Project information	
Full title:	**Remanufacturing, repurposing and recycling energy goods through advanced Mechatronic and Digital technologies**
Acronym:	R3-Mydas
Grant Agreement number:	101138738 (HORIZON-CL4-2023-TWIN-TRANSITION-01-04 – Innovation Action)

Deliverable

D5.4 – R3-Mydas life cycles assessment, including environmental, social and financial dimensions report

Dissemination level:	PU - Public, fully open
Type of deliverable:	R - Document, report
Contractual date of delivery:	31 March 2025
Deliverable leader:	AIMEN
Status - version, date:	Final – v1.0, 2025-05-12
Keywords:	Sustainability, Environmental, LCA, LCC, Circularity

Funded by the European Union

Executive Summary

Task 5.2 "Environmental Impact Assessment and Socio-economic Assessment" aims at developing Life Cycle Assessment (LCA) studies focusing on the environmental and economic dimensions and any impact on workers. In a first step, the aim and scope of the assessment and the definition of the functional basis were carried out during the first months of the project in close collaboration with the WP2, WP3, WP4 partners responsible for the three R3-Mydas demo cases. In a second step, inventory data for the development of LCA and LCC (Life Cycle Cost) were compiled to quantify all upstream and downstream energy and material flows, costs and environmental impact of the three remanufacturing processes.

As a first approach, AS-IS scenarios, which only considered linear value chains for the components in the demo cases, were compared with current AS-IS repair/reuse scenarios, which represent a first approach to circular economy value chains. At the end of the R3-Mydas project, TO-BE repair/reuse scenarios that include improvements developed in the project will be compared. In addition, key impacts of a safety analysis of a new battery remanufacturing process (Demo Case 2) were presented.

This approach provides first results on the potential of remanufacturing processes in circular economy systems. Environmental and economic impacts are identified, as well as hotspots and bottlenecks that will be a key challenge for new repair/reuse value chains. As results of this first analysis of the three demo cases considered in the R3-Mydas project, in terms in sustainability, new circular scenarios in the value chains considered are more sustainable than current linear ones. Nevertheless, some technical gaps to increase the size of the repair/remanufacturing market are needed.

This deliverable is the public version of D5.2. Here, all steps and scenarios are covered but certain sensitive information has been omitted.

Deliverable leader:	AIMEN
Contributors:	AIMEN, SPIN, LUT and ITML
Reviewers:	CSEM, IKERLAN
Approved by:	Athanasios Poulakidas, Irene Diamantopoulou (NCI)

Document History

Version	Date	Contributor(s)	Description
0.1	2025-03-31	Rocío Pena/Ana Fuentes	First draft
0.2	2025-04-24	Olegs Nikisins	Review
0.3	2025-05-06	Mikel Escalero	Review
0.4	2025-05-08	Rocío Pena/Ana Fuentes	Internal release addressing review comments
1.0	2025-05-12	Athanasios Poulakidas, Irene Diamantopoulou	Version to be submitted after final QA

Table of Contents

Table of Figures

List of Tables

Definitions, Acronyms and Abbreviations

Acronym/ Abbreviation	**Title**
LCA	Life Cycle Assessment
s-LCA	Social Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
EoL	End of Life
SbD	Sustainable by Design
SSbD	Safe and Sustainable by Design
WP	Work Package
AM	Additive Manufacturing
LIB	Lithium-Ion Battery
NMC battery	Lithium-nickel-manganese-cobalt battery
EV	Electric vehicle
SOH	State of Health
VC	Value chain
EF	Environmental footprint

1 Introduction

1.1 R3-Mydas Vision

Despite the multiple advantages of products remanufacturing, being widely recognised as an effective means for transitioning to a more circular economy, there is still need for improved research and experimental observations, to improve traceability and reliability of the final products from end-users' perspectives, as well as enhanced impacts monitoring. The primary R3-Mydas objective is to develop a multi-actor framework, integrating innovative digital technologies (ML for process and quality control, marketplace, graph models for defects detection, digital twins), advanced mechatronics (AM, laser-cladding, automated disassembly/reassembly) and newly developed approaches from SSH (extended TAM/UTAUT models, ethics and legal framework), for functionally, environmentally and economically sustainable circular value chains for remanufacturing of energy goods at the factory level (Oil&Gas crankshafts – demo 1, E-vehicles batteries – demo 2, Wind turbines gearboxes – demo 3).

R3-Mydas will deliver unprecedented impacts throughout the targeted value chains, as follows: up to 60% time reduction in programming for remanufacturing; up to 20% increased product quality; up to 30% rework reduction [Demo 1]; up to 30% improved detection of tiny deviations from normal behaviour; up to 50% faster anomaly localization; up to 30% increase the number of different modality data streams handled; up to 20% faster fusion process [Demo 2]; up to 99% reusage rate; -90% prevention rate; -75% lead time; up to 85% raw material savings potential [Demo 3]. R3-Mydas will deliver a marketplace associating to each remanufactured product or services/component for remanufacturing a Digital Passport-like set of information, ensuring full traceability. Finally, a dedicated training programme will be designed and delivered by EITM, targeting the P R3-Mydas project remanufacturing value chains (100+ training hours and 100+ diverse stakeholders engaged during the Project).

Table 1. The R3-Mydas consortium.

Number[1]	Name	Country	Short name
1(CO)	NETCOMPANY-INTRASOFT SA	Luxemburg	NCI
2	EUROPEAN FEDERATION FOR WELDING JOINING AND CUTTING	Belgium	EWF
3	EIT MANUFACTURING SOUTH SRL	Italy	EITM
4	FLENDER FINLAND OY	Finland	FLE-FI
4.1(AE)	FLENDER GMBH	Germany	FLE

---

[1] CO: Coordinator. AE: Affiliated Entity. AP: Associated Partner.

Number[1]	Name	Country	Short name
5	AVL LIST GMBH	Austria	AVL
6	TALLERES MECANICOS COMAS SLU	Spain	TMCOMAS
7	SPIN ROBOTICS IVS	Denmark	SPIN
8	ASOCIATION DE INVESTIGACION METALURGICA DEL NOROESTE	Spain	AIMEN
9	LAPPEENRANNAN-LAHDEN TEKNILLINEN YLIOPISTO LUT	Finland	LUT
10	INFORMATION TECHNOLOGY FOR MARKET LEADERSHIP	Greece	ITML
11	DEEP BLUE SRL	Italy	DBL
12	CHAROKOPEIO PANEPISTIMIO	Greece	HUA
13	IKERLAN S. COOP	Spain	Ikerlan
14	ZIKNES TECHNOLOGY SL	Spain	Ziknes
15 (AP)	CSEM CENTRE SUISSE D'ELECTRONIQUE ET DE MICROTECHNIQUE SA - RECHERCHE ET DEVELOPPEMENT	Switzerland	CSEM

1.2 Scope of the deliverable

The aim of this deliverable is to report the preliminary results obtained from the LCA studies that were developed for the three selected case-studies of the R3-Mydas project. These LCA studies are focused on environmental and economic dimensions, including details concerning safety issues related to battery remanufacturing activities, environmental impact assessments for the demo cases.

After defining the functional basis in each remanufacturing process, an inventory data was compiled to quantifying the upstream and downstream energy and material flows, costs and social perceptions of the 3 case-studies. Then, the preliminary LCA and LCC analyses which are described in this document were carried out and their results were studied. This way, it was possible to identify the most relevant aspects in the 3 selected case-studies.

This deliverable is the public version of D5.2. Here, all steps and scenarios are covered but certain sensitive information has been omitted.

1.3 Relation to other Tasks and Work Packages

WP5 focuses on the environmental and socio-economic impact of the 3 remanufacturing processes developed in the project. Therefore, its activities are interconnected with the demo cases work packages:

- WP2: Demo Case 1 – Oil & Gas components.

- WP3: Demo Case 2 – E-vehicles batteries.
- WP4: Demo Case 3 – Wind turbine gearboxes.

In a first step, definition of the functional basis was carried out in close collaboration with WP2, WP3, WP4 partners. Besides, each Work Package partners provided environmental and socio-economic data of its case-study that enabled the LCA studies to be developed. Specifically, the data was collected in 3 LCIs, one for each Work Package, that quantified the upstream and downstream energy and material flows, costs and social perceptions of the remanufacturing process studied.

The results of the preliminary LCA studies, which are reported in this deliverable, will affect the development of WP2, WP3 and WP4 since they show the most relevant aspects for each case study and this project follows the SbD and SSbD (for the E-vehicles batteries case) methodologies.

In the future, new data from WP2, WP3 and WP4 will be used to perform more detailed LCA studies, by means of the software SIMAPRO and databases.

1.4 Document Structure

This document es comprised of the following chapters:

Chapter 1: presents an introduction to the project and the document.

Chapter 2: explains the methodology used, including Safety by Design and Sustainable by Design.

Chapter 3: describes the circular value chains proposed for each case-study, comparing AS IS and TO BE scenarios.

Chapter 4: reports the analysis and results for Demo-case 1 – Oil & Gas components.

Chapter 5: reports the analysis and results for Demo-case 2 – E-vehicles batteries.

Chapter 6: reports the analysis and results for Demo-case 3 – Wind turbine gearboxes.

Chapter 7: presents the conclusions and recommendations.

2 Methodology

2.1 Safe and Sustainable by design

The SSbD Framework[2] is a general approach to steer innovation towards safe and sustainable chemicals and materials throughout the entire life cycle. The framework can be applied to the development of new chemicals and materials or to the re-assessment of those already in existence.

It combines established hazard and risk assessment approaches for chemicals and materials, with sustainability assessment techniques, such as Life Cycle Assessment (LCA) methods.

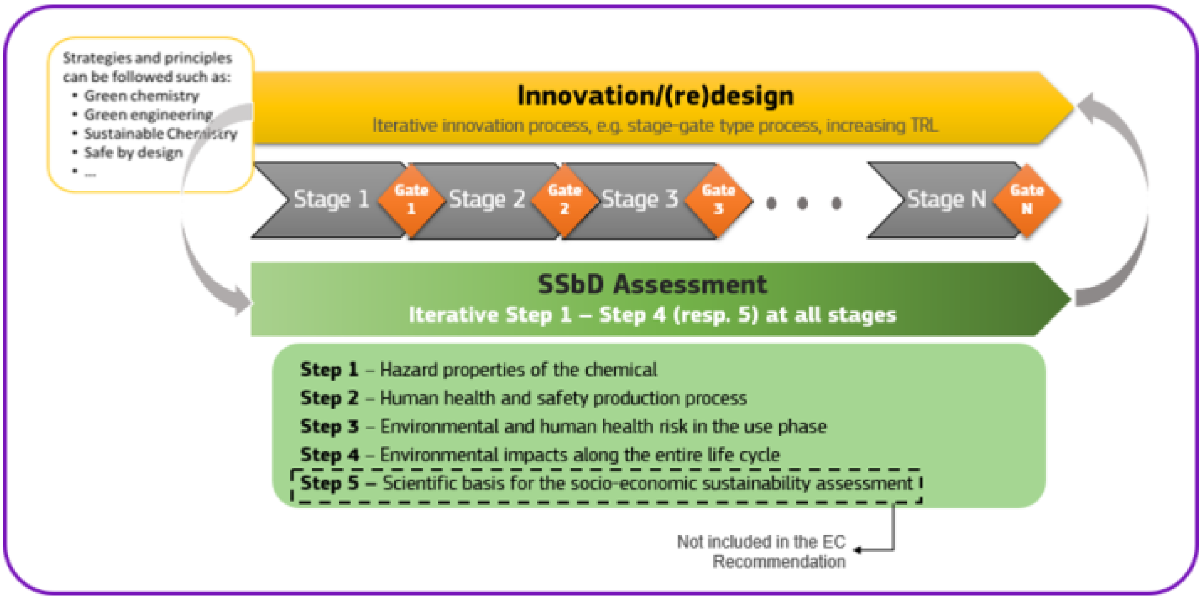


Figure 1. Overview of the SSbD framework[3].

The SSbD Framework has been developed by the Joint Research Centre, to promote the design, development, production and use of completely new, safer and more sustainable products considering their entire life cycle, steering the substitution of hazardous and less sustainable products. The overall goal is to help in preventing pollution whilst also reducing society's environmental footprint.

---

[2] Caldeira, C., Garmendia Aguirre, I., Tosches, D., Mancini, L., Abbate, E., Farcal, R., Lipsa, D., Rasmussen, K., Rauscher, H., Riego Sintes, J. and Sala, S., Safe and Sustainable by Design chemicals and materials - Application of the SSbD framework to case studies, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/329423, JRC131878.

[3] Abbate, E., Garmendia Aguirre, I., Bracalente, G., Mancini, L., Tosches, D., Rasmussen, K., Bennett, M.J., Rauscher, H. and Sala, S., Safe and Sustainable by Design chemicals and materials - Methodological Guidance, Publications Office of the European Union, Luxembourg, 2024, doi:10.2760/28450, JRC138035.

The assessment phase comprises of four steps: hazard, workers exposure during production, exposure during use and life-cycle assessment. The assessment can be carried out either on newly developed chemicals and/or materials, or on existing chemicals and/or materials to improve their safety and sustainability performance during production, use and/or end-of-life. Step 5 than belongs to LCC and sLCA are not obligatory but recommended for EC and included in the R3-Mydas framework.

2.2 Safety by design

Owing to the modern regulatory restrictions, like REACH regulation[4], a safety assessment is a crucial step in any innovation process that aims to minimize risks to human health and the environment before a new product enters in the market. Indeed, it is recommended to start the safety study as soon as possible to identify potential toxicity, persistence or bioaccumulation of the chemicals involved in the process and focus the research on substituting them or reducing workers exposure.

A complete safety assessment includes three steps: Step 1, focused on analysing the intrinsic hazardous properties of chemicals or materials; Step 2, focused on analysing occupational safety hazards; and Step 3, focused on analysing hazards related to the use phase. While the three steps could be performed qualitatively, a complete safety assessment must be supported by reliable experimental data like concentrations of the chemical in different media, that, lately, could be compared with toxicity benchmarks like the Occupational Exposure Limits (OELs), Derived No-Effect Level (DNEL) for consumers, or the Predicted No-Effect Concentration (PNEC) for the environment. Alternatively, if the concentrations overpass the threshold set by the benchmark, the safety assessment allows the quantification of other endpoint parameters like the Human Effect Factor (EF), which could be expressed in Disability-Adjusted Life Years (DALYs).[3]

In this context, R3-Mydas project is expected to perform a safety assessment to make preliminary analysis of one of the novel end-of-life scenarios proposed in the Demo Case 2, E-Vehicles Batteries.

2.3 Sustainable by design

Sustainable by Design revolves around integrating sustainability principles directly into the design process of products, services, and systems, ensuring that sustainability is considered at every stage of development. This proactive approach aims to minimize negative environmental, social, and economic impacts while maximizing value and

---

[4] Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency.

resource efficiency. Unlike traditional methods that may only address sustainability as a secondary concern, Sustainable by Design embeds it into the very foundation of the project, from ideation through to production and disposal.

Therefore, at the heart of Sustainable by Design is the commitment to creating products and services that contribute positively to the environment and society, while also meeting economic goals. It calls for a paradigm shift where sustainability is not an afterthought, but a core value embedded within the design process itself.

Sustainability requires integrated approaches, able to model complex systems. Life cycle-based approaches allow to compare options and solutions in terms of sustainability. Life cycle thinking can be applied to assess the environmental, social, and economic pillars using Life Cycle Assessment (LCA), the Life Cycle Costing (LCC) and the Social Life Cycle Assessment (sLCA), Figure 2.

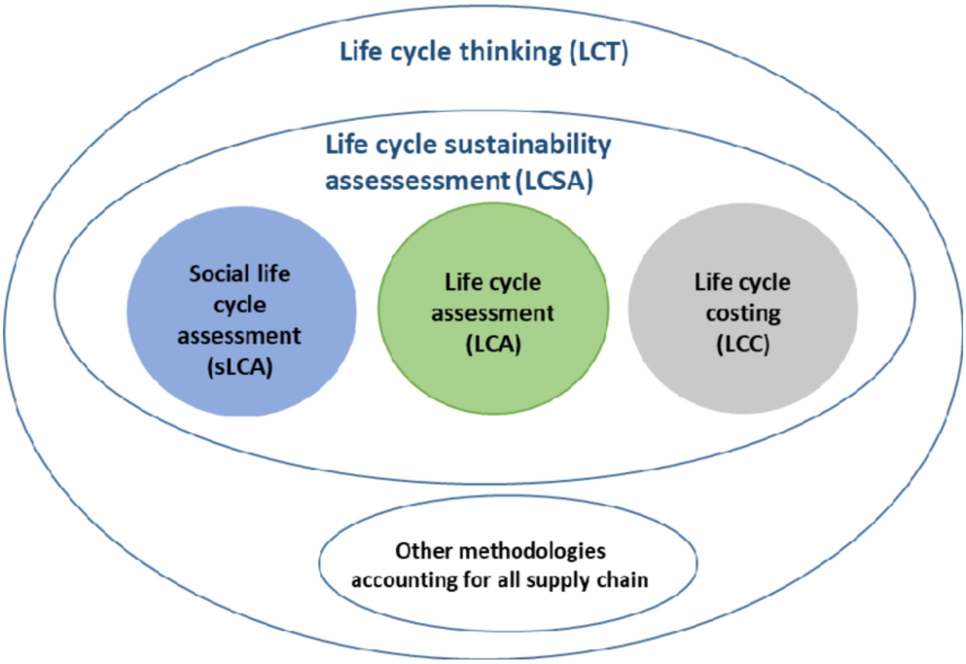


Figure 2. Overview of Life cycle thinking in the SSbD framework[3].

2.3.1 Life Cycle Assessment

To develop the study regarding the environmental impacts for all the value chains (VC) along the R3-Mydas Project, it has been proposed a preliminary Life Cycle Analysis (LCA), across the 3 fundamental pillars: environment, economic and social. The social aspect will not have a solid development at this time in the Project, due to the fact that all the data evaluated for this deliverable is preliminary, and there is no point in developing and studying the impacts on society of processes that are not fully defined.

The objective of this study is to assess the remanufacturing of each use case based on the data obtained during the life of the Project in every technical Work Package (WP): Oil

& Gas components (WP2), E-vehicles batteries (WP3) and Wind turbine gearboxes (WP4). The environmental impacts will be compared with the current process of each case-study in this Project.

The Life Cycle Assessment (LCA) measures the different environmental impacts of a product, process or system throughout all the phases that are included in the scope. The goal of the assessment is to collect and analyse the inputs and outputs of the system to obtain the results as potential environmental impacts, to establish the strategies of reduction.

The main idea of this tool is its holistic point of view, i.e. it is based on the fact that all properties of a system cannot be determined or explained only individually by the parts that compose it, an integration of all aspects involved is needed. That is why the whole life cycle of the system must be taken into account. The elements involved in the LCA are usually defined as inputs/outputs:

- Inputs: Use of Raw Materials, parts or products; Transport; Electricity; Energy Requirements, etc., which are considered in each process/phase of the defined system.
- Outputs: Emissions to air, water and soil; Wastes and By-products that are considered in each process/phase of the defined system.

All these inputs/outputs are collected within a Life Cycle Inventory (LCI), and it is the phase of the LCA which involves the collection and quantification of these items during their entire life cycle, Figure 3: the extraction of raw materials and the manufacturing of needed materials for the processing of components, the use phase of the final product and the recycling or final disposal/management. When there are transport, storage, distribution or other quite important activities, they should be included in the analysis. The name of this scope of this kind of LCA is "Cradle-to-Grave".

When the analysis does not take all the stages and stops when the product is on the market (just after de manufacturing step) is referred as "Cradle-to-Gate" scope.

Finally, when it is taken into consideration only the data of the manufacturing process, it's denominated "Gate-to-Gate" scope; on the other hand, when the output from the EoL system is evaluated and reuse it as raw material, then it will be a scope called "Cradle-to-Cradle".

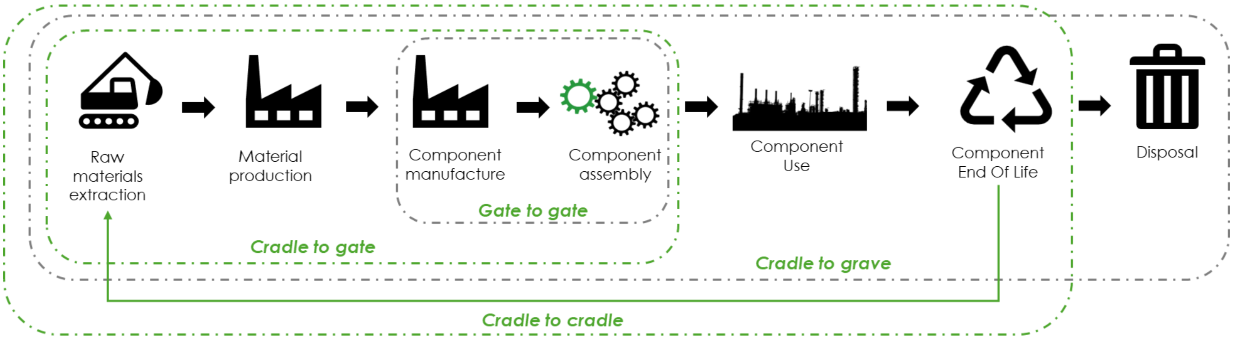


Figure 3. Different scopes for LCA.

The collection of all inputs/outputs are the basis for the subsequent analysis and assessment of the environmental effects related to the manufacturing of products. This summation of resources and emissions towards environmental and human damage is called Life Cycle Assessment (LCA).

The economic impacts (direct cost, indirect cost, ...) related with a product, service or building will be evaluated across the Life Cycle Costing (LCC), from the conception of the idea until the end of its life cycle, considering all the phases of the life cycle.

In the design phase, together with the environmental analysis, a thorough knowledge of the costs involved in all the stages of the product's life cycle allows take decisions to be made that include economic items that would otherwise not be assigned to the system under study. In this way, the LCC facilitates the integration of the economic and environmental aspects as pillars and values of the R3-Mydas project.

Therefore, LCC is not a business costing tool, but expresses the monetary value of an asset taking into account the internal costs associated with its life cycle. LCC quantifies the relationship between economic and environmental optimisation of the system under consideration to understand how economic activities affect environmental activities and vice versa. LCC is ideally suited for application to products and building components, providing cost savings and quantifying the economic value of the environmental improvements of these products and services.

After the environmental and economic pillars, the next one is social. This last impact analysis is developed with the social Life Cycle Assessment (s-LCA). It aims to identify the potential social effects associated with the product’s life cycle, extending the traditional Life Cycle Assessment (LCA). The main goal of s-LCA is to understand how a product impacts the well-being of workers, consumers, local communities, and society as a whole.

The s-LCA framework involves collecting qualitative and quantitative data about the social impacts at each stage of the product's life cycle. It takes into account a range of indicators that are then analysed across various categories, such as "worker health and safety," "human rights," "societal well-being," and "local community development." Through these assessments, businesses and organizations can gain valuable insights into the social consequences of their operations and supply chains, allowing them to identify areas for improvement or potential risks.

Despite its growing importance, s-LCA faces some challenges, primarily related to data availability, standardization, and the subjectivity of certain social impacts. Social impacts are often more complex and context-dependent than environmental ones, making it difficult to apply consistent metrics across diverse industries and regions. Nevertheless, as sustainability becomes increasingly important in business strategy, s-LCA provides a crucial tool for companies to assess and enhance the social dimensions of their operations, promoting more responsible and ethical practices throughout the product life cycle.

For this intermediate deliverable, social aspects have not been considered because the R3-Mydas project is not fully defined yet and all the data evaluated is preliminary, so there is no point in assessing the generated impacts on society. This analysis will be developed for the final deliverable (D5.3) at the end of the project in M36.

2.3.2 Methodology description

By considering sustainability from the outset, SbD methodology encourages designers and engineers to identify and address potential impacts early on, resulting in more efficient resource use, reduced waste, and better alignment with societal needs. It involves a holistic view, considering not just the technical aspects of a product or system, but also its social implications, life cycle impacts, and potential for long-term value creation. Therefore, the practices included in the sustainable by design methodology will guide the creation of solutions that are environmentally responsible, socially beneficial, and economically viable.

2.3.2.1 LCA Methodology

ISO, the International Organisation for Standardisation, has established a framework for the standardisation of the LCA methodology, according to the ISO 14.040 family of standards:

- **UNE EN ISO 14.040:2006:** Environmental management. Life Cycle Analysis. Principles and reference framework.
- **UNE EN ISO 14.044:2006:** Environmental management. Life Cycle Analysis. Requirements and guidelines. According to the standardisation carried out, four phases can be distinguished in an LCA study (Figure 4):
    - **Definition of Objectives and Scope**. Defines the objective and intended use of the study, as well as the scope according to the system boundaries,

the functional unit and flows within the life cycle, the required quality of the data, and the technological and evaluation parameters.

- **Development of the Life Cycle Inventory (LCI)**. This is the phase of the LCA in which data is collected on the inputs and outputs for all processes of the product system.
- **Life Cycle Impact Assessment (LCIA)**. This is the phase of the LCA in which the inventory of inputs and outputs is transferred into indicators of potential environmental impacts on the environment, human health and natural resource availability.
- **Interpretation**. This is the phase of the LCA in which the results of the LCI and LCIA are interpreted according to the objective and scope initially set. In this phase, an analysis of the results is carried out and conclusions are drawn.

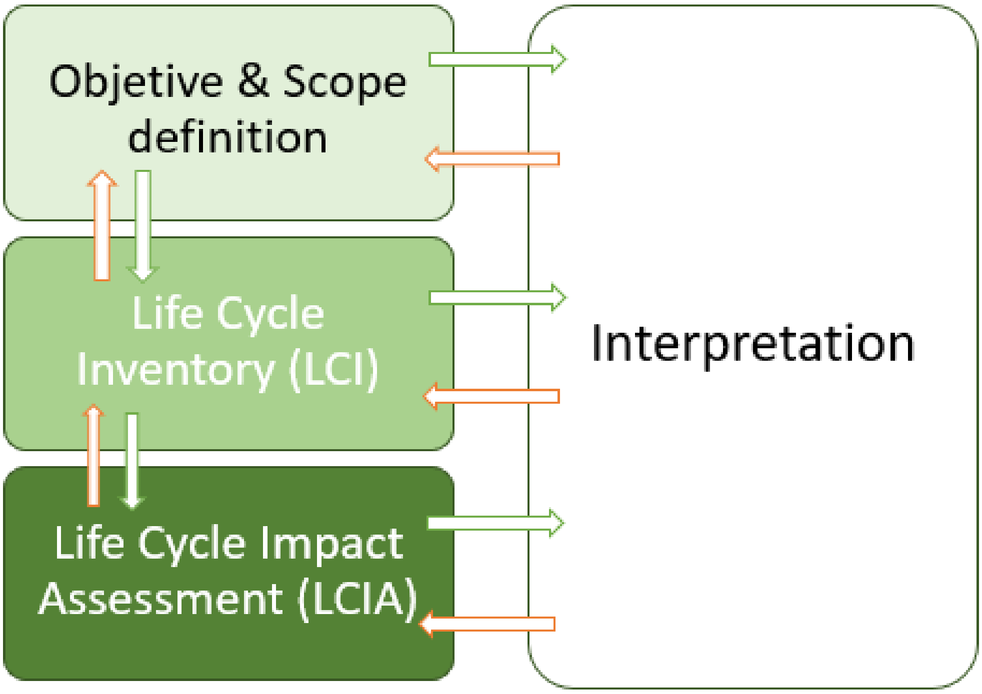


Figure 4. Steps of a LCA according to ISO 14.044.

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

LCIA is the phase inside the LCA which understand and assess the approach and the magnitude of the different environmental impacts of the system. With this step it takes place the transformation of data collected into environmental results.

The first step in the LCIA is to select the environmental impact categories to be considered in the study. These categories represent the environmental impacts of interest to which the results of the LCA will be assigned. In other words, the environmental impacts for which results are desired. There are a number of environmental impact categories and the choice for the LCA will depend on the objective of the study, the target audience and the level of precision of the results required. The Environmental Footprint (EF) 3.1 method, which is used in this study, addresses 16 impact categories. These are periodically updated to reflect the latest scientific knowledge and best practices, also informed by discussions within Commission's expert groups. The current impact categories in Environmental Footprint (EF) 3.1 method are discussed in Table 2.

Table 2. Environmental Impact Categories considered in LCA.

Environmental impact categories		***Indicator***	***Reference unit***
Climate Change	The potential of a greenhouse gas to trap extra heat in the atmosphere over time. The enhanced heat trapping is caused by the absorption of infrared radiation by a given gas	Radioactive forcing as Global Warming Potential (GWP100)	kg $CO2_{eq}$
Ozone depletion	Destruction of the protective ozone layer in the polar regions of the Earth's stratosphere brought about by interaction of gaseous (e.g. CFCs) emissions with NOX and UV radiation	Ozone Depletion Potential (ODP)	kg CFC-11_{eq}
Human toxicity, cancer	The toxicity impacts to humans posed by the system processes (waste/pollutant/emissions) which have potentially carcinogenic effects. The level will depend on estimates of environmental fate and human exposure	Comparative Toxic Unit for humans	CTUh
Human toxicity, non-cancer	The toxicity impacts to humans posed by the system processes (waste/pollutant/emissions) which have not carcinogenic effects. The level will depend on estimates of environmental fate and human exposure	Comparative Toxic Unit for humans	CTUh
Particulate matter formation	The release of fine particulates at ground level, which can have a negative impact on human health	Human health effects associated with exposure to PM2.5	Disease incidences
Ionising radiation, human health	Impact indicator for all the emissions of radioactive elements, which have potentially carcinogenic effects	Human exposure efficiency relative to U235	kBq U^{235}
Photochemical ozone formation, human health	Impact due to the release of metastable volatile organic compounds (NMVOC) which, in the presence of UV radiation and NOX, give rise to a series of photochemical reactions that ultimately lead to the formation of ozone and other secondary pollutants at ground level. These can have a negative impact on human health	Tropospheric ozone concentration increase	kg NMVOCeq
Acidification	Impact which quantifies potentially damaging effects of acidic acids atmospheric depositions (rain, sleet, snow) as a result of the natural hydration of acidic gaseous emissions (e.g. SOX, NOX) in the atmosphere	Accumulated Exceedance (AE)	mol H^+eq
Eutrophication, terrestrial	Impact of cumulative fertilization or excess supply of nutrients on land environments, particularly nitrogen, leading to increase plant growth and bacterial use of oxygen, which in	Accumulated Exceedance (AE)	mol N_{eq}

Environmental impact categories		***Indicator***	***Reference unit***
	turn leads to oxygen starvation and loss of biomass across all food chain levels		
Eutrophication, freshwater	Impact of cumulative fertilization or excess supply of nutrients on freshwater aquatic environments, particularly phosphorous, leading to increase plant and algae growth and bacterial use of oxygen, which in turn leads to oxygen starvation and loss of aquatic biomass across all food chain levels	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}
Eutrophication, marine	Impact of cumulative fertilization or excess supply of nutrients on marine aquatic environments, in particular nitrogen, leading to increase plant and algae growth and bacterial use of oxygen, which in turn leads to oxygen starvation and loss of aquatic biomass across all food chain levels	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}
Ecotoxicity, freshwater	Ecotoxicity impacts to freshwater ecosystems posed by the system processes (waste/pollutant/emissions). The level will depend on estimates of the environmental fate and ecosystem exposure	Comparative Toxic Unit for ecosystems (CTU_e)	CTU_e
Land use	All degradative land use. It takes into account the length of time over which such use is sustained, and the degree to which the land can be restored to its original condition after the use has ceased	Soil quality index	dimensionless (pt)
Water use	This impact quantifies the water withdrawal-to-availability ratio of the system under consideration. "Withdrawal" refers to all off-stream water use which excludes water extracted and subsequently returned to the environment unpolluted (e.g. cooling water)	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq. deprived water
Resource use, minerals and metals	The cumulative extraction of non-living, non-renewable resources such as minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg S_{eq}
Resource use, fossil	The cumulative extraction of non-living, non-renewable resources such as fossil fuels	Abiotic resource depletion-fossil fuels (ADP-fossil)	MJ

In the classification stage, each data from Life Cycle Inventory (LCI) is assigned to each impact category. If a substance/product is a contributor to more than one impact category, it should be considered in all impact categories.

2.3.2.2 LCC Methodology

For developing of LCC is followed the UNE-EN 60300[5]. This standard is oriented towards a LCC related with reliability, as operation, safety, maintainability, maintenance, support, requirements, etc., although it is the only published standard for the product and was therefore chosen for the development of this LCC. There are more well-known

---

[5] UNE-EN 60300-3-3:2017 (Ratified) "Reliability Management. Part 3-3: Application Guide. Life cycle cost calculation. (Ratified by the Spanish Association for Standardization in June 2017.)"

global standards to the development of the LCC, as UNE-EN 15643-4:2012[6], UNE-EN 16627:2016[7] or ISO 15686-5:2017[8], but all of them are not viable for using because are aimed to life cycle costing for buildings.

The performance for calculation of LCC has the following steps listed in the standard UNE-EN 60300, mentioned above:

- Quantify the differences in product performance, availability, and other relevant constraints between each of the alternatives considered, unless these differences are directly reflected in the results of the LCC model.
    - Data collection of all basic cost elements of the LCC model for all product options.
    - Perform LCC analysis of product operational scenarios defined in the analysis plan.
    - Identification of optimal support scenarios.
    - Review of baseline data and results of the LCC model to determine which cost elements have the most significant impact on the analysis.
- Quantify the differences in product performance, availability and other relevant constraints between the alternatives considered, unless these differences are directly reflected in the results of the LCC model.
- Classify and summarise the results of the LCC model according to a logical grouping (recurring or non-recurring costs, acquisition, ownership or disposal costs, etc.) that may be relevant to the users of the analysis results.
- Perform sensitivity analyses to examine the impact of assumptions and uncertainties about cost elements on the results of the LCC model, paying particular attention to key cost drivers and assumptions about product usage and the time value of money.
- Review the LCC results and compare them with the objectives defined in the analysis plan to ensure that all objectives have been met, and that sufficient information has been provided to support the required decision.

---

[6] UNE EN 15643-4:2012 Sustainability of construction works - Assessment of buildings - Part 4: Framework for the assessment of economic performance

[7] UNE EN 16627:2016 Sustainability of construction works - Assessment of economic performance of buildings - Calculation methods

[8] ISO 15686-5:2017 Buildings and constructed assets. Service life planning Life-cycle costing

TERMINOLOGY

In order to develop the LCC, several values related to economy have to be calculated and used in this analysis, which are defined below:

- NPV (Net Present Value): It is the sum of discounted future cash flows (i.e., discounted at a discount rate), both costs and revenues.
- Cash Flows: Are the (negative) expenses and (positive) revenues at a given time.
- Discount Rate (DR): It is the interest rate that has been adopted in order to be able to express the monetary values of the future in current values.
- Internal Rate of Return (IRR): The interest rate or return on an investment.
- Interest Rate: This is the amount paid in a time unit for each unit of capital invested.
- Nominal Interest Rate (TIN): It is profitability obtained in a financial operation that is capitalised in a simple way, allowing for only the main capital. It is the opportunity cost that a bank's client has (profitability that he obtains) for not having the money. In this rate the inflation rate is not discounted.
- Inflation: It is the widespread and sustained increase in the prices of goods and services in a country over a period, usually one year.

ASPECTS TO CONSIDER IN LCC ANALYSIS

The LCC takes into account the main aspects that affect the costs across the entire lifecycle. Some items that are generally considered are:

- Raw materials (including the auxiliary).
- Direct manufacture costs: energy consumption and labour (hours).
- Indirect manufacture costs: equipment purchases, waste management and other costs (5% of direct cost, to include maintenance, repairing and administrative cost).
- Manufacture profits: 7% of raw materials, direct and indirect manufacture costs.
- Environmental externalities.

In this deliverable, some of these aspects are not taken into account in order to simplify the analyse. Indirect cost and manufacture profits are not considered.

Although the LCC usually considers the costs in the whole lifecycle, in this case it was selected a “Gate-to-Gate” scope, including only some phases of the process in each demo case.

ENVIRONMENTAL EXTERNALITIES

Environmental externalities are the cost associated with the palliation of an affection achieved on the environment. For example, the energy consumption causes a series of emissions that cause impacts on the environment. These costs have an impact on the global economy of the process. To calculate the environmental externalities, a European method is used: "European Environmental Prices (2015)[9]. This method consisted of five steps:

1. Updating monetary values of the endpoint categories on basis of literature, General SCBA Guidelines and Discount Rate Working Group,
2. Updating the impact pathway analyses, which specify the relationship between emissions in the Netherlands and impacts on endpoints,
3. Valuation of 15 pollutants on basis of inputs from the previous steps and literature,
4. Allocation of those pollutants to midpoint impact categories in ReCiPe,
5. Deriving weighted average value for damage to midpoint categories in order to calculate the damage cost for each substance characterised in ReCiPe and midpoint damage factors.

2.3.2.3 s-LCA Methodology

Unlike environmental assessments, which can often be quantified in more standardized ways, social impacts are context-dependent, subjective, and vary significantly across different regions, industries, and cultural settings. Consequently, carrying out a s-LCA presents challenges, such as the lack of universally accepted indicators and methodologies and the lack of data.

However, the social dimension is essential to achieving a complete understanding of product systems and their overall sustainability, so the United Nations Environment Programme (UNEP) is supporting efforts in the ongoing process for the standardization of methods.

In fact, the UNEP has contributed to the development of several reports and frameworks for Social Life Cycle Assessment. A key document is the UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products, which were developed by the Society of Environmental Toxicology and Chemistry (SETAC) and UNEP to offer standardized guidance for practitioners to assess social impacts in a life cycle context.

The main methods proposed by the UNEP/SETAC Guidelines for s-LCA are the following ones:

---

9 CE Delft, 2018. S.M. de Bruyn, M, Bijleveld, L. de Graaff, E. Schep, A. Schroten, R. Vergeer, S. Ahdour Environmental Prices Handbook, EU28 version.

- **Goal and scope definition**. It includes elements similar to those in environmental LCA, such as defining the system, functional unit, and study scope. Additionally, it is crucial to identify relevant stakeholder categories and their associated social impact subcategories.
  In 2009, the UNEP/SETAC Guidelines established a framework with five stakeholder categories: Workers, Value Chain Actors, Local Communities, Society, and Consumers. In the updated 2020 UNEP Guidelines[10], a sixth category, Children, was added.
  Each of these stakeholder categories is addressed through various impact subcategories. The UNEP Guidelines provide a baseline list of almost 200 indicators across 31 social impact subcategories, outlined in the Methodological Sheets for Subcategories in Social Life Cycle Assessment[11]. However, it's important to note that not all of these indicators may be applicable to every sector.
- **Life Cycle Inventory**. This phase involves gathering the necessary information for the S-LCA. While some of the data is similar to what is required for environmental LCA (e.g., a list of components and raw materials used by the system), additional information specific to social aspects must also be collected. This includes social data needed to define the relevant impact indicators for assessing the identified and selected social impact subcategories.
- **Life Cycle Impact Assessment**. The inventory data is converted into indicators of potential social impacts, based on the categories and subcategories defined earlier during the system definition phase.
- **Interpretation**. The interpretation phase consists of analysing the impact assessment results to draw meaningful conclusions for decision-making and raising awareness. Its goal is to identify the key indicators among those assessed, highlighting the ones that have the most significant influence on the potential social impacts of the evaluated system, and thus represent the main hotspots.

---

[10] UNEP, 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G. (eds.). United Nations Environment Programme (UNEP)

[11] UNEP, 2021. Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021. Traverso, M., Valdivia, S., Luthin, A., Roche, L., Arcese, G., Neugebauer, S., Petti, L., D'Eusanio, M., Tragnone, B.M., Mankaa, R., Hanafi, J., Benoît Norris, C., Zamagni, A. (eds.). United Nations Environment Programme (UNEP).

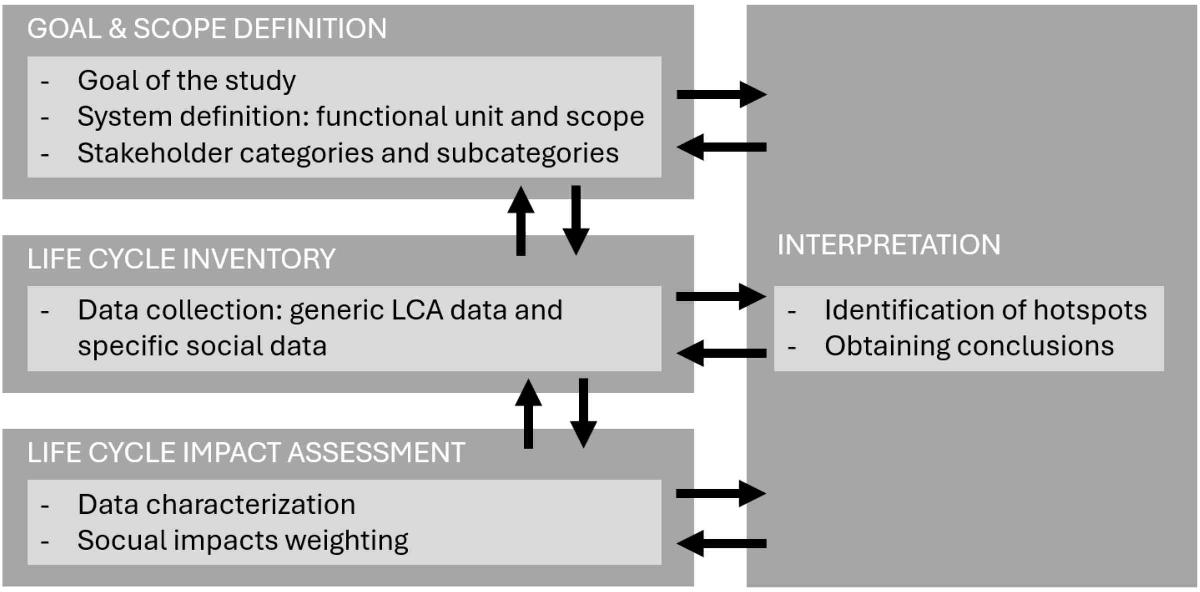


Figure 5. Steps of the s-LCA proposed by the UNEP/SETAC Guidelines.

Furthermore, the PSILCA database[12], developed by GreenDelta in line with the UNEP/SETAC S-LCA guidelines, is valuable for conducting s-LCA due to the fact that it provides standardized, accessible, and reliable data on the social impacts of products across their life cycles. The database includes data for 19 subcategories and 65 qualitative and semi-quantitative indicators on social and environmental risks and impacts. It is based on the EORA multi-regional input/output database, covering around 15,000 country-specific industry sectors and commodities in 189 countries[13].

PSILCA provides social indicators for the stakeholder groups (e.g. workers, society and consumers), all measured at specific points in time. Social risks are calculated using an activity variable (worker hours), which reflects the amount of working time required to produce 1 USD worth of output from a sector. Then, the risks are converted into medium-risk hours, representing the level of social risk associated with producing 1 USD of output. The final risk is adjusted by factors such as input sector prices[14], the number of work hours for the process, and categorization factors, ultimately yielding the risk results per impact category.

As outlined above, due to the lack of available data, a sLCA is not performed at this stage of the R3-Mydas project. It will be carried out at the end of the project and the results will

---

[12] PSILCA v.3.1, a Product Social Impact Life Cycle Assessment database. Greendelta, 2024. Kirill Maister, Claudia Di Noi, Andreas Ciroth, and Michael Srocka

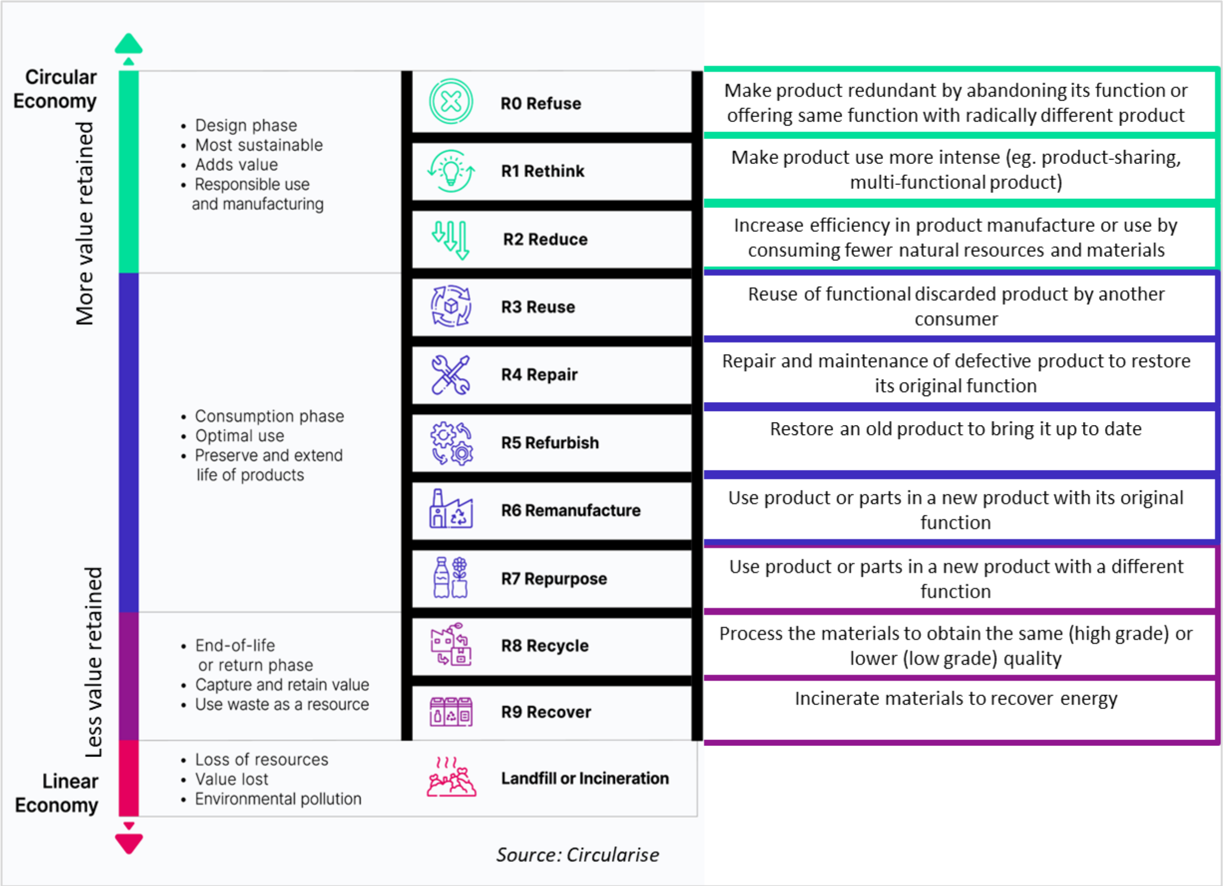
[13] Koese, M., et al. A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage. *Journal of Industrial Ecology*, 2023, vol. 27, no 1, p. 223-237.

[14] Di Noi, C., Ciroth, A., Mancini, L., Eynard, U., Pennington, D., & Blengini, G. Can S-LCA methodology support responsible sourcing of raw materials in EU policy context? *The International Journal of Life Cycle Assessment*, 2020, vol. 25, p. 332–349.

be included in deliverable D5.3.

3 New circular value chains

The circular economy is an innovative approach to resource management that aims to minimize waste and make the most of available resources. Unlike the traditional linear model of "take, make, dispose," the circular economy seeks to close the loop by promoting the continuous use of resources. It focuses on designing products and processes in a way that reduces environmental impact, conserves natural resources, and encourages sustainability.



Source: Circularise

Figure 6. Possible R-cycles of a product[15].

Central to the concept of circular economy are the R-cycles, which represent a series of strategies for maintaining product life cycles and reducing waste. The "R's", which are explained in detail in Figure 6, include Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover. It is highly important to consider that the earlier in the process a strategy is applied, the more value will be

---

[15] DACAPO Agile methodology. https://www.dacapo-project.eu/deliverables-publications (accessed March 2025)

retained. In this way, on the left side of Figure 6 are shown the 9 circular business model options, ranked from most circular to least circular. They are categorized in four groups:

- **Green group**: requires changes in your product design.
- **Blue group**: changes the consumption phase of your products.
- **Purple group**: focus on the end-of-life phase of your products.

However, all these cycles highlight ways to extend the life of products and materials, creating a more sustainable and restorative system. Through these strategies, the circular economy fosters not only environmental benefits but also economic opportunities by reducing costs, creating jobs, and encouraging innovation.

In this section, it will be explained not only the new circular value chains with the R-cycles proposed for all the three demo cases, but also their correspondent scenarios.

3.1 Demo case 1: oil & gas components

In the oil and gas industry, crankshafts are critical components in engines and pumps, providing power to a variety of systems used in drilling, extraction, and transportation processes. During these operations, crankshafts are subjected to demanding conditions, like high mechanical loads and aggressive environments, accelerating the wear process.

Any form of damage to the crankshaft, particularly wear, can lead to costly repairs, reduced operational efficiency, and unplanned downtimes. Therefore, in this demo case of the project, the objective is to improve the remanufacturing process, turning it into a more precise, cost effective and environmentally sustainable one. This will be achieved by using advanced technology to scan the worn-out areas of the damaged crankshaft and create a 3D model. Then, the needed clad layer will be designed and, ultimately, precisely deposited by using the laser cladding technique. All this process is explained in detail in the deliverable D2.1.

Therefore, the value chain for this demo case is the one shown in Figure 7. It is structured in two different parts:

- There is the classic linear process (the one in **black colour**), which includes the whole process for producing a new crankshaft made out of raw materials and the disposal right after getting to the End-of-Life phase.
- On the other hand, there are the circular economy strategies (**shown in green**) proposed for turning the classic process into a more sustainable one. These R-cycles are reuse, remanufacturing and recycling, depending on the state of the deteriorated crankshaft.

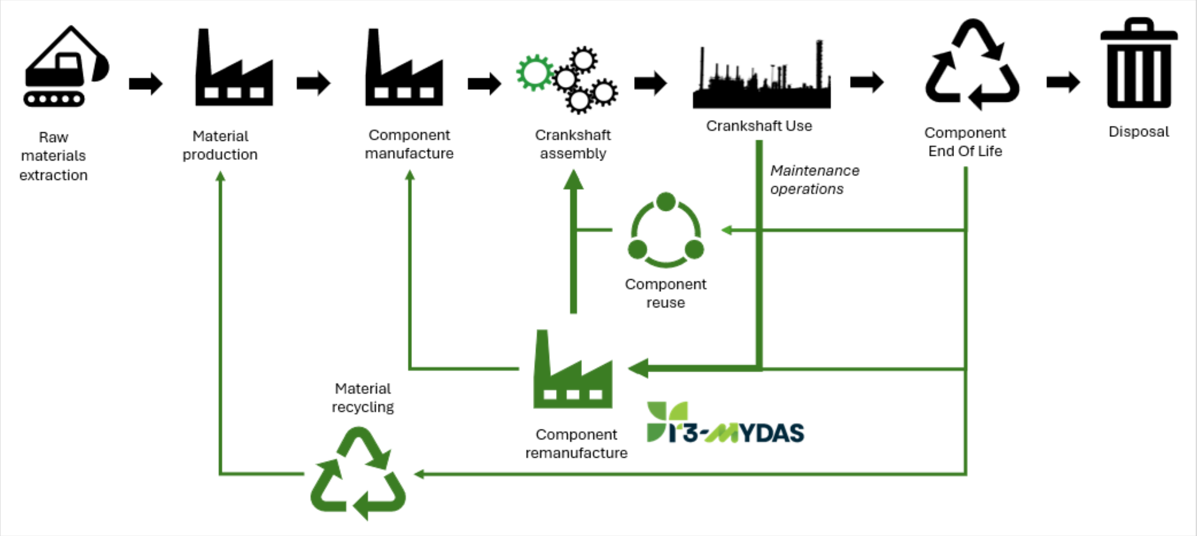


Figure 7. New value chain for demo case 1: oil & gas components.

It contains the next phases:

- **Raw materials extraction**. It consists of getting natural resources from the Earth and extracting from them the materials needed for the material production.
- **Material production**. This is the stage in which the raw materials turn into the different steel alloys, cast iron, or forged steel billets that will be used to create the crankshaft.
- **Component manufacture**. The different components that form the crankshaft are made during this phase, using different processes, like metal casting, forging, machining, and heat treatment to shape and strengthen the material.
- **Crankshaft assembly**. In this phase, all the finished components, like pistons, rods and bearings, are put together to get the crankshaft.
- **Crankshaft use**. This is the phase in which the crankshaft does its function. Effective maintenance and addressing wear-related issues are essential to ensure the crankshaft continues to function efficiently throughout its operational life.
- **Crankshaft End-of-Life**. At this point, the crankshaft is no longer operating, so an evaluation of the different alternatives, such as reuse, remanufacturing, recycling and disposal must be done.
    - **Component reuse**. If the crankshaft or any of their components were in good condition at its EoL stage, they could be reused without any repairing in industry. It would only be needed the assembly process if the crankshaft is not reused as a whole.
    - **Component remanufacture**. When the crankshaft or some of their pieces need some repairs, either at their EoL stage or during the maintenance operations at the use phase, they can be fixed so they are usable again. This is the stage in which R3-Mydas is focusing on. In this way, improve the

remanufacturing process will turn this option into a more attractive one, preventing the good enough old crankshafts to go into the recycling process or disposal.

- **Material recycling**. This is the R-cycle strategy which consists of obtaining the materials from the crankshaft. This way, they can be used in the material production process instead of extracting raw materials from nature.
- **Disposal**. It refers to the process of getting rid of the crankshaft in a proper and responsible manner. This is the worse option in terms of sustainability, so it is chosen when none of the previous ones can be implemented. The most common way for disposal is landfilling.

3.1.1 AS-IS scenario

Nowadays, damaged crankshafts can be remanufactured to return them to its original performance or even better. Dimensional build-up along the deteriorated zone is needed to restore original dimensions of the piece. This material build-up has been done historically with plating technologies, but they are very harmful for the environment.

Another option for the remanufacturing process could be renovating the crankshafts applying conventional TIG/MIG/MAG build-up welding, plasma transferred arc coating and thermal spraying. However, these techniques can be time-consuming, and cause deformations or damages to the part. Also, they need extensive post-processing for attaining the geometry desired.

Alternatively, the laser cladding method has recently been used to repair expensive equipment, offering significant cost savings over purchasing a new replacement, while ensuring that the repaired item performs at the same level as the original. Nevertheless, this technique is very expensive yet and needs automation and control. Therefore, laser cladding method needs to be improved, and this is where the R3-Mydas project is going to work on.

Considering both the remanufacturing and recycling processes, the workflow for the AS-IS scenario is in Figure 8. As shown, this workflow reveals that, after going through all the manufacturing and usage phases previously described, when a crankshaft reaches its End-of-Life stage, it can either be recycled or remanufactured, with remanufacturing being the preferred option if the crankshaft's condition permits.

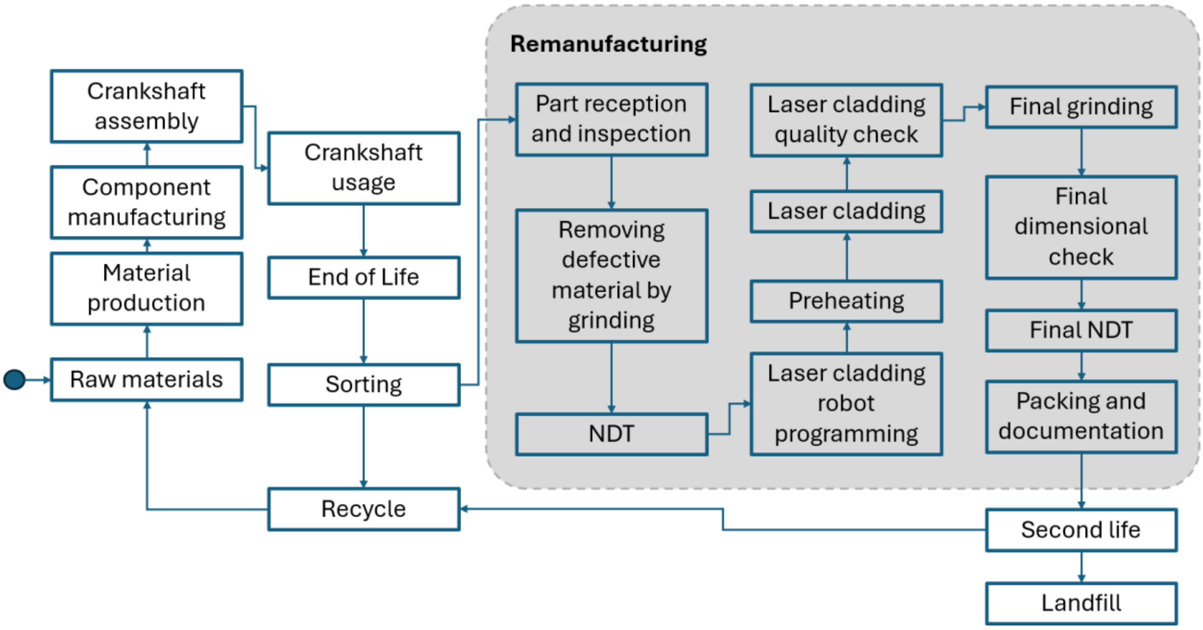


Figure 8. Workflow for demo-case 1: AS-IS scenario.

The current process for remanufacturing crankshafts contains the next steps:

- **Part reception and inspection**. As the components arrive, they are visually checked, first for transportation damages and then looking for the dimensions of the areas to be repaired. This is a manual operation done by using conventional tools.
- **Removing defective material by grinding**. The grinder performs the operation using the machine and a water-based liquid for cooling the part.
- **Non-Destructive Testing (NDT)**. Different manual techniques are utilized by certified inspectors to precisely inspect the crankpin journals.
- **Laser cladding robot programming**. As each deteriorated crankshaft is different, it is needed to program all the movements of the cladding head manually because every repair is unique. Additionally, the fact that the components often lack a common axis of revolution or consistent dimensions makes the programming process long and tedious.
- **Preheating**. In this stage begins the cladding process execution, which is well-known, so this phase of the remanufacturing process is not as challenging as the previous one. The preheating is mandatory because the crankshaft material is usually difficult to weld due to the high percentage of carbon in its composition. This operation takes from 5 to 60 minutes.
- **Laser cladding**. This step is key in the remanufacturing process. First, the laser operator sets manually some parameters like laser power and powder feed rate. Then, the automated cladding process starts, while the operator monitors the process to avoid any deviations.

- **Quality check**. Once the component is cooled down, the component is visually checked for the absence of cracks and the dimensions of the deposited material.
- **Final grinding or post-grinding**. Again, the grinder performs the operation using the machine and a water-based liquid for cooling the part for removing the excess material.
- **Final dimensional check**. The component is visually inspected to verify that its dimensions are the correct ones.
- **Final Non-Destructive Testing (NDT)**. Different manual techniques are utilized by certified inspectors to precisely inspect the final component.
- **Packing and documentation**. When the final NDT is finished, the component is cleaned using solvents and clothes. Then, the repaired and the critical areas are protected by packaging before the delivering.

All these steps are part of the three different phases of the crankshaft remanufacturing as it is showed in Figure 9.

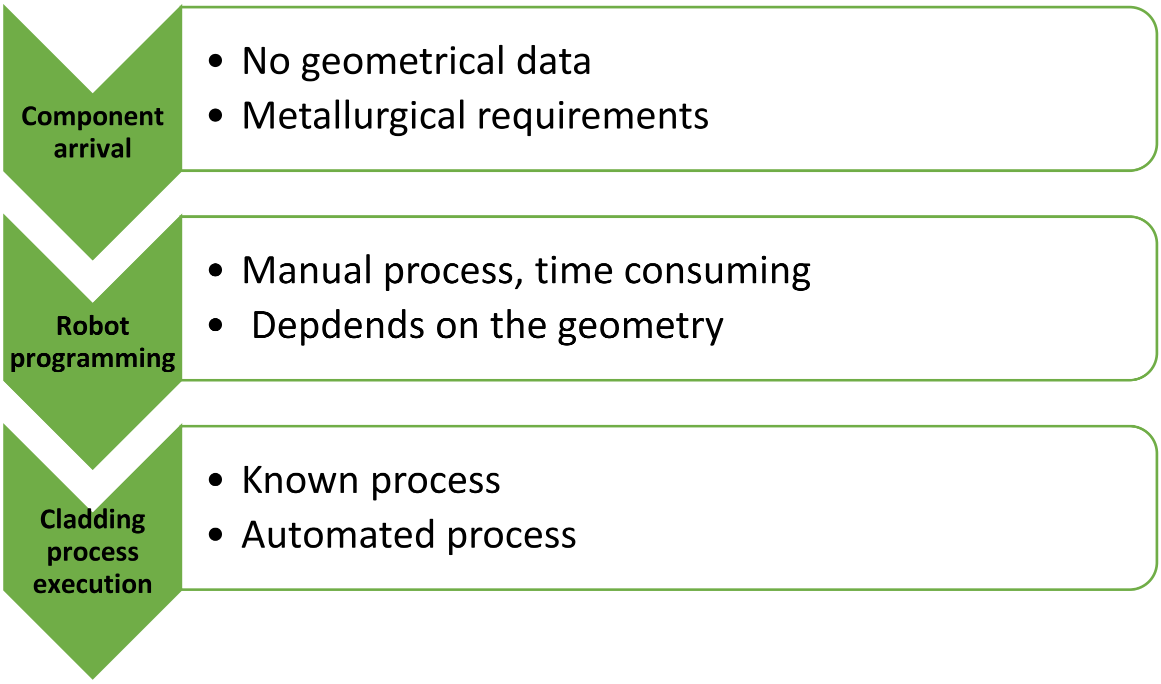


Figure 9. Phases of the crankshaft remanufacturing.

The difficulties encountered in the AS-IS scenario arise from the absence of automation during the robot programming phase, since the cladding process execution is well-known, automated and the materials typically used are familiar.

This lack of automation is mainly because of advanced digital tools not being integrated into the process. As noted earlier, repairing these components is a highly customized task that demands an adaptable approach to accommodate different geometries. This leads to lengthy and labour-intensive programming, as each repair must be individually adjusted. The lack of digital integration not only reduces efficiency but also raises the risk of errors, making it challenging to attain the precision and consistency required for high-quality repairs.

3.1.2 TO-BE scenario

The proposed TO-BE scenario seeks to improve the current state of the art (SoA) in remanufacturing end-of-life crankshafts by automating the robot programming process using onboard sensors. The goal is to enhance the restoration of damaged crankshaft parts using cutting-edge technologies such as reverse engineering, 3D scanning, and CAD design. This technological innovation will simplify the remanufacturing process, drastically cutting down the manual labour and the time needed for programming the laser cladding robot, while also boosting overall precision. The resulting workflow of the envisioned scenario is showed in Figure 10.

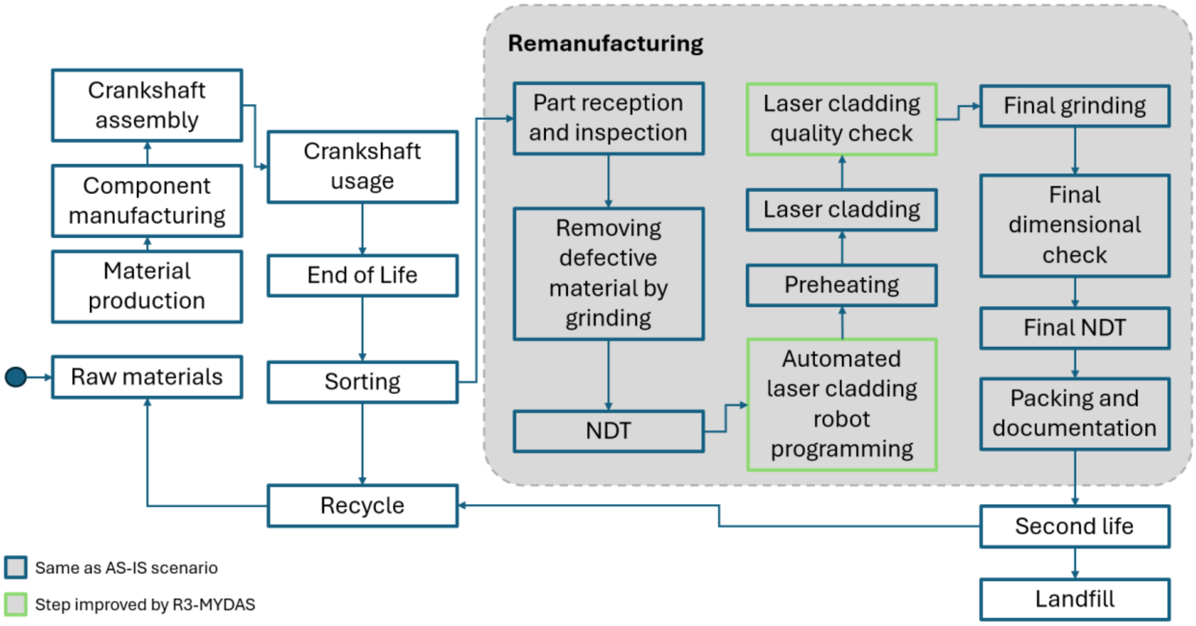


Figure 10. Workflow for demo-case 1: TO-BE scenario.

As illustrated in Figure 10, there are only two stages of the remanufacturing process that will be different from the AS-IS scenario:

- **Automated laser cladding robot programming**. In the TO-BE scenario, the system will scan the crankshaft part using the sensors for autonomously generating a detailed digital model of the damaged area and a robot program in few minutes. The resulting program will allow the laser cladding process to execute with no collisions between the robot and the component, Figure 11.

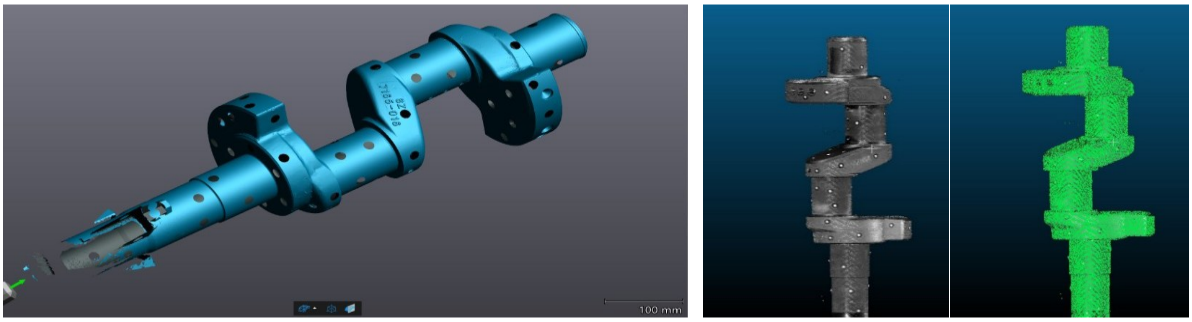


Figure 11. Scanned crankshaft using different methods.

- **Quality check**. This step could be done with the help of R3-Mydas solution. Furthermore, as the laser cladding process becomes more precise due to automated robot programming, the geometry of the component will more closely match the desired specifications. This means that there will be less excess material, and consequently, less final grinding will be required.

Through the automation of robot programming and the incorporation of digital modelling into the workflow, the TO-BE scenario enables a quicker, more consistent, and highly adaptable remanufacturing process. This approach enhances both the quality and consistency of repairs, while also promoting greater sustainability and efficiency by minimizing manual intervention.

3.2 Demo case 2: E-vehicle batteries

E-vehicles play a crucial role in the decarbonization of the road transportation sector, which is an important contributor to air pollution and climate change. By replacing traditional internal combustion engine vehicles with electric alternatives, the carbon emissions can significantly cut down, especially during the use phase.

However, the batteries used in E-vehicles rely on several challenges. On the one hand, these batteries degrade over time, losing efficiency and eventually requiring expensive replacement. The extraction of materials like lithium and cobalt for battery production also raises environmental and ethical concerns, such as habitat destruction and poor working conditions. Remanufacturing, repurposing and recycling these batteries could help mitigate some of these issues, extending their lifespan and reducing the demand for new materials. Nevertheless, the remanufacturing and the non-direct repurposing processes remain complex and costly, so improving technology is crucial for enhancing the sustainability of EVs in the long term.

The R3-Mydas project seeks to build trust and reduce uncertainty in battery performance by integrating digital technologies to assess and test EV mechatronic components during disassembly and reassembly. The focus will be on anomaly detection to overcome the limitations of traditional on-board diagnostics, which can be unreliable due to differing assumptions during battery development and real operational conditions. The approach will automatically identify relationships between variables by using a graph learning module.

On the other hand, a screwdriver SD35, currently available in the market, will be enhanced to improve the automated disassembly and reassembly of EV batteries. Key upgrades include precise pressure control to ensure a correct assembly and prevent damage to battery cells and better control of the robotics arms to automate the removal of screws in battery packages. The innovation proposed for the demo case 2: EV-batteries is explained in more detail in the deliverable D3.1.

The main objective of this project is to improve the lifespan of the EV-batteries and allow them to be non-direct repurposed in a more viable way. The resultant value chain for this demo case is the one shown in Figure 12. As well as in the previous demo case, it is structured in two different parts:

- There is the classic linear process (the one in **black colour**), which includes the whole process for producing a new EV-battery made from raw materials, the assembling of the battery pack inside the vehicle and the disposal right after getting to the End-of-Life phase.
- There are the circular economy strategies (shown in **green**) proposed for turning the classic process into a more sustainable one. These R-cycles are reuse, repurposing and recycling, depending on the state of the deteriorated battery.

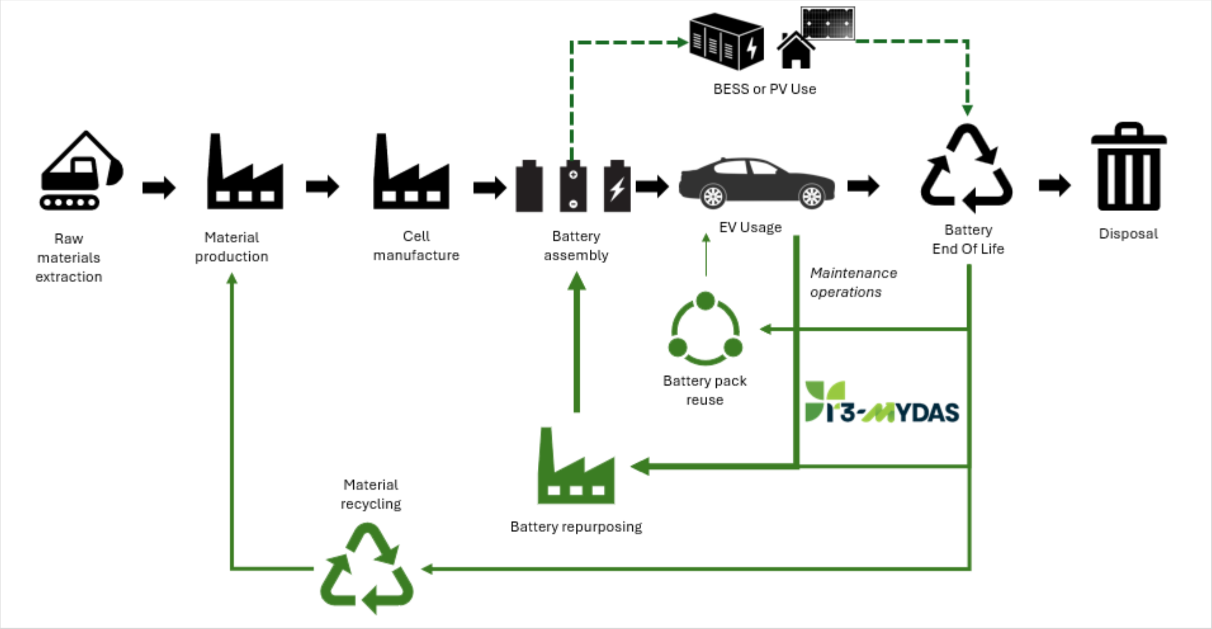


Figure 12. New value chain for demo case 2: E-vehicle batteries.

It contains the next phases:

- **Raw materials extraction**. It consists of getting natural resources from the Earth and extracting from them the materials needed for the material production.
- **Material production**. This is the stage in which the raw materials turn into the different materials needed for the battery production, like the cathode active material, which contains lithium, manganese, cobalt and nickel, or the anode, which is mainly made of graphite.
- **Cell manufacture**. The different components that form the battery cells, such us cathode, anode, separator, housing components current collectors and electrolyte, are made during this phase. After this, they are all put together in order to obtain the battery cells.
- **Battery assembly**. In this phase, all the finished cells are grouped and assembled with other battery components to form modules. These modules are then connected to create the battery pack, which is ultimately installed into the electric vehicle.
- **EV usage**. This is the phase in which the EV-battery does its function. Identifying any issues during the use phase is key to ensure the battery continues to function efficiently throughout its operational life.
- **Battery End-of-Life**. At this point, the battery is no longer operating, so an evaluation of the different alternatives, such as reuse, remanufacturing, repurposing, recycling and disposal must be done.
    - **Component reuse**. If the battery pack were in good condition at its EoL stage, it could be directly reused with little to no repairs needed. Therefore, in most of the cases, it would only be needed to disassembly the battery pack from the old EV and assembly it into the new vehicle. This scenario could occur, for instance, if an EV were involved in a crash and not repaired, but the battery remained unaffected.
    - **Component repurposing**. When the battery pack is too degraded for reuse but still in good enough condition to avoid recycling, it can be reconfigured to bring cells with a reasonably high state of health (SOH) a second life. This is the stage where R3-Mydas is concentrating its efforts. By enhancing this process with the upgraded SD35 screwdriver plus developing digital technologies to detect failures, this approach will become a more appealing option.
    - **Material recycling**. This is the R-cycle strategy which consists of obtaining the materials from the battery. This way, they can be used in the material production process reducing the need to extract raw materials from nature.
    - **Disposal**. It refers to the process of getting rid of the battery in a proper and responsible manner. This is the worse option in terms of sustainability, so it is chosen when none of the previous ones can be implemented.

3.2.1 AS-IS scenario

At this time, most EV batteries are not being repaired nor remanufactured. Instead, the focus is on both direct reusing them for secondary applications and improving the recycling processes, which are not optimizing yet for obtaining the components of the batteries. In particular, the main interest of recycling is in critical minerals like lithium, nickel, and cobalt, to use them in the production of new batteries. When it comes to repairing or remanufacturing, it has not reached large-scale adoption yet.

One of the reasons is the economic viability of the remanufacturing. Remanufacturing batteries to restore their full capacity is more costly and complex than simply recycling the materials. However, there are a few initiatives focusing on battery repurposing, although nowadays the EV-batteries are only being directly repurposed, without complete disassembling. For instance, EV batteries that are no longer suitable for vehicle use are being directly repurposed for energy storage solutions in homes or grid systems. These applications do not require the full performance of a new EV battery, and they extend the battery's lifecycle before recycling. The other main reason for the absence of remanufacturing in EV-batteries is the lack of standardization and logistics. There are still many challenges with setting up efficient systems for battery return, tracking their condition, and determining which batteries are worth remanufacturing. This lack of standardization makes it difficult to scale remanufacturing operations. Considering the current direct repurposing and recycling processes, the workflow for the AS-IS scenario is in Figure 13.

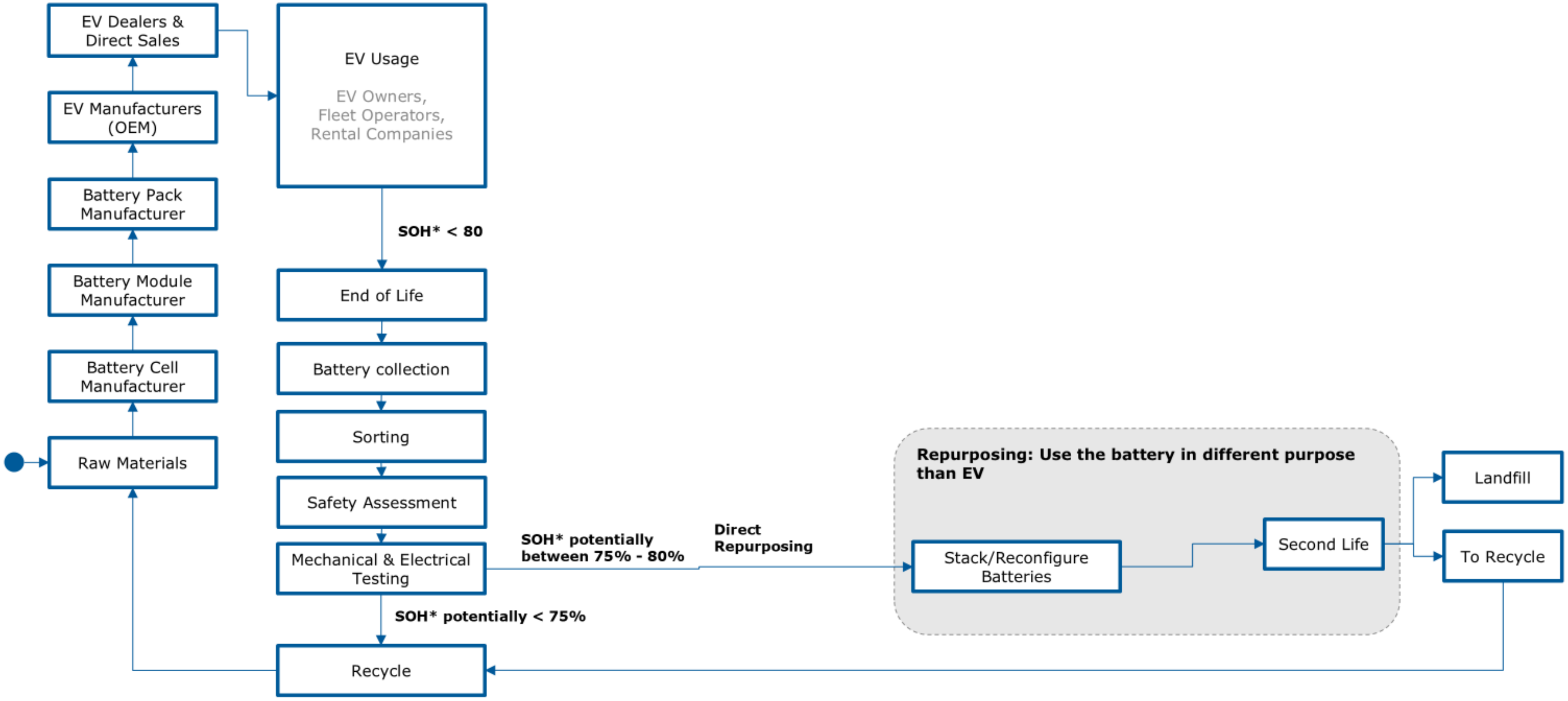


Figure 13. Workflow for demo-case 2: AS-IS scenario.

Figure 13 workflow shows that, after completing the manufacturing and usage phases outlined earlier, an EV-battery enters its End-of-Life stage when its State of Health (SOH) is below 80%. At this point, after going through some tests, it can either be recycled or directly repurposed, depending on the SOH estimation of the battery pack. Specifically, if the SOH is below 75%, the EV battery is sent for recycling. If the SOH is above this level, the battery is sent to direct repurposing.

The current process for direct repurposing EV-Batteries contains the next steps:

- **Stack/reconfigure batteries**. The new configuration of the battery is defined taking into account the second life needs, including voltage, capacity, power and fitting in a different space. Once the configuration is clear, the old EV-batteries are stacked or reconfigured depending on the requirements.
- **Second life**. This refers to the second use phase of the batteries. These second life batteries are usually used either in a Battery Energy Storage System (BESS) or for photovoltaic applications.

3.2.2 TO-BE scenario

The proposed scenario aims to enhance the state of the art (SoA) of EV battery end-of-life management by incorporating digital technologies for evaluation, with an emphasis on anomaly detection. Furthermore, the disassembling/assembling process will be more automated using the SD35 screwdriver, that although is already available in the market, it will be upgraded and adapted in R3-Mydas project with precise pressure control to both prevent damage to battery cells while ensuring a correct disassembly and have more control to automate cell dismantling process.

These improvements will reduce the time needed for the dismantling process and making it safer for workers and environment. In result, they will also allow reusing and repurposing to be more viable options, enlarging the EV-batteries lifespan. The workflow of the TO-BE scenario will be the one in Figure 14.

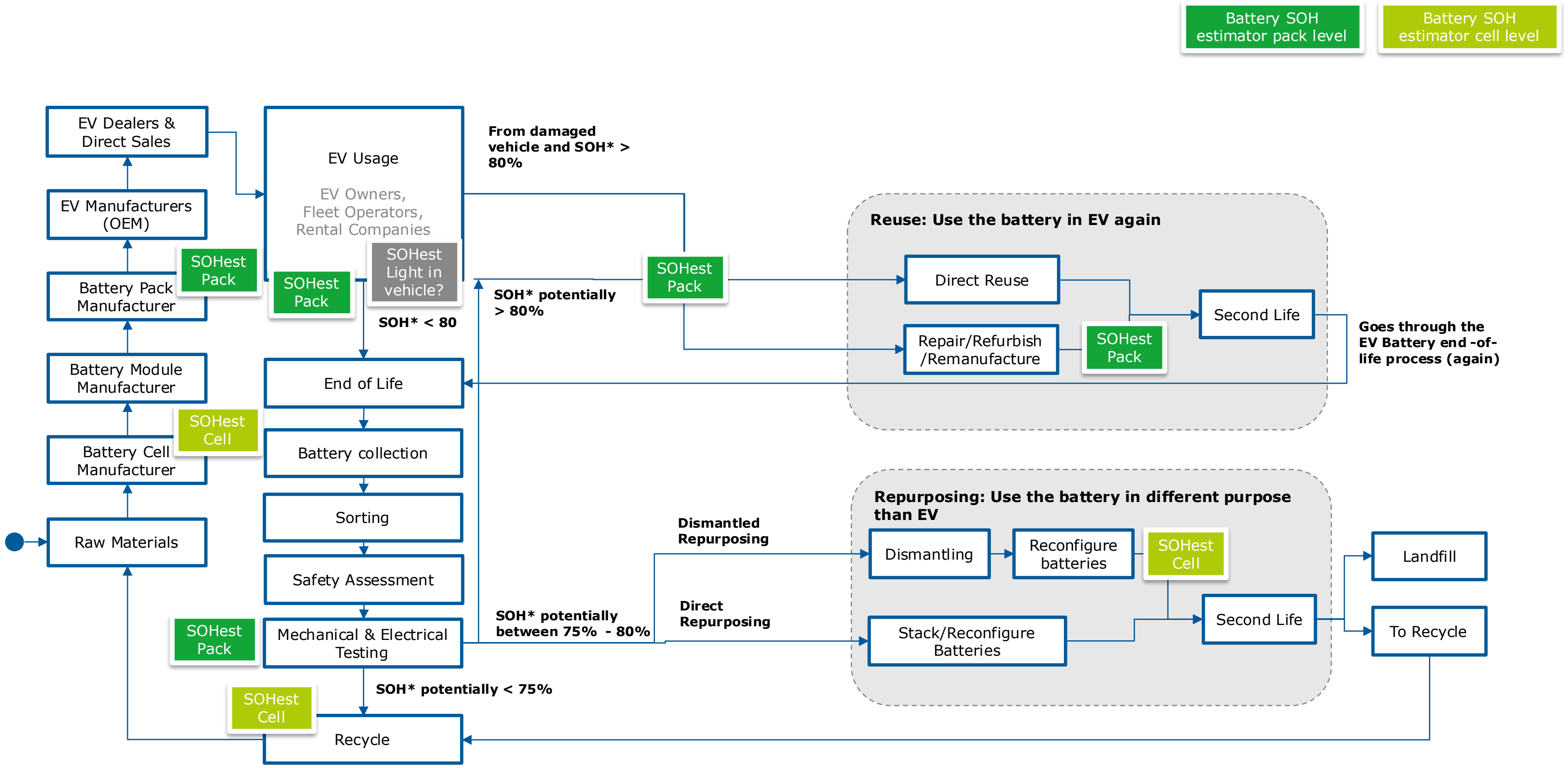


Figure 14. Workflow for demo-case 2: TO-BE scenario.

As shown, the workflow for the TO-BE scenario builds upon the AS-IS scenario workflow by adding additional options after the first use phase of the EV batteries. Therefore, there are several different possibilities:

- **SOH potentially > 80%: Reusing**. When an electrical vehicle is damaged, but its battery remains unaffected or the EV-battery ends its usage phase with potentially more than 80% of its SOH, the EV-battery is proposed for reusing in EV. At this point, there are two different options depending on the SOH estimation of the battery pack:
  - **Direct reusing**. This consists of taking the EV-battery pack outside of the old vehicle and directly installing it in another one. This is done when the SOH estimation for the whole battery pack is considerably high.
  - **Repairing, refurbishing or remanufacturing**. When the SOH of the battery pack is lower but over 80%, it is sent to a minimum repairing phase. Then, it is carried out again the SOH estimation for ensuring that the repaired battery is suitable for the EV industry. Finally, it is assembled in the new vehicle.
- **SOH potentially between 75 – 80%: Repurposing**. As well as it happened in the AS-IS scenario, when an EV-battery reaches the EoL stage and its pack SOH estimation is between 75 and 80%, after going through some tests, it is proposed for repurposing. However, in the TO-BE scenario there are two types of repurposing:
  - **Direct repurposing**. This is the one present in the current state of the art. As it was explained in the previous section, it consists of reconfiguring the old batteries, taking into account the requirements of the second life (usually BESS or photovoltaic uses). Then, the battery is installed.
  - **Dismantled repurposing**. Another option is the dismantled repurposing. Here, thanks to the automation provided by the enhanced SD35 screwdriver, the old EV-battery can be easily dismantled to cell level. In this way, it is possible to perform an SOH estimation of every cell in the battery and reconfigure them for being suitable for the second life usage. Finally, the battery pack is assembled.
- **SOH potentially < 75%: Recycling**. If the battery SOH estimation is below 75%, it is directly sent to the recycling process.

3.3 Demo case 3: wind turbine gearboxes

Wind energy plays a crucial role in the global energy transition, offering a sustainable and increasingly cost-effective alternative to fossil fuels. As the world faces the urgent need to reduce greenhouse gas emissions, reduce non-renewable energy and combat climate change, wind power provides a clean source of electricity that significantly lowers carbon footprints. Additionally, with advancements in turbine technology and efficiency, wind energy is becoming more accessible, scalable, and competitive in both onshore and offshore markets.

However, wind turbines typically have a lifespan of 20 to 30 years, and at the end of that period, the components, including blades, gearboxes, and nacelles, need to be managed. Unfortunately, materials like fiberglass and composite resins used in turbine blades are not easily recyclable due to the lack of efficient recycling technologies, leading to substantial waste that ends up in landfills.

When it comes to the gearbox components, like bearings, gear wheels and joints, the capacity for remanufacturing them is still limited. Some efforts are being made to repair or adapt used parts for new designs, but there is significantly needed to develop repair technologies for specific parts. Besides, many wind farms replace components like bearings or gearboxes during ongoing maintenance even when they could be repaired or reused, which leads to unnecessary waste.

R3-Mydas focuses on enhancing the remanufacturing of gearboxes. As detailed in deliverable D4.1, the proposed innovation aims to improve the remanufacturing process for three key components of the gearbox. This will be achieved by using updated technology to remove the worn sections of the components, effectively obtaining the remanufactured parts that can be either integrated into a new design or used in the original gearbox. Additionally, the process will involve the use of additive manufacturing and the application of coating techniques and heat treatments, which will enhance the component's strength and wear resistance.

The new value chain proposed for this demo case is shown in Figure 15. As well as in the other demo cases, it is structured in two different parts:

- There is the classic linear process (the one in black colour), which includes the whole process for producing a new gearbox made out of raw materials and the disposal right after getting to the End-of-Life phase.
- There are the circular economy strategies (shown in green) proposed for turning the classic process into a more sustainable one. These R-cycles are reuse, remanufacturing and recycling, depending on the state of the deteriorated gearbox component.

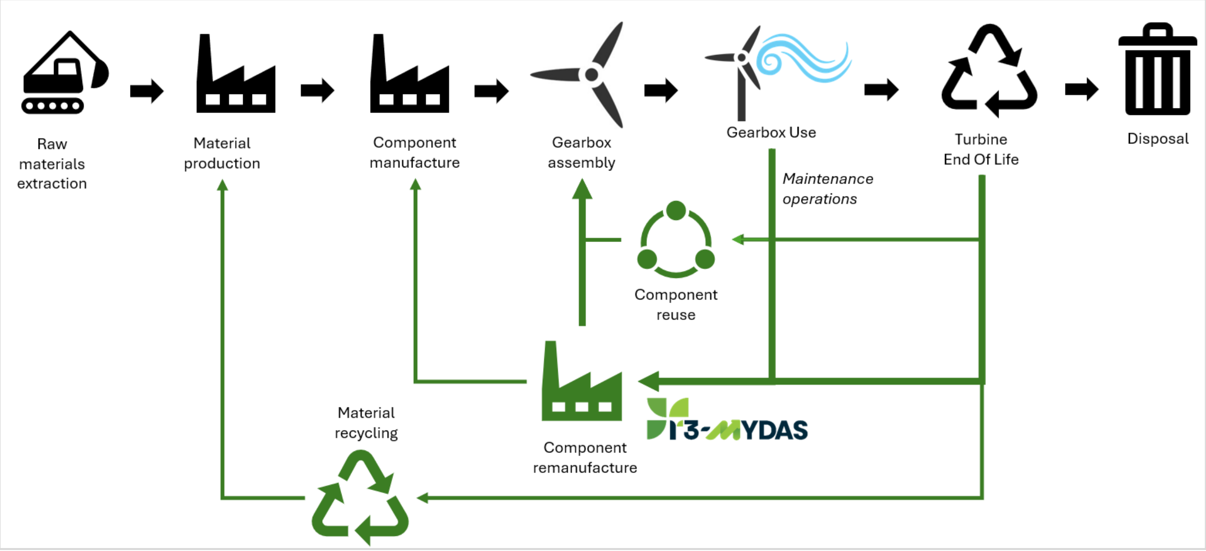


Figure 15. New value chain for demo case 3: wind turbine gearboxes.

It contains the next phases:

- **Raw materials extraction**. It consists of getting natural resources from the Earth and extracting from them the materials needed for the material production.
- **Material production**. This is the stage in which the raw materials turn into the different materials that will be used to create the components in the gearbox, like steel alloys, aluminium, copper, neodymium and dysprosium.
- **Component manufacture**. The different components that form the gearbox are made during this phase, using different processes, like metal casting, forging, machining, and heat treatment to shape and strengthen the material.
- **Gearbox assembly**. In this phase, all the finished components, like journal bearings, joints and gear wheels, are put together to obtain the finished gearbox.
- **Gearbox use**. This phase refers to when the wind turbine, with the gearbox installed, is generating energy. During this time, maintenance operations are carried out, which are essential for extending the gearbox's lifespan. However, a common practice today involves replacing certain gearbox components with new ones, even when the existing components show little to no damage. This approach leads to an increased demand for raw materials, making it a practice that needs to be reconsidered.
- **Gearbox End-of-Life**. At this point, the gearbox is no longer operating, so an evaluation of the different alternatives for the gearbox components must be done. The main alternatives are the next:
  - **Component reuse**. If any of the gearbox components were in good condition at its EoL stage, they could be reused without any repairing in industry. It would only be needed the disassembly, testing and assembly processes.

  - **Component remanufacture**. When some of the gearbox pieces need repairs due to wear, either at their EoL stage or during the maintenance operations in the use phase, they can be fixed so they are usable again. This is the stage in which R3-Mydas is focusing on. In this way, improve the remanufacturing process will turn this option into a more attractive one, preventing the good enough old gearbox components to go into the recycling process or disposal.
  - **Material recycling**. This is the R-cycle strategy which consists of obtaining the materials from the gearbox. This way, they can be used in the material production process instead of extracting raw materials from nature.
  - **Disposal**. It refers to the process of getting rid of the gearbox in a proper and responsible manner. This is the worse option in terms of sustainability, so it is chosen when none of the previous ones can be implemented.

3.3.1 AS-IS scenario

Today's circular economy referred to wind turbine gearboxes focuses more on recycling materials than on reusing or remanufacturing entire components. This requires energy intensive processes to recover materials and create new parts. Although recycling allows to reduce the need of raw materials, it retains much less value compared to reusing and remanufacturing, which can extend the lifespan of components and reduce the need for gearbox components.

When it comes to remanufacturing, it is somewhat implemented in the gearbox industry, but it is primarily focused on minor wear at gear flanks and regrinding visible defects. However, reusing gears or bearings has not been common practice. In fact, even functional, undamaged bearings are typically replaced during maintenance as a safety precaution, given that the cost of removing and reinstalling the gearbox can sometimes equal the cost of a new one.

As it was commented before, the R3-Mydas project will address the remanufacturing process of three of the different components in the wind turbine gearboxes: journal bearings, gear wheels and joints. Together, they represent the main causes of failure, offering the greatest potential for extending product lifecycles and enhancing circularity. Therefore, the Figure 16, which shows the workflow for the AS-IS scenario of the demo case 3, includes the different technologies used in the current remanufacturing process for each component.

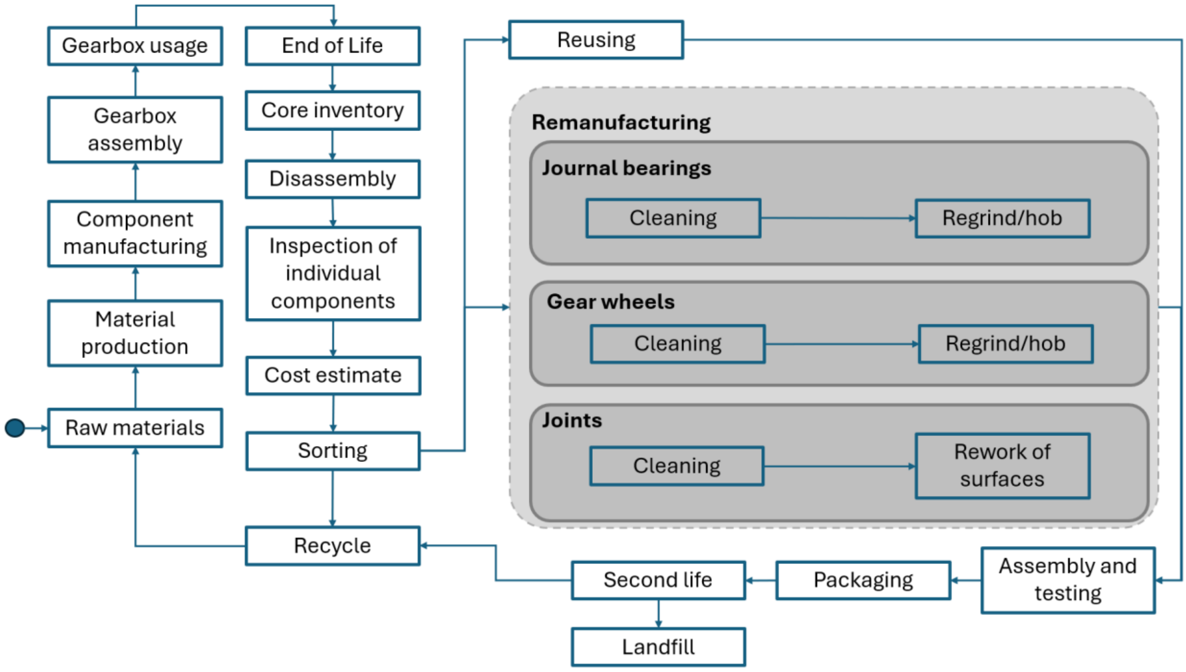


Figure 16. Workflow for demo-case 3: AS-IS scenario.

This workflow shows that, after going through all the manufacturing and usage phases previously described, when a gearbox reaches its End-of-Life stage, it goes through the next phases:

- **Disassembly**. It is necessary to disassembly the gearbox in order to obtain all the different components.
- **Inspection of individual components**. Every component must be thoroughly inspected to allow the economical evaluation of each possibility to be carried out.
- **Cost estimation**. The estimated cost of reusing, remanufacturing and recycling will affect the decision of which process is going to go through each component.

After this, the different components are sorted depending on the chosen process, being reusing a non-common option.

The current processes for remanufacturing the three key components in wind turbine gearboxes are the following ones:

- **For both journal bearings and gear wheels**, the first step is cleaning the piece. This will ensure that all oil, grease lubricants, or metal shavings are removed, which could otherwise prevent proper remanufacturing. The second step is either regrinding or hobbing, depending on the needs of the component. Regrinding is commonly used to address defects like pitting and involves using grinding tools to smooth the surfaces and restore the piece to their original specifications. When it comes to hobbing, it is a machining process used to create gear teeth.

- **For the joints**, the first step is cleaning too. Due to the fact that the joint surfaces might be worn, or corroded over time, reworking these surfaces is the second step. It involves techniques like grinding, polishing, or applying coatings to restore the proper shape and the dimensional accuracy of the joints.

Before the component is given a second life, either after having chosen remanufacturing or reusing, it has to be assembled in the gearbox and testes, to ensure that it works properly. Then, it is packed and ready for its second life.

3.3.2 TO-BE scenario

The main objective of the TO-BE scenario for the demo case 3 is improving the current remanufacturing process of the wind turbine gearboxes. Particularly, R3-Mydas focuses on three key components of the gearboxes: journal bearings, gear wheels and joints, introducing specific new technology to be developed for each one.

These improvements will enlarge the remanufactured gearboxes lifespan, mitigating specific problems and, therefore, minimizing future failure rate. Thus, the remanufactured gearboxes will turn into a more competitive option, causing a reduction in raw material needs, energy needs and waste. The workflow for the proposed scenario will be the shown in Figure 17.

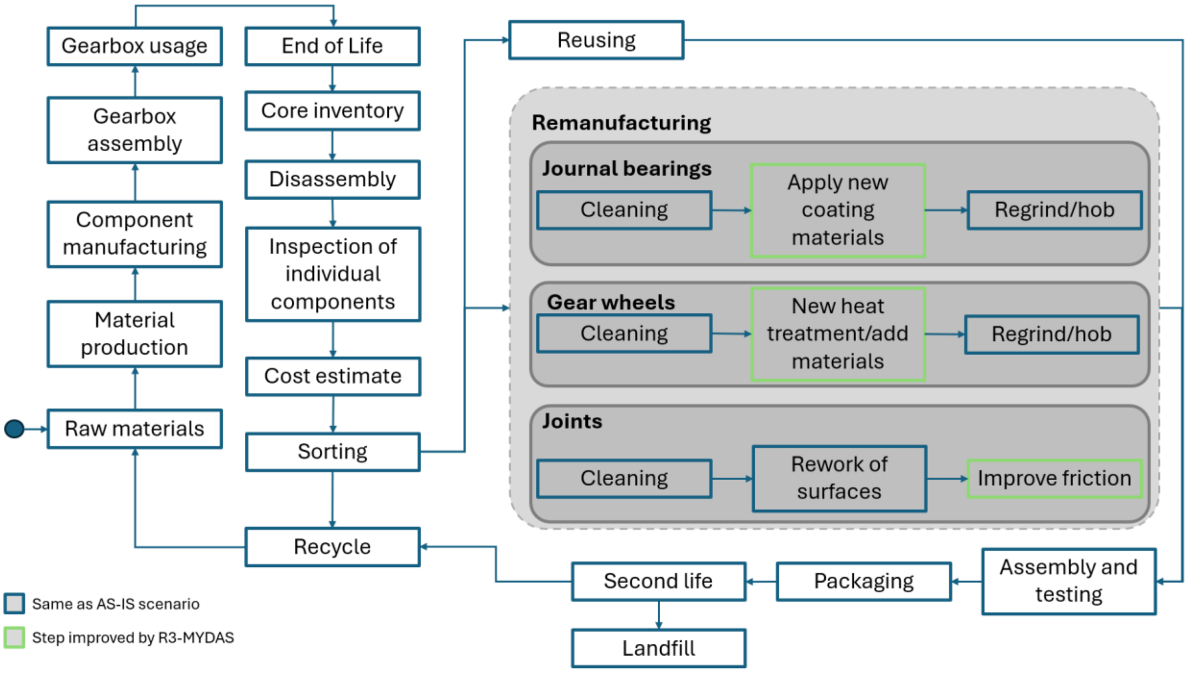


Figure 17. Workflow for demo-case 3: TO-BE scenario.

As shown, in the remanufacturing process, the workflow of the TO-BE scenario only adds to the AS-IS scenario one step further with a specific new technology to be developed and applied to each key component in the gearbox. Additionally, each one will be associated with a separate testing setup.

The added steps are the following ones:

- **For the journal bearings**, between the cleaning and the regrind or the hobbing steps, there is proposed applying new coating materials.
- **For the gear wheels**, it is suggested that, after the cleaning step, the component goes through a heat treatment and, if necessary, new materials will be added using additive manufacturing (AM).
- **For the joints**, there will be a final step which seeks to improve friction, either applying coatings or using friction inserts.

By incorporating additive manufacturing, heat treatments, and additional coating processes, the component gains enhanced strength, increased resistance, and improved wear durability. When it comes to the friction inserts, they are based on hard particles which are placed between the two joining parts. They increase the static friction coefficient and allow higher torque to be transmitted, while reducing noise and vibrations.

4 Demo-case I

4.1 Sustainability analysis framework

In order to assess the impact of the new circular value chain in comparison with other alternative scenarios, a **cradle-to-cradle analysis** will be performed, considering the main input the damaged crankshaft and the raw materials and energy needed to perform each process. In this way, it is expected to compare these three different scenarios by the end of the project:

- **AS IS scrap scenario:** The End-of-Life crankshaft is directly sent to steel scrap recycling to recover the material. This scenario does not consider any type of remanufacturing, so it is needed a new crankshaft to substitute the damaged one.
- **AS IS repair scenario:** The damaged crankshaft is repaired using the current laser cladding. Then, it is given a second life in the oil&gas plant.
- **TO BE R3-Mydas scenario** (results expected at the end of the project, D5.3): The End-Of-Life crankshaft is repaired through the new laser cladding process, utilising all the tools developed in the R3-Mydas project. The repaired crankshaft will have a second life in the oil&gas plant.

The Functional Unit considered for the LCA was defined as **one damaged crankshaft**.

The SimaPro 9.6[16] software, developed by Pré-Consultants was used to calculate the different life cycle analyses. The database selected was Ecoinvent 3.10[17], and the method selected for the calculation was EF3.1, which includes the impact categories described in Table 2.

4.2 Life cycle inventory (LCI)

In this section, it will be described the considered LCI for each assessed scenario. Specific transport of intermediate flows and products have not yet been considered, as this is a preliminary study. Nevertheless, in this study uses inputs for Ecoinvent that take into account average European distance for materials transport impacts. However, in deliverable D5.3 could include a sensitivity analysis on this aspect.

---

[16] Pré-Consultants SimaPro 9.6, version 9.5; Product Ecology Consultants; PRé Consultants B.V.: Amersfoort, The Netherlands, 2018.

[17] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230.

4.2.1 AS-IS repair scenario

The main input for this scenario is the EoL crankshaft, which is made of steel. To simplify the analysis, and due to the absence of data from the manufacturing process (as it is out of the scope of the project), the amount of raw material will be considered by applying a factor of 1.5 to the final weight of the component.

Additionally, a generic metalworking process from the Ecoinvent database will be used as the manufacturing process, and data from griding process in TCOMAS was used to estimate the cost. Besides the crankshaft, it is considered that this manufacturing process generates iron scrap as well, which is a recyclable co-product.

In this scenario, when the crankshaft reaches its EoL stage, the damaged crankshaft goes through a repairing process using the current laser cladding technique. For this process, it is needed a cobalt alloy and a protective gas (argon) as input materials. Data were obtained from TCOMAS current process.

Lastly, the equipment needed for the repair process is considered based in TCOMAS production facilities, such as powder feeder, laser, grinding machine and anthropomorphic robot. Their information includes operation time, energy consumption, cost and lifetime, as this data required for both the LCA and LCC.

4.2.2 AS-IS scrap scenario

In the AS IS scrap scenario, the manufacturing of two components was considered in order to replace the first damaged crankshaft with a second one. Therefore, the raw material and energy needs as well as the steel scrap produced will be the double of the ones in the AS-IS repair scenario.

4.3 Results

4.3.1 LCA

The main impacts of AS IS repair scenario are shown in Figure 18. In most of the categories analysed, crankshaft manufacturing is the main impact, followed by the additive manufacturing repair process. When it comes to final grinding or post-grinding operations, they account for less than 0.1% of total impact and recycling of scrap in the end-of-life operations less than 0.4%.

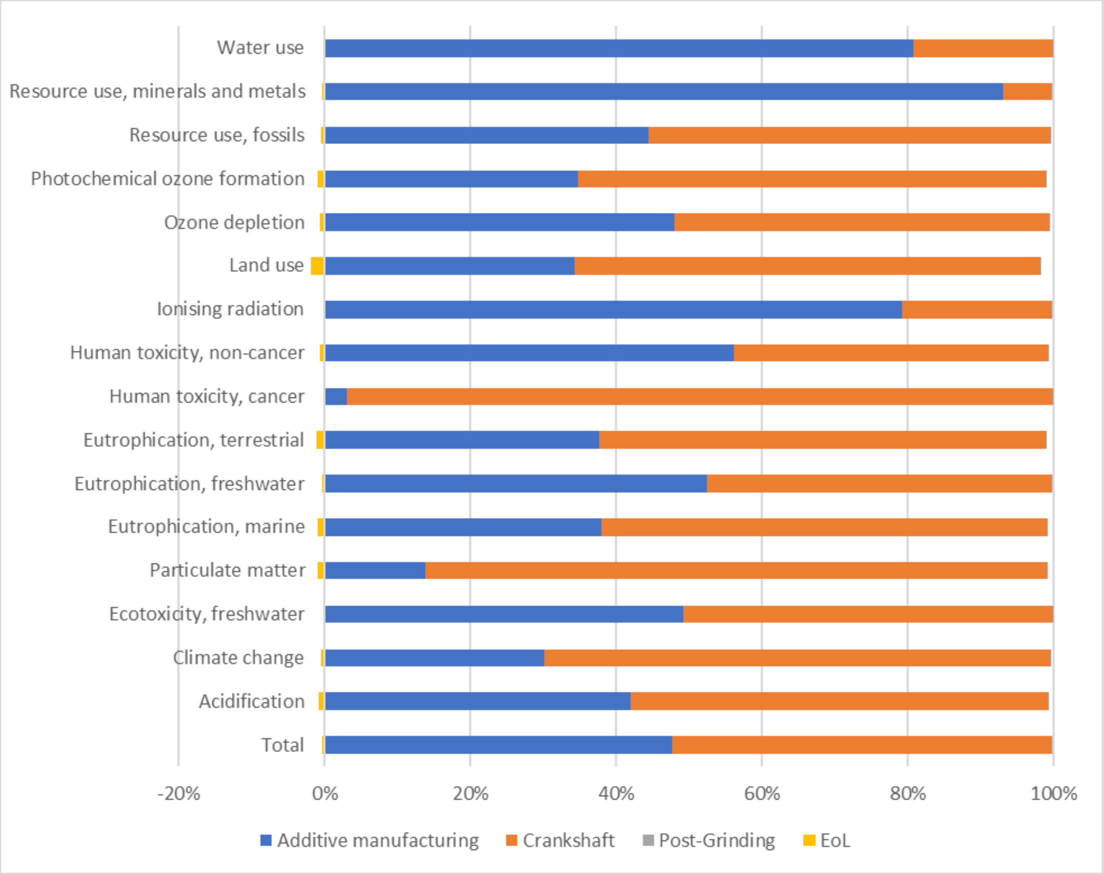


Figure 18. AS IS repair scenario impact for different inputs.

The high impact of cobalt in the Stellite alloy used in AM, since it accounts for more than 37% in Endpoint analysis and 10% in the carbon footprint. Nevertheless, the crankshaft manufacturing process is environmentally more harmful than additive manufacturing, either in terms of endpoint or carbon footprint.

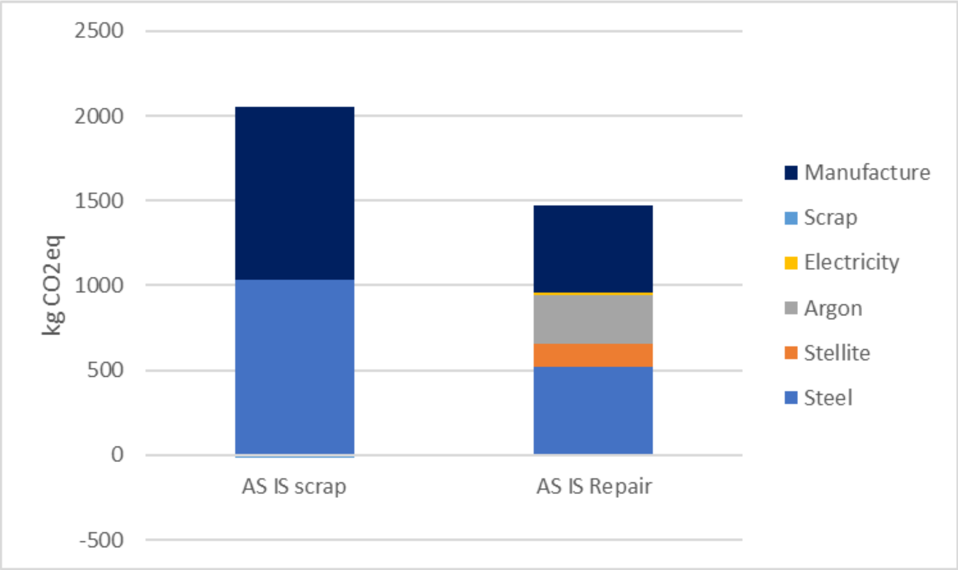


Figure 19. Comparison AS IS scrap and AS IS repair scenarios, carbon footprint.

Comparing AS-IS repair to AS-IS scrap scenarios, as shown in Figure 19, demonstrates that the AS-IS repair scenario delivers a better outcome. The carbon footprint reduction exceeds 25%, while the improvement in Endpoint is less than 5%. The minimal Endpoint improvement is due to the significant impact of cobalt in the resource use of the AS-IS repair scenario.

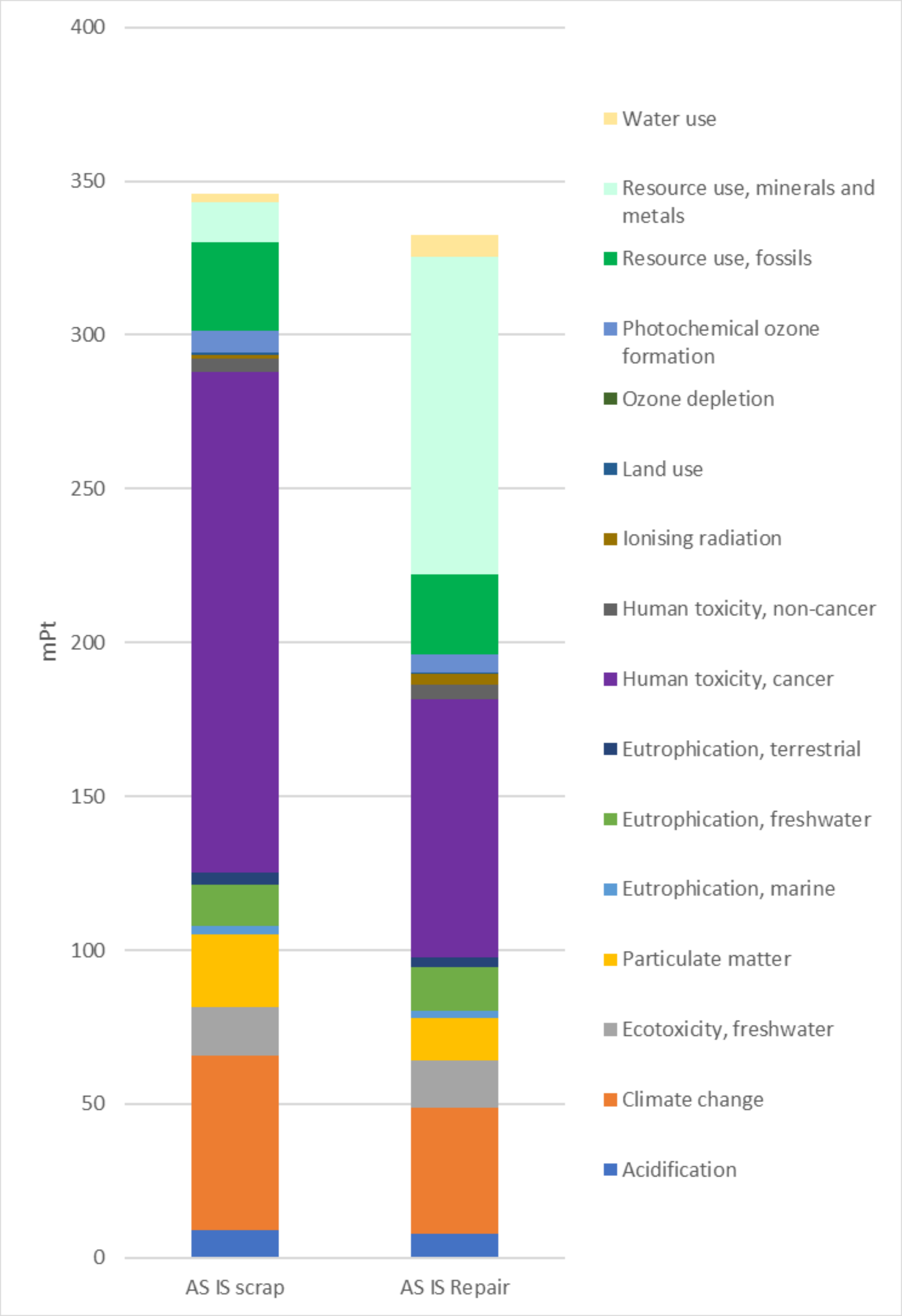


Figure 20. Comparison AS IS scrap and AS IS repair scenarios, Endpoint and different impact categories.

In Figure 20 expressed in milipoints (mPt), it is exposed the comparison between the AS-IS repair and AS-IS scrap scenarios, detailing each impact category. In the AS-IS repair scenario, the 'Human toxicity: cancer' category has had the greatest influence in terms of reducing environmental impact. On the other hand, the 'Resource use: minerals and metals' category has greater impact in the AS-IS repair scenario because of the cobalt present in the Stellite alloy used, as previously mentioned.

4.3.2 LCC

In the LCC analysis for the AS-IS repair scenario, if environmental costs are not considered, the primary impact is the labour cost in crankshaft manufacturing (36%), followed by the raw material (Stellite) costs in the repair process (16%). However, if environmental costs are taken into account, they become the main cost driver (48%).

Figure 21 compares AS-IS scrap and AS-IS repair scenarios, both with and without considering the environmental cost, which represent almost 50% of the total cost in each case. In addition to environmental cost, labour and steel are the primary costs in both scenarios, which are lower in AS-IS repair scenario. In fact, the total NPV for the AS-IS repair scenario is 25% lower than for AS-IS scrap.

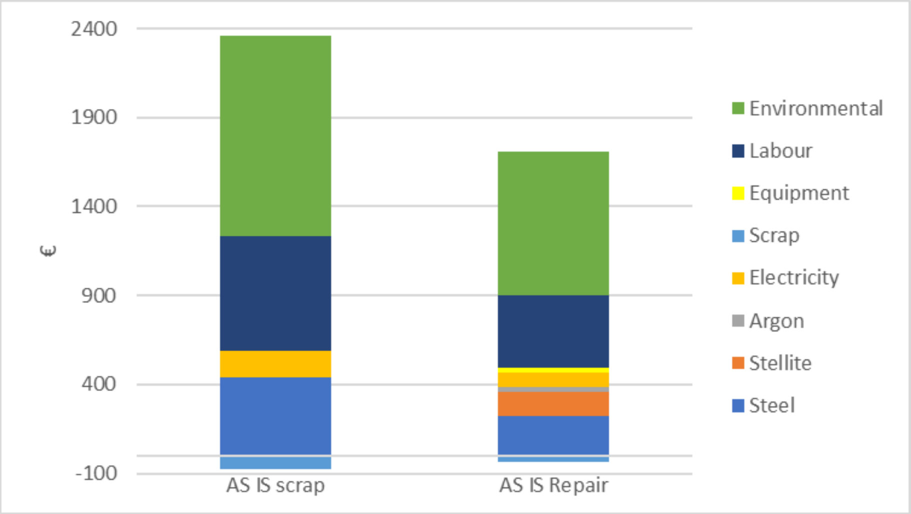


Figure 21. LCC results comparison for AS IS scrap and AS IS repair scenarios.

5 Demo-case 2

5.1 SSbD analysis framework

5.1.1 Sustainability analysis framework

When it comes to the sustainability, it will be performed a **cradle-to-cradle analysis** to allow the new circular value chain to be assessed. The inputs will be the EoL battery, and the different materials and energy required to each scenario. The three scenarios that are expected to compare by the end of the project are the next:

- **AS IS scrap scenario:** The End-of-Life battery is directly sent to hydrometallurgical recycling to recover materials. This scenario does not consider reuse, repairing nor remanufacturing, so instead of giving the damaged battery a second life, it is produced a new battery.
- **AS IS repurposing scenario:** The EoL battery modules are rearranged for giving the battery a second life with another purpose, either as battery energy stationary storage (BESS) or in photovoltaic applications.
- **TO BE R3-Mydas scenario** (results expected at the end of the project, D5.3): The End-Of-Life battery is reused, repaired or repurposed, depending on the SOH estimation and using all the digital tools developed in the R3-Mydas project. Then, the battery will have a second life, either as an EV-battery or in another application.

The Functional Unit considered for the LCA was defined as **the nominal capacity of 1 kWh LIBs**.

The SimaPro 9.6[16] software, developed by Pré-Consultants was used to calculate the different life cycle analyses. The database selected was Ecoinvent 3.10[17], and the method selected for the calculation was EF3.1, that includes the impact categories described in Table 2.

5.1.2 Safety analysis framework

In order to assess the safety of the "*Remanufacture*" scenario included within the TO BE R3-Mydas scenario, a qualitative safety assessment will be carried following the three steps methodology described in JRC guidelines for SSbD.[3]

The Step 1 of safety assessment is focused on evaluating the chemicals involved in the processes to identify potential risks for workers and the environment that could arise while using them. In order to complete this step, it is necessary to collect an inventory in which all the chemicals or materials involved in the processes could be identified along with their toxicity (e.g. carcinogenicity, mutagenicity or reproductive toxicity) and ecotoxicity (e.g. effect on aquatic life, bioaccumulation or persistence).

Complementary, the Step 2 is focused on determining the exposure assessment. In an exposure assessment is essential to determine who (target of exposure), how, where, and to what extent people or the environment will encounter a specific hazardous chemical. So, while the Step 1 identifies the intrinsic toxicity of a substance, the Step 2 evaluates the real risks of using this substance in the processes by considering the dose, duration, and different exposure routes. To complete the Step 2, it is necessary to provide reliable data about concentrations and doses that could be quantified. However, it is possible to complete a qualitative second step only describing some of the points above-mentioned.

Finally, the Step 3, is focused on evaluating the human health and environmental aspects in the use phase. Therefore, as the "*Remanufacture*" scenario will not include the later use phase, this step will be unnecessary to complete the assessment.

5.2 Qualitative Safety Assessment

The remanufacturing scenario is described in the EoL scenario **TO BE R3-Mydas**. It is supposed to be carried out when the estimated State of Health (SoH) of some packs is between 75 and 80%. As there is not a complete description of the new remanufacturing process, as it is under development, the bibliography was used to fill in the gaps in the information provided by AVL. Therefore, a coherent workflow based on some assumptions and not considering economic aspects will be proposed before starting the assessment, based on the information provided by AVL and included in deliverable D3.1.

5.2.1 Remanufacturing scenario description

Owing to the enormous structural complexity of an EVB, in this preliminary analysis it was decided to focus the remanufacturing process only in the electric parts: the packs containing the cells and other electric components, the high voltage wires or other accessories like fusels. Components like the BMS system or the casings are supposed to last the two life cycles. In the case of the cooling system, the necessity of substituting or recharging it during remanufacture is not yet clear, so we prefer to not include it in the process.

An easier remanufacture process could be substituting the fully packs when they do not reach the desired SoH (75-80%). However, it would be more interesting to model a more complex process in which the workers replace the cells inside the packs. The damaged cells are sent to be recycled but, as other EoL scenarios are considering this process, this process will not be studied within the "*Remanufacturing*".

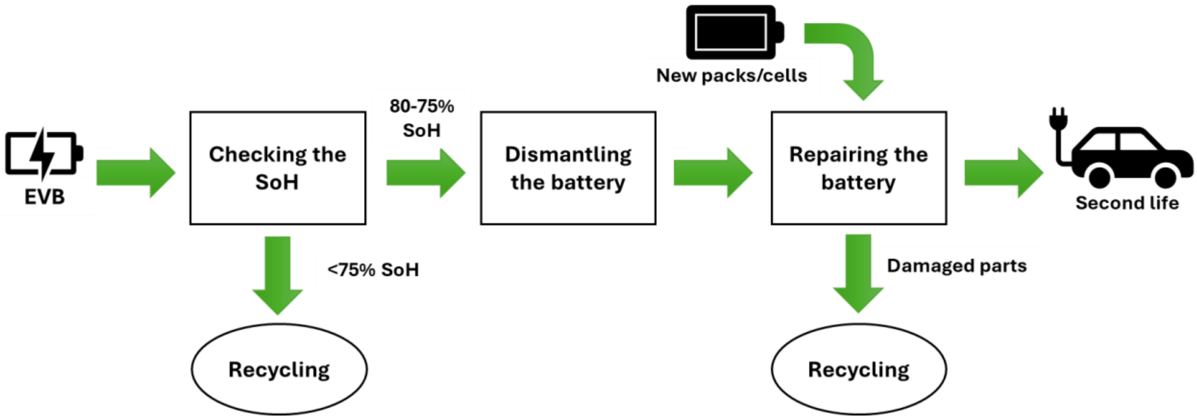


Figure 22. Workflow of the "Remanufacturing" scenario for the EVB considered for the safety by design analysis.

Therefore, the process starts transporting the battery to the remanufacturing facility. At this point, the battery could have a remaining charge so, before handling it, it is discharged powering electric systems within the facilities. Then, the SoH is checked using the BMS system (Figure 22, *Checking the SoH*) and if the battery is in the desired interval (75-80%), it continues the workflow. If not, it is sent to other facilities to continue through different scenarios (Figure 14).

Following that, the battery is disassembled by unscrewing the outer and inner casings to access the packs. Although this process is currently made manually, R3-Mydas will implement a screwdriver automate. After the first dismantling, it is possible to replace the full pack or some damaged electronic components (e.g. wires, fusel), if it is required.

The packs are composed by a series of modules, which, in turn, contain the lithium-ion battery cells connected in parallel and in series. At this point, having access to the cells, it is possible to check directly their SoH. Then, detaching the cells from the module is the next step. Owing to the wide variety of cells shapes this is probably the most challenging process of the remanufacture. For example, in case of using cylindrical cells, they are fit in a metallic support and glued together using different adhesives like epoxy resins, that must be removed to replace the damaged cells (Figure 22, *Dismantling the battery*).

Afterwards, the EVB is repaired substituting the damaged electronic components and lithium-ion battery cells by new ones that have to be glued in the metallic support (with adhesives, like epoxy resins). Finally, the EVB battery was manually assembled using the same casings and installed in a new EV to begin a second use phase (Figure 22, *Repairing the battery*).

5.2.2 Step 1: Hazard assessment of chemical/materials.

The "*Remanufacturing*" scenario only requires the use of chemicals to detach or attach the cells into the modules but, unfortunately, in this stage of the project adhesives or removal solution are not considered in order to simplify the analysis. Therefore, the only materials that will be considered in the Step 1 are the chemicals contained in the battery cells and the metals or polymers used in the battery cell casing, since it is necessary to check if they will remain inert in contact with these chemicals.

To complete the hazard profile of a chemical, there are four main strategies: searching in list of chemicals covered by legislation and regulatory documents, searching in lists covering potentially hazardous chemicals (i.e. the SIN-list), conducting in vitro assays for toxicity, and predicting the hazard profile with *in silico* model like QSARS[18] or read-across approaches like VERA[19]. Herein, the CLP European regulation[20] is used to make a preliminary check of the hazard profile of the chemicals.

For the inner part of the lithium-ion battery cell:

- Lithium nickel manganese cobalt oxide (NMC oxide), used to prepare the cathode, is a mixed black oxide with a melting point over 290 ºC that may cause allergic skin reactions (H317) and is suspected of being a carcinogenic agent (H351). It is considered not persistent, bioaccumulative or toxic (PBT) and not endocrine disruptor at levels of 0.1% of higher.
- Graphite, used to preparate the anode, a dark grey powder with a very high melting point (<3600 ºC) that is not suspected of being hazardous.
- Polyvinylidene fluoride (PVDF), a polymer used to bind between the cathode oxide to the current collector with the appearance of a white powder, not suspected of being hazardous.
- Lithium hexafluorophosphate ($LiPF_6$), an off-white powder with a high melting point used as electrolyte salt. It could be toxic if is swallowed (H302) or is absorbed through the skin (H311) and causes severe burns if enters in contact with skin or with eyes (H314). It is not considered PBT or endocrine disruptor.
- Ethylene carbonate (EC), an electrolyte that is solid at room temperature (m.p. of 35-37 ºC). It is harmful if swallowed (H302), causes eye irritation (H319) and is especially toxic for the kidney (H373). It is not considered PBT or endocrine disruptor.

---

[18] Gozalbes, R., & Vicente de Julián-Ortiz, J. (2018). Applications of Chemoinformatics in Predictive Toxicology for Regulatory Purposes, Especially in the Context of the EU REACH Legislation. *International Journal of Quantitative Structure-Property Relationships (IJQSPR), 3*(1), 1-24. http://doi.org/10.4018/IJQSPR.2018010101
[19] Virtual Extensive Read-Across (https://www.vegahub.eu/vera-a-new-read-across-tool/)
[20] Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures.

For the casing of the lithium-ion battery cells:

- Aluminium alloy (AA) (<99%), considered not hazardous unless it is transformed in a thin powder, which is not expected to happen during the scenario.
- Polyethylene terephthalate (PET), considered not a hazardous substance.
- Polypropylene (PP), considered not hazardous as well.

All of these materials were described in the LCI and were considered in the LCA as well.

Alternatively, it was previously described in literature that during continuous redox processes dangerous gases are formed inside the lithium-ion battery cells. In the year 2020, Sung *et al.* studied the composition of these gases detecting H_2, CH_4, CO and even HF in the mixture.[21]

- Molecular Hydrogen (H_2), a colourless extremely flammable gas (H220) that could explode if the air concentration is higher than 4%. Not considered PBT or endocrine disruptor.
- Methane (CH_4), a colourless extremely flammable gas (H220) that could explode if the air concentration is higher than 5%. Not considered PBT or endocrine disruptor.
- Carbon monoxide (CO), a colourless flammable gas (H220) that could explode if the air concentration is higher than 12.5%, is toxic if inhaled (H331), could damage unborn children (H360D) and could damage the heart through repeated exposure (H372). Not considered PBT or endocrine disruptor.
- Hydrogen fluoride (HF), a yellowish liquid with acute toxicity via oral (H300), dermal (H310) or inhalation exposure (H330) and corrosive in contact with skin (H314) or eyes (H318). It is not considered PBT either.

Accidental exposition to these gases supposes one of the biggest hazards while working with EVB or battery cells. Indeed, some of them have very small OEL, like the HF with 1.5 mg/m^3.

To conclude the preliminary assessment of Step 1 in the "*Remanufacturing*" scenario, the risk only arises if the environment or specially the workers are accidentally exposed to the inner chemicals inside the cells, specially the NMC oxide used in the cathode, the electrolyte salt, the ethylene carbonate or the hazardous gases generated inside the battery cells.

5.2.3 Step 2: Exposure scenarios

According to ECHA guidelines, all the activities considered inside the assessed process could be considered *uses* (e.g. transfer a chemical between two containers) and when the *uses* are evaluated from an environmental perspective, they could be named

---

[21] Sun, P., Bisschop, R., Niu, H., & Huang, X. (2020). A Review of Battery Fires in Electric Vehicles. *Fire Technology*, *56*(4), 1361–1410. https://doi.org/10.1007/s10694-019-00944-3.

contributing scenarios (CS). A CS is defined in the JRC guidelines as a descriptor for each contributing activity within the identified use, e.g. transferring a chemical between two containers in a close loop system.[2, 22]

Therefore, the CSs could be understood as an attempt to organise the wide variety of activities performed in different industrial sectors in a limited, but representative, number of situations that could be collected in exposure scenarios (ES). The JRC methodological guidance for SSbD characterises the CSs using four types of descriptors depending mainly on the target exposure:

- *Process category* (**PROC**), used to describe the application techniques or process types, the operational conditions and risk management measures (RMM) to determine the level of occupational exposure for workers or professional users.
- *Environmental Release Category* (**ERC**), used to describe the broad conditions of use from an environmental perspective, based on the characteristics that give a first indication of potential release of the substance to the environment.
- *Product category* (**PC**) or *Article Category* (**AC**), both targeting the consumer. The **PC** is used to describe the type of chemicals products in which a substance is used (e.g. **PC9a**: coating and paints, that will be included in all the paintings but not describes the article itself), while the **AC** is focused on describing the type of article in which the substance has been processed (e.g. **AC13**: plastic articles, that will include all the chemicals used to prepare it).[3]

The "*Remanufacturing*" scenario must be understood as an industrial process without automatization, in which the target exposures are the workers and the environment. Hence, the **PROC** and **ERC** are the correct descriptors to define the CSs. In the 2023, Caldeira *et al.* tested the Safe and Sustainable by Design methodology guidance[2] in a plasticiser in food contact materials. In this example, the defined CSs are referred to **PROC2** (use in closed, continuous process with occasional controlled exposure), **PROC3** (Use in closed batch process like synthesis or formulation) or **PROC9** (Transfer of substances or preparation into small containers) among others, proving their effectiveness to represent chemical industry processes. In the case of **ERC**s, they use examples as **ERC1** (Manufacture of substances), **ERC2** (Formulation of preparations) or **ERC5** (Industrial use resulting in inclusion into or onto a matrix).[23]

---

[22] Guidance on Information Requirements and Chemical Safety Assessment, Chapter R.12: *Uses* description. Version 3.0, 2015.

[23] European Commission: Joint Research Centre, Caldeira, C., Garmendia Aguirre, I., Tosches, D., Mancini, L. et al., *Safe and sustainable by design chemicals and materials – Application of the SSbD framework to case studies*, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2760/329423.

Table 3. Contributing Scenarios defined for the three stages of "Remanufacturing" End-of-Life scenario, using the recently created PROCs 28-31.

	CS	***Name***	***New PROC***
Checking the SoH	**1**	Transporting heavyweight materials	**PROC32**
	2	Disassembling metallic materials used in presence of high voltages.	**PROC30**
Dismantling of the battery	**1**	Transporting heavyweight materials	**PROC32**
	2	Disassembling/assembling metallic materials used in presence of high voltages	**PROC30**
	3	Disassembling/assembling materials containing battery cells	**PROC31**
Repairing the battery	**1**	Transporting heavyweight materials	**PROC32**
	2	Assembling/assembling metallic materials used in presence of high voltages	**PROC30**
	3	Disassembling/assembling materials containing battery cells	**PROC31**
	4	Use of chemicals in industrial not-automatised processes	**PROC29, ERC8A**

Thus, according to the previous criteria, it was decided to divide the "*Remanufacture*" stages "*Checking the SoH*", "*Dismantling the battery*" and "*Repairing the battery*" (Figure 22) in different CSs. However, while doing this it was evident that ECHA's 28 **PROC**s are inefficient to describe scenarios in which not chemical agents are used, leading to catalogue almost all the CSs as **PROC0** (Other process or activity). The latest update, **PROC28** (manual maintenance of machinery), is only focused on cleaning or repairing the machinery, so it does exemplify the "Remanufacturing" processes either. If the current descriptors do not represent the analysed scenarios, we consider that it is necessary to create new descriptors, i.e. new **PROC**s. The new descriptor that we suggest are:

- **PROC29** - Use of chemicals in industrial not-automated processes (not cleaning or repair).
- **PROC30** – Disassembling/assembling metallic materials that could contain high voltages.
- **PROC31** – Disassembling/assembling materials containing battery cells
- **PROC32** – Disassembling/assembling or transporting heavyweight materials.

With this new PROCs, it is possible to summarize the three stages of "*Remanufacture*" in 4 types of CS with their own **PROC**s (Table 3). In the case of the **ERC** it was decided that only the CS 4 (*Use of chemicals in industrial not-automated processes*) might suppose a potential hazard for the environment, represented by the descriptor **ERC8A** (wide dispersive indoor use of processing aids in open systems).

5.2.4 Conclusions: qualitative risk assessment

With all the information gathered during Step 1 and 2 it is possible to define the risks and suggest risk management measures (RMM) for each CS. RMM could be defined as complementary safety measures that are implemented within the process to protect the workers' health or prevent environmental emissions. However, to decide whether they will be necessary the quantitative part of the Step 2 is required.

5.2.4.1 Worker's exposure and Risk Management Measures

CS 1 - Transporting heavyweight materials

The EVB weights around 450 Kg while the complete EV could weight around 2000 Kg. Therefore, transporting either the battery or the car to the "*Remanufacture*" facilities (or move it inside them) possess a substantial risk of accidentally dropping the weight.

To prevent accidental falls, we suggest the use of suitable vehicles and trained workers to transport such weights. Additionally, it is recommended to adapt areas solely used for this type of operations with the corresponding signalization. In the case of the initial transport of the battery to the facilities, it must be discussed whether is better to transport the entire EV and dismantle it in the factory in terms of profit and safety.

CS 2 - Disassembling/assembling metallic materials used in presence of high voltages

The EVB has a voltage between 400-800 V depending on the model and will be sent to the remanufacture facility with an uncertain level of remaining charge. This voltage is more than enough to kill a person. After the battery is discharged inside the facility, this risk is reduced but still considerable.

To prevent accidental electrocution, the use of insulating individual protective equipment must be mandatory in all the processes in which the full battery or the full packs are handled. It is also advisable to check the battery charge before handling it to verify the completion of the discharging process. Catching fire is another possible risk in this case of working with high voltages. Therefore, all the workers must be trained to act following fire protocols and to use fire extinguishers, which must be accessible while the related operations are being carried out.

CS 3 - Disassembling/assembling materials containing battery cells

Causing mechanical damage to the battery cells could expose the workers to their hazardous inner chemicals and, as it was described in the Step 1, among these chemicals there are substances of concern.

Therefore, we consider mandatory the use individual protective equipment (protective gloves, protective glasses, face mask and protective uniform) and performing all the disassembly, assembly, detaching or attaching processes in groups of at least two people with constant ventilation.

CS 4 - Use of chemicals in industrial not-automated processes

During the process of gluing or removing the glue of the battery cells, workers could be exposed to VOCs like the solvent used in the epoxy resin formulations or the additives used in the adhesive removal formulations. Again, the workers must be trained to do it safely and the use of individual protective equipment (protective gloves, protective glasses, face mask and protective uniform) must be mandatory.

5.2.4.2 Environment exposure and Risk Management Measures

In this case, as not chemical are used in the CS 1-3, we consider the "*Remanufacturing*" scenario will not suppose a serious environmental risk unless the very unlikely events of accidentally leaking the cell content or catching fire happens. Even in this case, the situation will be especially hazardous for the workers, but not for the environment if the facilities are correctly prepared.

The most hazardous environmental situation could arise during CS 4. In this contributing scenario, either while detaching or while attaching the cells, chemicals containing VOC will be required, providing continuous emissions of hazardous organic compounds. In this case, without so much information to provide a more complete assessment, we suggest the use of air extraction equipment that carry this VOC to special filters that prevent their emission as much as possible.

At the end of the project a more complete safety by design analysis will be performed considering the new R3-Mydas remanufacturing process for batteries. It is expected to include STEP3 in the analysis considering second life uses.

5.3 Life cycle inventory (LCI)

In this section, it will be described the considered LCI for each assessed scenario. Specific transport of intermediate flows and products have not yet been considered, as this is a preliminary study. Nevertheless, this study uses inputs for Ecoinvent that take into account average European distance for materials transport impacts. However, the final version could include a sensitivity analysis on this aspect.

5.3.1 AS-IS repurposing scenario

The LCA begins with the LIB, which, in this case, will be considered an NMC battery due to the fact that it is one of the most commonly used batteries in EVs. Furthermore, the data provided by AVL refers to a specific type of NMC cell: the one with a cathode of

$Li(Ni_{0.65}Mn_{0.19}Co_{0.15})O_2$. The gaps in the information provided by AVL were filled using literature.

The input components for this battery cell are housing, separator, copper current collector for anode, silicon coated graphite anode, aluminium current collector for cathode, cathode and electrolyte.

The equipment needed for the cell manufacturing includes a slot die coating machine with drying zone, NMP recovery, calendaring equipment and slitting equipment. Additionally, it is considered a generic injection moulding process for the polymeric part of the cell housing.

For standardization purposes, the complete battery pack is assumed to consist of 20 modules, each containing 10 cells. Additionally, the input materials that were considered for the modules, including cooling plates, casting, cell interconnection, SOC regulation and spacers are from Ma *et al.*, 2024[24]. For the battery pack, the material needs, considering accessories, BMS, coolant, and jacket are considered from the same reference[24].

When it comes to the energy of the modules and pack manufacturing, there are considered the welding and the injection moulding process for the jacket. Considering that the average specific energy of an NMC 622 battery is 150 Wh/kg[25], the manufacturing process for 1 kWh would be equivalent to that of 0.028 packs.

When the NMC battery reaches its EoL stage, in the AS-IS repurposing scenario, the battery pack is disassembled and then reassembled for its second life. No equipment or energy is considered in this process, as it is a primarily a manual operation. Additionally, there is not material inputs requirements. However, labour costs are taken into account, with an estimated need of 5 hours per pack[26].

At the end of the second life of the NMC battery, the battery cells are recycled following the hydrometallurgy recycling process, as this is the most widely used method of recycling for batteries[24].

On the other hand, the chemical reactions for the cathode are the following ones[24].

---

[24] Ma, R., Tao, S., Sun, X. *et al.* (2024). Pathway decisions for reuse and recycling of retired lithium-ion batteries considering economic and environmental functions. *Nat Commun* **15**, 7641. https://doi.org/10.1038/s41467-024-52030-0

[25] Saaid, F. I., Kasim, M. F., Winie, T. *et al.* (2024). Ni-rich lithium nickel manganese cobalt oxide cathode materials: A review on the synthesis methods and their electrochemical performances. *Heliyon*, *10*(1). https://doi.org/10.1016/j.heliyon.2023.e23968

[26] Lander, L., Tagnon, C., Nguyen-Tien, V. *et al.* (2023). Breaking it down: A techno-economic assessment of the impact of battery pack design on disassembly costs. *Applied Energy*, *331*, 120437. https://doi.org/10.1016/j.apenergy.2022.120437

$$Li(Ni_{0.65}Mn_{0.19}Co_{0.19})O_2 + \frac{1}{2}H_2SO_4 + \frac{1}{3}NH_3 \rightarrow \frac{1}{2}Li_2SO_4 + \frac{1}{6}N_2 + 0.65\ Ni(OH)_2 + 0.19\ Co(OH)_2 + 0.19\ Mn(OH)_2$$

$$Li_2SO_4 + Na_2CO_3 \rightarrow Li_2CO_3 + Na_2SO_4$$

Therefore, the sulfuric acid, the ammonia and the soda ash are material inputs of the recycling process, while the nitrogen and the sodium sulphate are co-products. The recovered cathode materials are nickel(II) hydroxide, cobalt(II) hydroxide, manganese(II) hydroxide and lithium carbonate.

When it comes to energy consumption, the whole battery pack must first be disassembled to the cell level, after which only the cells undergo the recycling process. The energy requirements for both stages are considered from bibliography[24,27].

The total cost or benefit obtained from the hydrometallurgy recycling process of the NMC batteries is extremely variable. Nevertheless, for the LCC, it was assumed a cost of 5$/kWh, as this seems to be the average data for NMC batteries which SoH is below 75%[24]. Again, for adapting the data of the recycling process to the FU, it is considered 150 Wh/kg[25] as the specific energy of the battery.

In the AS-IS repurposing scenario, there will be manufactured 1 kWh of LIBs for EVs, specifically NMC batteries, following the inventory that was explained above. Then, when the battery gets to the EoL stage, it will be repurposed, meaning that the battery pack will be disassembled and then reassembled, with a second life out of the EV industry. When this second life is over, the 1 kWh battery is sent to the hydrometallurgy recycling process.

5.3.2 AS-IS scrap scenario

In the AS-IS scrap scenario, as in the previous one, it is proposed to manufacture 1 kWh of LIBs to use in the EV industry. However, once they reach the EoL stage, they will not be repurposed but will be sent directly to hydrometallurgical recycling instead. Therefore, in order to compare both scenarios, it is assumed that another 1 kWh of LIBs will need to be manufactured to cover the second life usage phase of AS-IS repurposing scenario. Subsequently, this second batch of batteries will also be sent to hydrometallurgical recycling when they reach their EoL stage. The whole AS-IS scenario is summarized in Table 4.

---

27 Philippot, M., Costa, D., Hosen, M. S. *et al*. (2022). Environmental impact of the second life of an automotive battery: Reuse and repurpose based on ageing tests. *Journal of Cleaner Production*, *366*, 132872. https://doi.org/10.1016/j.jclepro.2022.132872

Table 4. Processes in AS-IS scrap scenario.

Phase description	***Amount required in the process phase***
Manufacturing process	1 kWh of LIBs x2
Recycling process	1 kWh of LIBs x2

The manufacturing process and the recycling process used in this scenario are explained in detail in Section 5.3.1, as they are the same as the ones used in the AS-IS repurposing scenario.

5.4 Results

5.4.1 LCA

Figure 23 illustrates the main impacts of AS-IS repurposing scenario. In all the categories analysed, the manufacturing process contributes to environmental drawbacks, while the hydrometallurgical recycling process yields benefits across all aspects, reducing the overall impact of the AS-IS repurposing scenario.

When it comes to the repurposing process, it is not considered in any of figures in the LCA because, as it was explained in the previous section, the process does not require input materials or energy, being carried out manually. However, the LCC assessment will account for the labour hours reflected in the LCI.

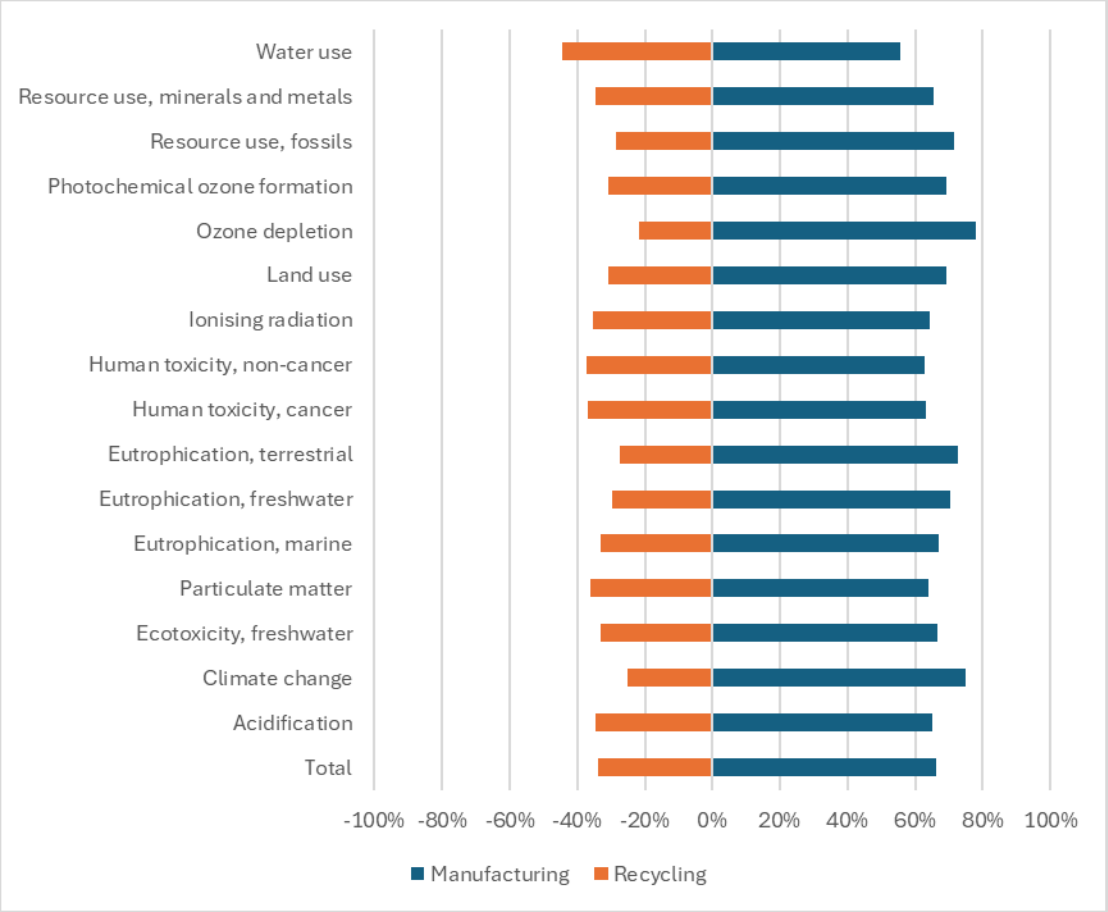


Figure 23. AS-IS repurposing scenario impact for different inputs.

The greatest environmental impact of the manufacturing process comes from cell manufacturing, which represents more than 72% of the total negative environmental impact in mPt. In contrast, cathode recycling is the most beneficial input in the recycling process, accounting for over 65% of the total positive effect in mPt. Regarding recycling, both waste production and electricity requirements are the only considered inputs that have a detrimental impact on the environment.

The comparison between the AS-IS recycling and AS-IS repurposing scenarios, illustrated in Figure 24, indicates that the AS-IS repurposing scenario achieves a better result. Both the carbon footprint reduction and the improvement in Endpoint account for 50%. This is due to the requirements of each scenario, including the manufacturing and recycling of 1 kWh of LIBs in the AS-IS repurposing scenario, which is half the needs of the AS-IS recycling scenario.

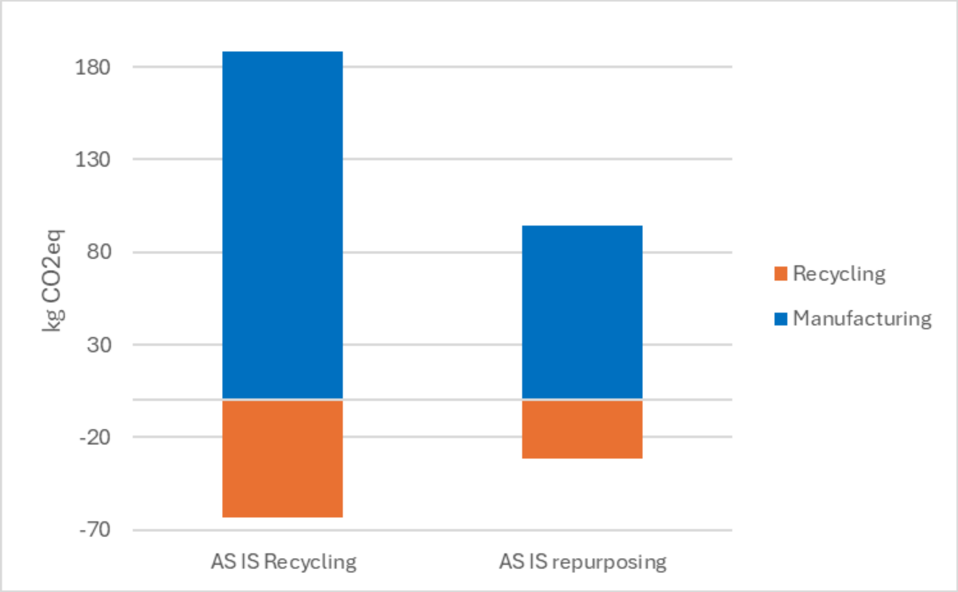


Figure 24. Comparison AS IS recycling and AS IS repurposing scenarios, Carbon footprint.

The comparison between the AS-IS recycling and AS-IS repurposing scenarios, with the corresponding units for each category and visually represented in Figure 25 (expressed in milipoints, mPt), highlights each impact category. In both scenarios, the 'Resource use, minerals and metals' category has the greatest environmental impact, accounting for almost 50% in mPt in each case. This is primarily due to the materials used in cell manufacturing, some of which are critical, and contribute to significant environmental issues such as resource depletion and pollution from mining activities.

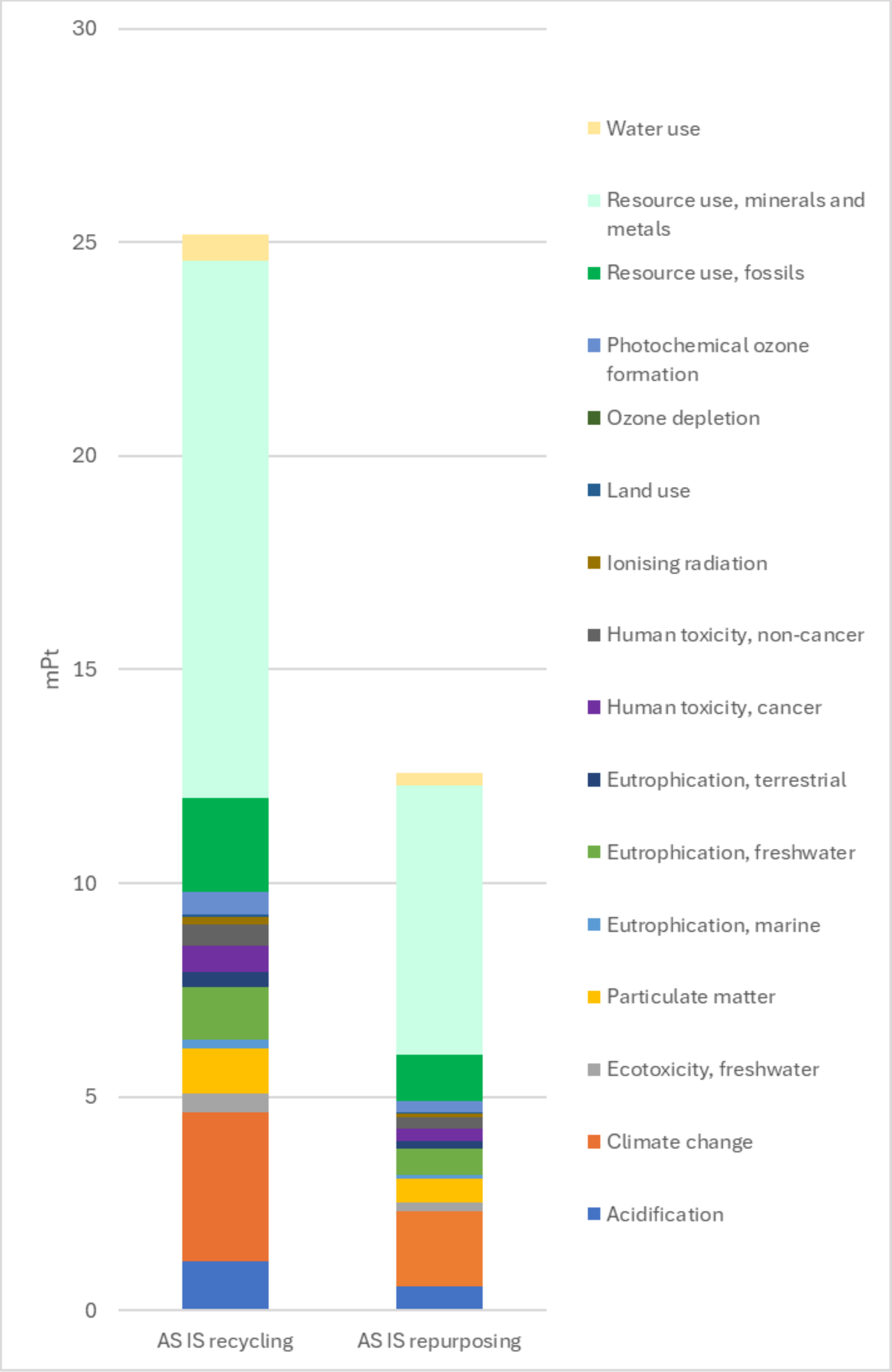


Figure 25. Comparison AS IS recycling and AS IS repurposing scenarios, Endpoint and different impact categories.

5.4.2 LCC

In the LCC analysis for AS IS repurposing scenarios, the main impact are cells manufacturing 80% and 61%, if environmental cost is not considered and if it is taking into account respectively. Repurposing costs are not negligible as in the case of LCA due to the intensive manual labour involved in these operations, around a 4%. Also, it is necessary to consider the positive impact of environmental externalities of the recovery of critical raw materials during recycling operations.

Figure 26 compares AS IS recycling and AS IS repurposing scenarios for EV batteries. If both scenarios the main impact are the cells with around 60% and 80% of the impact considering and not environmental externalities. The second main impact are the environmental externalities with around 24% of the total cost. AS IS repurposing scenario costs are 48% lower than AS IS recycling one, even considering environmental externalities. Considering this, there is a large gap between the scenarios to consider additional operations to increase the number of batteries being repair/repurposed, so that it is expected that the TO BE R3-Mydas scenario would have a positive impact.

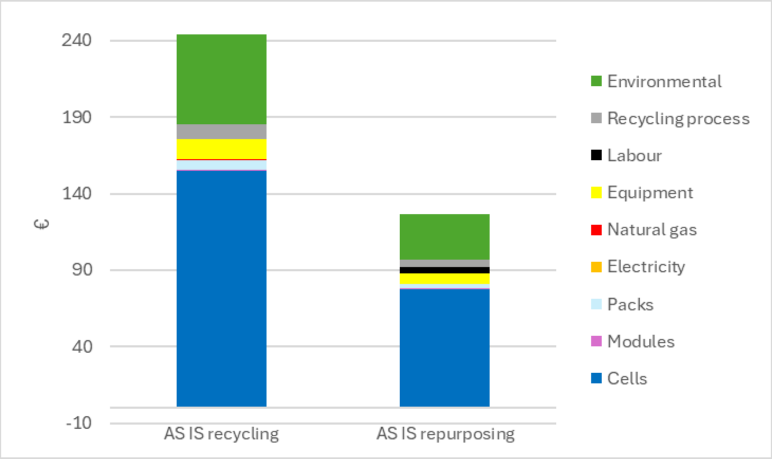


Figure 26. LCC results comparison for AS IS scrap and AS IS repair scenarios.

6 Demo-case 3

6.1 Sustainability analysis framework

The R3-Mydas repairing process for the wind turbine gearbox focuses on its components. Nowadays, this process is limited to the regrinding of visually observed defects and micro pitting based minor wear at gear flanks. However, the project will introduce additive manufacturing, new coating materials and heat treatments to the current process to improve the reuse of damaged parts of the gearbox, mitigating specific problems and minimizing the future failure rates.

There will be performed a **cradle-to-cradle analysis** and a comparison with other alternative scenarios for assessing the new circular value chain, which is described in detail in Section 3.3. The inputs will be the damaged gearbox and other raw materials, and energy needed to perform each process. It is expected to compare these three different scenarios by the end of the project:

- **AS IS scrap scenario:** The End-of-Life gearbox component is directly sent to steel scrap recycling to recover the material. This scenario does not consider any type of remanufacturing, so it is needed a new component to substitute the damaged one.
- **AS IS repair scenario:** The damaged component is repaired using the current non-complex process. Then, it is given a 2nd life in the wind turbine.
- **TO BE R3-Mydas scenario** (results expected at the end of the project, D5.3): The End-Of-Life gearbox component is repaired through the R3-Mydas process, which is based in additive manufacturing (AM), heat treatment and new coating materials. The repaired gearbox will have a 2nd life in the wind turbine. This complex repair process will be suitable for mayor failures.
  For performing this LCA, data generated during WP4 execution will be needed. Therefore, it will be included in the final version of the derivable (D5.3), at the end of the project.

The Functional Unit considered for the LCA was defined as **one damaged gearbox**.

The SimaPro 9.6[16] software, developed by Pré-Consultants was used to calculate the different life cycle analyses. The database selected was Ecoinvent 3.10[17] and the method selected for the calculation was EF3.1, that includes the impact categories described in Table 2.

6.2 Life cycle inventory (LCI)

In order to analyse sustainability, data from this Demo-case were gathered. Same general considerations than in Demo-Case 1 and Demo-Case 2 were taking into account, such as transport, electricity and labour cost (see Section 4.2). Data was provided by FLE based in their current production and repair process.

6.2.1 AS-IS repair scenario

The assessment starts with the main input material in this scenario, which is the EoL gearbox. It is only made of steel and lubricating oil as auxiliar material, while the generated waste during the manufacturing process,

Additionally, the equipment needed for the manufacturing process comprehends two turning machines, a gear milling cutter, a robot, an oven, a quench press and a grinding machine.

Due to the lack of data, in the AS-IS repair scenario, the impact of a direct reuse of the gearbox in the End-of-Life was supposed. To make this hypothesis, it was considered also that the current repair process for the pieces is low energy and material consuming, so its impact could be considered negligible compared to the new component manufacturing. This hypothesis is based in the current practice in Flender that only components with small damages are considered for repair processes.

In the AS IS repair scenario, it is supposed that just 0.1% of the total weight of the component is needed to be repaired, in order to consider new coating application or rework with an additive manufacturing process (AM). Due to lack of information and the low amount of material needed, it was not considered in the inventory.

6.2.2 AS-IS scrap scenario

As it was explained before, in the AS-IS scrap scenario, there will be considered the manufacturing of two components to substitute the first one with the second one. Therefore, although the equipment needs to the manufacturing process will be the same as in the AS-IS repair scenario, the amount of input materials will differ.

For the AS IS scrap scenario, the impact of manufacture two components is considered and the End-of-Life steel scrap produced is considered to be recycling. For the AS IS scrap scenario, the impact of manufacture two components is considered and the End-of-Life steel scrap produced is considered to be recycling. Additionally, the equipment needed for the manufacturing process includes two turning machines, a gear milling cutter, a robot, an oven, a quench press and a grinding machine.

6.3 Results

6.3.1 LCA

The main impacts for gearbox manufacture are showed in Figure 27. The main impact is the steel that is the main raw material in the 1st machining process. Steel is more than 97% of the total impact.

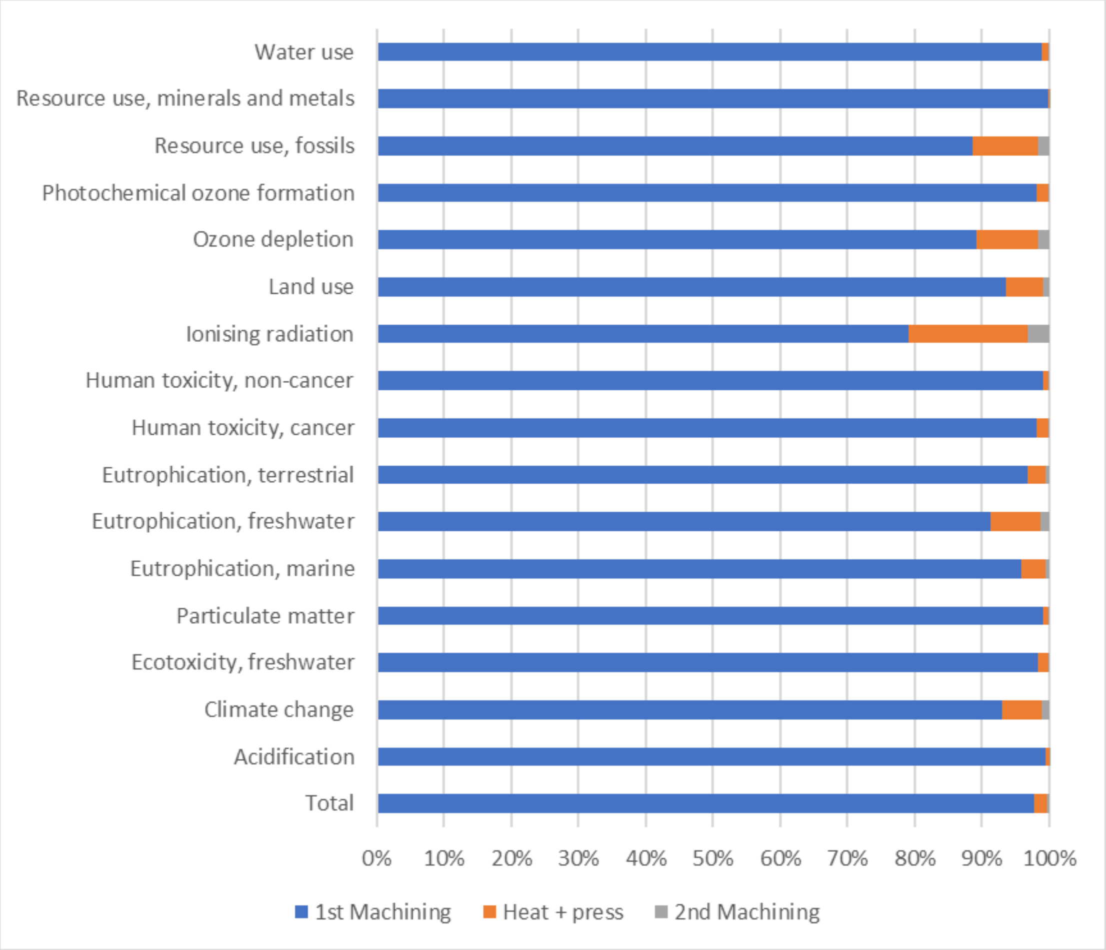


Figure 27. Gearbox manufacture LCA impact for different inputs.

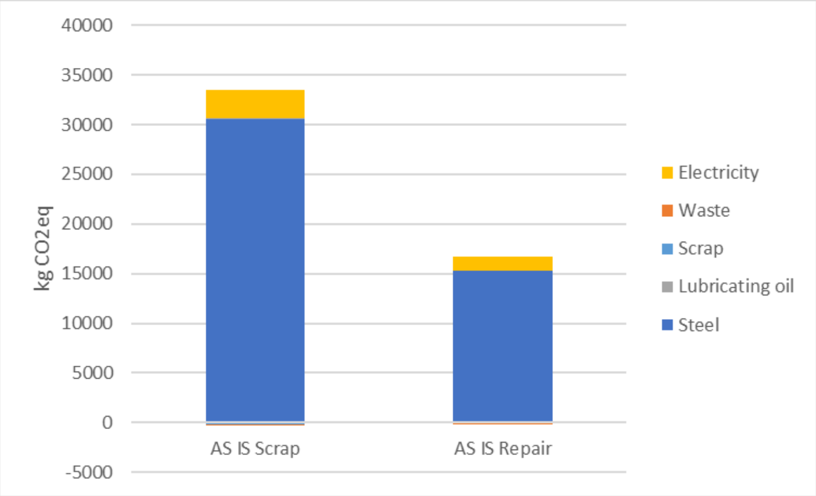


Figure 28. Comparison AS IS scrap and AS IS repair scenarios, Carbon footprint.

If both scenarios are compared, improvement AS IS repair vs AS IS scrap is showed, Figure 28. In carbon footprint and in the Endpoint the reduction is 50%. This is due to the high impact of stell as raw material in the manufacture phase. In both, positive impact of recycling phase is negligible, less than 1%.

The most important impact categories are resource use, minerals and metals, 31% and acidification, 24%, both related with steel as raw material in the manufacture phase, Figure 29.

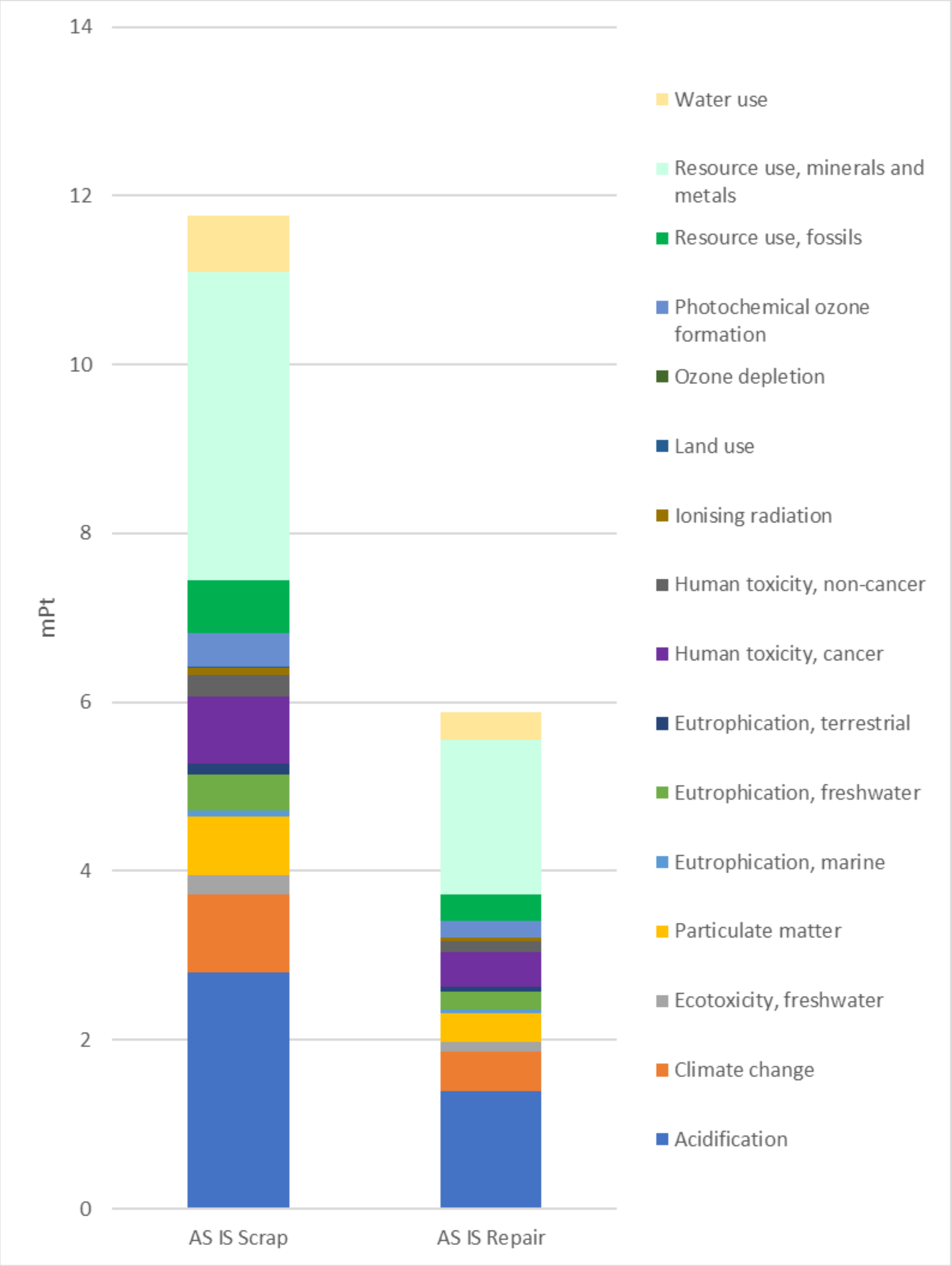


Figure 29. Comparison AS IS scrap and AS IS repair scenarios, Endpoint and different impact categories.

6.3.2 LCC

Related with LCC analysis, the main impact for gearbox manufacture is steel, 80% of total if environmental costs are not considered. If environmental costs are considered, it is the main impact with more than 56%. If AS IS scrap and AS IS repair scenarios are compared, AS IS repair is the most favourable scenarios with less than 50% of the impact. Figure 30.

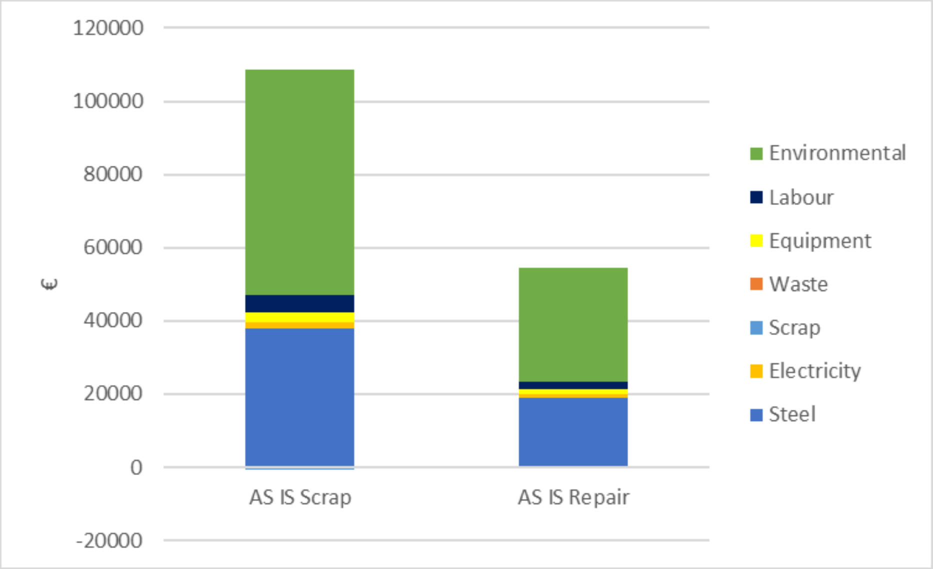


Figure 30. LCC results comparison for AS IS scrap and AS IS repair scenarios. with and without environmental cost.

7 Conclusions & Recommendations

In deliverable D5.2 a first Sustainability assessment was performed in terms of environmental and economic impacts. Also, for Demo-case 2, a first Safety assessment was carried out. For all the deliverable SSbD guidelines were followed.

As results of this first analysis of the three demo cases considered in the R3-Mydas project, in terms in sustainability, new circular scenarios in the value chains considered are more sustainable than current linear ones. Reuse/repair/remanufacturing options considered in each demo-case seems to be more advantageous in terms of environmental and economic sustainability. Nevertheless, some technical gaps to increase the size of the repair/remanufacturing market are needed and R3-Mydas will address them. At the end of the project is expected an improvement of the sustainability of the three new circular value chains. Some general recommendations could be concluded for this first sustainability analysis:

In Demo-case 1 AS IS repair scenario the main impact is cobalt used as raw material in repair process. It would be advantageous to check the technical feasibility of other steel alloys with similar properties in order to reduce environmental impact of repair process. Furthermore, a more efficiency process will decrease the energy and raw materials consumption and increase the sustainability in terms of environmental and cost. R3-Mydas developments could help to achieve this technical feasibility due to new possibilities in laser cladding process.

In Demo-case 2, the environmental impact of the AS IS repurposing scenario is half that of the AS IS recycling one, with the largest occurring in the 'Resource use, minerals and metals' category due to the materials used in cell manufacturing. This is primarily due to the materials used in cell manufacturing, which is the process with the greatest environmental effect in both scenarios. When it comes to the LCC, AS IS repurposing scenario costs are half of the AS IS recycling one as well. Considering this, there is a large gap between the scenarios to consider additional operations to increase the number of batteries being repair/repurposed, so that it is expected that the TO BE R3-Mydas scenario would have a positive impact.

In Demo-case 3, AS IS repair scenario is quite advantageous compare AS IS scrap one that there is a huge gap for new and more complex remanufacturing process in terms of environmental and economic impact. Therefore, all the remanufacturing processes proposed in R3-Mydas (additive manufacturing, thermal treatment…) could be suitable to increase the number of possible components to be repaired. The results of D5.2 show that a new circular value chain based on remanufactured components could be environmentally and economically sustainable.