

D5.5 - Environmental, criticality and circularity assessment of materials systems and components



Reinventing High-performance pOwer converters for heavy-Duty electric trAnSport

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ABBREVIATIONS

AD	Abiotic Depletion
ADP	Abiotic Depletion Potential
BEOL	Back End of Line
BM	Business Model
BOM	Bill of Materials
CB-PWM	Carrier-Based Pulse Width Modulation
CR	Concentration Risk
EI	Economic Importance
EoL	End of Life
FDR	Future Demand Risk
FEOL	Front End of Line
FU	Functional Unit
GAM	General Assembly
GWP	Global Warming Potential
IGBT	Insulated-Gate Bipolar Transistor
IMD	Integrated Motor Drive
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PCB	Printed Circuit Board
PCR	Product Category Rule
RoHS	Restriction of Hazardous Substances
RR	Recirculation Risk
SR	Supply Risk
TMS	Thermal Management System
TRL	Technology Readiness Level
TUW	Technische Universität Wien
WBG	Wide Band Gap

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EXECUTIVE SUMMARY

This report evaluates an Integrated Motor Drive (IMD) developed for electric trucks, with the aim of reducing environmental impacts and improving the circular use of materials. The IMD consists of four main components: inverter, electric motor, gearbox, and heatsink. The study focuses on how design improvements, reparability, reuse, remanufacturing, and new business models can improve sustainability over the full product life cycle. A life cycle assessment with a cradle-to-grave scope was carried out for 3 million kilometers of truck operation. The improved modular design enables easier repair, extends the IMD lifetime and reduces the number of units required while lowering the material demand. Three end-of-life scenarios were assessed. The baseline scenario reflects current practice and delivers limited benefits. Improved remanufacturing in the second scenario leads to clear gains in circularity and resource efficiency. The strongest results are achieved with an advanced circular business model scenario based on a leasing model, where the manufacturer retains ownership of the IMD. This approach enables high return rates, extensive reuse, and effective remanufacturing. Environmental results show that circular strategies mainly reduce impacts related to resource use and critical raw materials, while climate change impacts are dominated by electricity consumption during use. Reuse and remanufacturing are especially important for reducing dependence on critical materials such as neodymium used in motor magnets. The study concludes that combining efficient design, improved reparability, and suitable business models can significantly enhance the environmental and resource performance of electric truck powertrains.

1 INTRODUCTION

1.1 DESCRIPTION OF THE DOCUMENT AND PURSUE

This report describes the RHODAS Ecodesign considerations. Within the RHODAS project the integrated motor drive (IMD) powertrain was analysed on an environmental basis. The Technical University of Vienna (TUW) guided the project in this direction and performed several assessments on the environmental burdens, the material criticality and on the material circularity. This document presents the results that were achieved during the project period M18 to the end and builds upon the results of D1.3 M15, which explains the development of the applied ecodesign methods.

The key questions that have driven the research on ecodesign considerations were the following.

- Product development: How can the product development process be supported for an environmentally optimised powertrain concept?
- Environmental performance, benchmarking, -30%: What is the actual environmental performance of the developed concept? Under what scenarios can this environmental performance be achieved?
- Factsheet: How can the environmental performance of the powertrain be assessed and communicated?

Different methodologies were used to approach these questions which are explained in the next section.

1.2 STRUCTURE OF THE DOCUMENT

In chapter 2 the methodology is explained, including the methodology for the screening life cycle assessment, the circularity assessment and the criticality assessment. Here, all assumptions that have been used for the assessments are described. Also, three scenarios are defined that are assessed in chapter 5. The assumptions for a baseline, used for a final comparison are described.

In chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** the results of the reference, used for finding ecodesign hotspots system, are described and interpreted. Parts of these results have already been described in D1.3 M15.

In chapter 4 the results of the iterative product development are described, which include circular design concepts and business models, that has been developed with project partners based on the findings of chapter 3.

In chapter 5 the assessment of the developed IMD, the additional design concepts, the circular business models and a comparison with the baseline are performed and analysed.

In chapter 6 the necessity of a circular vehicle passport and ideas how it could look like for this product are described.

1.3 WPS AND TASKS RELATED WITH THE DELIVERABLE

This document relates to the WP5 tasks T5.6: “Environmental and criticality assessment of materials and components” and T5.7: “Circularity assessment of materials and components”.

Task T5.6 Environmental and criticality assessment of materials and components. (M18-M42) (Lead: TUW; Participants: UPC, AU, AIT, NION, VAL, VS)

The whole powertrain development process is supported through environmental assessment and ecodesign considerations derived from T1.6. The selection and definition of relevant environmental indicators and impact categories, to analyse specific SiC/GaN semiconductor components, is carried out by TUW. Life Cycle Impact Assessment (LCIA) and Life Cycle Assessment (LCA) of the powertrain and its components are performed by TUW according to ISO 14040 / 14044. The analyses consider different initial concepts, as well as the final, detailed design to guide partners in their product development processes and serves as a monitoring reference for future Technology Readiness Level (TRL) advances. To provide environmental information and show environmental benefits of the improved powertrain an environmental performance fact sheet is defined and included in D5.5.

Task T5.7 Circularity assessment of materials and components. (M18-M42) (Lead: TUW; Participants: UPC, AU, AIT, BOS, VIC, NION, VAL, VS)

This circularity assessment will guide partners in the product and process development, process and serves as a monitoring reference, providing input for improvement, leading towards more circularity as TRL advances. The opportunities for circularity (e.g., reusability, remanufacturability, repairability or recyclability) of the IMD prototypes are identified in a circularity assessment using considerations and method development from Task 1.7. The definition of relevant use scenarios for powertrains and its parts considering circular economy strategies is made available as input for T1.8, T5.1 and the Business Modell (BM) development in Task 6.7. and Deliverable 6.3.

2 METHODOLOGY

The ecodesign process followed in principle the applied methodology of D1.3 M15, which is presented in Figure 2.1. The methodology for circularity and criticality assessment had to be developed for this project and was explained in detail in D1.3 M15. Based on the definition of a reference product and an initial assessment of environmental impact, circularity and criticality, hotspots were identified that could be used for further improvements. Together with some material and component selection matrices, the results were presented in an ecodesign guideline in D1.3 M15. This was to be used for iterative ecodesign, which was carried out simultaneously with the design of the electrical and electronic components in WP2, the thermal management system in WP3 and the development of the circular business model in WP6. As the product design began at the same time as the definition of a reference system and its evaluation, it was neither possible nor intended to fully integrate all ecodesign considerations into the final project prototype. Nevertheless, circular concepts were developed that highlight potential for improvement and can serve as a starting point for future projects.

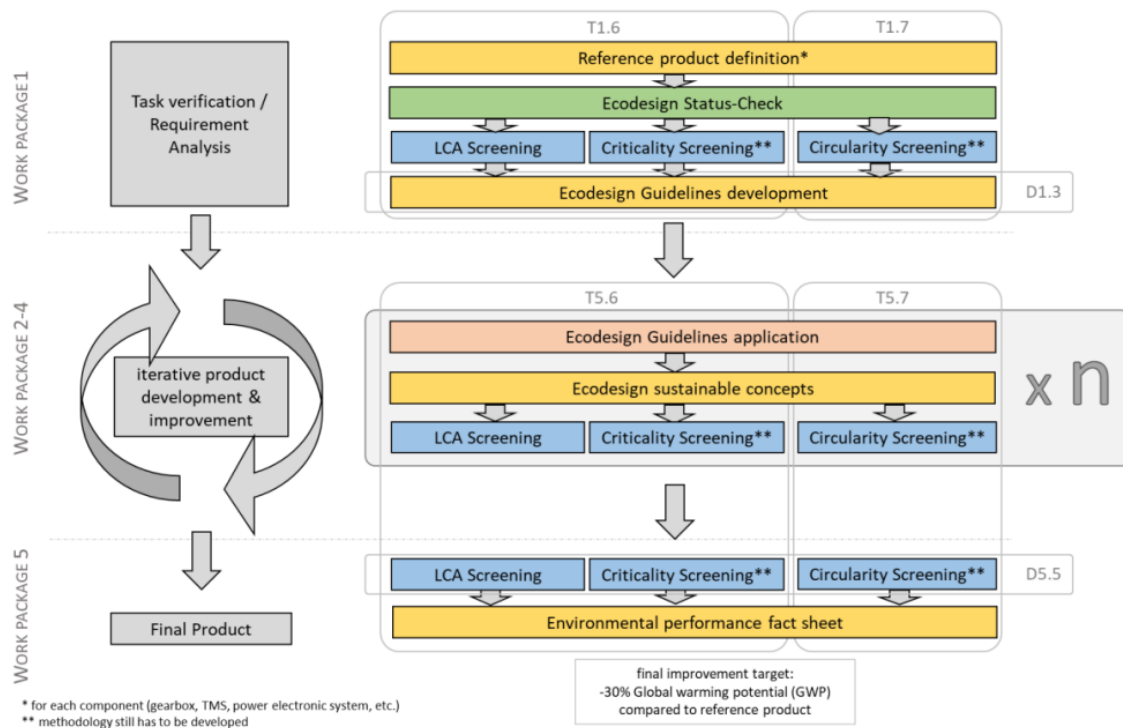
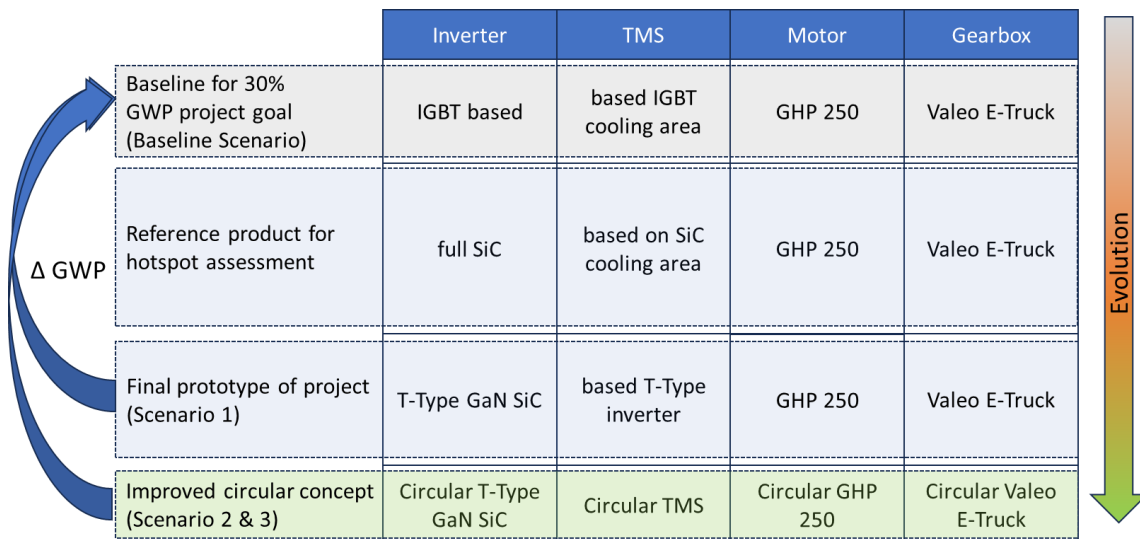


Figure 2.1: Methodology (own depiction).

The reference product for environmental hotspot assessments should be as similar to the designed product as possible. As presented in Figure 2.2, the reference-product does not necessarily have to be the product that is currently the market standard. In case of the inverter, Insulated-Gate Bipolar Transistor (IGBT) based inverters are the current standard. As Wide Band Gap (WBG) inverters have a different overall design, it is better to use a WBG based inverter as a reference product for the planned T-type GaN/SiC based inverter to find improvement hotspots. For later comparison for achieved improvements an IGBT based

inverter is assumed as a baseline, as depicted in Figure 2.2. During the project the methodology the circularity and criticality assessment was developed and improved, as described below.



	Inverter	TMS	Motor	Gearbox
Baseline for 30% GWP project goal (Baseline Scenario)	IGBT based	based IGBT cooling area	GHP 250	Valeo E-Truck
Reference product for hotspot assessment	full SiC	based on SiC cooling area	GHP 250	Valeo E-Truck
Final prototype of project (Scenario 1)	T-Type GaN SiC	based T-Type inverter	GHP 250	Valeo E-Truck
Improved circular concept (Scenario 2 & 3)	Circular T-Type GaN SiC	Circular TMS	Circular GHP 250	Circular Valeo E-Truck

Figure 2.2: Environmental assessment methodology for improvement and validation (own depiction).

2.1 SCREENING LIFE CYCLE ASSESSMENT

The environmental impacts of the final IMD are assessed with a Screening Life Cycle Assessment according to ISO 14040/44.

In Figure 2.3 the LCA Process is shown. First, the goal and the scope of the assessment is defined. In this step the functional unit, observed life cycle stages, products, processes, boundaries, cut-off rules, assessment method and the intended target group of the product system are specified. In the second step the life cycle inventory is analysed. This means all input and output energy and material flows within the chosen system are considered. All this energy and material flows are then environmentally assessed in the life cycle impact assessment through impact categories, e.g., Global Warming Potential, Land Use, Acidification Potential, etc, which are depending on the assessment method that has been chosen. At the end the results are interpreted, summarized and clearly communicated. Each step is of iterative nature and can always be adapted if needed. Below the associated sections are described.

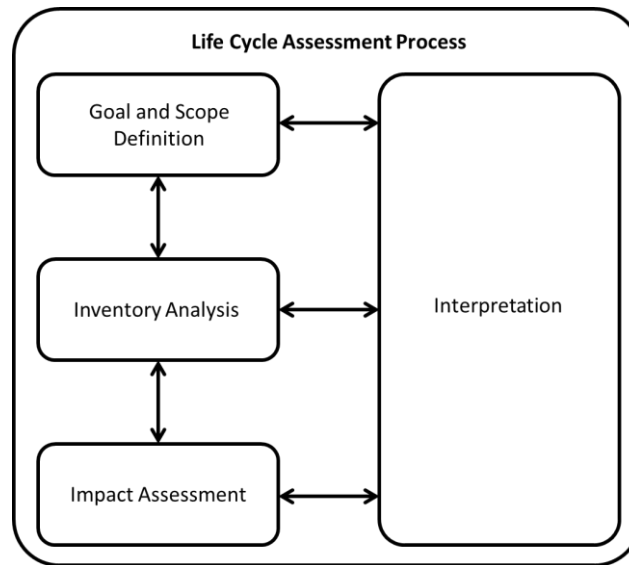


Figure 2.3: Life Cycle Assessment Framework according to ISO14040 [1].

2.1.1 GOAL AND SCOPE

The product system to be studied are the four components of which the power-train consists of (inverter, motor, gearbox and heatsink), see Figure 2.4. In the case of the inverter, only the printed circuit board, its electronic parts and the housing were examined, and the mechanical mountings etc. In the case of the cooling system, only the heatsink itself and not the pump or the use of cooling liquid was considered. Also, no interfaces between the elements have been taken into account, such as couplings, cables, hoses for coolant etc.

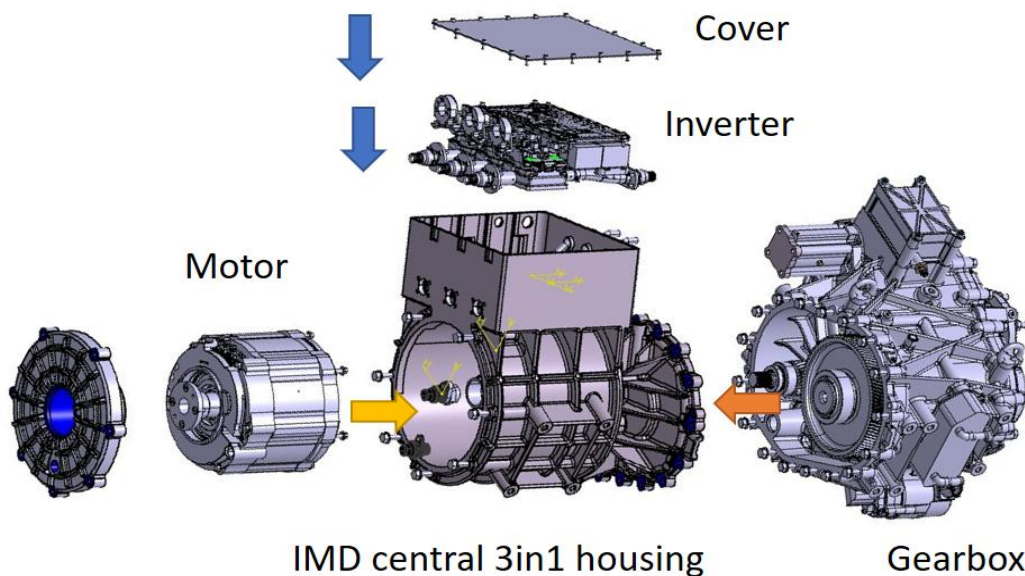


Figure 2.4: IMD components [2]

The functionality of the drive train is to convert electrical energy (dc voltage) into mechanical drive power for e.g., for electric trucks.

The goal of the LCA is to evaluate the environmental impacts of the powertrain prototype. The results will be used to proof a possible reduction of GWP due to circular concepts.

For the final modelling the LCA software SimaPro 10.2.0.3 and the ecoinvent v3.10 cut-off by classification, system database is used. As for the first modelling of the reference products in D1.3 M15 the software SimaPro v9.3.0.3 and the database ecoinvent v3.8 cut-off by classification, system was used, some results may differ slightly due to the software and database update. For calculation of results the EN15804 + A2 method was used. Long term emissions have been excluded in this assessment.

Until the end of the project, no dedicated Product Category Rule (PCR) existed for electric trucks. However, one PCR is under development for industrial trucks, which will expectedly be published shortly after the end of the project [3]. To get an idea on which cut-off rules to set, which boundaries to choose, etc. two similar PCRs, for passenger buses (PCR 2016:04) and for electric motors (PCR 2022:06), were used.

The following definitions are among others suggested by the PCRs [4, 5]:

- The scope is “cradle to grave”, including material extraction, material production, assembly, transportation, use and waste management
- The boundaries towards nature are where the flows enter the technical system (e.g., product system) and where emissions are emitted to air, water, soil
- Polluter pays principle is used: for recycling material used in the manufacturing phase the transportation from the scrapyard to the recycling plant, the recycling process, and the transportation from the recycling process to the manufacturer is considered. For material that is going to recycling, only the transportation to the scrapyard is considered
- The temporal boundary for emissions is set to 100 years
- A cut-off rule of 1% is applied to the mass, environmental impacts, and energy use
- The use of the energy mix in the region/country where the vehicle is operated will be used, or is approximated with EU27 electricity mix
- ISO 22628:2002 is used for modelling the end of life

Environmental impacts from packaging of supplier parts, the assembly caused by energy or auxiliary materials (assembly of the gearbox, the motor or the thermal management system), energy overhead by HAVAC, etc., or waste treatment of production waste if not explicitly modelled or included in datasets were not taken into account, due to lack of data as e.g., the gearbox is still in the development stage and not yet in series production.

The functional unit (FU) is defined as “Providing 3 Mio km of driving of a heavy-duty truck with a T-type based integrated motor drive”.

The data collection period covers the results obtained by the project consortium within the project duration and represents the project status as good as possible.

The geographical scope follows the manufacturing countries of manufacture of the respective elements of the powertrain, as far as known and datasets are available, if not, then at least the global (GLO) datasets are used.

No allocations issues are identified in this LCA study.

For properly assessing the extended lifetime of components through refurbishment, repair, etc., a system expansion is necessary. This means that in addition to the raw material extraction and the manufacturing life-cycle phase (**cradle to gate** approach) also the use phase and the end-of-life phase of the product’s life cycle are considered, also known as **cradle to grave** (see Figure 2.5) approach.

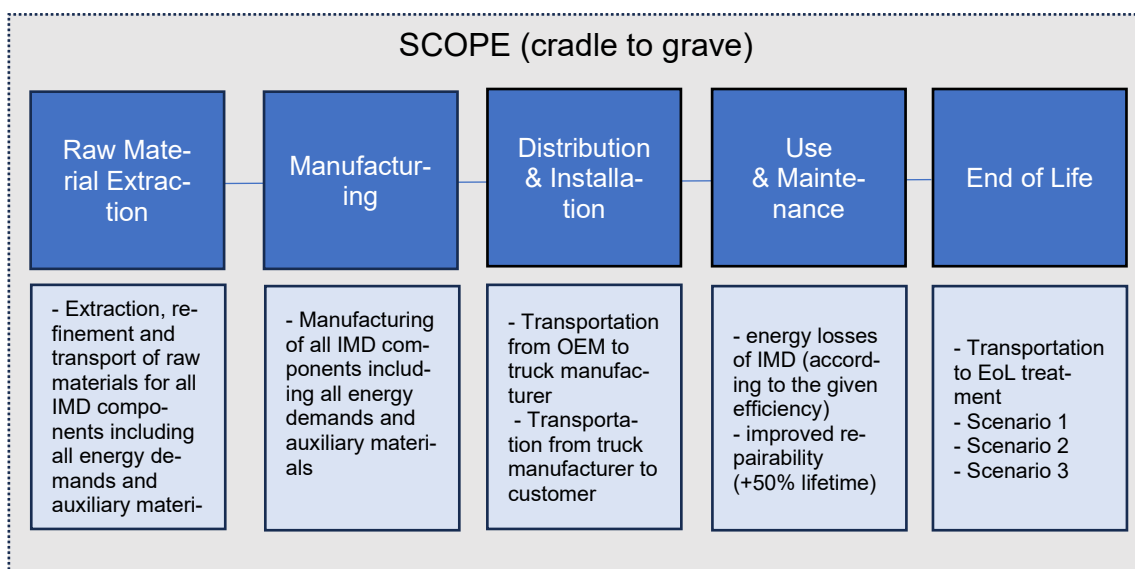


Figure 2.5: Cradle to grave approach (own depiction).

2.1.2 LIFE CYCLE INVENTORY ANALYSIS

The assessments are based on the bill of materials available from the corresponding project partners. Some of these contain sensitive information and are therefore not listed in this report. This study tries to follow the cut off rules of the PCRs mentioned in the beginning of this chapter.

The following raw assumptions along the five life cycle phases have been used for all assessments if not specified otherwise.

For the Raw Material Extraction and Manufacturing the following assumptions have been made:

- ➔ Heat treatments of components: energy and material demand
- ➔ Energy required in bearings production

- Transport distances of supplier parts: market datasets or 500km lorry
- Amount of metal working for the heatsink parts
- For the motor only Prio1 and Prio2 parts were considered as suggested by the corresponding project partner
- Process for punching the motor's steel sheet parts (stator, rotor)
- Additional material production processes for offcuts due to production of the motor's steel sheet parts (stator, rotor)
- Dataset for magnets have been adapted according to the findings of D1.3; In theecoinvent dataset the Global Warming Potential (GWP) per kg of permanent magnets is 31,6 kg CO₂-eq. The dataset was adapted by adding more CO₂ emissions, to receive a GWP of 76 kg CO₂-eq without influencing unintentionally the other impact categories
- Material for those offcuts is not considered (100% material waste feedback)
- Detailed composition of electronic components like voltage sensor or DC/DC supply modules
- Dataset for SiC power semiconductor modules
 - Packaging's are similar to Si power semiconductors from material and production perspective.
 - Energy required for wafer processing (Front End of Life (FEOL), Back End of Life (BEOL), "back end processing" and packaging) are the same as for Si power semiconductors.
 - Production of raw SiC wafers require about 6 times more energy than Si wafers [6].
 - The die size in the packaging gets smaller by about 63,5% [7].
 - In the same ratio, less energy, less chemicals and auxiliary materials are needed for wafer processing, bonding, etc.
 - As the die size becomes smaller, also less waste is generated per produced device. But the process yields of SiC device production are still lower, this could balance itself out. Thus, the assumption is that the production waste stays the same as with standard Si power semiconductors.
- For the baseline that is used for comparison the following additional assumptions have been made for the raw material and manufacturing phase:
 - As no IMD or inverter has been identified that can be used as a baseline for a comparison, the IGBT based baseline is roughly estimated, based on the findings of [8]. This source states that moving from an IGBT based inverter to a SiC based inverter might lead to an overall reduction of up to 30% in GWP in the raw material and manufacturing phase.
 - To reduce biased results, the baseline inverter is conservatively assumed to have a 10% lower total GWP in the raw material and manufacturing phase than the new developed prototype.

- The motor and gearbox are considered with the same GWP as no development has been done in the first place.
- As WBG based inverters usually have a smaller size, also the heatsink will be smaller and most likely lighter. [8] states that a reduction of 50% is to be expected when moving from IGBT to WBG based inverters. However, for the same reason as for the inverter, also the heatsink baseline is set to have a 10% lower environmental impact than the developed heatsink.

For the distribution phase the following assumptions have been made:

- ➔ The IMD is assumed to be shipped 2000 km using a EURO 6, 32t lorry. This distance is set, as within 2000 km most destinations in Europe can be reached from a central start point (e.g., Paris).

For the use phase the following assumptions have been made:

- ➔ The service life of the IMD is defined for 1 Mio. km. To fulfil the functional unit of 3 Mio. km, three IMDs are needed, as presented in Table 2.1.
- ➔ Based on the higher reparability of the developed prototype IMD, a service life extension of 50% compared to the baseline is assumed, which means a service life of the IMD of 1,5 Mio km. For the repair 10% of a new IMD is considered as additional input material, as presented in Table 2.1.
- ➔ The developed SiC based 3L IMD prototype transforms 0,8014 kWh/km with an efficiency of 89,23% according to the driving cycle "Urban_Delivery_16T"
- ➔ The baseline IMD transforms 0,8076 kWh/km with an efficiency of 88,87 % according to the driving cycle "Urban_Delivery_16T". These results were obtained when using a SiC Based 2L Inverter as a baseline. The initial project baseline is an IGBT based 2L inverter, which is assumed to be even less efficient than the SiC based 2L inverter.
- ➔ As the truck will travel around Europe, the EU energy mix is used as an average approximation
- ➔ Only the powertrain losses during conversion of electrical energy to mechanical energy have been considered, excluding the energy demand from all other parts of the truck (Delta approach) [9]

Table 2.1: Assumptions for improved repairability

	Unit	no improved repairability	improved repairability (+50% improved lifetime)
Functional Unit (FU)	km	3.000.000	3.000.000
IMD Lifetime	km	1.000.000	1.500.000
Number of IMDs for FU	#	3	2
Additional IMDs for repair (+10%)	#	0	0,2
Number of transportations	#	3	2,2
Number of EoL Phases	#	3	2,2

For the end-of-life phase the following scenarios were defined:

→ **Scenario 1: The baseline end-of-life scenario**

- based on the most common process around the world, which includes following steps: transportation, pre-treatment, dismantling, metals separation, and non-metallic residue treatment processes according to the ISO 22628:2002 [10].
- Treatment rates are based on the dataset Municipal solid waste (waste scenario) (EU27)| Treatment of waste | Cut-off, S. (= average waste scenario)
- The transportation distance of the waste is assumed to be 500 km.
- 5% of IMDs are dismantled; 95% are disposed.
- From the dismantled IMDs 50% of motors and 50% of gearbox are reused.

→ **Scenario 2: Improved remanufacturing, magnet reuse, reuse of inverter modules**

- 20% of IMDs are dismantled; 80% are disposed.
- From the dismantled IMDs 30% of inverters, 50% of gearboxes, 50% of motors and 50% of heatsinks are reused. The rest is disposed.
- From the 50% of motors that are disposed, all magnets are reused
- From the 70% of inverters that are disposed, all SiC and GaN modules are reused
- Rest as Scenario 1

→ **Scenario 3: Improved reuse and remanufacturing; Leasing system is established**

- 30% direct reuse of IMDs; 60% of IMDs are dismantled; 10 % are disposed
- Rest as Scenario 1 & 2

2.2 CIRCULARITY ASSESSMENT

For the circularity assessment the 10-R strategies of the circular economy (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycling, Recover) have been clustered in three different loops: long, medium and short loop. The main idea of summarizing the 10 R-strategies to three loops was to reduce complexity and make it easier to be used in a workshop setting with participants who are not familiar with the circular economy strategies.

For a better understanding of the previous description Figure 2.6 can be used. All processes that keep the value of materials are summarized in the long loop. The most prominent strategy here is recycling. All processes that keep the value of parts (components, modules, subassemblies) are summarized in the medium loop. Here strategies like remanufacture and refurbishment are relevant. All processes that keep the value of products (finished goods) are summarized in the short loop. This includes processes like repairing and reusing. The value rises from material to product level. The main goal is to keep the value as high as possible, therefore, to prioritize the smallest loop possible.

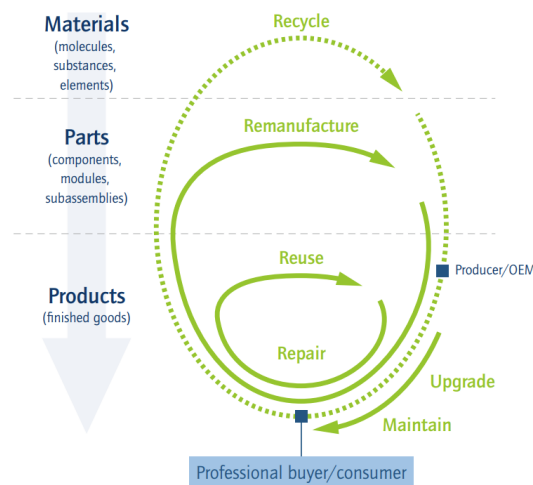


Figure 2.6: Different circular loops [11].

The methodology for assessing and improving the circularity that has been defined in D1.3 M15 was further developed. The final methodology is depicted in Figure 2.7. The methodology follows a double-diamond based four-step approach [12]. In the first step, the most relevant loop(s) for a specific product/component are assessed. For this a questionnaire was developed, which has been presented already in D1.3 M15. According to the relevant loop, a set of 34 different design criteria are assessed in step two.

Workshops proved to be a good method to get participants motivated and inspired to think together about the circularity potentials of the analysed components. For the workshops the questionnaire of step one and design criteria of step two were prepared as printables, see Figure 2.8 and Figure 2.9, but were also realized as an online questionnaire, which proved to be very useful in workshops

with participants that are not present on site. It is also advantageous to give participants more time to fill out the questions as they would have in a face-to-face workshop.

Based on the collected results a quantitative assessment with the help of a developed excel tool (see Figure 2.10) has been done as presented in D1.3 M15. The quantitative assessment for the reference product has been done based on the knowledge and assumptions of the partners from TUW.

Collected inputs from the workshop and the online questionnaires from the first two steps were then further analysed internally and clustered. Fulfilled and not relevant criteria were filtered out. Uncertainties need to be clarified with the responsible partner. The online tool Miro helped for this purpose. In order to prioritise the design criteria, a pairwise comparison has been done. To ease this process, the 34 design criteria were first summarized to 15 categories, as presented in Table 2.2, and then compared to each other for the short, medium and long loop. From the result of the pairwise comparison, a cut-off at 66% of the total sum of points was made. All design criteria that are above this threshold were not considered.

Additionally, a deeper focus was set on priority parts. Those parts are likely to fail or need replacement, basically never need maintenance, are reusable after their first life, are especially important because they are expensive, critical, or environmentally relevant. For this purpose, results of the life cycle assessment, the criticality assessment and other assessment methods were taken into consideration. Based on the filtered and clustered results, follow up tasks were formulated and used in step 3.

In step three of the assessment methodology ideas were collected on how the not fulfilled criteria can be fulfilled. For circular concepts, an established circular business model is essential to fully use the potential of those concepts. The discussion on circular business models was done as part of the third step. The tool "Make it Circular" can help to support this process (see 2.2.1 Make it Circular!).

In step four of the process, based on the collected ideas final concepts were defined and their feasibility discussed. At the end, a quantitative circularity assessment as described in step two was performed again.

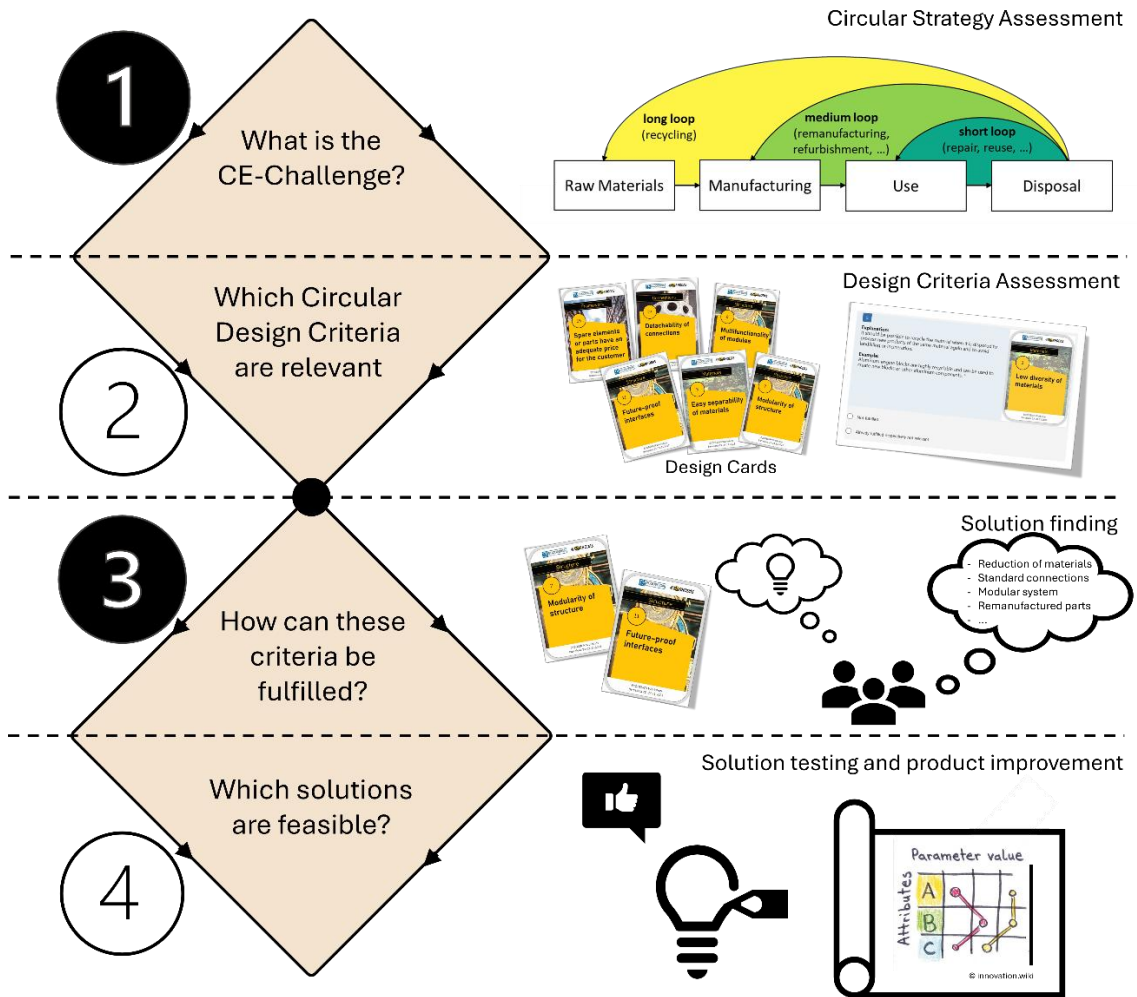


Figure 2.7: Updated methodology for Circularity Assessment (own depiction).

Table 2.2: Simplification of design criteria (own depiction).

	Simplified Category	Design Criteria
1	Detectability of failure of parts	Detectability of wear on exposed parts
	Detectability of failure of parts	Availability of performance feedback
	Detectability of failure of parts	Handling of common errors
2	Easy to dismantle into parts	Short disassembly time
	Easy to dismantle into parts	Low complexity of disassembly
	Easy to dismantle into parts	Low probability of damage during disassembly
	Easy to dismantle into parts	Automated disassembly is possible
3	Identifiability of materials	Identifiability of relevant materials
4	Low complexity of system	Low complexity of structure
5	Low Diversity of materials	Low diversity of materials
6	Modularity of system	Suitable modularity of structure
7	Multifunctionality of parts	Multifunctionality of modules
8	Re-assembleability of parts' connections	Detachability of connections
	Re-assembleability of parts' connections	Re-assembleability of connections
	Re-assembleability of parts' connections	Long-term usability of connections
9	Recyclability of materials	Recycleability of materials
10	Replaceability of wear parts	Easy replaceability of wear parts
	Replaceability of wear parts	Easy replaceability of defective parts
11	Returnability and reprocessability of parts	Reprocess-ability of IMD's elements
12	Robustness of parts	High aging resistance and long life time of parts
	Robustness of parts	Robustness of the product under non-optimal conditions
	Robustness of parts	Robustness for a "second life"
	Robustness of parts	High endurance of relevant parts
13	Separability of materials	Easy separability of materials
14	Spare parts availability	Share of standard and common parts
	Spare parts availability	Availability of spare elements or parts
	Spare parts availability	Spare elements or parts have an adequate price for the customer
	Spare parts availability	Integration of reprocessed elements or parts is possible
	Spare parts availability	Availability of repair instructions
	Spare parts availability	Possibility of product return
15	Upgradeability of system	Upgradeability of the power train
	Upgradeability of system	Upgradeability of the elements
	Upgradeability of system	Future-proof interfaces
	Upgradeability of system	Uniformity of connections

Circularity Long - / Medium - / Short-Loop?

Assessed Product:
Inverter

Step 1 Does your product match the following scenario?

- The materials of the product can be recycled.
- Established recycling methods exist and can be performed economically in the main market of the product.
- In case the product contains critical raw materials, they can be extracted and recovered.

✔

Focus on long loop.
Design for Recycling.
Go on to Step 2 and check if the medium or short loop fits too.

✘

Go on to Step 2 and check if the medium loop fits.

Justification

No established recycling methods

Step 2 Does your product match the following scenario?

- The product has further circularity potential.
- Parts or subassemblies have high environmental impacts and cause high costs.

✔

Go on to Step 3.

✘

Try to focus primarily on long loop.
Design for Recycling. →END

Justification

High energy consumption for the production, raw materials for electronics
→ raw earth materials

Step 3 Does your product match the following scenario?

- The product consists of some parts or subassemblies that have a longer lifetime than the product is used.
- For the product a take back strategy exists or can be established.

✔

Focus on medium loop.
Design for Refurb. / Remanufacturing
Go on to Step 4 and check if the short loop fits too.

✘

Go on to Step 4 and check if the short loop fits.

Justification

Yes, e.g. aluminum heatsink, housing
→ long lifetime
→ inverter in the car gets back to the manufacturer (they have to take it back)

Step 4 Does your product match the following scenario?

- Common defects or damages occur unpredictable

✔

Go on to step 5.

✘

Focus primarily on medium loop, if possible.
(Design f. Refurb. / Remanufacturing)
Focus primarily on long loop (Design for Recycling) if the medium loop is not appropriate. →END

Justification

Condition monitoring possible

Step 5 Does your product match the following scenario?

- The product's functionality can be restored by replacing broken or worn out parts.
- Spare parts are available or can be provided. The user of the product prefers repair rather than replacement.

✔

Focus primarily on short loop.
Design for Repair.
→END

✘

Focus primarily on the medium loop. If not possible, focus primarily on the long loop.
→END

Justification

Whole Inverter will be replaced

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Figure 2.8: Circularity Assessment Step 1 – Questionnaire for relevant Circular Loop (own depiction).

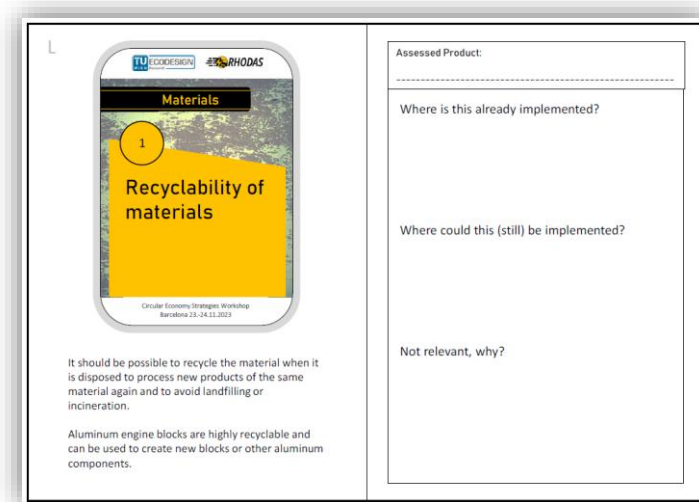


Figure 2.9: Circularity Assessment Step 2 - Design Criteria Cards (own depiction).

Assessment

		True	Fairly true	Fairly false	False	Not relevant because	relevant for
Structure							
5	High aging resistance and long life time of parts		x				s, m
6	Low complexity of structure		x				s, m
7	Suitable modularity of structure	x					s, m
8	Multifunctionality of modules			x			m
9	Upgradeability of the power train	x					m
10	Upgradeability of the elements		x				m
11	Future-proof interfaces	x					m
12	Reprocess-ability of IMD's elements		x				m
13	Share of standard and common parts	x					s, m
Framework							
14	Availability of spare elements or parts		x				s, m
15	Spare elements or parts have an adequate price for the customer		x				s
16	Integration of reprocessed elements or parts is possible		x				s, m
17	Availability of repair instructions					x	s
18	Possibility of product return			x			m
Wear and Failure							
19	Detectability of wear on exposed parts	x					s, m
20	Availability of performance feedback	x					m
21	Easy replaceability of wear parts	x					m
22	Handling of common errors		x				s, m
23	Easy replaceability of defective parts		x				s
24	Robustness of the product under non-optimal conditions				x		m
25	Robustness for a "second life"		x				m
26	High endurance of relevant parts		x				m
Connections							
27	Detachability of connections	x					s, m, l
28	Re-assembleability of connections	x					s, m
29	Long-term usability of connections	x					s, m
30	Uniformity of connections	x					m
Disassembly							
31	Short disassembly time		x				s, m, l
32	Low complexity of disassembly	x					m, l
33	Low probability of damage during disassembly	x					s, m
34	Automated disassembly is possible		x				m, l

Fulfillment 75,6%

Figure 2.10: Quantitative Circularity Assessment

2.2.1 MAKE IT CIRCULAR!

For identifying potentials and creating ideas for circular business models, the tool “Make it Circular!” was used. The game was developed by ACATECH– National Academy of Science and Engineering together with WWF Germany and Johannes Kepler University Linz funded by the German Federal Environmental Foundation (DBU). The game consists of a well-designed set of cards and an accompanying moderation guide, that help companies to create and execute strategies for adopting comprehensive circular economy business models during workshops without any prior knowledge on circular economy.

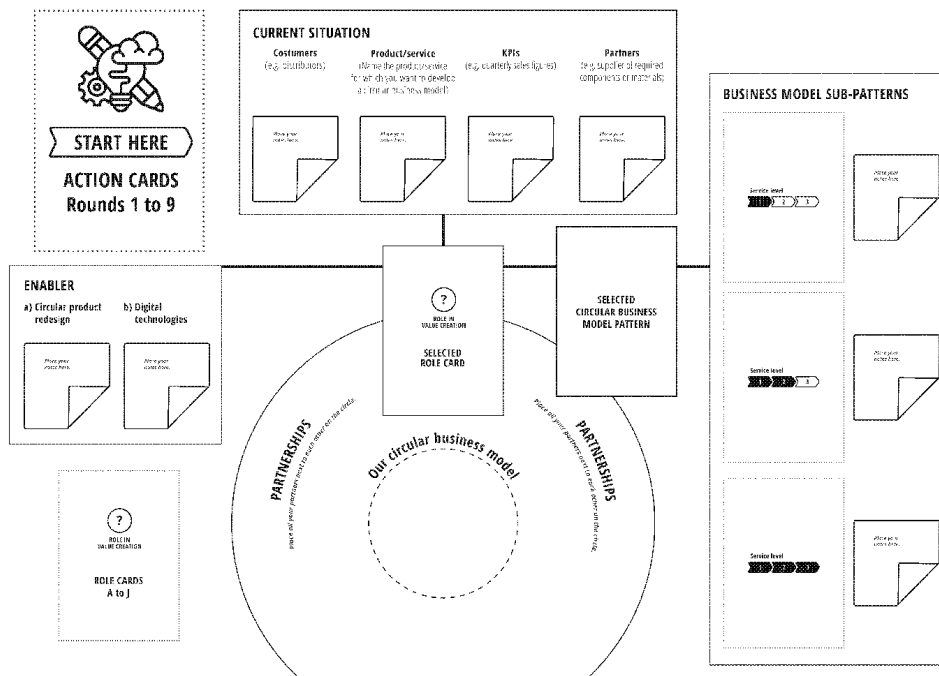
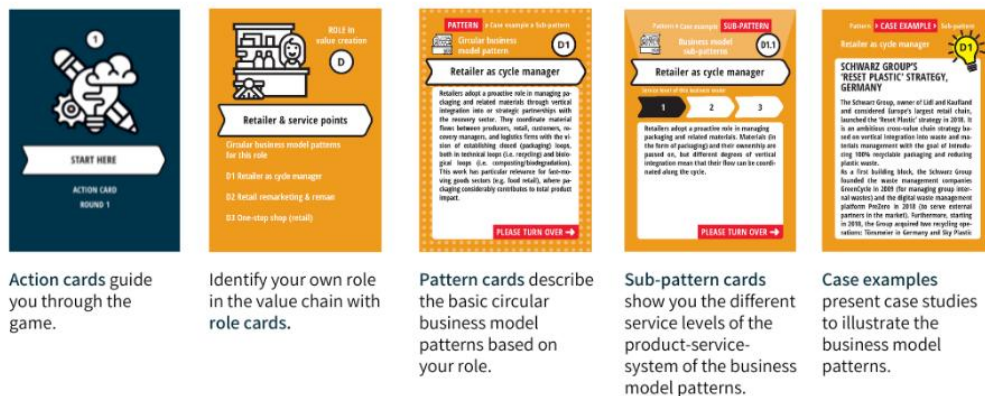


Figure 2.11: Make it Circular! game board (own depiction) [13].



Action cards guide you through the game.

Identify your own role in the value chain with role cards.

Pattern cards describe the basic circular business model patterns based on your role.

Sub-pattern cards show you the different service levels of the product-service-system of the business model patterns.

Case examples present case studies to illustrate the business model patterns.

Figure 2.12: Make it Circular! type of cards [13].

2.3 CRITICALITY ASSESSMENT

The developed methodology of D1.3 combines different assessment methods for assessing a material's criticality, e.g., Economic Importance (EI), Supply Risk (SR), Future Demand Risk (FDR), Recirculation Risk (RR), Concentration Risk (CR), etc. However, all these parameters only indicate if a **material** is considered critical. To assess the criticality of a **product**, an approach needs to be used, that translates the parameters to a **product level**. Such an approach was developed by Koch et al. [14]. They use the Life Cycle Impact Assessment (LCIA) method of Abiotic Depletion (AD) [15] and combine it with relevant critical raw material parameter - in this case EI and SR - to weigh the results. The AD indicates how much a product contributes to the scarcity of specific resources. The combination of both indicators helps to bring the criticality assessment to the product level, to include the scarcity and to prioritize the results. [14] divides the weighed product's AD through the non-weighed product's AD, to get the average product criticality. The same can be performed for each subcomponent. This step is optional.

For assessing the product's criticality, a Bill of Material (BOM) is needed that represents all materials that are used in the product. Although it is called BOM, they are mostly not detailed enough to see all materials used and only represents the components, e.g. for electronic parts. Some available factsheets of those components list all the included materials, but that is not an obligatory practise and not common in general for materials that are not subject to be reported according to the Restriction of Hazardous Substances (RoHS) regulation [16]. Also, for the involved experts in the project, the material composition of components is often seen as a black box, especially for supplied parts. The only realistic and not too complex approach to access the material level of components has been seen by using a generic Life Cycle Inventory (LCI) database (e.g., ecoinvent), as it can estimate the material composition from components on a generic level. The disadvantage is, that the LCI database also includes all materials that are used in the upstream supply chain processes of a product and do not reflect only the materials that are in the component itself.

Other researched methodologies that assess the criticality of components or products either also need data availability for all components on material level [17], or vast information of production processes in the supply chain [18], which has not seen to be feasible in the scope of the project.

The software SimaPro 10.2 in combination with the ecoinvent 3.10 database and the LCIA method Environmental Footprint 3.1 (adapted) was used to calculate the AD of the reference product. As the list of Abiotic Depletion Potential (ADP) characterization factors in ecoinvent 3.10 only covers 48 elements out of 109, the updated ADP characterization factors from van Oers, L et.al. [15] were used, which covers 76 elements out of 109. From the elements that have been classified as critical raw materials by the EU, the following are not considered, due to a lack of characterization factors: Natural graphite, Barite, Feldspar, Fluorspar, Beryllium, Bismuth, Coking coal, Germanium, Helium, Iridium, Phosphate Rock, Ruthenium, Tungsten.

3 ENVIRONMENTAL HOTSPOT ASSESSMENT OF REFERENCE SYSTEM

The life cycle assessment, criticality assessment and circularity assessment of the IMD components' reference products serves as a basis for identifying environmental hotspots and potential ecodesign improvement measures. The results are therefore not intended to be used for a quantitative comparison with the final prototype's components, but rather for understanding the main drivers of environmental impacts within each component under the defined system boundaries.

3.1 INVERTER

A low power 15 kW SiC based inverter has been used as a reference product for the inverter. For the inverter, the assessment was limited to the electronic components and the printed circuit board, including their manufacturing processes. Additional elements such as the housing were excluded, and the inverter represents a smaller unit used for testing and development in the first phase of the RHODaS project rather than the final power stage of the powertrain.

3.1.1 ENVIRONMENTAL ASSESSMENT RESULTS

The environmental impacts of the inverter are largely driven by the production of electronic components, with capacitors and integrated circuits for inverter control being the most relevant contributors. Power semiconductors and Printed Circuit Board (PCB) production also show notable contributions, while the remaining impacts are associated with other electronic components such as inductors, sensors, connectors, and headers. These results indicate that ecodesign measures for the inverter should primarily focus on component selection and electronic design.

3.1.2 CRITICALITY ASSESSMENT RESULTS

The criticality assessment has been reworked. The new assessment results are presented in chapter 5.3.

3.1.3 CIRCULARITY ASSESSMENT RESULTS

According to the circularity assessment, the inverter should be designed primarily for the short loop (and in addition also the medium loop) and shows only a theoretical fulfilment of 42,2% of the design criteria for these two loops.

To validate the circularity assessment of the reference product, the first day of the 4th General Assembly (GAM) was used to collect answers and input from the project partners for the first two steps of the circularity screening. The assessment validated that the inverter should be designed primarily for the short and additionally for the medium loop. The relevant circular design criteria that need to be focused on are presented in the following list.

Relevant criteria for short loop:

- Share of standard and common parts
- Availability of spare elements or parts

- Spare elements or parts have an adequate price for the customer
- Integration of reprocessed elements or parts is possible
- Availability of repair instructions
- Possibility of product return
- Detectability of wear on exposed parts
- Detachability of connections
- Re-assembleability of connections
- Long-term usability of connections

Additional relevant criteria for medium loop:

- Reprocess-ability of IMD's elements
- Availability of performance feedback
- Handling of common errors

On day two of the 4th GAM, for some of these criteria, ideas and information were collected, how they could be fulfilled or what difficulties are faced, presented in Figure 3.1.

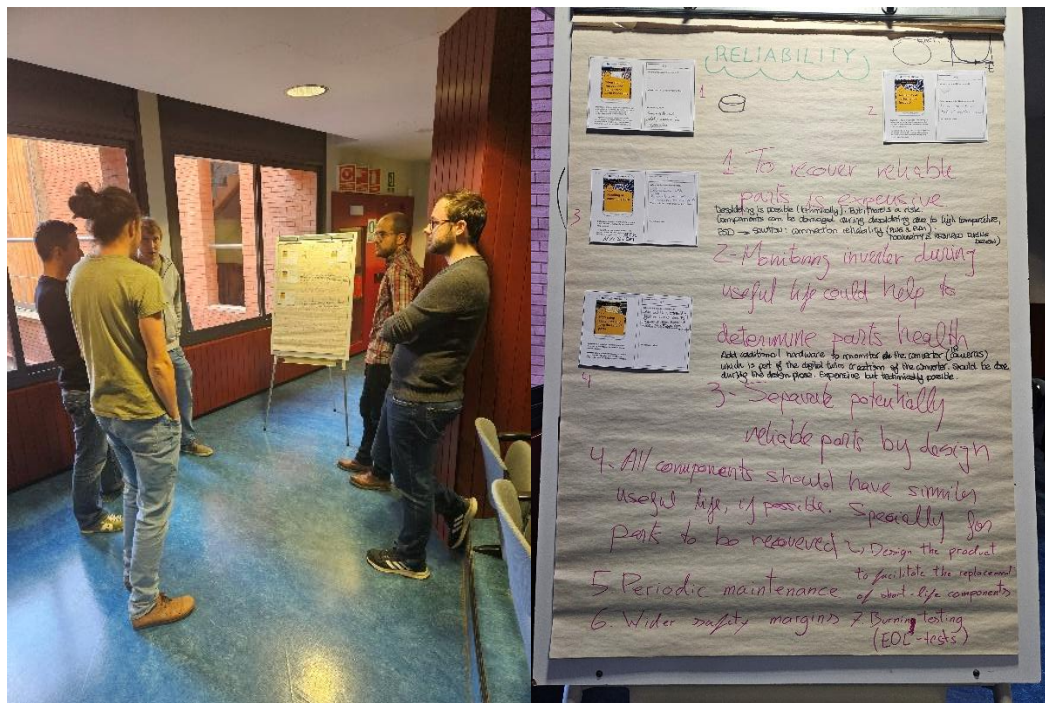


Figure 3.1: Workshop at the GAM in Barcelona - Developing of Ideas for Improvement (own depiction).

The analysis of the criteria shows that a reprocess-ability of IMD elements has not yet been implemented, but is technically feasible for mechanically robust components. Sensitive components such as power switches, power modules, gate drivers, DC-link capacitors, transistors, and sensors are most affected by aging and may require replacement rather than reuse. In contrast, mechanically robust and high-value components such as housings, heatsinks, busbars, current sensors, control boards, CPUs, and other large passive components are more suitable for integration into a new inverter. However, the recovery of reliable parts is

currently expensive, mainly due to costly dismantling, inspection, and testing procedures.

To reduce reprocessing costs, design measures such as pressure-based electrical connections, sockets, and connector-based architectures could be introduced. Designing the inverter specifically for repair and reuse would simplify component removal, although this would negatively affect size, reliability, and initial system cost. Cheaper functionality checks could be enabled by integrating test points and standardized test protocols into the inverter design and by automating testing processes on assembled equipment.

Regarding connections, detachable interfaces are already used for components such as heatsinks and control boards. Extending detachable connectors to signal paths, sensor interfaces, and modular power-stage connections would support modularization and reuse. These connections mainly serve control, sensing, and communication functions and are not intended for frequent disconnection. In practice, reconnection would typically occur only during repair or reuse, possibly once every several years. Long-term reliability is therefore more critical than high mating-cycle capability. Established connector solutions, such as Molex-type connectors, are suitable for these applications, while alternative approaches, including wireless data transmission, may be considered for specific use cases.

Product return concepts are currently not implemented, but could be realized if the inverter were designed as a maintainable device. In a second-life scenario, mechanical components and control electronics could often be reused, while power-stage components, especially capacitors and semiconductors, would likely need replacement due to wear and ageing.

Handling common errors is already partially supported through cloud connectivity, where software-based diagnostics allow service providers to identify recurring faults. Minor defects could justify repair, whereas major failures would typically lead to full inverter replacement. Periodic maintenance or intentional replacement of short-lifetime components such as capacitors, power modules, connectors, and thermal interface materials could significantly extend the inverter lifetime. Increasing safety margins, particularly in thermal management, power loops, and protection systems, would further reduce stress and slow degradation. Failures in power semiconductors can trigger chain reactions that damage surrounding components. Performance and wear feedback are identified as key enablers for repair and reuse.

Repair instructions are currently not available, since the developed inverter is in a prototype phase.

3.2 ELECTRIC MOTOR

For the electric motor a permanent magnet synchronous motor, called GHP250, has been chosen as reference, which is also used for the final prototype of the IMD.

3.2.1 ENVIRONMENTAL ASSESSMENT RESULTS

The electric motor assessment reveals that several material-related hotspots are present, depending on the environmental impact category considered. For climate change, aluminium parts, the rotor–stator subassembly, permanent magnets, and copper windings all contribute substantially to the overall impact of the reference motor. In contrast, copper windings become particularly relevant in non-climate-related impact categories such as photochemical ozone formation, acidification, freshwater and terrestrial eutrophication, water use, and resource use of minerals and metals. Permanent magnets dominate marine eutrophication. These findings underline the importance of material choice and material intensity in the motor design when deriving ecodesign improvement options.

A key methodological aspect of the motor assessment concerns the modelling of neodymium permanent magnets, which introduces considerable uncertainty into the results. The baseline modelling relies on the Ecoinvent 3.8 dataset for permanent magnets used in electric motors, assuming a global market average. However, literature values for primary magnet production show wide variability. A literature-based sensitivity analysis demonstrates that higher emission factors would significantly increase the relevance of magnets in the climate change impact category. In consultation with the responsible project partner, a lower but still literature-consistent value was considered more appropriate for the reference product. Due to these uncertainties, the absolute results for the magnet-related impacts, as well as their relative importance across different impact categories, must be interpreted with caution. Nevertheless, the analysis clearly identifies permanent magnets as a critical focus area for ecodesign, for example through material reduction, longer lifetime, or increased use of recycled content.

3.2.2 CRITICALITY ASSESSMENT RESULTS

The criticality assessment has been reworked. The new assessment results are presented in chapter 5.3.

3.2.3 CIRCULARITY ASSESSMENT RESULTS

According to the circularity assessment, the motor suits best for the medium loop and secondarily to the long loop. The design criteria are fulfilled around 60%. Mainly lacking design for the medium loop.

To validate the circularity assessment of the reference product, the first day of the 4th GAM was used to collect answers and input from the project partners for the first two steps of the circularity screening.

The assessment validated that the E-Motor should be designed primarily for the medium and additionally for the long loop. The relevant circular design criteria that need to be focused on are presented in the following list.

Relevant criteria for medium loop:

- Share of standard and common parts
- Availability of spare elements or parts
- Spare elements or parts have an adequate price for the customer
- Integration of reprocessed elements or parts is possible
- Availability of repair instructions
- Possibility of product return
- Detachability of connections
- Re-assembleability of connections
- Long-term usability of connections
- Reprocess-ability of IMD's elements
- Detectability of wear on exposed parts
- Availability of performance feedback
- Handling of common errors

Additional relevant criteria for long loop:

- Recyclability of materials
- Easy separability of materials
- Identifiability of relevant materials
- Short disassembly time
- Low complexity of disassembly
- Low probability of damage during disassembly
- Automated disassembly is possible

The analysis of the workshop results revealed that requirements are either partially fulfilled or considered not relevant at the current design level, primarily because the electric motor and its main components are highly customized and safety-critical products.

Regarding the share of standard and common parts, the analysis concluded that, wherever technically feasible, standard components are already used. In particular, stator and rotor designs, including the embedded magnets, are closely optimized for torque, efficiency, and packaging and are therefore only standardizable with significant effort. Mechanical customer interfaces such as housings and vehicle-specific mounting features additionally limit standardization. In contrast, electrical interfaces could be standardized, although this would require alignment across manufacturers rather than technical innovation.

Criteria related to spare parts availability, pricing, repair instructions, and product return were largely classified as business-model related rather than design related and were therefore not treated as limiting factors at the design stage. On

the design side, the integration of reprocessed elements was assessed as feasible mainly at stator and rotor level, where large and robust assemblies can be replaced or reused if appropriate processes are available.

Detachability of connections was identified as a mixed outcome. While the overall product is highly customized and therefore not designed for systematic detachability, the main motor components can be separated, such as housing from stator stack or shaft from rotor stack. Re-assembleability and long-term usability of these connections are generally fulfilled to meet typical lifetime expectations of around 8000 operating hours. However, detachable connections are primarily implemented to support manufacturing and service efficiency, not circularity.

Performance feedback and condition monitoring were identified as clear gaps. The current design does not provide sufficient feedback to assess the state of health during operation, and end-of-life assessment typically requires return to the manufacturer. Although lifetime requirements are defined, the lack of operational performance data limits predictive maintenance and reuse decisions. Handling of common errors was not considered a major design criterion in this context, as fault management is typically addressed at system or vehicle level.

From a material and recycling perspective, the long-loop criteria are largely fulfilled. The main materials used in electric motors, aluminium, copper and steel are recyclable, and the main assemblies can be separated to enable material recovery. Material identifiability is supported through labeling of plastic and aluminium parts above defined weight thresholds, and the dominant materials of the motor are well known.

In contrast, disassembly-related criteria represent a major limitation. Short disassembly time and low complexity of disassembly are not fulfilled, as the customized design requires special tools and processes to separate components. The electric motor is a high-voltage component, and easy disassembly is restricted due to safety considerations. As a result, the probability of damage during disassembly is high, and rework or refurbishment is feasible only for specialized workshops with trained personnel and dedicated equipment.

Automated disassembly was discussed as a theoretical option but was ultimately assessed as impractical. While automation is standard in manufacturing, the complexity, variability, and safety constraints associated with disassembling customized high-voltage motors make automated disassembly economically and technically unviable in the current design.

The main hotspots that need to be addressed are the low level of standardization of active motor parts, the difficult and restricted disassembly caused by safety and high-voltage requirements, the missing feedback on component condition during operation, and the high technical and economic effort needed to reuse or reprocess components beyond the stator and rotor level.

3.3 THERMAL MANAGEMENT SYSTEM

The thermal management system (TMS) analysed in this study consists exclusively of the liquid-cooled aluminium heatsink mounted on the inverter. As a reference product an Infineon HybridPACK Drive Module (IGBT Module) heatsink has been chosen.

3.3.1 ENVIRONMENTAL ASSESSMENT RESULTS

The heatsink comprises a main aluminium profile and two aluminium endcaps that are screwed and sealed to the profile. Given its limited functional scope and relatively small size within the overall IMD, the environmental impacts of the thermal management system are very small within the defined reference system. The results mainly reflect the use of aluminium and associated manufacturing processes, suggesting that material efficiency and design optimisation could be considered as potential improvement strategies.

3.3.2 CRITICALITY ASSESSMENT RESULTS

The criticality assessment has been reworked. The new assessment results are presented in chapter 5.3.

3.3.3 CIRCULARITY ASSESSMENT RESULTS

From the circularity perspective the TMS suits primarily the long loop, which is not surprising, since it is a relatively simple, cheap, (mainly) mono-material product out of aluminium. The assessment reveals that all relevant design criteria are theoretically fulfilled (100% fulfilment). The thermal management system analysed in this study consists exclusively of the heatsink mounted on the inverter, all other parts (e.g., hoses, pumps, etc.) of the TMS are not considered, as they are standard, no customized parts. From the circularity perspective the TMS suits primarily the long loop.

Relevant criteria for long loop:

- Recyclability of materials
- Easy separability of materials
- Identifiability of relevant materials
- Short disassembly time
- Low complexity of disassembly
- Low probability of damage during disassembly
- Automated disassembly is possible

The heatsink is made from aluminium and can be disassembled using conventional tools and methods, making material identification and recycling straightforward. Disassembly can generally be carried out in a short time. Automated disassembly is challenging due to the system's complexity and is only expected to be feasible if very large recycling volumes justify the required automation effort.

3.4 GEARBOX

The TWIN SPEED E-Truck GBX, which is also used for the final prototype of the IMD has been used as reference product for the gearbox.

3.4.1 ENVIRONMENTAL ASSESSMENT RESULTS

The assessment identifies the casings, shafts, and gears as the main contributors to environmental impacts within the reference design. The casings account for a large share of the impacts due to their mass and material intensity, while the output shaft and layshaft are also relevant contributors. Although components related to lubrication contribute only marginally to climate change, they become more relevant in other impact categories, such as ozone depletion and resource use of minerals and metals. A more detailed analysis of the layshaft and output shaft subassemblies shows that the impacts of individual subcomponents are distributed relatively evenly across impact categories, which can be attributed to the similar steel-based material composition and comparable machining processes. The largest gears and shafts emerge as the main drivers within these subassemblies.

3.4.2 CRITICALITY ASSESSMENT RESULTS

The criticality assessment has been reworked. The new assessment results are presented in chapter 5.3.

3.4.3 CIRCULARITY ASSESSMENT RESULTS

According to the circularity assessment, the gearbox suits best for the medium loop and secondarily to the long loop. The design criteria are fulfilled around 60%. Mainly lacking design for the medium loop.

To validate the circularity assessment of the reference product, the first day of the 4th GAM was used to collect answers and input from the project partners for the first two steps of the circularity screening.

The assessment validated that the gearbox should be designed primarily for the medium and additionally for the long loop. The relevant circular design criteria that need to be focused on are in the following list.

Relevant criteria for medium loop:

- Share of standard and common parts
- Availability of spare elements or parts
- Spare elements or parts have an adequate price for the customer
- Integration of reprocessed elements or parts is possible
- Availability of repair instructions
- Possibility of product return
- Detachability of connections
- Re-assembleability of connections
- Long-term usability of connections
- Reprocess-ability of IMD's elements

- Detectability of wear on exposed parts
- Availability of performance feedback
- Handling of common errors

Additional relevant criteria for long loop:

- Recycleability of materials
- Easy separability of materials
- Identifiability of relevant materials
- Short disassembly time
- Low complexity of disassembly
- Low probability of damage during disassembly
- Automated disassembly is possible

From a mechanical perspective, detachability, re-assembleability, and long-term usability of connections are generally fulfilled. Most gearbox components are assembled using nuts, bolts, and screws, which allows repeated disassembly and reassembly without special tools. Gears are mounted on the shaft using a spline with a press-fit connection. The absence of welding is an advantage, as it allows more easy gear removal in principle.

The share of standard and common parts in the gearbox is high. An established aftermarket already exists, and gearboxes for commercial vehicles are routinely repaired and overhauled. As a result, standardization is largely fulfilled and does not represent a major design challenge.

Remanufacturing concepts and validation procedures are already in place for clutches, and remanufacturing is further developed for other components of the gearbox as production volumes increase. The gearbox housing can generally be reused without major issues. The main limitations to reuse are linked to shaft-gear interfaces and gear tooth wear. However, the press-fit between shaft and gear remains a critical interface. While gear removal is technically possible, re-fitting is difficult. In practice, when a gear is removed, the shaft is usually removed as well, as reliable reassembly is challenging. A lower press-fit force would improve disassembly and could be technically feasible without compromising functionality. Re-machining shafts is problematic because material removal changes dimensions. This would require new gear designs, which are often low-volume and not standardized. Adding material is feasible for aluminium castings, but much more difficult for steel components. However, the reprocess-ability of gearbox components is considered mostly fulfilled. If certain parts cannot be remanufactured, they can usually be replaced without affecting the rest of the gearbox. Product return schemes are already known from commercial vehicle applications and are considered feasible.

Wear detection is generally possible for mechanical parts, especially those made from aluminum and steel. Visual inspection and measurement techniques are well established. Validation processes and visual inspections during maintenance contracts are used to detect global risks and wear patterns. These methods work well for identifying major defects, but become less reliable at very high mileages. Wear measurement is mainly focused on gear teeth and pulleys and is divided

into defined wear stages. After approximately 1 million kilometers, accurate wear assessment becomes more difficult. While 3D measurement of gear teeth is technically possible, it is expensive and complex, which limits its large-scale use in remanufacturing.

From a recycling perspective, the gearbox performs well. Key materials such as aluminum casings and steel components are already recyclable and, in some cases, already reused in existing processes. Most components are marked with material information or can be clearly identified using technical drawings, supporting material separation.

The gearbox is largely designed for easy disassembly, resulting in low disassembly complexity and a low probability of damage during teardown. Disassembly time is generally short for mechanical parts.

Automated disassembly is currently limited. Gearbox disassembly and remanufacturing are mainly performed manually, which is acceptable due to the robustness of the components and existing service practices. Automation is constrained by variability and repair-oriented workflows rather than by fundamental design barriers.

Concluding the findings, no further design improvements are recommended. From a technical perspective, the gearbox shows strong potential for extended remanufacturing and second-life validation, even beyond 1 million kilometers.

4 ITERATIVE PRODUCT DEVELOPMENT AND IMPROVEMENT

The product development in RHODaS carried out in WP2 was supported iteratively with workshops and bilateral meetings. In the following the results of the workshops and bilateral meetings that were held with the corresponding project partners as well as the internal reviewing and clustering processes are described along the four components.

4.1 INVERTER

4.1.1 DEVELOPMENT OF NEW CONCEPTS AND IDEAS FOR THE INVERTER

The discussed and gained ideas and open issues from the reference assessment were further clustered and follow-up questions were defined. The main objective was to collect ideas for assessing the condition of inverter components over their entire lifetime in order to detect aging effects, enable predictive maintenance, and support reuse or reusability of components.

To achieve this, **additional condition monitoring** is required beyond conventional inverter measurements. Continuous monitoring of temperature, current, voltage, transferred power, and operating time, particularly for power semiconductors, gate drivers, DC-link capacitors, and DC bus elements, could significantly improve the predictability for reuse and repair. These measurements must be interpreted in relation to environmental conditions, operating time, and driving or load profiles, as isolated values do not allow meaningful long-term assessment. In combination with semiconductor aging models and statistical failure data, wear can be predicted, although this will require additional computational resources. Meaningful evaluation further depends on access to a database containing laboratory and experimental reference data.

The existing inverter control CPU has limited processing and memory resources and cannot handle extensive data acquisition, storage, and communication. For this reason, a secondary CPU within the power converter is likely required to pre-process sensor data and manage data uploads. A gateway is needed to transmit selected data to an IoT cloud platform, where long-term historical data can be stored. Due to memory and bandwidth limitations, not all measured data can be retained, making selective data storage necessary.

Based on the collected information, a “**digital inverter passport**” could be implemented as a digital lifecycle record that documents operating conditions, stress history, and relevant events. This passport enables condition-based decision-making, predictive maintenance, and an assessment of reuse potential for individual components or modules.

Reuse of inverter components is possible but faces several constraints. The economic effort required for dismantling and reuse must be justified, and reuse is often more feasible when components originate from the same manufacturer. Components differ significantly in lifetime, susceptibility to damage, economic

value, and importance within the electrical design. Grouping components according to these aspects allows a structured replacement.

For this purpose, the inverter can be divided into **functional modules**. These modules could be: the power switches and power drives, the cooling system, the capacitors, and other electronics such as CPUs and sensor interfaces. Modularization enables easier replacement of individual parts and improves fault isolation, but it also introduces technical challenges.

One major challenge of modularity is the increase of parasitic loops, which can negatively affect electromagnetic compatibility and efficiency. Shielding concepts, such as a Faraday cage, may be required to mitigate these effects. Furthermore, connectors used between modules can be costly and must be able to withstand vibration, thermal cycling, and other environmental stresses over the inverter's lifetime. Modularity may also lead to an increase in system size and potentially impact efficiency and reliability due to the higher number of interfaces. The connections between modules must therefore be designed to minimize electrical losses, ensure mechanical robustness, and maintain long-term reliability under harsh operating conditions. While modular interconnections are technically feasible, they must be carefully balanced against cost, performance, and lifetime considerations.

4.1.2 FINAL DESIGN CONCEPT

The **final inverter prototype** that was developed during the project is presented roughly in Figure 4.1. Aspect from circularity perspective have been mainly integrated through building the design on a modular structure, where each of the three phases is implemented on its own dedicated board.

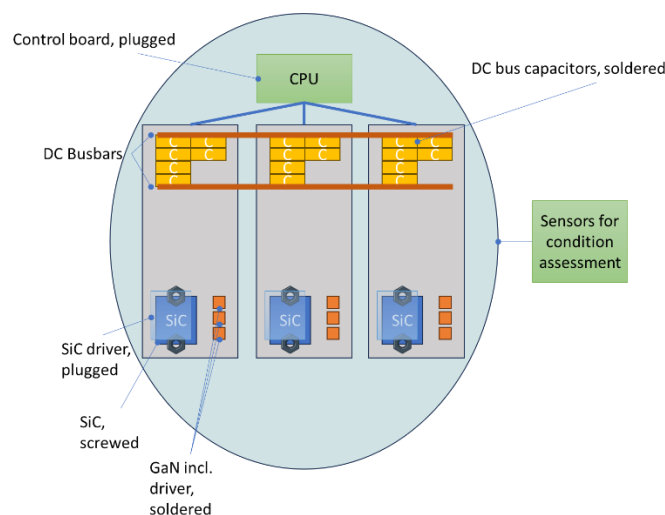


Figure 4.1: Final project inverter prototype (own depiction)

On each phase board, several film capacitors are soldered and together form the DC-link for that phase. The SiC power module is mechanically screwed onto the

board, while the corresponding SiC gate driver is plugged in as a separate component. In addition, GaN power modules with integrated drivers are used, but these are complex to assemble, as they are permanently soldered onto the board. The DC-link voltage is distributed between the three phase boards via copper busbars, which electrically connect the intermediate circuits of all phases. A central control board controls the inverter and communicates with all three phase boards. Sensors for current, voltage, and temperature are already distributed throughout the inverter, close to the relevant components.

This prototype demonstrates a high level of electrical performance and partial modularity, but still relies on soldered components, multiple interfaces, and a relatively high part count.

Building on the existing prototype, the workshops and follow-up meetings led to an **advanced inverter concept** with an improved architecture, with a stronger focus on modularity, reliability, and circularity, presented in Figure 4.2.

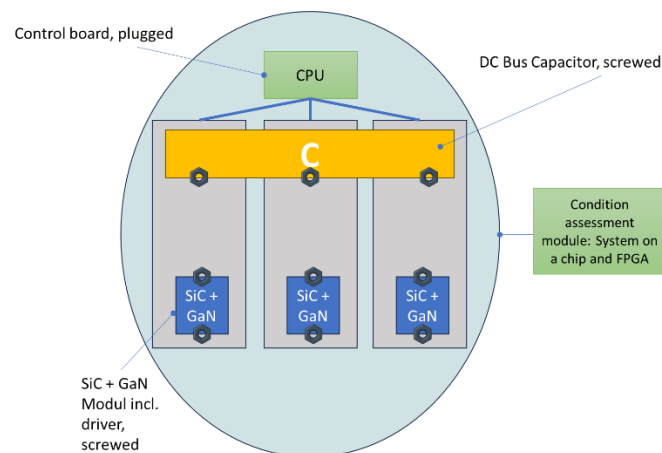


Figure 4.2: Advanced modular concept for inverter (own depiction)

The concept retains the idea of one board per phase but further strengthens this modularity. Power semiconductor modules based on SiC and GaN technologies are designed to be screw-mounted, avoiding complex soldering processes. For GaN devices in particular, the gate driver is fully integrated into the power module, allowing their high switching performance to be fully utilized while reducing parasitic effects and assembly errors.

Instead of multiple soldered film capacitors per board and separate busbars, the concept introduces a central DC-link capacitor that also functions as a busbar and electrical connector between the three phase modules. This reduces the number of discrete capacitors, copper busbars, and electrical interfaces, leading to a lower overall part count and fewer potential failure points.

The control structure is also further modularized. The CPU remains a separate module, and an additional condition assessment module is introduced. This module, implemented as a System-on-Chip combined with an FPGA, uses the inverter's existing sensors to perform fast data acquisition, condition monitoring,

and ageing prediction. This forms the technical basis for a digital inverter passport and predictive maintenance.

Overall, the further-developed concept builds directly on the existing prototype but improves it by reducing soldered connections, integrating functions into fewer components, and clearly separating power control, and diagnostic functions. This evolution improves manufacturability, reliability, and reuse potential without compromising the inverter performance.

4.1.3 CIRCULAR BUSINESS MODEL FOR INVERTER

In parallel and in line with the circular design concept a circular business model concept was developed for the inverter. The circular business model game has been discussed in a workshop setting together with UPC and AIT, as shown in Figure 4.3. The workshop focused on exploring circular business model concepts for the inverter, taking the perspective of a supplier delivering power converters to OEMs or Tier-1 customers.

The overall aim was, in line with the circularity assessment result, to identify how value from inverter components can be maintained for as long as possible through repair, remanufacturing, and reuse, rather than through traditional linear replacement and recycling.



Figure 4.3: Business Model workshop together with UPC (own depiction)

Among the investigated circular business patterns, remanufacturing and **selling inverter components “as new”** was identified as the most relevant option.

Key concepts discussed included **take-back schemes** in cooperation with OEMs, dismantlers, logistics providers, supported by incentives such as **discounts** on new or remanufactured components. Returned inverters would be repaired, refurbished by a Remanufacturer. Reliable testing and quality classification are essential to ensure performance and acceptance of remanufactured components. The concept is presented in Figure 4.4.

The reintroduction to the market can be potentially for the same application or, with significant design changes, for secondary applications. One idea would be an additional module which is plugged onto the inverter if it is used for e.g., PV systems. However, reuse in other applications was considered as technically challenging due to application-specific hardware and closed software systems. If the production of different inverter types (e.g., automotive and PV) is done by the same manufacturer, the realization would be easier.

→ **Business model Inverter: Design for repair and remanufacturing including take back incentives**

The workshop also highlighted significant **barriers to implementation**. Major challenges include high costs for take-back logistics, dismantling, testing, and labour costs, as well as uncertainty regarding residual value and market acceptance of remanufactured products. Additional barriers arise from limited standardization, closed software systems, lack of lifecycle data, and the need for strong coordination across an extended automotive supply chain see Figure 4.4. The workshop concluded that successful implementation of **such circular business models requires early design-for-circularity decisions**, including standardized modules, detachable interfaces, and digital support such as monitoring and product passports. While technically feasible, these models face economic and organizational challenges and require strong cooperation across an extended automotive value chain.

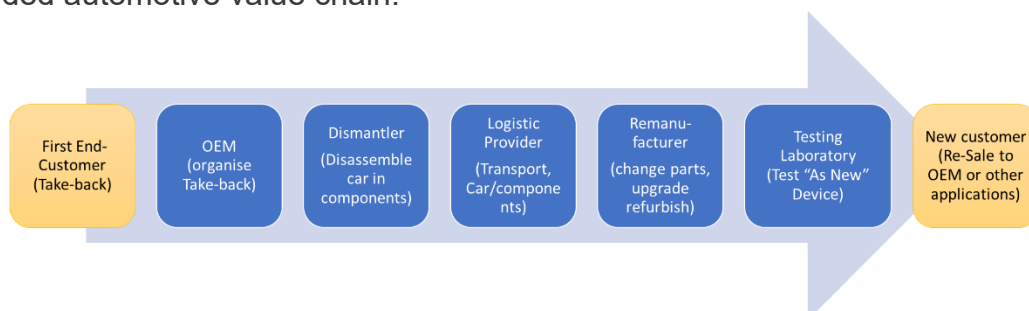


Figure 4.4: Circular supply chain for the Inverter (own depiction)

4.2 E-MOTOR

4.2.1 DEVELOPMENT OF NEW CONCEPTS AND IDEAS

The information collected was further clustered and follow-up questions were defined. A key finding was that magnets contribute the most to the global warming potential of the motor (50% of GWP). They also contain critical raw materials (e.g., Neodym) and are expensive components (30% of costs). Therefore, in a workshop, presented in Figure 4.5, partners mainly focused on reuse concepts for magnets. The question was how magnets can be installed, removed, and potentially reused in a more circular way. Draft ideas that were collected at the workshop are presented in Figure 4.6.



Figure 4.5: Circularity Workshop at the GAM in Amiens (own depiction)

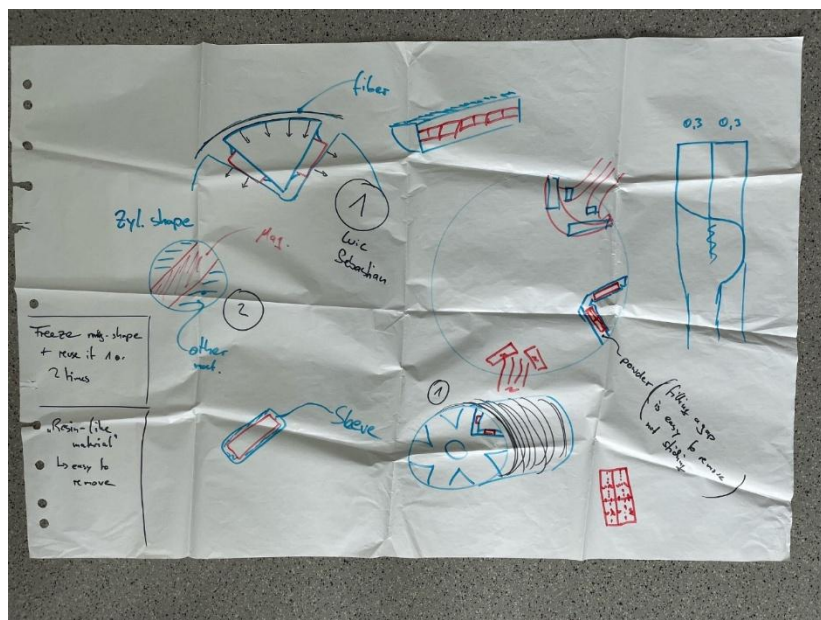


Figure 4.6: Circularity Workshop at the GAM in Amiens – Results for E-Motor (own depiction)

Current designs usually fix magnets with a resin inside the rotor to ensure mechanical stability and high performance. Magnets that are fixed with resin recovered by destroying the resin through thermal treatment, in an oven at 200°C. After heating, the magnets can be removed and cleaned and can then be reused, presented in Figure 4.7.

This approach does not require changes to the original motor design and can therefore be applied to existing products. After cleaning and quality checking, the magnets may be reused for the same application, provided that their magnetic properties have not been significantly degraded by the thermal process.

The main disadvantages are the high energy demand of the thermal treatment, the risk of partial demagnetization or material degradation, and the additional effort required for cleaning and testing. Therefore, alternative design concepts were developed, as described below.

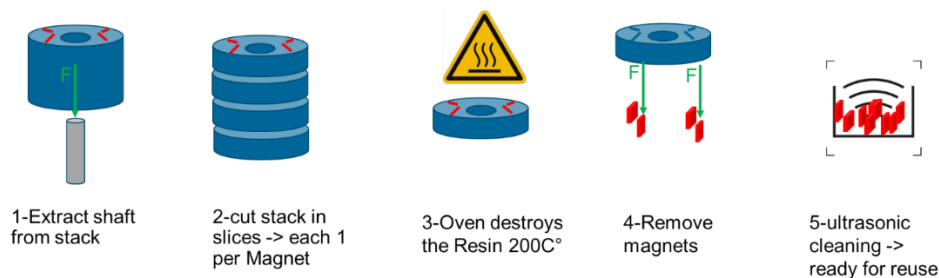


Figure 4.7: Removal of magnets (own depiction)

“Piece-of-Cake” Rotor with Fibre Sleeve Fixation

In this concept, the rotor consists of pole stacks shaped like pieces of a cake, as presented in Figure 4.8. The magnets are located between the pole stacks and the lamination stack and are held in position by an outer fiber sleeve, made from carbon or glass fibers. The sleeve provides the necessary radial compression and mechanical stability during operation.

A key advantage of this design is the simple teardown. By removing the fiber sleeve, the pole stacks can be separated and the magnets can be removed non-destructively, without the use of glue or resin. This significantly improves magnet recoverability and reuse potential.

The main challenges are the increased mechanical complexity, rotor balancing, and ensuring sufficient mechanical stability of the segmented rotor at high rotational speeds.

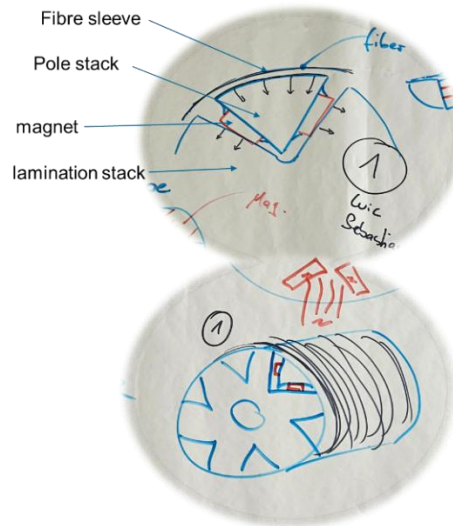


Figure 4.8: "Piece of cake" idea (own depiction)

Magnet with Expandable Retention Sleeve

In this concept, each magnet is placed into a rotor pocket within a non-adhesive sleeve. The sleeve holds the magnet in place by mechanical pressing only and does not stick to the magnet or the rotor. The sleeve can be expanded during assembly, for example by air, heat or UV activation, and provides the required stability during operation.

During disassembly, the sleeve can be relaxed or destroyed in a controlled way, allowing the magnet to be removed without damage. This enables magnet recovery and reuse.

At the current stage, the fixation mechanism for the sleeve to reliably prevent magnet movement at very high rotational speeds is not yet defined. This remains an open technical question and requires further mechanical and safety validation. Therefore, this concept is considered an early-stage design idea.

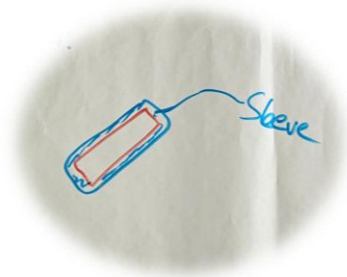


Figure 4.9: Magnet with sleeve idea (own depiction)

Magnet Powder Instead of Solid Magnets

In this concept, solid permanent magnets are replaced by magnetic powder, such as NdFeB powder, which is inserted into defined rotor cavities, as presented in Figure 4.10. The powder is inserted in an unmagnetized state and magnetized

after installation. Compression is required to prevent movement of individual particles.

A positive effect of this approach is that the powder can act as a mechanical damper and allows high geometric freedom, enabling different applications for reuse.

However, this concept introduces major challenges. The rotor cavities must be completely sealed to prevent powder leakage. After magnetization, removal becomes very difficult, as magnetic powder strongly adheres to surrounding metallic parts. Clean and complete extraction of the powder is therefore a major issue, making circular reuse difficult in practice, unless full demagnetization processes are available.

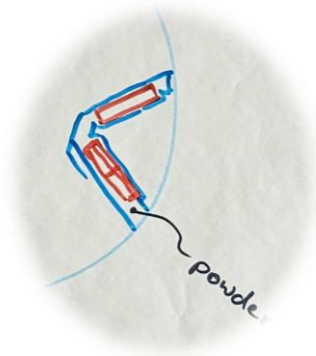


Figure 4.10: Magnet powder idea (own depiction)

Standardized Magnet as a Press-Fit Interface Component

In this concept, magnets are designed as standardized components with a defined mechanical interface, for example a cylindrical shape, as shown in Figure 4.11. The magnet is fixed in the rotor using a press-fit connection, based on standardized dimensions and tolerances.

The press-fit provides a simple and robust fixation method that is well understood in industrial applications. Standardized magnet dimensions could allow reuse across different motor variants and potentially across manufacturers.

The main challenge of this concept is the trade-off between secure fixation and removability. Press-fits increase extraction forces and may complicate non-destructive removal. In addition, standardization may limit performance optimization for specific motor designs. Nevertheless, this concept offers an improved reusability if extraction processes can be controlled.

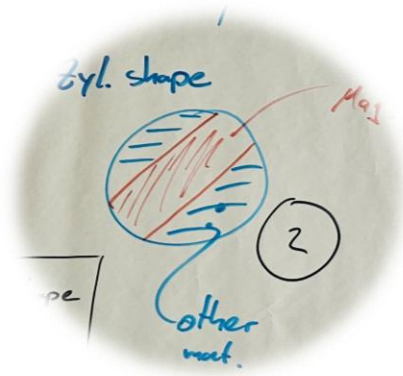


Figure 4.11: Cylindrical pressfit idea (own depiction)

Together, these four ideas illustrate different pathways to improve magnet circularity, each with specific trade-offs between circular performance, technical feasibility, environmental performance and economic feasibility, presented in Figure 4.12. The rating is based on a qualitative assumption.





	Technical feasibility	Circular performance	Environmental performance	Economic feasibility
 Solution 1	high performance due to best flux guidance with no stray losses	cured carbonfibre/glassfibre sleeve not easy to be reused	Additional sleeve/ring needed	CFP/GFP Sleeve/ring not too expensive but more energy intensive to cure
 Solution 2	Sleeve is a challenge	Easy to disassemble	Additional sleeve needed	Sleeve seems costly
 Solution 3	Difficult to realise – powder is not allowed to move. Magnetic strength could be reduced	Tear down simple, but powder is not easy to handle. Could be used in different shapes and scenarios	Additional cover needed	Technical costly to realise. Especially for demagnetization and magnetization
 Solution 4	Pressfit is technical standard	High pressure needed for dismantling. Unclear if remanufacturing is needed (dimension)	If reuse is possible (remanufacturing necessary?)	Pressfit not expensive, but Magnets may need to be reworked

Figure 4.12: Comparison of different design ideas for circular magnets (own depiction)

4.2.2 CIRCULAR BUSINESS MODEL FOR E-MOTOR

The circular business model game has been used to develop and discuss circular business models together with Valeo Siemens in a workshop setting, as shown in Figure 4.13. In the business model workshop, the participants identified Pattern B2 – “**System components as new**” as the most suitable circular business model for the e-motor. Within this pattern, the focus was placed on sub-pattern B1.2 – “**Leasing system components as new.**” The aim here was to be in line with the approach for the circular design concepts and its focus on medium loop.



Figure 4.13: Circular Business Model Workshop with Valeo Siemens (own depiction)

The core idea of this leasing model is that e-motors remain the property of the OEM or the component supplier, while being leased as part of a vehicle or fleet. In most cases the OEM will operate the leasing model for the whole vehicle. Then an additional contract with the suppliers is needed. The suppliers alone cannot introduce leasing at vehicle level, just in the case where the vehicle manufacturer who also acts as a fleet operator uses a leasing system for all or some of the components of the vehicle. This is the case with London taxis. In this scenario, the component manufacturer leases the component to London taxis, while keeping the ownership. This would also allow easier takeback and remanufacturing of components.

→ **Business model E-Motor: Leasing of components + Design for repair and remanufacturing to extend the lifetime**

For such a circular business model the supply chain will differ to the traditional one and other players on the market will become partners like take back partners, Dismantlers, Remanufacturers or Recyclers as show in Figure 4.14. If a leasing model should be implemented, the Design4R (covering reduction, reuse, repair, refurbishment, and recycling) introduced by Valeo would become even more important. Design improvements must be carefully evaluated using key performance indicators, including Total Cost of Ownership for the customer, Total Cost to Company, and CO₂-equivalent emissions over the full lifecycle.

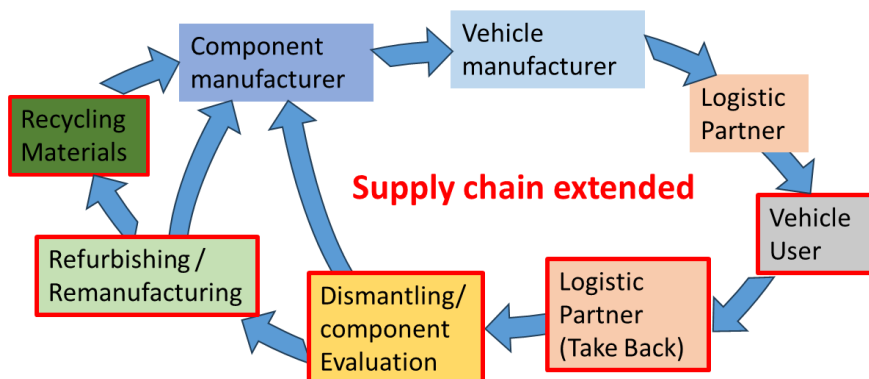


Figure 4.14: Supply chain for a circular business model (own depiction)

4.3 THERMAL MANAGEMENT SYSTEM

4.3.1 CIRCULAR BUSINESS MODEL FOR TMS

A circular business model for the heatsink has not been considered as meaningful, as the TMS is made from a mono-material with a well-established recycling path, where a well established business model already exists. A reuse of a TMS would be limited to the same application, as the design is very customized for a specific inverter. The existing circular business model of the Thermal Management System is presented in Figure 4.15.

→ **Business model Thermal Management System: Design for recycling**

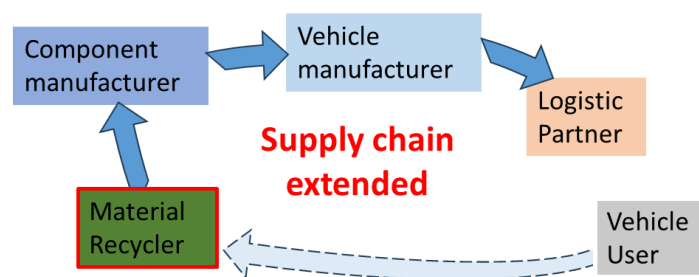


Figure 4.15: Supply chain for a circular business model for TMS (own depiction)

The supply chain (details see Deliverable 6.3) for the Thermal Management System (TMS) is mainly focused on the internal design requirements of a **"Design for Recycling"** resulting in a monomaterial design and a Recycler as key partners by processing the mono-material TMS through well-established recycling paths.

4.4 GEARBOX

4.4.1 CIRCULAR BUSINESS MODEL FOR GEARBOX

The workshops and follow-up discussions confirm that **remanufacturing is a mature circular business model for Valeo**. It is already well established for mechanical components such as clutches, stators, rotors, and is now being systematically **expanded to electrified powertrain systems**, including the gearbox, e-motor, inverter, and complete e-axle. Valeo remanufactures their own parts but also have a list of companies/brands that are remanufacturing for them.

Based on the workshop discussions, Pattern C2 – **"Product as New"** was selected as the most relevant circular business model. In the current practice (Sub-pattern C2.1 – "Selling product as new"), OEMs already work in partnership with suppliers such as Valeo to integrate used or remanufactured parts into products that are sold as equivalent to new with a given discount. This model is well established and fits with existing OEM strategies and market structures.

A key enabler for this approach is that many automotive parts are designed for demanding customer requirements, typically around 200,000 km, and for operation under very different environmental conditions (e.g. alpine, desert). As a result, these components are often over-engineered, and at the end of vehicle life they still have remaining service life. Pattern C2 allows this remaining value to be recovered by reusing parts in products.

In the workshops sub-pattern C2.2 – “**Product leasing as new**” was also discussed as a more advanced extension of the current practice. Leasing is not considered unfeasible, but it would require significant coordination. One fundamental barrier is the horizontal integration of the automotive industry. The introduction of leasing would require greater vertical integration of supply chain, stronger coordination between OEMs and suppliers, and aligned business models. It’s also important that the OEM itself operates a leasing model, including a contract with the suppliers. The suppliers alone cannot introduce leasing at system level.

→ **Business model Gearbox:** *Leasing of components + Design repair and remanufacturing to extend the lifetime*

Feedback from Valeo’s marketing department further clarified that leasing concepts are most suitable for large, high-value systems with long lifetimes, such as powertrains or e-axes in buses and trucks. For smaller components with typical values below 300 €, the organizational and contractual effort of leasing would likely outweigh the benefits. It was therefore stated that leasing concepts should be in a next step, after this project, be validated through a proof of concept before a broader rollout.

At present, only a small share of products (around 2–4%) is actually remanufactured, which highlights the importance of improved return flows and better control over product lifecycles. One advantage of a leasing-based model would be that Valeo could retain ownership of products, enabling structured returns and reducing competition in remanufacturing. However, Valeo currently has no direct contracts with truck manufacturers, which represents a barrier.

If a leasing model is implemented the design of the gearbox should be adapted to fulfill the requirements related to the leasing model, towards remanufacturing and reuse.

5 ASSESSMENT OF FINAL IMD PROTOTYPE & CIRCULAR CONCEPTS

In this chapter the assessment of the developed final IMD prototype and the circular concepts including the circular business models are presented. The assumptions for the assessed scenarios are described in chapter 2.1.2.

5.1 LIFE CYCLE IMPACT ASSESSMENT AND INTERPRETATION

In the following sections the life cycle impact assessment results and their interpretation for the three defined scenarios are presented. The results of the scenarios were calculated for the defined functional unit, which includes the provision of 3 Mio km of transportation. As common IMDs are not designed to last that long, multiple IMDs are needed to provide this distance. This approach helps to present the benefits of repair and reuse.

However, to have a clear result of one IMD, the life cycle assessment of the raw material and manufacturing phase of one IMD is presented at the beginning.

5.1.1 RAW MATERIAL AND MANUFACTURING PHASE (CRADLE TO GATE)

As depicted in Figure 5.1, the environmental impacts of the IMD are mainly driven by the gearbox, the e-motor and the inverter. The heatsink has a minor contribution. The results are evenly distributed for most of the impact categories. The e-motor dominates the impacts of eutrophication, human toxicity (non cancer) and land use. The inverter mainly contributes to the ozone depletion, and resource use (minerals and metals), while the gearbox dominates the impact on human toxicity (cancer), ionising radiation and resource use (fossils). The calculated values are presented in Table 5.1.

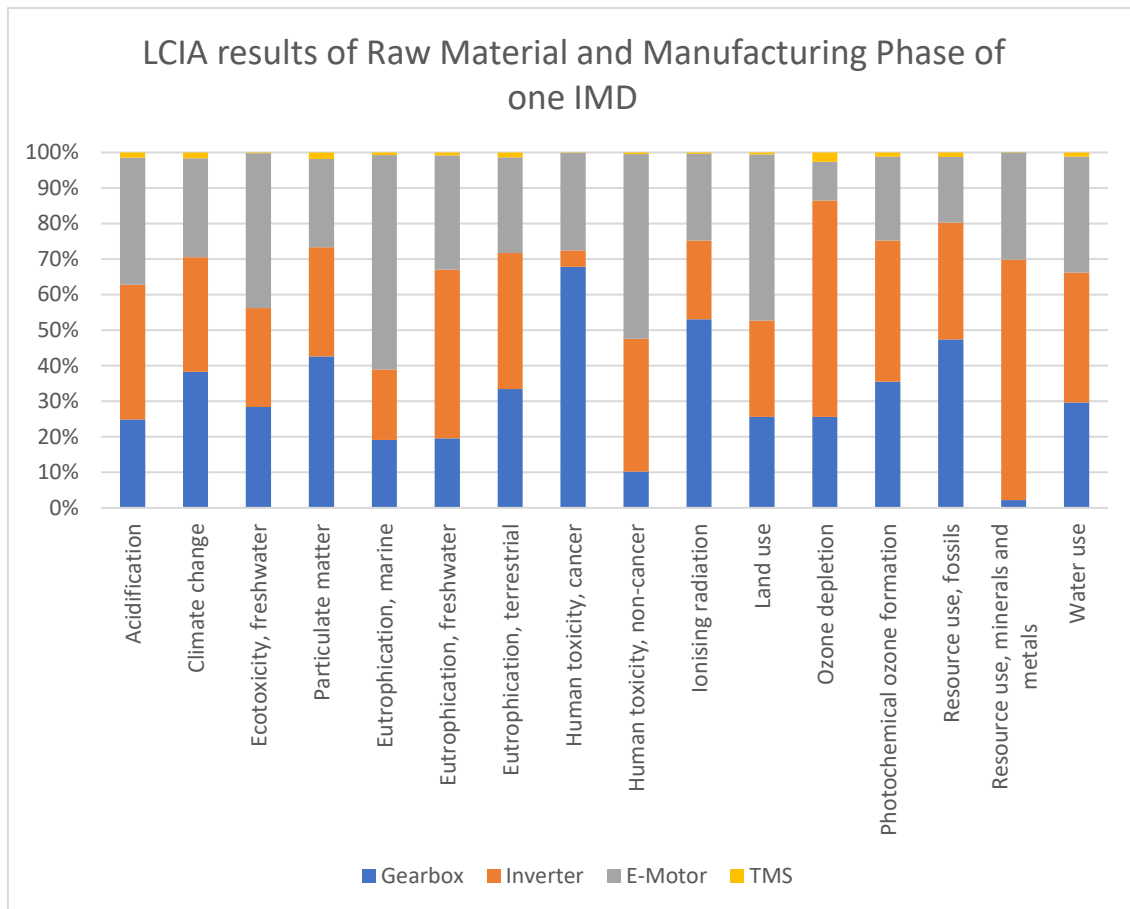


Figure 5.1: LCIA results of Raw Material and Manufacturing Phase of IMD (own depiction)

Table 5.1: LCIA results of Raw Material and Manufacturing Phase of IMD (own depiction)

Impact Category	Unit	Summe	Gearbox	Inverter	E-Motor	TMS
Acidification	mol H+ eq	1,41E+01	3,51E+00	5,36E+00	5,05E+00	1,98E-01
Climate change	kg CO2 eq	1,79E+03	6,83E+02	5,77E+02	4,97E+02	2,90E+01
Ecotoxicity, freshwater	CTUe	3,34E+04	9,48E+03	9,26E+03	1,45E+04	7,56E+01
Particulate matter	disease inc.	1,21E-04	5,16E-05	3,72E-05	3,02E-05	2,14E-06
Eutrophication, marine	kg N eq	3,64E+00	6,95E-01	7,21E-01	2,20E+00	2,71E-02
Eutrophication, freshwater	kg P eq	1,20E+00	2,35E-01	5,69E-01	3,86E-01	9,82E-03
Eutrophication, terrestrial	mol N eq	2,02E+01	6,73E+00	7,73E+00	5,42E+00	2,72E-01
Human toxicity, cancer	CTUh	3,64E-05	2,47E-05	1,69E-06	9,98E-06	2,99E-08
Human toxicity, non-cancer	CTUh	7,72E-05	7,84E-06	2,88E-05	4,01E-05	3,74E-07
Ionising radiation	kBq U-235 eq	2,36E+02	1,25E+02	5,23E+01	5,75E+01	9,47E-01
Land use	Pt	8,17E+03	2,09E+03	2,21E+03	3,82E+03	4,61E+01
Ozone depletion	kg CFC11 eq	3,16E-05	8,09E-06	1,93E-05	3,46E-06	8,20E-07
Photochemical ozone formation	kg NMVOC eq	7,02E+00	2,50E+00	2,79E+00	1,66E+00	8,46E-02
Resource use, fossils	MJ	2,07E+04	9,79E+03	6,79E+03	3,81E+03	2,63E+02
Resource use, minerals and metals	kg Sb eq	1,59E-01	3,42E-03	1,07E-01	4,79E-02	3,45E-05
Water use	m3 depriv.	4,08E+02	1,21E+02	1,49E+02	1,33E+02	4,75E+00

The inverter is the only component that has faced a relevant change in comparison to D1.3 M15, a closer look at the contribution of the inverters components is given in Figure 5.2. The results for the gearbox and e-motor are already documented in D1.3. The heatsink only consists of aluminium and will therefore not be analysed more in detail.

It can be seen that a huge contribution from the inverter’s environmental impacts comes from the housing, which consists mainly of aluminium and the GaN power board, where the GaN transistors share the main impact.

The optical SiC driver board has a major impact on the impact category resource use (minerals and metals), where the inverter dominates the overall IMDs results, presented in Figure 5.1. Also, in all other impact categories this component is most relevant for the impact of the Optical SiC driver board. A closer look at the model reveals that this is due to the used optical transmitters. Unfortunately, there is no specific dataset available for this component, therefore an average dataset for active components was used, which leads to some uncertainty in the results. In the used average dataset, the included gold content is mainly driving the impacts.

The Power Control Unit, the SiC driver board, the Copper Bars as well as the Pressure Plates share only around 10-20% of the overall inverter impact. In the SiC power module, which shares around 15% of the impact categories, the SiC MOSFET are most responsible.

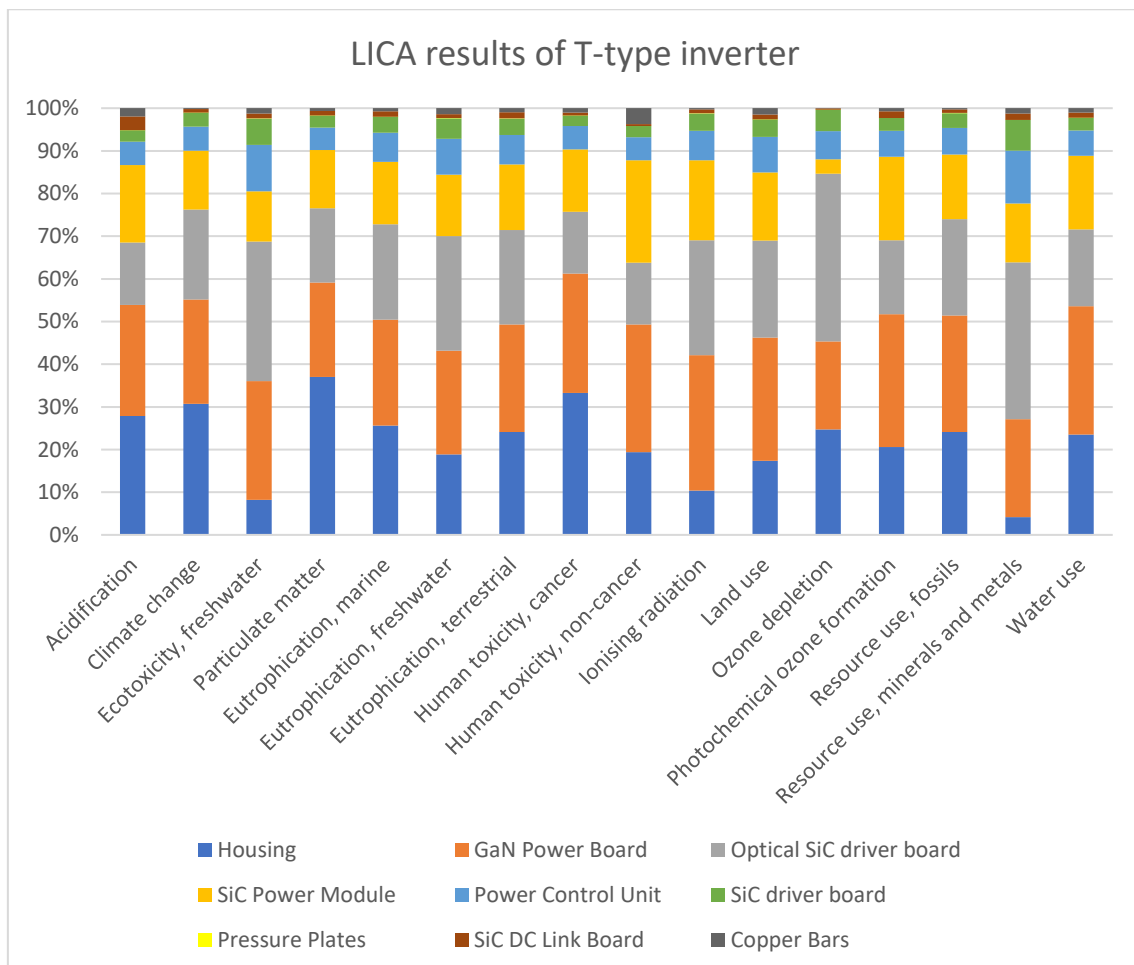


Figure 5.2: LCIA results of T-type inverter

5.1.2 SCENARIO 1

In Figure 5.3, the final LCIA results on system perspective (cradle to grave) of the developed IMD prototype are presented. The figure highlights, that the use phase dominates most of the assessed impact categories. Only in the impact category resource use, minerals and metals, the raw material and manufacturing phase dominates. As presented in Table 5.2 the overall Global Warming Potential (GWP) is calculated as $4,77 \cdot 10^4$ kg CO₂ eq, of which around 92% are related to the inverter's losses. The impact category resource use (minerals and metals) is calculated as $4,38 \cdot 10^{-1}$ kg Sb eq, of which around 79% are related to the raw material and manufacturing phase. The distribution phase is not having a relevant impact on the overall results. Savings that result from the EoL phase, are also of minor relevance, as they are reducing the impact less than 2%. Even if there is a manufacturing of around 5% of the motor and the gearbox.

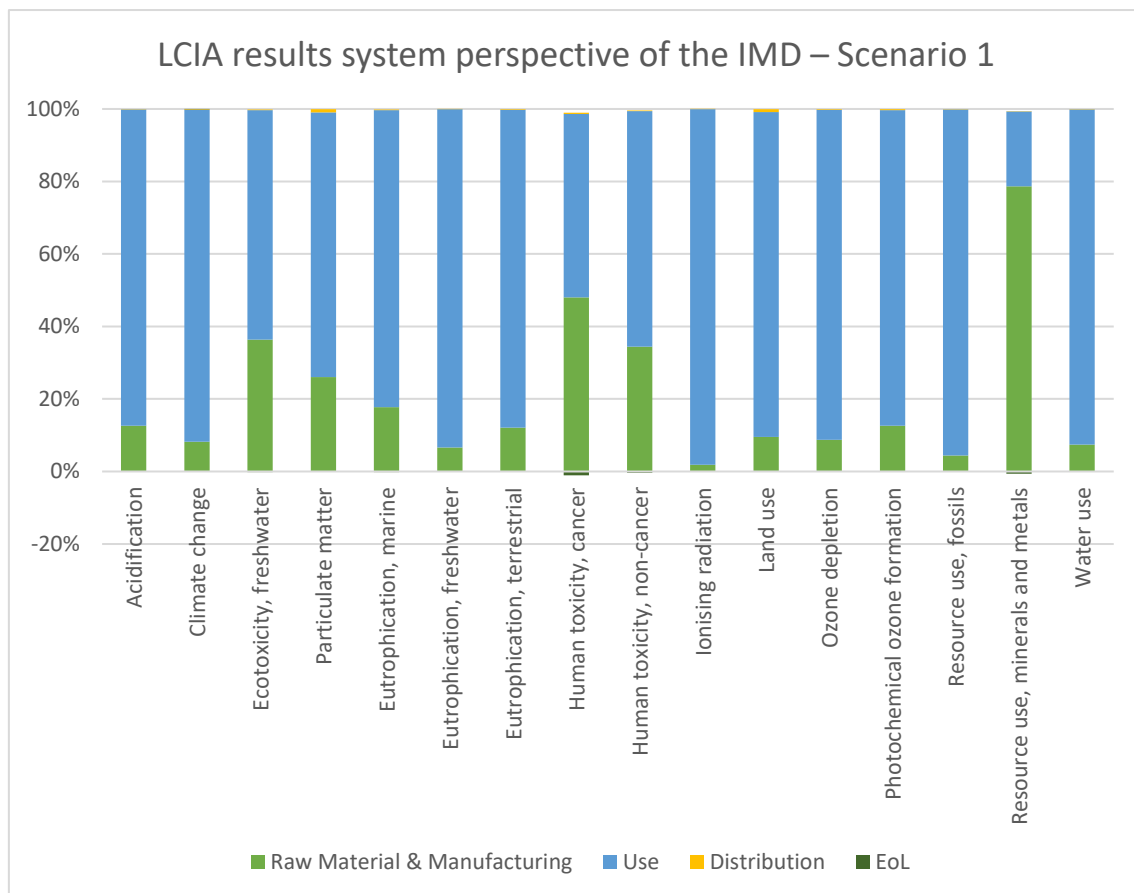


Figure 5.3: LCIA results system perspective (cradle to grave) of the IMD – Scenario 1 (own depiction)

Table 5.2: LCIA results system perspective (cradle to grave) of the IMD – Scenario 1 (own depiction)

Impact Category	Unit	Summe	Raw Material & Manufacturing	Use	Distribution	EoL
Acidification	mol H+ eq	2,45E+02	3,11E+01	2,14E+02	2,29E-01	-1,71E-01
Climate change	kg CO2 eq	4,77E+04	3,93E+03	4,36E+04	9,69E+01	3,49E+01
Ecotoxicity, freshwater	CTUe	2,01E+05	7,34E+04	1,28E+05	3,44E+02	-2,72E+02
Particulate matter	disease inc.	1,02E-03	2,66E-04	7,46E-04	9,43E-06	-5,15E-07
Eutrophication, marine	kg N eq	4,51E+01	8,01E+00	3,71E+01	6,00E-02	-6,94E-02
Eutrophication, freshwater	kg P eq	4,00E+01	2,64E+00	3,74E+01	6,82E-03	-1,54E-02
Eutrophication, terrestrial	mol N eq	3,67E+02	4,43E+01	3,22E+02	6,49E-01	-7,90E-02
Human toxicity, cancer	CTUh	1,63E-04	8,00E-05	8,41E-05	6,19E-07	-1,75E-06
Human toxicity, non-cancer	CTUh	4,90E-04	1,70E-04	3,21E-04	9,32E-07	-1,84E-06
Ionising radiation	kBq U-235 eq	2,82E+04	5,19E+02	2,77E+04	1,77E+00	-7,50E+00
Land use	Pt	1,88E+05	1,80E+04	1,69E+05	1,46E+03	-1,04E+02
Ozone depletion	kg CFC11 eq	7,99E-04	6,96E-05	7,27E-04	2,02E-06	-1,60E-07
Photochemical ozone formation	kg NMVOC eq	1,23E+02	1,55E+01	1,07E+02	3,97E-01	-3,76E-02
Resource use, fossils	MJ	1,04E+06	4,54E+04	9,91E+05	1,45E+03	-1,74E+02
Resource use, minerals and metals	kg Sb eq	4,38E-01	3,49E-01	9,16E-02	2,71E-04	-2,60E-03
Water use	m3 depriv.	1,21E+04	8,97E+02	1,12E+04	6,92E+00	-9,21E+00

5.1.3 SCENARIO 2

In Figure 5.4, the final LCIA results on IMD system perspective (cradle to grave) of Scenario 2 are presented. Compared to Scenario 1, especially the impact category resource use (minerals and metals), but also the impact categories climate change, human toxicity (cancer and non-cancer) and eutrophication show relevant reductions of impacts due to the improved remanufacturing and design. Around 4% up to over 8% of emissions are saved through the EoL phase. In Table 5.3 the exact calculations for Scenario 2 are shown.

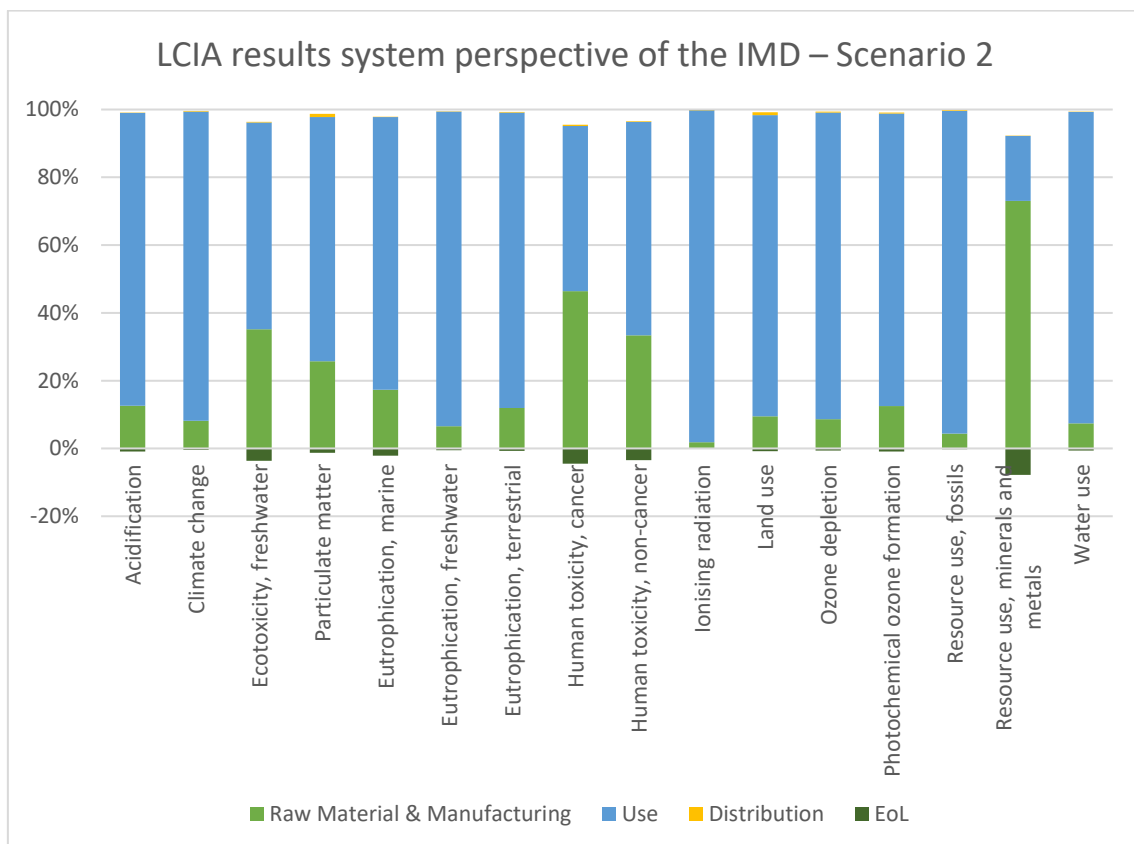


Figure 5.4: LCIA results system perspective (cradle to grave) of the IMD – Scenario 2 (own depiction)

Table 5.3: LCIA results system perspective (cradle to grave) of the IMD – Scenario 2 (own depiction)

Impact Category	Unit	Summe	Raw Material & Manufacturing	Use	Distribution	EoL
Acidification	mol H+ eq	2,43E+02	3,11E+01	2,14E+02	2,29E-01	-2,31E+00
Climate change	kg CO2 eq	4,75E+04	3,93E+03	4,36E+04	9,69E+01	-2,12E+02
Ecotoxicity, freshwater	CTUe	1,94E+05	7,34E+04	1,28E+05	3,44E+02	-7,61E+03
Particulate matter	disease inc.	1,01E-03	2,66E-04	7,46E-04	9,43E-06	-1,37E-05
Eutrophication, marine	kg N eq	4,42E+01	8,01E+00	3,71E+01	6,00E-02	-9,84E-01
Eutrophication, freshwater	kg P eq	3,98E+01	2,64E+00	3,74E+01	6,82E-03	-2,22E-01
Eutrophication, terrestrial	mol N eq	3,64E+02	4,43E+01	3,22E+02	6,49E-01	-2,79E+00
Human toxicity, cancer	CTUh	1,57E-04	8,00E-05	8,41E-05	6,19E-07	-7,69E-06
Human toxicity, non-cancer	CTUh	4,74E-04	1,70E-04	3,21E-04	9,32E-07	-1,74E-05
Ionising radiation	kBq U-235 eq	2,82E+04	5,19E+02	2,77E+04	1,77E+00	-5,39E+01
Land use	Pt	1,86E+05	1,80E+04	1,69E+05	1,46E+03	-1,60E+03
Ozone depletion	kg CFC11 eq	7,94E-04	6,96E-05	7,27E-04	2,02E-06	-5,18E-06
Photochemical ozone formation	kg NMVOC eq	1,22E+02	1,55E+01	1,07E+02	3,97E-01	-1,11E+00
Resource use, fossils	MJ	1,04E+06	4,54E+04	9,91E+05	1,45E+03	-2,82E+03
Resource use, minerals and metals	kg Sb eq	4,04E-01	3,49E-01	9,16E-02	2,71E-04	-3,71E-02
Water use	m3 depriv.	1,20E+04	8,97E+02	1,12E+04	6,92E+00	-7,88E+01

5.1.4 SCENARIO 3

In Figure 5.5, the final LCIA results on the IMD system perspective (cradle to grave) of Scenario 3 are presented. Due to the defined business model and the optimized take-back solution, more components can be remanufactured and re-used, which leads to a reduction of up to 50% of emissions in the impact category resource use (minerals and metals), around 29% in human toxicity (cancer) but only 4% in climate change in the EoL phase. In Table 5.4 the exact calculations for Scenario 3 are shown.

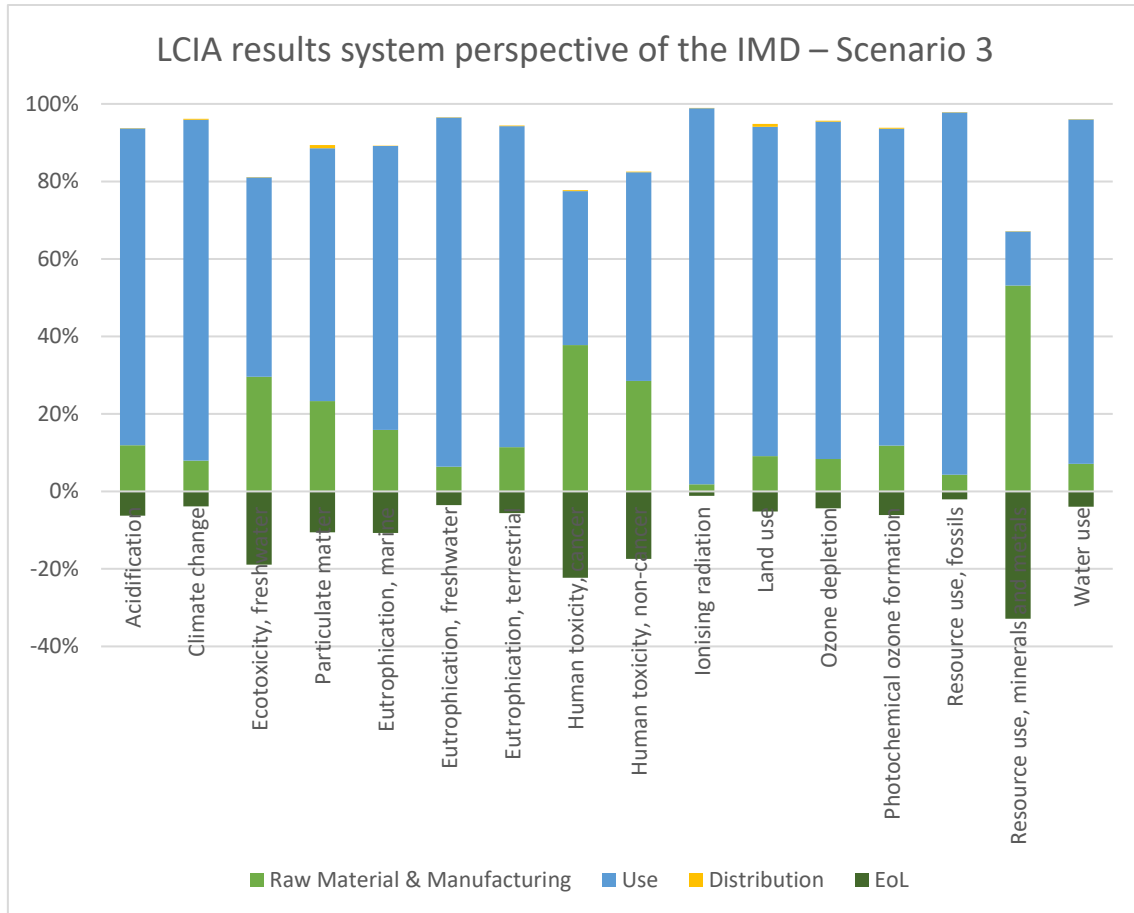


Figure 5.5: LCIA results system perspective (cradle to grave) of the IMD – Scenario 3 (own depiction)

Table 5.4: LCIA results system perspective (cradle to grave) of the IMD – Scenario 3 (own depiction)

Impact Category	Unit	Summe	Raw Material & Manufacturing	Use	Distribution	EoL
Acidification	mol H+ eq	2,29E+02	3,11E+01	2,14E+02	2,29E-01	-1,63E+01
Climate change	kg CO2 eq	4,57E+04	3,93E+03	4,36E+04	9,69E+01	-1,92E+03
Ecotoxicity, freshwater	CTUe	1,55E+05	7,34E+04	1,28E+05	3,44E+02	-4,68E+04
Particulate matter	disease inc.	9,01E-04	2,66E-04	7,46E-04	9,43E-06	-1,21E-04
Eutrophication, marine	kg N eq	3,97E+01	8,01E+00	3,71E+01	6,00E-02	-5,44E+00
Eutrophication, freshwater	kg P eq	3,86E+01	2,64E+00	3,74E+01	6,82E-03	-1,47E+00
Eutrophication, terrestrial	mol N eq	3,45E+02	4,43E+01	3,22E+02	6,49E-01	-2,18E+01
Human toxicity, cancer	CTUh	1,18E-04	8,00E-05	8,41E-05	6,19E-07	-4,71E-05
Human toxicity, non-cancer	CTUh	3,88E-04	1,70E-04	3,21E-04	9,32E-07	-1,04E-04
Ionising radiation	kBq U-235 eq	2,79E+04	5,19E+02	2,77E+04	1,77E+00	-3,17E+02
Land use	Pt	1,78E+05	1,80E+04	1,69E+05	1,46E+03	-1,02E+04
Ozone depletion	kg CFC11 eq	7,62E-04	6,96E-05	7,27E-04	2,02E-06	-3,64E-05
Photochemical ozone formation	kg NMVOC eq	1,15E+02	1,55E+01	1,07E+02	3,97E-01	-8,00E+00
Resource use, fossils	MJ	1,02E+06	4,54E+04	9,91E+05	1,45E+03	-2,21E+04
Resource use, minerals and metals	kg Sb eq	2,25E-01	3,49E-01	9,16E-02	2,71E-04	-2,16E-01
Water use	m3 depriv.	1,16E+04	8,97E+02	1,12E+04	6,92E+00	-5,01E+02

5.1.5 COMPARISON WITH THE BASELINE

This chapter brings together all the findings and compare them with baseline, defined in chapter 2.1.2.

The RHODaS hybrid inverter operates in three-level (3L) mode using SiC and GaN devices up to 50 kW. Above this power level, the inverter transitions to two-level (2L) operation using only SiC devices, up to 150 kW nominal power and 250 kW limit operation. In this high-power region, the inverter therefore operates in the same configuration as the 2-level SiC inverter used for efficiency comparison as the current state-of-the-art baseline.

Experimental validation of the IMD has so far been performed up to an inverter switching frequency of 14 kHz, using standard modulation, showing an inverter efficiency improvement of approximately 2.5% below 50 kW, in good agreement with simulation results (2.3%). Based on these experimentally validated conditions, a first energy-consumption simulation over representative driving cycles was carried out, resulting in a conservative overall IMD efficiency improvement of about 0.4%.

However, the hybrid inverter is expected to operate at higher switching frequencies and with Carrier-Based Pulse Width Modulation (CB-PWM), where its advantages become more evident. When operating at higher switching frequencies (e.g., 50 kHz) and compared with a high-performance SiC-based 2-level inverter using standard modulation, simulation results show an average inverter efficiency improvement of about 5.8% over the full operating range, and up to 14.7% below 50 kW, where the GaN devices are active. Compared to a conventional IGBT-based inverter, the efficiency improvement would be even greater.

These higher efficiency gains are expected to lead to a larger reduction in energy consumption over driving cycles, depending on how much time the system operates at low power. For this reason, in addition to the current 0.4% efficiency improvement, three additional scenarios assuming 3%, 5%, and 10% overall IMD efficiency improvements over representative driving cycles were considered to evaluate the environmental impact.

It was assumed in chapter 2.1.2, that the increased modularity of the inverter, leads to an extension of 50% of the whole IMDs lifetime, as it can be easier repaired. This lifetime extension results in the reduction of the input materials along the functional unit. The more relevant the raw materials and manufacturing phase is for an impact category, the more influence the repair will have on the result.

In Figure 5.6 the impact difference of repair for the first three scenarios with 0,4% efficiency improvement is shown for the impact categories climate change and resource use. It can be seen, that in the impact category climate change, the improved repair leads to additional 3% of reduction in all three scenarios. In the impact category resource use (minerals and metals), without an improved repair the impact is even higher in Scenario 1 compared to the baseline, as there is barely any reuse of components and the baseline is conservatively assumed to

need 10% less materials (for inverter and heatsink). With an improved repair, between additional 9% (Scenario 3) and 20% (Scenario 1) can be saved.

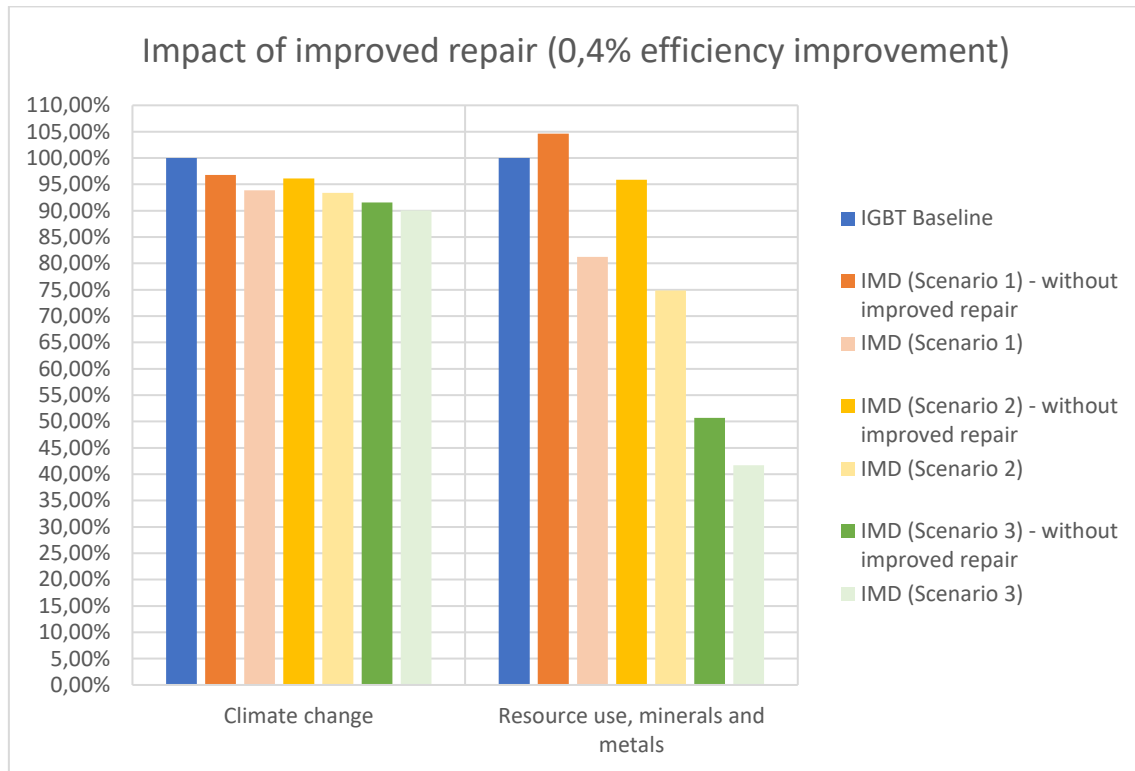


Figure 5.6: Impact of improved repair (0,4% efficiency improvement)

In Figure 5.7 it can be seen, that an efficiency improvement mainly has an influence on the impact category climate change, as this impact category is dominated by the use phase. The impacts of improved reuse and remanufacturing of components in scenario 2 (S2) and scenario 3 (S3) have a minor impact in this impact category. The results of other impact categories that share a similar profile behave in a similar manner and are not presented below to keep it readable. A graphic of all impact categories is presented in the Appendix (see Figure A. 1).

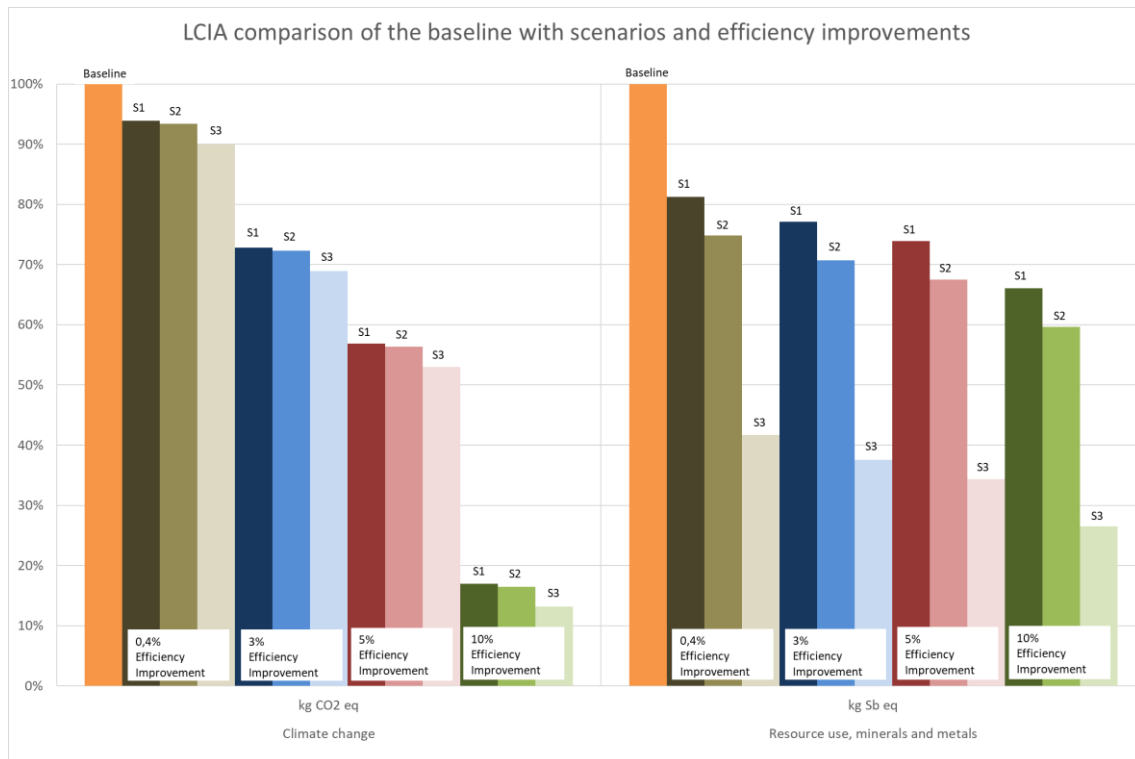


Figure 5.7: LCIA comparison of the baseline with scenarios and efficiency improvements (improved repair included)

The impact category resource use (minerals and metals) is the only calculated impact category that is dominated by another life cycle phase, namely the raw material and manufacturing phase. Here the efficiency improvement has a minor impact, while the improvements on reuse and remanufacturing in scenario 2 and scenario 3 have a more relevant impact.

Overall, compared to the baseline, a difference of emissions between **-3%** (Scenario 1, 0.4% efficiency improvement, no improved repair included) up to **-87%** (Scenario 3, 10% efficiency improvement, improved repair included) in the impact category climate change can be achieved. For the impact category resource use (minerals and metals), a difference between **+4%** (Scenario 1, 0.4% efficiency, no improved repair included) up to **-70%** (Scenario 3, 10% efficiency improvement, improved repair included) can be observed.

5.1.6 SENSITIVITY ANALYSIS

The use phase is calculated based on the energy mix of the European Union. To include an analysis of the sensitivity of this dataset, a comparison with the energy mix of Spain, Austria, France, Germany was done. As can be seen in Figure 5.8, depending on where the IMD is used the results for Scenario 1 differ considerable, except for the impact category resource use (minerals and metals), as it is barely related to the energy consumption. Using the energy mix from Germany, a higher impact on climate change can be expected, due to the higher portion of coal. Using the energy mix of France, a higher impact on ionising radiation can be expected due to the higher portion of nuclear power. The other impact categories are presented in the Appendix (see Figure A. II).

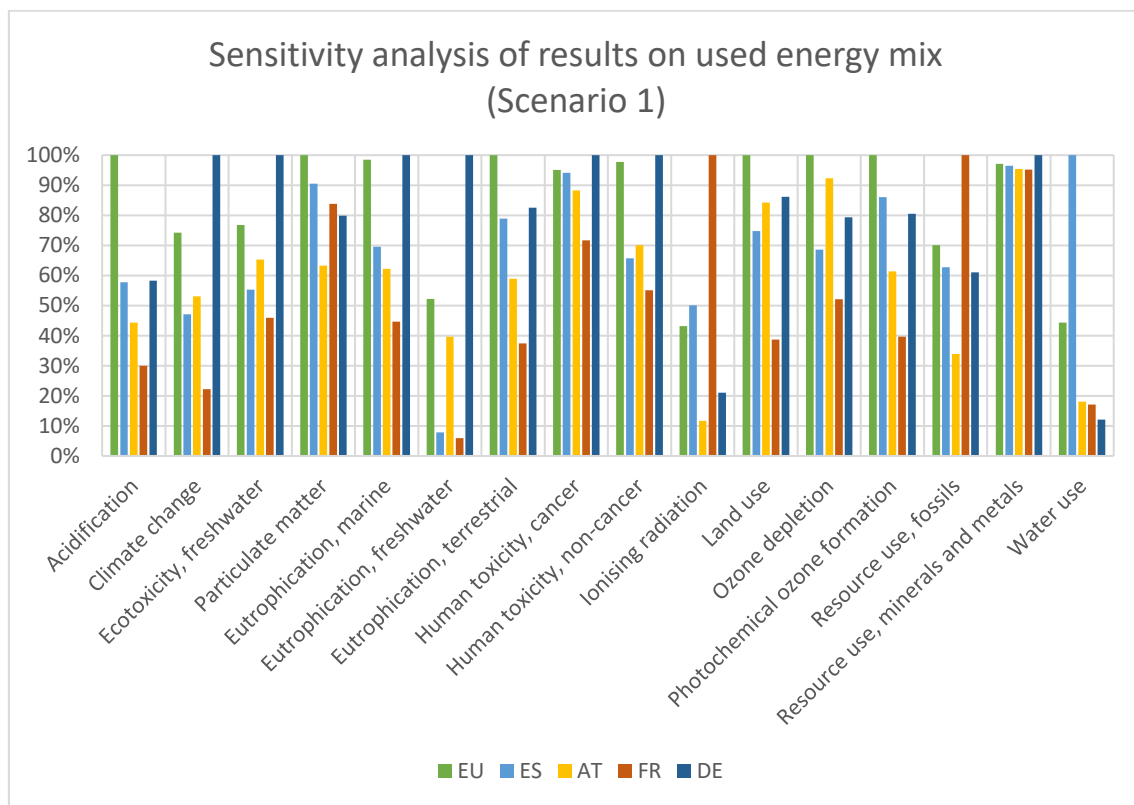


Figure 5.8: Sensitivity Analysis of results on used energy mix (Scenario 1)

5.2 CIRCULARITY ASSESSMENT

In the following, the circularity of the developed IMD is assessed along the four components and the three defined scenarios.

5.2.1 SCENARIO 1

The inverter faces several changes, as described in chapter 4.1.2. The results of the circularity assessment of the inverter prototype are presented in Table 5.5. The criteria that have been improved are highlighted with green. The light green fields show, how much the criteria has improved compared to the reference system.

The results show that especially the established modularity of the component improves its complexity, reprocess-ability, detachability and disassemblability. In total, the overall circularity of the developed inverter prototype is assessed for 60%, which means an absolute improvement of around 18% compared to the reference system.

The design of the Gearbox and Motor remain unchanged compared to the reference system as presented in Table 5.6 and Table 5.7. The Heatsink has changed, but still consists of a mono-material, which can be simply recycled, and is therefore not further analyzed.

The criteria 14, 15, 17 and 18 are related especially to the business model, which have been addressed during the workshops. Combined with the further improved design concepts, an increase in the overall circularity is expected in scenario 2 and 3.

Table 5.5: Circularity Assessment of Inverter Prototype (Scenario 1) (own depiction)

		True	Fairly true	Fairly false	False	Not relevant because	relevant for
Structure							
5	High aging resistance and long life time of parts		x				s, m
6	Low complexity of structure		x				m
7	Suitable modularity of structure		x				s, m
8	Multifunctionality of modules			x			s, m
9	Upgradeability of the power train	x					m
10	Upgradeability of the elements			x			m
11	Future-proof interfaces		x				m
12	Reprocess-ability of IMD's elements		x				m
13	Share of standard and common parts	x					s, m
Framework							
14	Availability of spare elements or parts		x				s, m
15	Spare elements or parts have an adequate price for the customer		x				s
16	Integration of reprocessed elements or parts is possible		x				s, m
17	Availability of repair instructions				x		s
18	Possibility of product return				x		m
Wear and Failure							
19	Detectability of wear on exposed parts	x					s, m
20	Availability of performance feedback	x					m
21	Easy replaceability of wear parts		x				m
22	Handling of common errors			x			s, m
23	Easy replaceability of defective parts		x				s
24	Robustness of the product under non-optimal conditions			x			m
25	Robustness for a "second life"		x				m
26	High endurance of relevant parts		x				m
Connections							
27	Detachability of connections		x				s, m, l
28	Re-assembleability of connections		x				s, m, l
29	Long-term usability of connections	x					s, m
30	Uniformity of connections		x				m
Dissassembly							
31	Short disassembly time			x			s, m, l
32	Low complexity of disassembly		x				m, l
33	Low probability of damage during disassembly		x				s, m
34	Automated disassembly is possible				x		m, l

Fulfillment 60,0%

Table 5.6: Circularity Assessment of Electric Motor (Scenario 1) (own depiction)

		Assessment				Not relevant because:	relevant for
		True	Fairly true	Fairly false	False		
Materials							l
1	Recycleability of materials	x					l
2	Low diversity of materials	x					l
3	Easy separability of materials		x				l
4	Identifiability of relevant materials	x					l
Structure							s, m
5	High aging resistance and long life time of parts	x					m
6	Low complexity of structure	x					s, m
7	Suitable modularity of structure		x				s, m
8	Multifunctionality of modules				x		m
9	Upgradeability of the power train				x		m
10	Upgradeability of the elements	x					m
11	Future-proof interfaces			x			m
12	Reprocess-ability of IMD's elements		x				m
13	Share of standard and common parts		x				s, m
Framework							s, m
16	Integration of reprocessed elements or parts is possible	x					s, m
18	Possibility of product return				x		m
Wear and Failure							s, m
19	Detectability of wear on exposed parts				x		m
20	Availability of performance feedback	x					m
21	Easy replaceability of wear parts		x				m
22	Handling of common errors	x					s, m
24	Robustness of the product under non-optimal conditions		x				m
25	Robustness for a "second life"	x					m
26	High endurance of relevant parts	x					m
Connections							s, m, l
27	Detachability of connections		x				s, m, l
28	Re-assembleability of connections		x				s, m
29	Long-term usability of connections		x				s, m
30	Uniformity of connections			x			m
Disassembly							s, m, l
31	Short disassembly time			x			m, l
32	Low complexity of disassembly			x			m, l
33	Low probability of damage during disassembly		x				s, m
34	Automated disassembly is possible		x				m, l

Fulfillment 65,6%

Table 5.7: Circularity Assessment of Gearbox (Scenario 1) (own depiction)

		Assessment				Not relevant because:	relevant for
		True	Fairly true	Fairly false	False		
Materials							l
1	Recycleability of materials	x					l
2	Low diversity of materials	x					l
3	Easy separability of materials	x					l
4	Identifiability of relevant materials	x					l
Structure							s, m
5	High aging resistance and long life time of parts			x			m
6	Low complexity of structure			x			s, m
7	Suitable modularity of structure		x				s, m
8	Multifunctionality of modules			x			m
9	Upgradeability of the power train	x					m
10	Upgradeability of the elements			x			m
11	Future-proof interfaces			x			m
12	Reprocess-ability of IMD's elements	x					m
13	Share of standard and common parts			x			s, m
Framework							s, m
16	Integration of reprocessed elements or parts is possible		x				s, m
18	Possibility of product return				x		m
Wear and Failure							s, m
19	Detectability of wear on exposed parts	x			x		m
20	Availability of performance feedback			x			m
21	Easy replaceability of wear parts			x			m
22	Handling of common errors	x					s, m
24	Robustness of the product under non-optimal conditions				x		m
25	Robustness for a "second life"			x			m
26	High endurance of relevant parts			x			m
Connections							s, m, l
27	Detachability of connections	x					s, m, l
28	Re-assembleability of connections	x					s, m
29	Long-term usability of connections	x					s, m
30	Uniformity of connections		x				m
Dissassembly							s, m, l
31	Short disassembly time			x			m, l
32	Low complexity of disassembly			x			m, l
33	Low probability of damage during disassembly		x				s, m
34	Automated disassembly is possible			x			m, l

Fulfillment 60,0%

5.2.2 SCENARIO 2

The assessment of scenario 2 reveals that the circular design concept of the inverter further improves the modularity of the component, as presented in Table 5.8. Additionally, due to the screwed connection, the upgradeability and the future-provability of interfaces are enhanced, as components can easily be replaced or adapted, without risk of damage through soldering. It will also be much easier to integrate reprocessed parts, detach connections and to disassemble the component. Due to the improved condition monitoring common errors will be easier to be managed. As it is planned that more components can be remanufactured, especially including parts from electric drives (e.g.; inverters) the returnability of the inverter is assumed to be slightly better.

In total, the overall circularity of the developed circular inverter concept is assessed by around 76%, which means an absolute improvement of around 34% compared to the reference system.

The modularity of the magnets in the electric motor leads to an improved separability of materials, and a reduced disassembly time and complexity, as presented in Table 5.9. The improved remanufacturing of IMDs also affects the returnability of the motor. The overall improvement of the circular concept for the motor is calculated of around 71%, which is a total improvement of more than 5% compared to the reference system. For the Gearbox no improvement has been made to the circularity performance in Scenario 2.

Table 5.8: Circularity Assessment of Inverter Prototype (Scenario 2) (own depiction)

		Assessment				
		True	Fairly true	Fairly false	False	Not relevant because relevant for
Structure						s, m
5	High aging resistance and long life time of parts		x			m
6	Low complexity of structure		x			s, m
7	Suitable modularity of structure	x				s, m
8	Multifunctionality of modules			x		m
9	Upgradeability of the power train	x				m
10	Upgradeability of the elements		x			m
11	Future-proof interfaces	x				m
12	Reprocess-ability of IMD's elements		x			m
13	Share of standard and common parts	x				s, m
Framework						s, m
14	Availability of spare elements or parts		x			s
15	Spare elements or parts have an adequate price for the customer		x			s
16	Integration of reprocessed elements or parts is possible		x			s, m
17	Availability of repair instructions				x	s
18	Possibility of product return			x		m
Wear and Failure						s, m
19	Detectability of wear on exposed parts	x				m
20	Availability of performance feedback	x				m
21	Easy replaceability of wear parts	x				m
22	Handling of common errors		x			s, m
23	Easy replaceability of defective parts		x			s
24	Robustness of the product under non-optimal conditions			x		m
25	Robustness for a "second life"		x			m
26	High endurance of relevant parts		x			m
Connections						s, m, l
27	Detachability of connections	x				s, m, l
28	Re-assembleability of connections	x				s, m
29	Long-term usability of connections	x				s, m
30	Uniformity of connections	x				m
Dissassembly						s, m, l
31	Short disassembly time		x			m, l
32	Low complexity of disassembly	x				m, l
33	Low probability of damage during disassembly	x				s, m
34	Automated disassembly is possible		x			m, l

Fulfillment 75,6%

Table 5.9: Circularity Assessment of Electric Motor (Scenario 1) (own depiction)

		Assessment				Not relevant because:	relevant for
		True	Fairly true	Fairly false	False		
Materials							l
1	Recycleability of materials	x					l
2	Low diversity of materials	x					l
3	Easy separability of materials	x					l
4	Identifiability of relevant materials	x					l
Structure							s, m
5	High aging resistance and long life time of parts	x					m
6	Low complexity of structure	x					s, m
7	Suitable modularity of structure	x					s, m
8	Multifunctionality of modules				x		m
9	Upgradeability of the power train				x		m
10	Upgradeability of the elements	x					m
11	Future-proof interfaces			x			m
12	Reprocess-ability of IMD's elements		x				m
13	Share of standard and common parts		x				s, m
Framework							s, m
16	Integration of reprocessed elements or parts is possible	x					s, m
18	Possibility of product return			x			m
Wear and Failure							s, m
19	Detectability of wear on exposed parts				x		m
20	Availability of performance feedback	x					m
21	Easy replaceability of wear parts		x				m
22	Handling of common errors	x					s, m
24	Robustness of the product under non-optimal conditions		x				m
25	Robustness for a "second life"	x					m
26	High endurance of relevant parts	x					m
Connections							s, m, l
27	Detachability of connections		x				s, m, l
28	Re-assembleability of connections		x				s, m
29	Long-term usability of connections		x				s, m
30	Uniformity of connections			x			m
Disassembly							s, m, l
31	Short disassembly time		x				m, l
32	Low complexity of disassembly		x				m, l
33	Low probability of damage during disassembly		x				s, m
34	Automated disassembly is possible		x				m, l

Fulfillment 71,1%

5.2.3 SCENARIO 3

For scenario three, an improvement for the Inverter, the E-Motor and the Gearbox can be seen, especially due to the improved business model, which helps to return products, as presented in Table 5.10, Table 5.11 and Table 5.12. Also, the integration of reprocessed parts is seen simpler, as the producer keeps ownership of all parts and can reintegrate repaired ones easier into the whole system. The producer is also interested in providing spare parts in order to make components to last as long as possible. Also, a better understanding and availability of repair instructions is expected.

The absolute circularity performance for the third scenario is 89%, 73% and 64% for the Inverter, E-Motor and Gearbox respectively. This means an improvement of 47%, 8%, and 4% for the Inverter, E-Motor and Gearbox respectively, compared to the reference system.

Table 5.10: Circularity Assessment of Inverter Prototype (Scenario 3) (own depiction)

		Assessment					
		True	Fairly true	Fairly false	False	Not relevant because	relevant for
Structure							s, m
5	High aging resistance and long life time of parts		x				m
6	Low complexity of structure	x					s, m
7	Suitable modularity of structure	x					s, m
8	Multifunctionality of modules		x				m
9	Upgradeability of the power train	x					m
10	Upgradeability of the elements		x				m
11	Future-proof interfaces	x					m
12	Reprocess-ability of IMD's elements		x				m
13	Share of standard and common parts	x					s, m
Framework							s, m
14	Availability of spare elements or parts	x					s
15	Spare elements or parts have an adequate price for the customer	x					s
16	Integration of reprocessed elements or parts is possible	x					s, m
17	Availability of repair instructions	x					s
18	Possibility of product return	x					m
Wear and Failure							s, m
19	Detectability of wear on exposed parts	x					m
20	Availability of performance feedback	x					m
21	Easy replaceability of wear parts	x					m
22	Handling of common errors	x					s, m
23	Easy replaceability of defective parts		x				s
24	Robustness of the product under non-optimal conditions			x			m
25	Robustness for a "second life"		x				m
26	High endurance of relevant parts		x				m
Connections							s, m, l
27	Detachability of connections	x					s, m, l
28	Re-assembleability of connections	x					s, m
29	Long-term usability of connections	x					s, m
30	Uniformity of connections	x					m
Disassembly							s, m, l
31	Short disassembly time	x					m, l
32	Low complexity of disassembly	x					m, l
33	Low probability of damage during disassembly	x					s, m
34	Automated disassembly is possible		x				m, l

Fulfillment 88,9%

Table 5.11: Circularity Assessment of Electric Motor (Scenario 3) (own depiction)

		Assessment				Not relevant because:	relevant for	
		True	Fairly true	Fairly false	False			
Materials								l
1	Recycleability of materials	x					l	
2	Low diversity of materials	x					l	
3	Easy separability of materials	x					l	
4	Identifiability of relevant materials	x					l	
Structure								s, m
5	High aging resistance and long life time of parts	x					m	
6	Low complexity of structure	x					s, m	
7	Suitable modularity of structure	x					s, m	
8	Multifunctionality of modules				x		m	
9	Upgradeability of the power train				x		m	
10	Upgradeability of the elements	x					m	
11	Future-proof interfaces			x			m	
12	Reprocess-ability of IMD's elements		x				m	
13	Share of standard and common parts		x				s, m	
Framework								s, m
16	Integration of reprocessed elements or parts is possible	x					s, m	
18	Possibility of product return	x					m	
Wear and Failure								s, m
19	Detectability of wear on exposed parts				x		m	
20	Availability of performance feedback	x					m	
21	Easy replaceability of wear parts		x				m	
22	Handling of common errors	x					s, m	
24	Robustness of the product under non-optimal conditions		x				m	
25	Robustness for a "second life"	x					m	
26	High endurance of relevant parts	x					m	
Connections								s, m, l
27	Detachability of connections		x				s, m, l	
28	Re-assembleability of connections		x				s, m	
29	Long-term usability of connections		x				s, m	
30	Uniformity of connections			x			m	
Dissassembly								s, m, l
31	Short disassembly time		x				m, l	
32	Low complexity of disassembly		x				m, l	
33	Low probability of damage during disassembly		x				s, m	
34	Automated disassembly is possible		x				m, l	

Fulfillment 73,3%

Table 5.12: Circularity Assessment of Gearbox (Scenario 3) (own depiction)

		Assessment				Not relevant because:	relevant for
		True	Fairly true	Fairly false	False		
Materials							l
1	Recycleability of materials	x					l
2	Low diversity of materials	x					l
3	Easy separability of materials	x					l
4	Identifiability of relevant materials	x					l
Structure							s, m
5	High aging resistance and long life time of parts			x			m
6	Low complexity of structure			x			s, m
7	Suitable modularity of structure		x				s, m
8	Multifunctionality of modules			x			m
9	Upgradeability of the power train	x					m
10	Upgradeability of the elements			x			m
11	Future-proof interfaces			x			m
12	Reprocess-ability of IMD's elements	x					m
13	Share of standard and common parts			x			s, m
Framework							s, m
16	Integration of reprocessed elements or parts is possible	x					s, m
18	Possibility of product return	x					m
Wear and Failure							s, m
19	Detectability of wear on exposed parts	x			x		m
20	Availability of performance feedback			x			m
21	Easy replaceability of wear parts			x			m
22	Handling of common errors	x					s, m
24	Robustness of the product under non-optimal conditions				x		m
25	Robustness for a "second life"			x			m
26	High endurance of relevant parts			x			m
Connections							s, m, l
27	Detachability of connections	x					s, m, l
28	Re-assembleability of connections	x					s, m
29	Long-term usability of connections	x					s, m
30	Uniformity of connections		x				m
Dissassembly							s, m, l
31	Short disassembly time			x			m, l
32	Low complexity of disassembly			x			m, l
33	Low probability of damage during disassembly		x				s, m
34	Automated disassembly is possible			x			m, l

Fulfillment 64,4%

5.3 CRITICALITY ASSESSMENT

The criticality assessment was performed, based on the updated methodology, presented in chapter 2.3. In Figure 5.9 the supply risk weighted ADP results for the four IMD components are presented. As all materials from the whole supply chains of the components were taken into account, this does not necessarily mean, that these materials also occur in the final component. To get a more precise analysis for the IMD's components a more detailed bill of materials would be needed, that excludes all materials that occur in the supply chain.

As can be seen, the results are mainly driven by Palladium and Platinum, mainly used for the production of the inverter and electric motor, but also for the gearbox and heatsink. In order to see the next most important materials, palladium and platinum are filtered out in Figure 5.10. Here, one can see that Manganese should be used with care, especially for the gearbox, but also for the electric motor. Indium is very present in the inverter. Lanthanum, Boron and Neodymium have a more relevant contribution in the e-motor's criticality.

Manganese is used for steel in the gearbox. Platinum and palladium are used for steel in the gearbox, for capacitors and in small amounts for transistors in the inverter, and for copper winding wires in the electric motor. Indium is used for brass in the housing of the inverter, and boron is used for power electronics such as transistors and MOSFETs. Neodymium, boron, lanthanum, and cerium are used for the magnets in the electric motor.

According to the findings, the magnets of the e-motor were seen as one of the most important parts to be considered. In Figure 5.11 to Figure 5.14, the reductions that can be achieved through the three end-of-life scenarios are presented for all four components. The reductions do not occur in the current product, but in case the components are remanufactured or recycled, the provided second hand components and materials can reduce the demand for virgin critical raw materials.

For the inverter and the e-motor and gearbox scenario 1 barely has an influence. For the heatsink, this scenario already reduces the demand for virgin materials by two thirds, as aluminium has a good recyclability. The improved remanufacturing rate in scenario 2 leads to an average reduction of around 10% for the inverter, the e-motor and the gearbox, and for the heatsink around 70% can be saved. Scenario 3 leads to an improvement of at least 60% for each component. For the e-motor, 65% can be achieved, and for the heatsink even 87%.

A closer look at the improvement for neodymium reveals that for scenario 1 around 3%, for scenario 2, around 20%, and for scenario 3, around 90% of virgin material can be avoided, presented in Figure 5.15.

This result underline, that only reuse related processes (e.g., remanufacturing) can reduce the demand for most of the critical raw materials, as recycling process

barely exist. The influence of improved repairability has not been taken into account, but it can be assumed that a lifetime extension through repair processes will lead to a resource reduction, as presented in Figure 5.6.

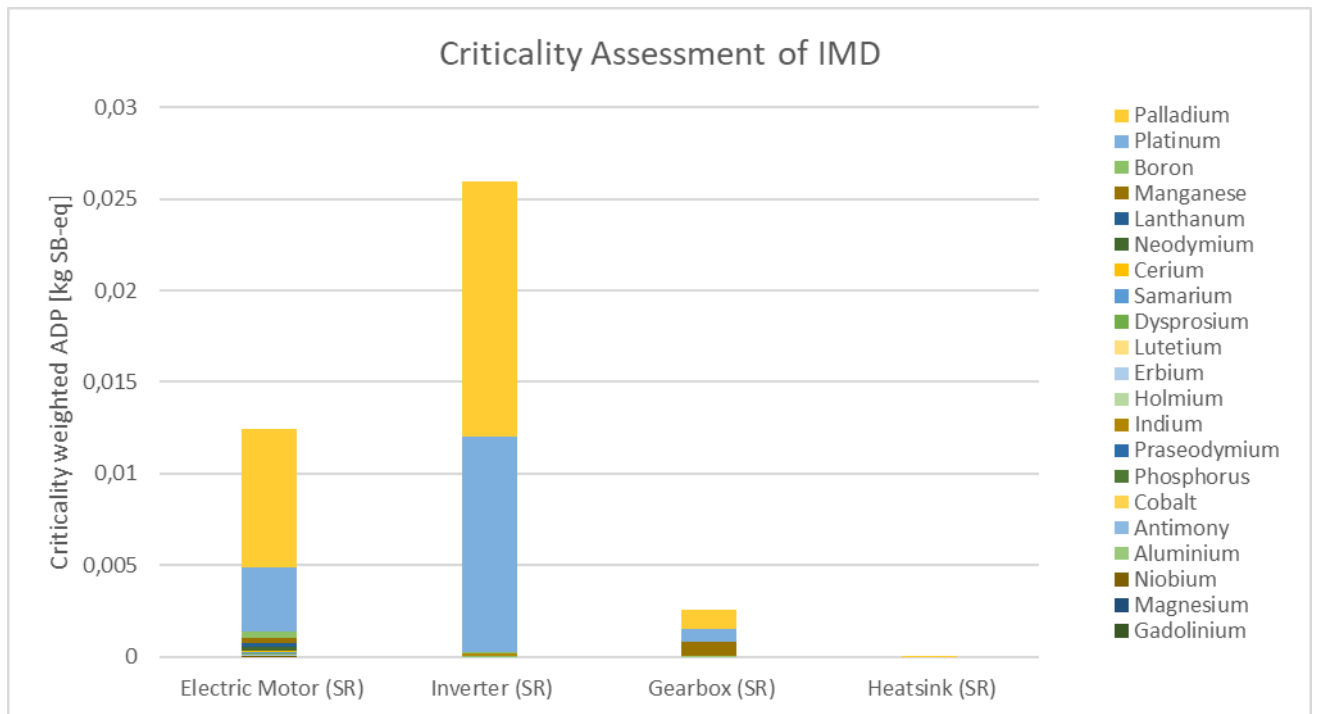


Figure 5.9: Criticality assessment of IMD (own depiction)

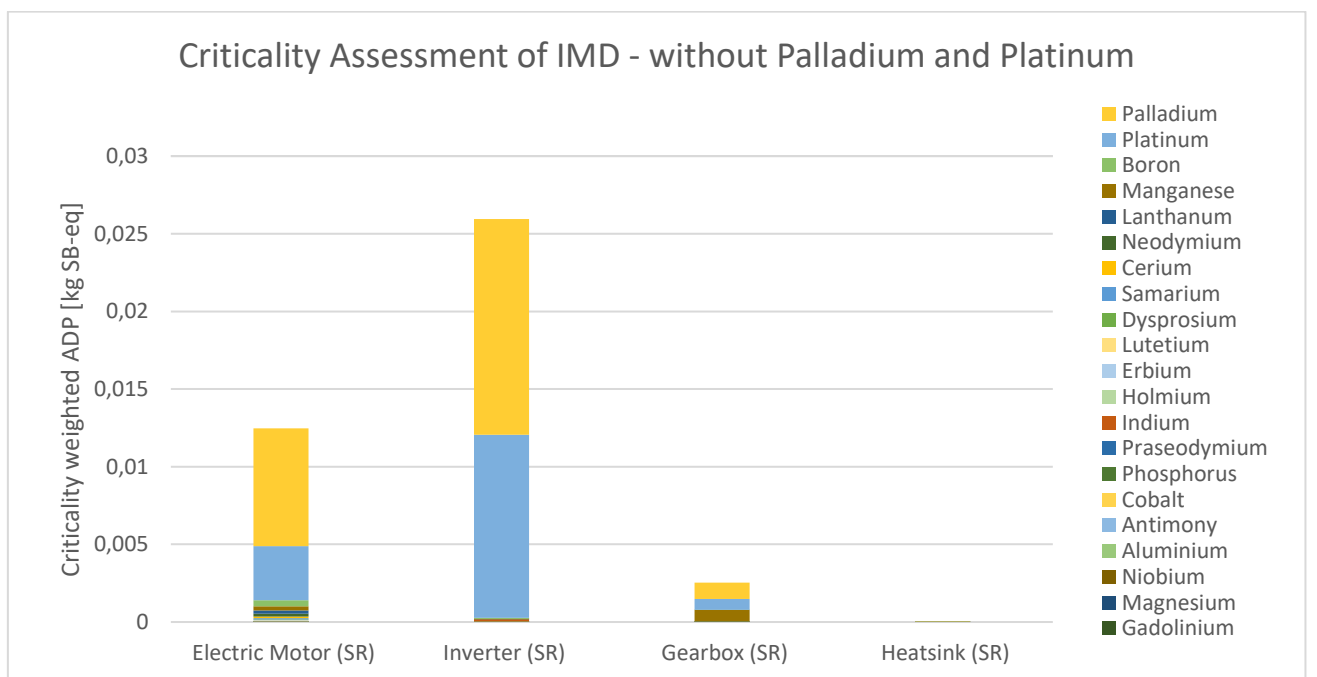


Figure 5.10: Criticality assessment of IMD - without Palladium and Platinum (own depiction)

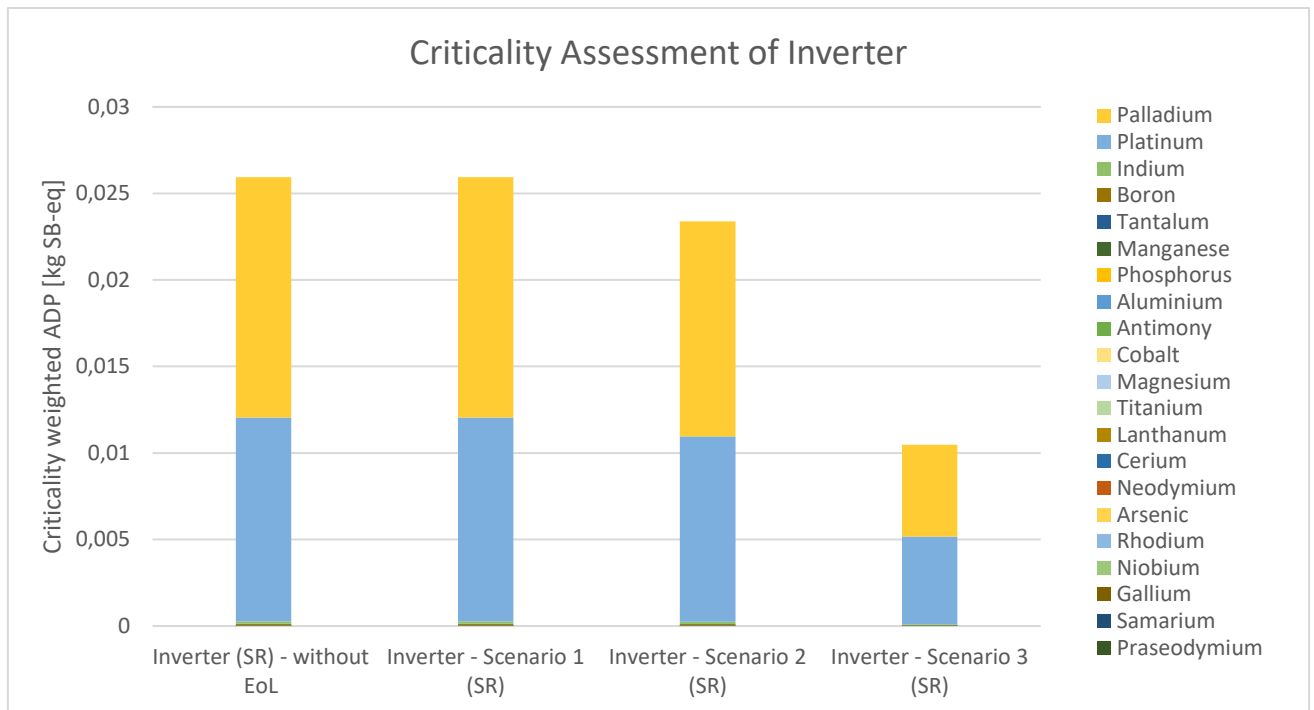


Figure 5.11: Criticality Assessment of Inverter - with EoL improvements (own depiction)

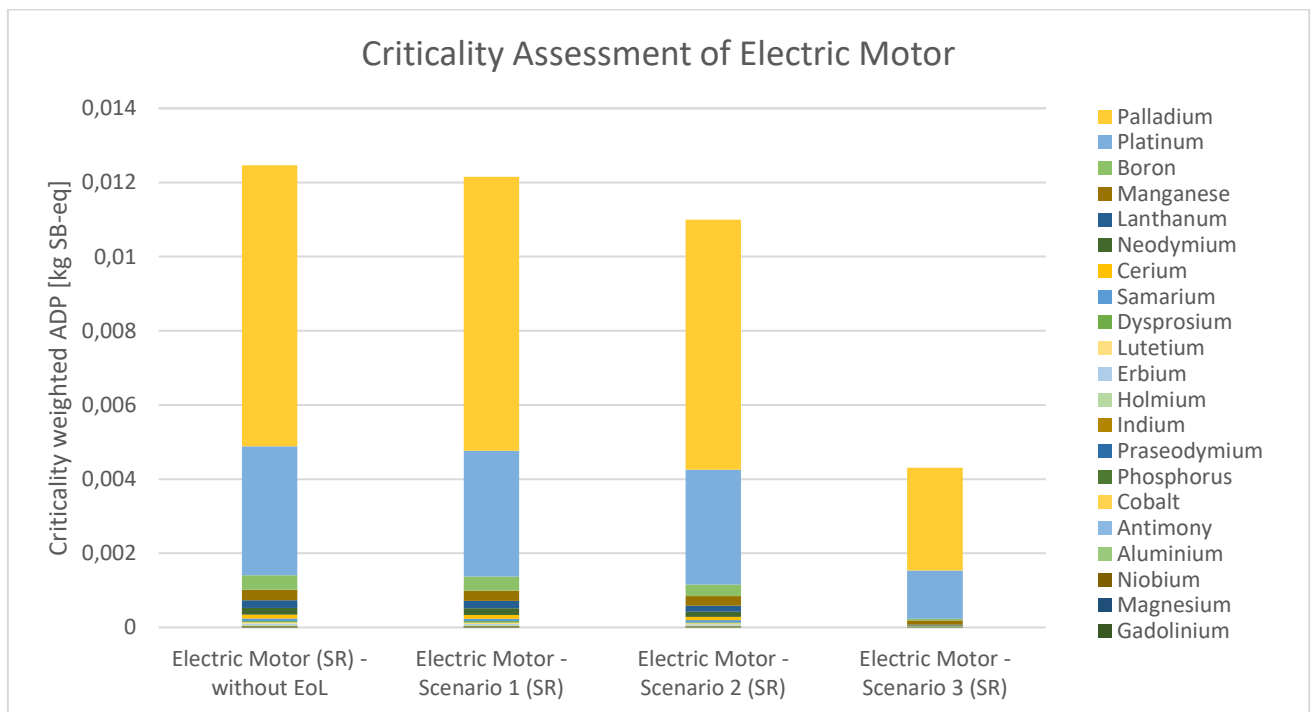


Figure 5.12: Criticality Assessment of Electric Motor - with EoL improvements (own depiction)

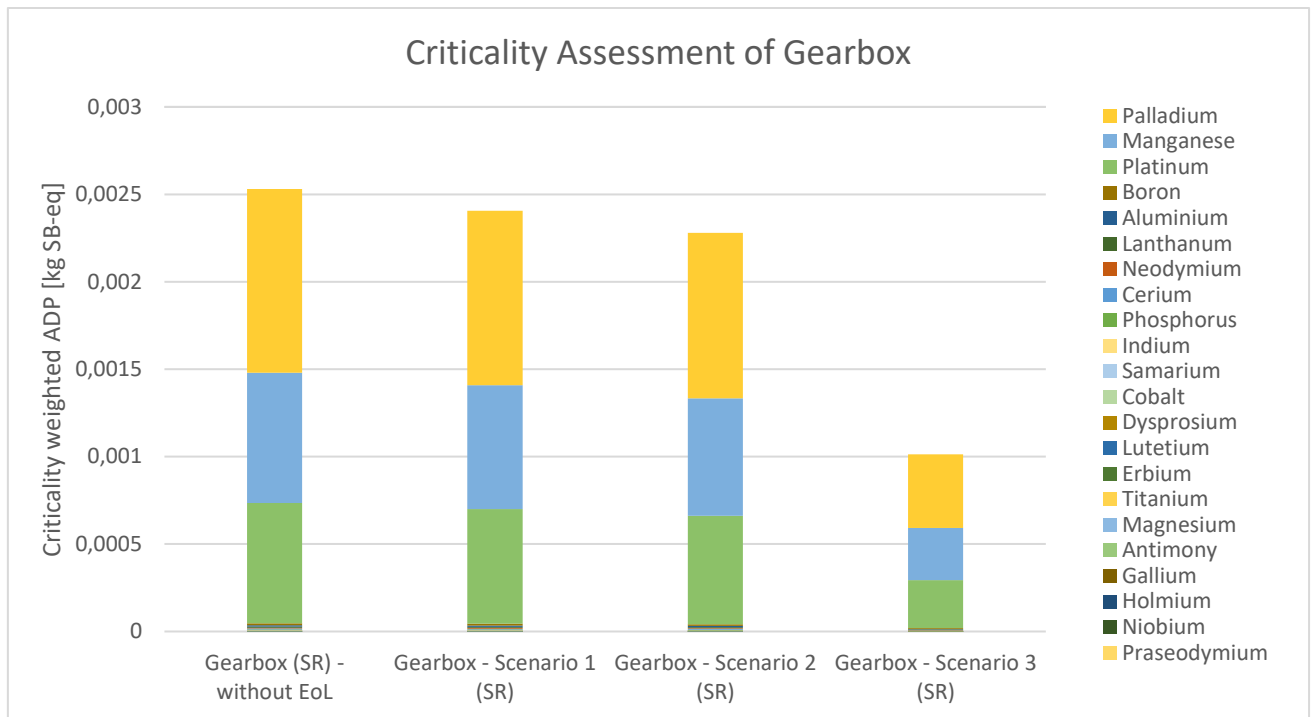


Figure 5.13: Criticality Assessment of Gearbox - with EoL improvements (own depiction)

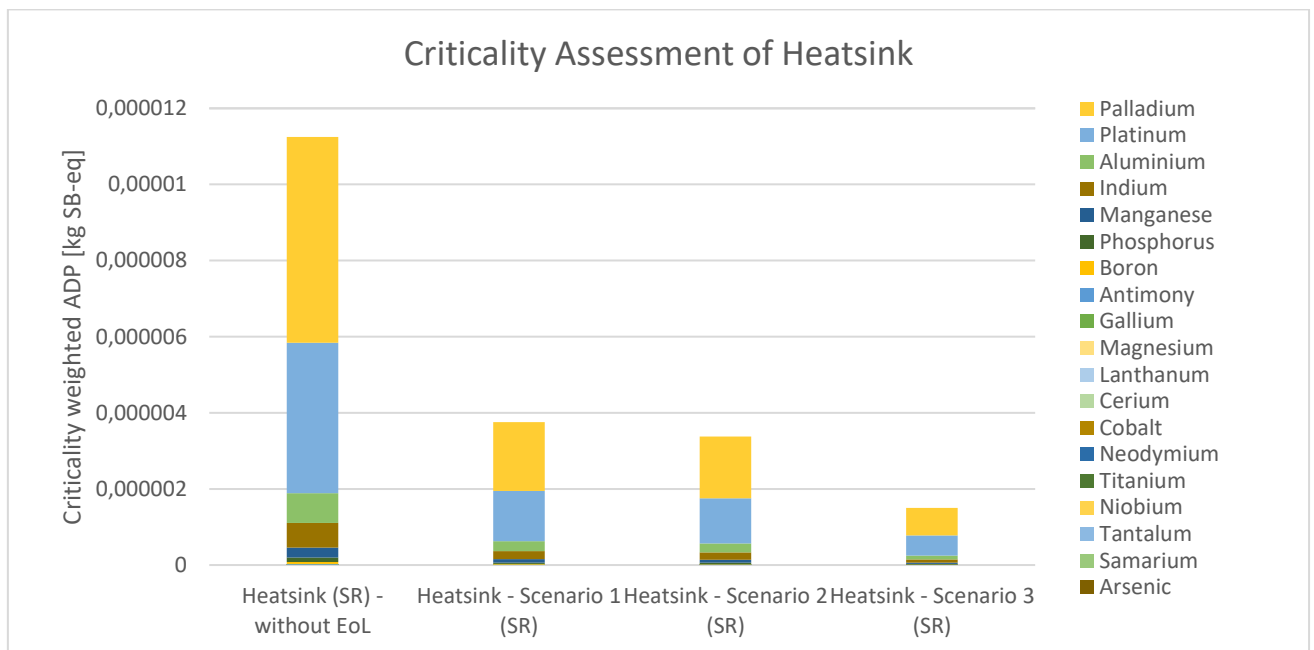


Figure 5.14: Criticality Assessment of Heatsink - with EoL improvements (own depiction)

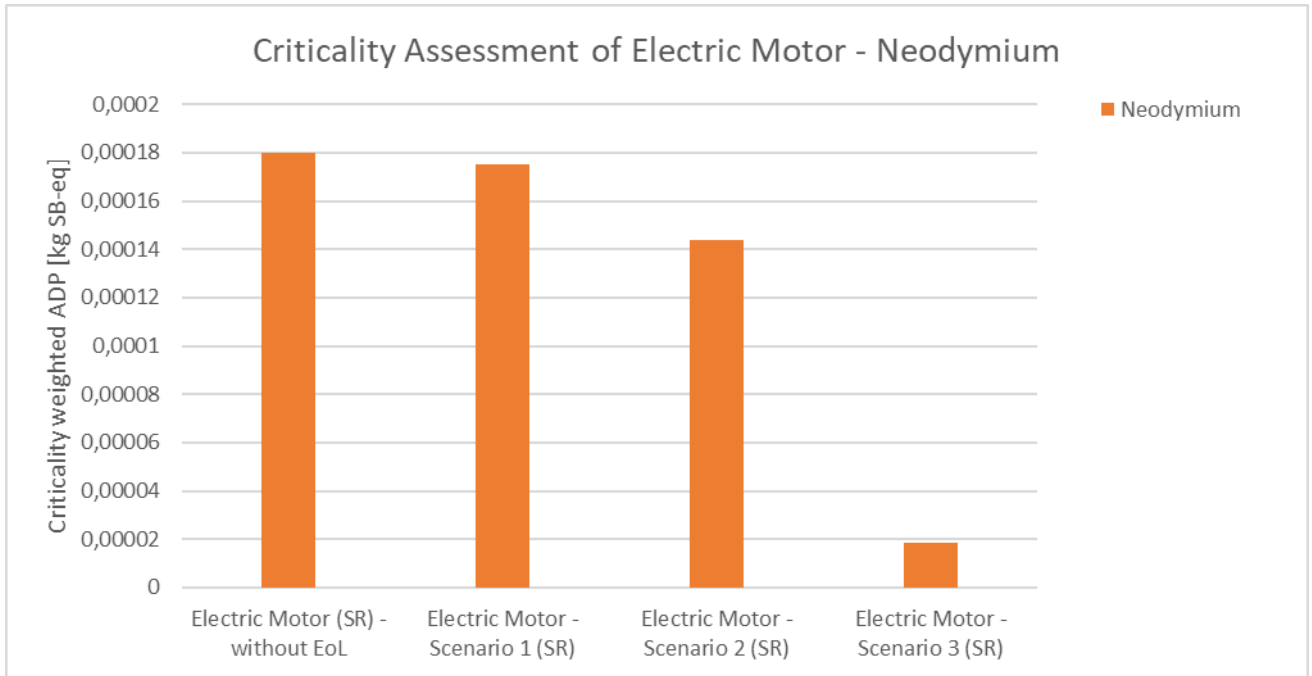


Figure 5.15: Criticality Assessment of E-Motor: Focus on Neodymium(own depiction)

6 FACT SHEET

After researching current and upcoming European regulations, it became clear that the planned factsheet should be developed as a Digital Vehicle Passport. The development of the Digital Vehicle Passport is mainly driven by the Ecodesign for Sustainable Products Regulation [19], which introduces the Digital Product Passport (DPP). According to this regulation, products must comply with defined information requirements that will be specified in delegated acts. These requirements ensure that relevant sustainability information is available to all actors along the value chain.

The DPP must contain basic passport information and information on substances of concern used in the product. It must also include information on the performance of the product in relation to sustainability parameters such as repairability, durability, carbon footprint, or environmental footprint. Furthermore, the passport must provide clear guidance for customers and other users on how to install, use, maintain, and repair the product in a way that minimises environmental impact and ensures optimal durability. Where relevant, information on the installation of third-party operating systems must be included. In addition, the passport must explain how the product can be collected for refurbishment or remanufacturing and how it should be returned or handled at the end of its life.

The DPP must also provide information for treatment and recycling facilities. This includes guidance on disassembly, reuse, refurbishment, recycling, and disposal at end-of-life. Additional information requirements may be introduced in the future through delegated acts.

Another key regulatory driver is the proposed Regulation on circularity requirements for vehicle design and the management of end-of-life vehicles [20]. This regulation amends the existing EU vehicle regulations and replaces earlier directives related to vehicle type approval and end-of-life vehicles. It introduces new obligations for vehicle manufacturers with the goal of improving circularity and resource efficiency.

Under the proposed regulation, manufacturers are required to develop a recyclability strategy and to declare the proportion of recycled materials used in their vehicles. They must also provide detailed information to service providers and disposal companies on the removal and replacement of vehicle parts, components, and materials. In addition, components and materials used in vehicles must be clearly labelled. A further requirement is the creation of a circular vehicle passport, which supports transparency and traceability over the vehicle life cycle.

During the project, a draft for the digital vehicle passport was developed and made available online as part of the digital twin, developed in T4.5. It is presented in Figure 6.1. The findings of this deliverable can be used to provide some of the included data, e.g., Critical raw materials, GHG emissions.

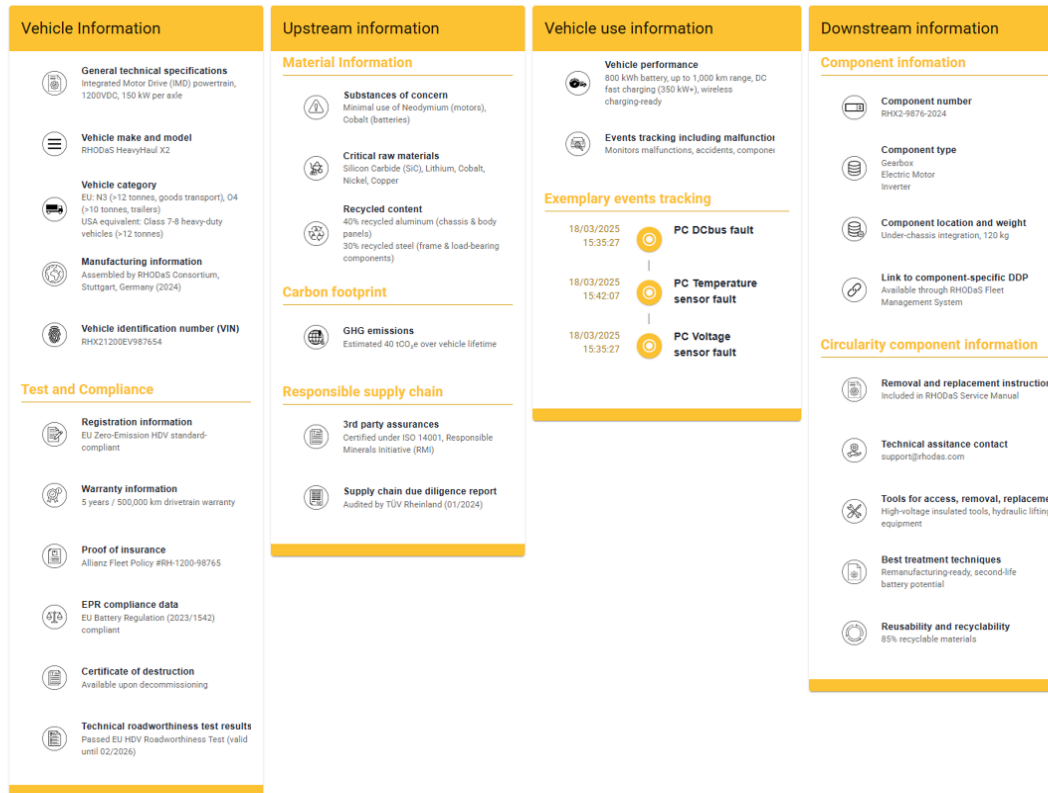


Figure 6.1: Draft of the digital vehicle passport [21, adapted from 22]

The regulation also defines minimum recycled content requirements for vehicles that are type-approved seventy-two months after the regulation enters into force. For plastics, at least twenty-five percent of the plastic used in a vehicle must come from consumer plastic waste, and a defined share of this recycled plastic must originate from end-of-life vehicles. Minimum recycled content requirements will also apply to materials such as steel, aluminium, magnesium and their alloys, as well as several critical raw materials including neodymium, dysprosium, praseodymium, terbium, samarium, and boron. The exact minimum values and feasibility assessments for these materials have not yet been fully defined and will be specified at a later stage.

In addition to recycled content requirements, the regulation sets targets for reusability, recyclability, and recoverability. Vehicles that are type-approved seventy-two months after the regulation enters into force must be at least eighty-five percent reusable or recyclable by mass and at least ninety-five percent reusable or recoverable by mass. To meet these targets, manufacturers must collect relevant data from their supply chains and maintain detailed documentation on the material composition of vehicles. They are also required to calculate reusability, recyclability, and recoverability rates using a defined or equivalent methodology. Parts and components made of polymers and elastomers must be labelled, and specific parts listed in Annex VII, Part E must not be reused.

7 CONCLUSION

This report evaluates an Integrated Motor Drive (IMD) developed for electric trucks. The IMD consists of four main components: an inverter, an electric motor, a gearbox, and a heatsink for thermal management. The main objective of the study is to assess how circular design strategies, such as improved repairability, reuse, remanufacturing, and new business models, can reduce environmental impacts and the use of critical raw materials over the full life cycle of the product.

The analysis is based on a life cycle assessment carried out according to ISO 14040/44 standards. The system boundary follows a cradle-to-grave approach, covering raw material extraction, manufacturing, transport, use, and end-of-life treatment. The functional unit is defined as 3 million kilometres of truck operation. Since a single IMD normally does not last that long, multiple IMDs are considered. In the baseline scenario, three IMDs are needed, each with a lifetime of 1 million kilometres. For the developed prototype, improved repairability is assumed, extending the lifetime to 1.5 million kilometres and reducing the number of required IMDs to two. Electricity consumption during use is calculated using the EU electricity mix, and only powertrain energy losses are included.

Measurements show that the developed 3L SiC based IMD prototype has a slightly higher energy efficiency than the baseline. For efficiency measurements a 2L SiC based inverter was used as baseline, assuming that a 2L IGBT based inverter will be even less efficient than a 2L SiC based inverter.

The prototype reaches an efficiency of 89.23%, compared to 88.87% for the baseline, based on an urban driving cycle. Although the improvement of about 0.4% seems small, it becomes relevant over long driving distances and leads to measurable reductions in energy use and related emissions. Higher efficiency improvements are expected under other driving conditions, but no additional measurement data was available at the time of the study.

A central finding of the report is the importance of repairability and lifetime extension. The modular design of the inverter and improved accessibility of components make repairs easier and allow the IMD to remain in use for a longer time. Extending the lifetime by 50% significantly reduces the need for new materials and manufacturing processes. The life cycle assessment shows that improved repairability alone can reduce climate change impacts by around 3% and reduce the use of mineral and metal resources by up to 20%, depending on the end-of-life scenario.

Three different end-of-life scenarios are analysed. The first scenario represents current practice, where most IMDs are disposed of and only a small share of components is reused. This scenario shows only limited improvements in circularity and resource efficiency. The second scenario assumes improved dismantling and remanufacturing, including the reuse of motors, gearboxes, inverter modules, magnets, and power electronics. This leads to clear improvements in circularity and a reduction in the demand for virgin materials. The third scenario is based on an advanced circular business model with leasing. In this case, the IMD remains the property of the original manufacturer or supplier, which enables

high return rates, better control of components, and extensive reuse and remanufacturing. This scenario delivers the best overall results.

From an environmental perspective, the life cycle impact assessment shows that scenario three performs best. In the end-of-life phase, reductions of up to 50% are achieved in the impact category “resource use of minerals and metals,” while human toxicity impacts are reduced by around 29%. The reduction in climate change impacts at end of life is smaller, at about 4%, because greenhouse gas emissions are mainly dominated by electricity consumption during the use phase. This highlights that circular strategies are especially effective for conserving resources rather than reducing use-phase CO₂ emissions.

The circularity assessment shows strong differences between the components. The inverter benefits most from modular design and improved connections, such as screwed interfaces instead of soldered joints. Its circularity performance increases from about 42% in the reference system to nearly 90% in the most advanced scenario. The electric motor has good recycling potential, but disassembly is difficult due to safety requirements. Significant improvements are achieved through magnet reuse and remanufacturing, especially in the leasing scenario. The gearbox already shows relatively good repair and remanufacturing performance in the reference design, as such practices are common in commercial vehicles. Therefore, most improvements for the gearbox come from changes in the business model rather than from design changes. The heatsink, which is mainly made of aluminium, already has very high circularity because it is easy to disassemble and recycle. Its environmental impacts are small compared to the other components.

The criticality assessment highlights that a few materials dominate supply risks. Palladium and platinum strongly influence the results, followed by materials such as neodymium, boron, lanthanum, and cerium used in electric motor magnets, indium used in the inverter, and manganese used in steel components. A key finding is that recycling alone is not sufficient to reduce the demand for many critical raw materials, especially rare earth elements. Reuse and remanufacturing are much more effective. For neodymium, for example, only about 3% of virgin material can be avoided in the baseline scenario (Scenario 1), while around 90% can be avoided in the advanced leasing scenario (Scenario 3).

Business models play a crucial role in enabling circularity. Workshop discussions identified “product as new” concepts and leasing as promising approaches, especially for large, high-value components such as powertrains in trucks and buses. Leasing allows manufacturers to retain ownership of components, which improves product return, simplifies remanufacturing, and reduces competition for used parts. However, such models require strong coordination across the value chain and active involvement of vehicle manufacturers. As a result, leasing concepts should first be tested in pilot projects before being implemented on a larger scale.

The study concludes that combining improved efficiency, better repairability, circular design, and suitable business models can significantly reduce environmental impacts and the use of critical raw materials for electric truck powertrains.

While efficiency gains mainly affect energy use during operation, circular strategies are particularly important for conserving resources and reducing supply risks. Future regulations, such as the Digital Product Passport and new EU rules on vehicle circularity, are expected to further support the implementation of these approaches. A draft for a Digital Product Passport has been presented.

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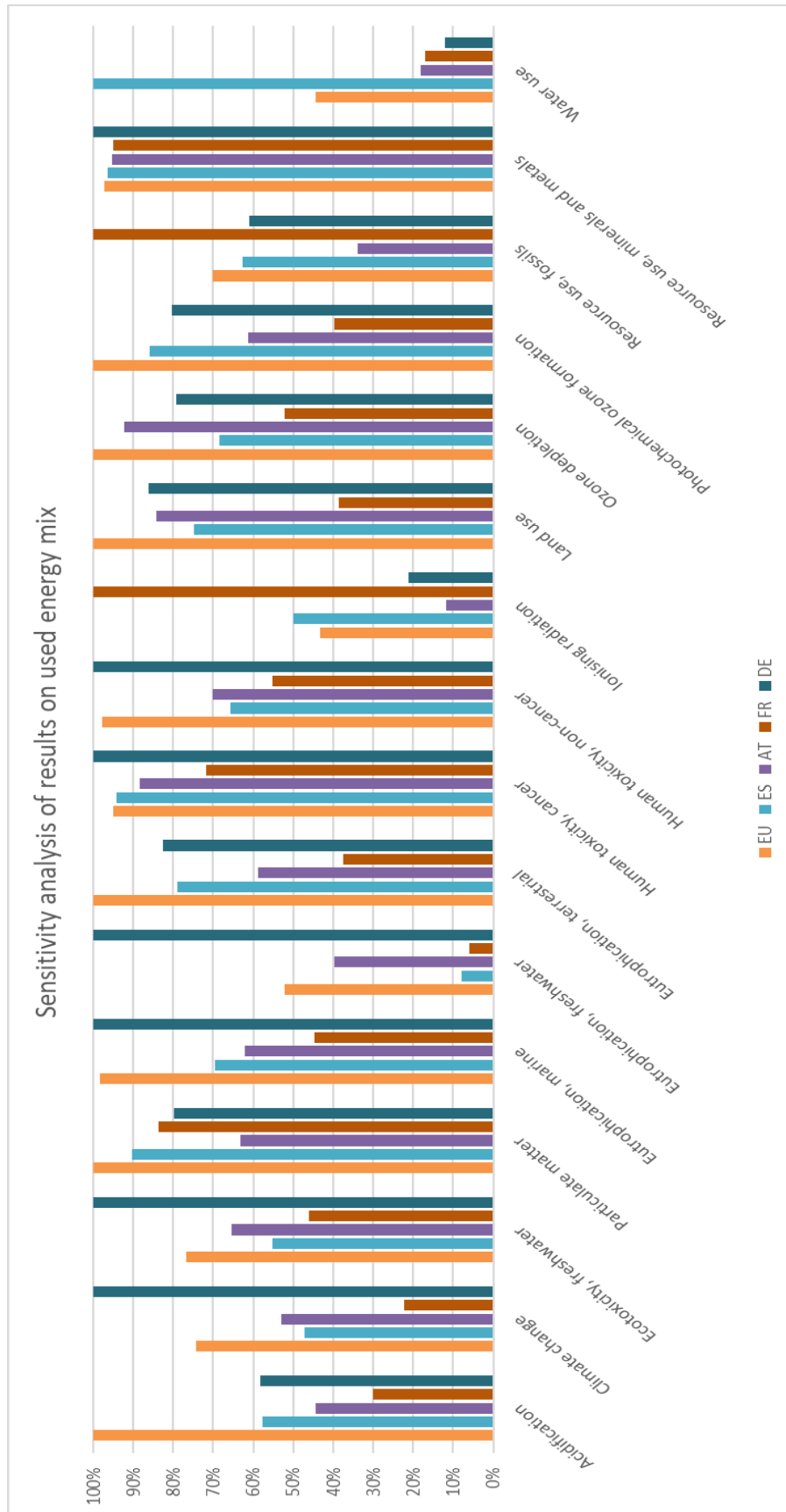


Figure A. II: Sensitivity analysis of results on used energy mix (Scenario 1)