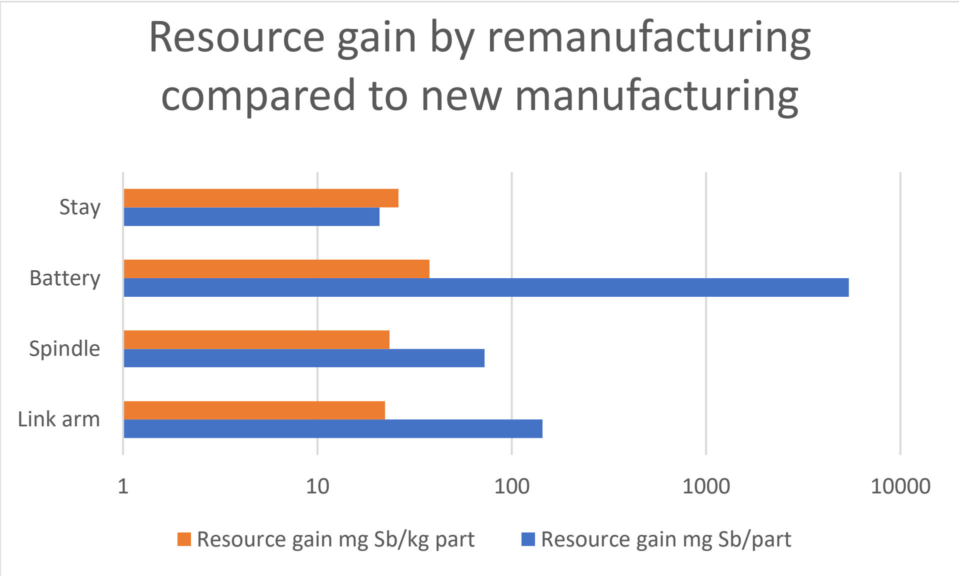

Figure 29 Resource savings in mg antimony (Sb) when remanufacturing a damaged part instead of new production. Note logarithmic scale.

5 Discussion and conclusions

5.1 Guidelines for decision-making

5.1.1 The decision to remanufacture

The five studies of metal components that have been carried out focusing remanufacturing, all indicate that the specific vehicle components studied is environmentally beneficial compared with scrapping and new manufacture of the specific component. However, there is a big difference in how great the environmental benefit is between different components, and it is not possible to draw the conclusion that it is environmentally beneficial to remanufacture any vehicle component. However, the result is so unequivocally positive and the components so different that one should be able to assume that, if it is economically advantageous to remanufacture, it is in all probability also environmentally beneficial.

The difference between the stay in steel and the aluminium parts indicates that you can count on more environmental benefit the nobler metal used. If you still want to ascertain the environmental benefit and/or quantify it, the LCA methodology developed and used in the project can be used.

Both the battery and the electric motor indicate potentially very large environmental benefits from remanufacturing. However, it is important that driveline components do not lose efficiency due to remanufacturing, as the use phase dominates the environmental impact of driveline components (Nordelöf et al 2018, Tillman et al 2020, Zackrisson 2021). However, there is nothing in the outlined remanufacturing methods that indicates that they can lead to efficiency losses. On the other hand, the evolution of the electric driveline is still in its infancy.

5.1.2 LCA methodology

One difficulty and weakness with the methodology used is the uncertainty in how material recycling gains (recycling credits, avoided burdens) should be calculated. The rule of crediting with the same material dataset that is used for modelling new production provides some security, but further guidelines would be desirable. Lundberg et al (2020) use cut-off methodology, which means that the avoided environmental impact from the material recycling is not credited to the studied system. In general, cut-off methodology is easier to use, but will disadvantage end-of-life and new production compared to checking and remanufacturing, as no crediting of the avoided climate impact is made. Lundberg et al find that repairing a typical damage (including right front fender and headlights, front bumper, bonnet and paintwork and rust protection) is made most climate-friendly by repairing the damaged parts, i.e. largely the same results as in our study. Using cut-off methodology and thus simply not calculating with any material recycling gains can be an acceptable solution to the uncertainty problem in these calculations.

New manufacturing is often complex and thus resource-intensive to model. An alternative is to use one or more studies of similar components, which were done here in the cases of the battery and the electric motor.

As was already stated in the feasibility study, the components that are changed in the remanufacturing can be off-set against the same details in the new manufacturing, i.e., subtracted from both sides of the model, or rather, not included in the first place. However, this simplification presupposes a separate, or so detailed LCA model, of the new production, that the replacement parts can be removed there.

5.1.3 Societal level

The current electrification of the vehicle stock makes future predictions of remanufactured vehicle components difficult. Increased use of rare earth elements, REEs, and critical raw materials, CRM, in electric vehicles, seem to strengthen rather than weaken the argument for remanufacturing. In addition, many vehicle parts have less climate impact if remanufactured compared to new production. An achievable level of remanufacturing of electric motors (30%) in the European fleet of cars could achieve 25% climate impact reduction compared to no remanufacturing. The conclusion of this report that if it is economically advantageous to remanufacture, it is also environmentally beneficial, should be used by the automotive industry to fully implement design for remanufacturing and circular business systems in all product planning. More circular business systems for vehicles would also likely mean increased service life of vehicles; an excellent way of using materials longer. Use of remanufactured parts should also be considered in new vehicles. Insurance companies should continue their work of developing repair protocols/instructions that allow remanufactured parts in repairs, and incentivize car owners to accept such parts.

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