Project acronym: **PASSENGER**

Project title: "**Pilot Action for Securing a Sustainable European Next Generation of Efficient RE-free magnets"**

Grant agreement number: **101003914**

Start date of project: **1 May 2021,** Duration: 48 months

PASSENGER
FOR SUSTAINABLE AND EFFICIENT RE-FREE MAGNETS

**Deliverable No. 4.3**

# Report on preliminary LCA and MFA-R2

| | |
|---|---|
| Due date of deliverable | 30/04/2024 |
| Submission date | 28/05/2024 |
| File Name | D4.3 Report on preliminary LCA and MFA-R2 |
| Organisation Responsible of Deliverable | MNLT Innovations PC |
| Author name(s) | I. Yakoumis, V. Alexiou, G. Koutsikou, M., Montes, A. Amato, I. Torres |
| Revision number | 15 |
| Status | Final[1] |
| Dissemination Level | CO[2] |

[1] Document will be a draft until it is approved by the coordinator
[2] PU: Public, PP: Restricted to other programme participants (including the Commission Services), RE: Restricted to a group specified by the consortium (including the Commission Services), CO: Confidential, only for members of the consortium (including the Commission Services)

# PARTNERS

| |
|---|
| Fundación IMDEA Nanociencia |
| Metalpine GmbH |
| Fundación ICAMCYL |
| Ingeniería Magnética Aplicada SL |
| MBN Nanomateralia SPA |
| MATRES Material Research & Design |
| Kolektor Group d.o.o. |
| Centro Ricerche FIAT SCPA |
| EIT Raw Materials GmbH |
| Technical University Darmstadt |
| European Science Foundation |
| Industrie Ilpea SPA |
| OSLV Italia SRL |
| Asociación Española de Normalización |
| Balrog Plastics GmbH |
| MNLT Innovations PC |
| Tizona Motors SL |
| Jožef Stefan Institute |
| Smart Waste Engineering SRL |
| WILO SE |
| Less Common Metals Ltd |

# REVISION HISTORY

| Version | Date | Modified by | Comments |
|---|---|---|---|
| 1 | 04/01/2023 | Anna Frengkou | First draft |
| 2 | 20/02/2023 | Stylianos Spathariotis | Second draft |
| 3 | 12/03/2023 | Konstantinos Sakkas | Third draft |
| 4 | 21/04/2023 | Iakovos Yakoumis | Forth dhraft |
| 5 | 24/04/2023 | Myriam Montes/Eva Vicente-Barragán | Fifth draft |
| 6 | 17/05/2023 | Ignacio Torres | Six draft (edition) |
| 7 | 20/05/2023 | Alberto Bollero | Seventh draft (edition and revision) |
| 8 | 05/06/2023 | Stylianos Spathariotis | Eighth draft (Additional input and corrections). |
| 9 | 05/07/2023 | Vasiliki Alexiou | Nineth draft (additions and modifications) |
| 10 | 06/07/2023 | Myriam Montes/Eva Vicente-Barragán | Tenth draft |
| 11 | 02/04/2024 | Iakovos Yakoumis /Vasiliki Alexiou/ Georgia Koutsikou | Eleventh draft |
| 12 | 08/04/2024 | Alessia Amato | Twelfth draft |
| 13 | 18/04/2024 | Iakovos Yakoumis /Vasiliki Alexiou/ Georgia Koutsikou | Thirteenth draft (final revision) |
| 14 | 25/04/2024 | Myriam Montes/Eva Vicente-Barragán | Fourteenth draft (final revision) |
| 15 | 20/05/2024 | Ignacio Torres | Edition and validation |

# ACKNOWLEDGEMENT AND DISCLAIMER

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101003914.

# LIST OF ACRONYMS

| Abbreviation | Meaning |
|---|---|
| FU | Functional Unit |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Cost |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MFA | Material Flow Analysis |
| REE | Rare Earth Elements |
| WP | Work Package |
| EC | European Commission |

# SUMMARY

This document is the updated version of D4.2 Report on preliminary Life Cycle Assessment and Material Flow analysis-R1 within the framework of WP4 - Raw Materials. Sustainability, techno-economic, health and safety assessment. The present report contains the main results of the WP4 of PASSENGER project based on the latest data obtained from the technical WPs during the project implementation. The purpose of the present report is to present a preliminary assessment of the Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Material Flow Analysis (MFA) based on advanced data of the processes that are being developed inside the PASSENGER project. The latest data from Task 4.1 and literature data on the full value chain were utilised for updating the Material Flow Analysis. The scope of D4.3 is to perform several revised LCA/LCC/MFA studies in order to incorporate the environmental and economic results in the technologies and products and quantify raw materials use in PASSENGER solution.

The LCA study has been performed following the ISO 14040 standards. The Life Cycle Inventory (LCI) was updated using the latest available data provided by the partners regarding the mass and energy balances or their technologies and processes. All these data were collected in deliverable 4.4 “Collect all required life cycle inventory data at material, process and prototype level”. The database LCI was built by gathering information on inputs (consumption of different production parameters, energy, and water) and outputs (wastes and emissions) related to the production process. The filled database was processed with LCIA (Life Cycle Impact Assessment) methods for the quantification of the absolute impact, considering a full set of environmental indicators (carbon and water footprint, particular matter formation, cumulative energy demand, ecotoxicity etc.) for the identification of the environmental hotspots within the developed technology. In this report, a benchmarking LCA study of the conventional technologies is also presented for comparison purposes and evaluation of the environmental benefits of the PASSENGER solution. Moreover, the economic life cycle assessment of the proposed PASSENGER solution was investigated including CAPEX and OPEX calculations as part of the Life Cycle Costing analysis. Finally, the framework of the Social Life Cycle assessment study aiming to investigate the societal impact of PASSENGER project with a time horizon for 5, 25 and 50 years is presented in the present deliverable.

# TABLE OF CONTENTS

# 1. INTRODUCTION

The PASSENGER project contributes to a green, sustainable Europe by developing an alternative to raw materials in the construction of permanent magnets and testing their performance in the electromobility sector. Specifically, PASSENGER project focuses on removing the EU's dependence on CRMs like REEs. Today's the Europe's industries have a total dependence on imported materials for its REE-based magnets. The huge disparity in the numbers is extremely worrying as the EU imports almost 100% of its REE, while the rate of REE recycling is less than 1%. The currently available recycling routes are just too energy intensive and accompanied with large environmental footprints. There are also severe material losses during the product's lifecycle, which makes REE recycling commercially unattractive currently.

The PASSENGER project aims to demonstrate manufacturing of improved hard ferrites while avoiding the use of critical materials as proposed by PASSENGER, will enable a sustainable partial substitution of bonded rare earth-based magnets based on elements available in Europe.

PASSENGER proposes improved strontium ferrite (Sr-ferrite) and a Manganese-Aluminium-Carbon (MnAlC) alloy as a substitute to guarantee a sustainable production of permanent magnets in Europe: two alternatives without critical raw elements, based on resources that are widely available in Europe and/or with a guaranteed access through established alliances, with enough research to provide a solid base for a successful transition from the lab to the industrial production in the Pilot Plans.

The aim of WP4 is to assess the sustainability, techno-economic, health and safety impacts of the PASSENGER value chains and to provide knowledge and support to the different stakeholders and decision makers like the investors, industries, European commission services, research institutions and government agencies.

The sustainability in the PASSENGER project will be addressed through 3 well known pillars aimed at evaluating social, economic and environmental impacts along the value chains. Additionally, safety assessment which is an implicit aspect of the three pillars of sustainability will also be carried out. As a first step, a comprehensive process design and integration of the novel PASSENGER value chains will be performed.

This deliverable is based on the work that has been conducted on Tasks 4.3, 4.4, and Task 4.9 till M34. The following key activities will be considered in this deliverable that are distributed among the different Tasks:

- Life Cycle Inventory (LCI) description of the processes.
- Define and structure scenarios. Develop relevant and aligned scenarios for the up-scaled processes/technologies of PASSENGER for LCA.
- Benchmark LCA of conventional technologies. Perform a baseline LCA for the existing current technology and value chain based on recent literature and on project partners' input.
- Preliminary LCA of the processes and technologies.
- Material Flow Analysis (MFA) of PASSENGER. Perform MFA to position PASSENGER results and commercialized solution in the European and global material supply chain.

## 1.1. OBJECTIVES

In the context of Task 4.3 Environmental Life Cycle assessment (LCI) Data and Scenarios a structured methodology and activities will take place for the data collection in a uniform way from the technological WPs and respective partners following international standards, inventory flows (e.g. energy consumption, emissions, waste) for the definition of the scenarios that will be the basis for the Sustainability assessment based on hotspot analysis (eco-design approach) and monitoring of the technologies products. In the context of this task ICAMCYL and MNLT set the frame and familiarized the partners with the main principles of this WP objectives, and secondly structured the data compilation process from the involved partners as an ongoing activity. Data sharing and reliability is of high importance for the successful implementation of WP4. The aim of Task 4.4 is to perform several LCAs in order to incorporate the environmental results in the technologies and products. A benchmark LCA of the conventional technologies was performed as a baseline LCA for the existing current technology and value chain for comparison purposes. The main part of this task is focused on LCA of the technologies. That approach allows early quantification of the eventual large-scale environmental impacts of up-scaled technologies, which allows the use of them to make comparisons between benchmark solutions and circular economy solutions of the project.

The environmental LCA shall be articulated as follows:

- An environmental LCA was performed (M12, M24, M34),
- A more detailed final environmental LCA will follow (M25-M42),
- The data collected in Task 4.3 and the preliminary mass and energy balances, the preliminary environmental LCA will prepare the framework for the final LCA, help identify the most probable hotspots along the life cycle and provide recommendations on the most promising options and configurations from an environmental point of view. The data collection shall build upon the preliminary output from WP1-2 and be completed by expert judgment from the technical partners and by data from the literature when needed. The results of the preliminary LCA will be fed back to the partners to guide the design and development strategy towards more sustainable solutions and provide best-practice recommendations. Also in the context of Task 4.9 is the execution of a Material Flow Analysis (MFA) in order to evaluate and interpret the contribution of PASSENGER in the context of the European and global value chains. Data from Task 4.1 will be utilized along with literature data on the full value chain. The MFA will have a European and global scale with a particularly focus on analyzing the potential of PASSENGER technologies and products to contribute to circular economy targets of EU countries. Outcomes will be utilized in the impact and commercial outreach of the project. In addition, a Material Flow Accounting and Material Flow Cost Accounting will be conducted to assess the level of resource intensity of the commercial solution, and to reduce their operational costs and improve environmental performance In Figure 1 is presented the WP4 timeline.

## 1.2. INTENDED AUDIENCE

The present deliverable is confidential and only intended for the members of the consortium (including the Commission Services). The type of dissemination and public communication of the other WP4 deliverables vary between confidential and intended for public disclosure.

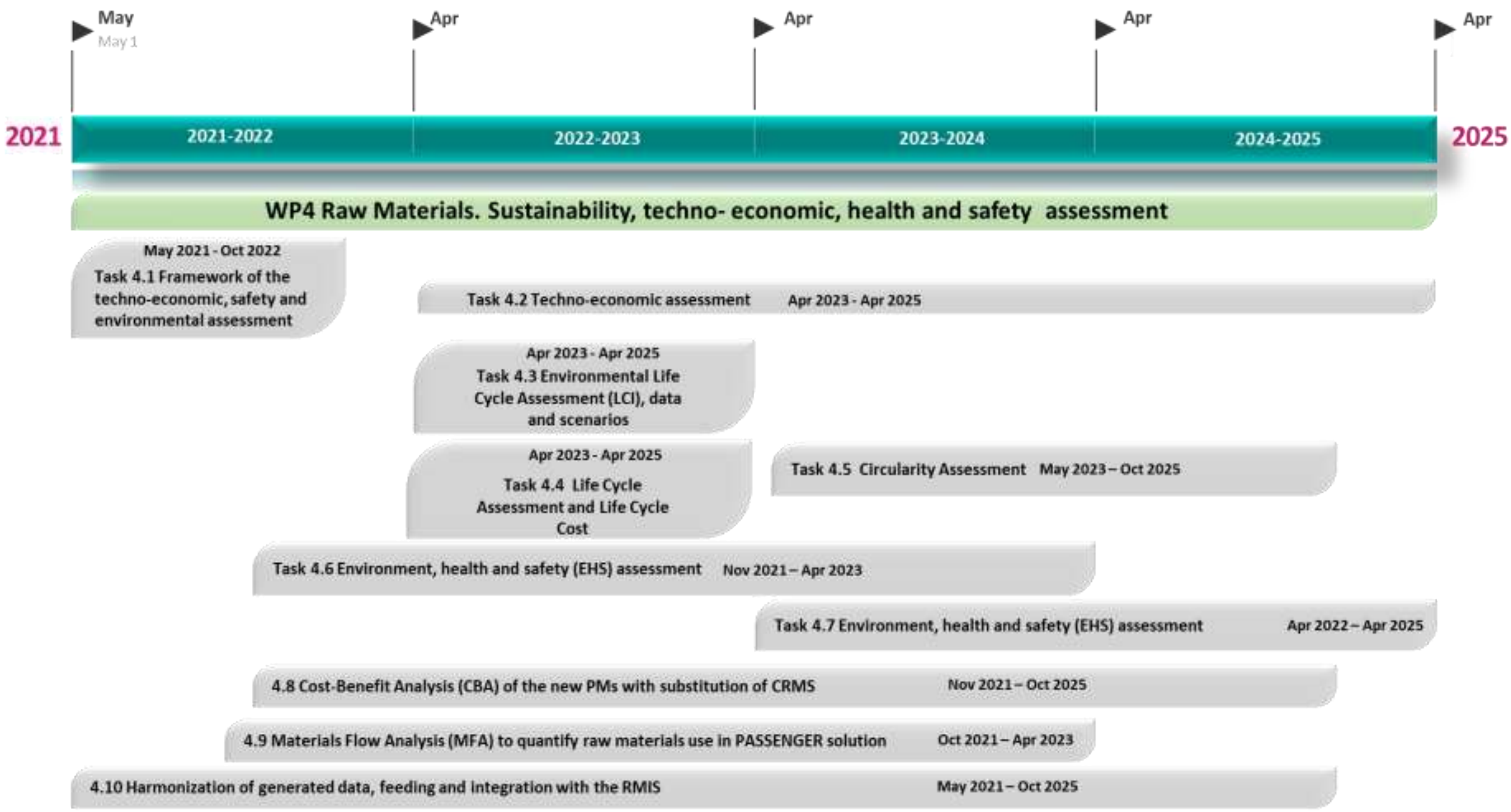



*Figure 1. WP4 Timeline*

# 2. LIFE CYCLE SUSTAINABILITY ASSESSMENT

## 2.1. SUSTAINABILITY

Sustainability: Specific definitions of sustainability are difficult to agree on and have varied in the literature and over time. The UN World Commission on Environment and Development defined it as: Sustainability is commonly described as having three pillars: environmental, economic, and social. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. According to UCLA Sustainability Committee: Sustainability is the integration of environmental health, social equity and economic vitality in order to create thriving, healthy, diverse and resilient communities for this generation and generations to come [1]. The practice of sustainability recognizes how these issues are interconnected and requires a systems approach and an acknowledgement of complexity. Sustainability is the balance between the environment, equity, and economy. Life cycle sustainability assessment (LCSA) (Figure 2) refers to the evaluation of all environmental (E-LCA), social (S-LCA) and economic (LCC) negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle.


*Figure 2. Life Cycle Sustainability Assessment representative scheme*

The Sustainable Development Goals (SDGs) (Figure 3) were established in 2015 by the international community as part of the UN 2030 Agenda for Sustainable Development through which countries of the world collectively pledged to eradicate poverty, find sustainable and inclusive development solutions, ensure everyone’s human rights, and generally make sure that no one is left behind by 2030. The UN’s Sustainable Development Goals [2], or SDGs, sit at the heart of the 2030 Agenda for Sustainable Development.


*Figure 3. Sustainable Development Goals (SDGs)*

PASSENGER addresses at least 4 Sustainable Development Goals, focusing mainly on SDG9 ‘Industry Innovation and Infrastructure’ through the joint efforts of the consortium partners, to propose the improvement of strontium ferrite (Sr-ferrite) and Manganese-Aluminium-Carbon (MnAlC) alloy as a substitute to guarantee a sustainable production of permanent magnets in Europe. In the context of SDG 8 ‘Decent work and economic growth’ the upgrade of technology results in achieving a higher level of economic productivity in a labour-intensive sector (like mining), as well as achieving sustainable management and the use of natural resources (Target 12.2 – SDG 12 ‘Responsible Production and Consumption). PASSENGER will make responsible and sustainable use of Europe’s natural resources, preserving the ecosystem and designing fully recyclable permanent magnets.

The international PASSENGER consortium, through its incorporated knowledge triangle, will further contribute substantially to SDG 17 'Partnership for The Goals'. In particular it addresses: Target 17.6 by stimulating international cooperation, and increasing level of access to science, technology, and innovation and enhancing knowledge sharing; Target 17.7 by promoting the development transfer, and disseminating and diffusing the environmentally sound processes and technologies; Through communication and dissemination PASSENGER project will raise awareness about the impact of the sustainable production of PMs and will Inform about PASSENGER benefits in sustainability and environment protection as well as will draw attention to the project results and potential impact on local economies with relevance to economic regional development, social and environmental sustainability. Target 17.16 by enhancing global partnership starting at EU scale by the multi-stakeholder partnership which mobilizes knowledge, expertise, technology know-how sharing.

# 3. FRAMEWORK OF THE LIFE CYCLE ASSESSMENT - LCA

## 3.1. CONTEXT & BACKGROUND

A leading tool for assessing environmental performance is Life Cycle Assessment (LCA), a method defined by the International Organization for Standardization (ISO) 14040-14044 standards [3,4,5]. LCA is an internationally recognized approach that evaluates the relative potential environmental and human health impacts of products and services throughout their life cycle, beginning with raw material extraction and including all aspects of transportation, manufacturing, use, and end-of-life treatment. It is important to note that LCA does not exactly quantify the real impacts of a product or service due to data availability and modelling challenges. However, it allows to estimate and understand the potential environmental impacts which a system might cause over its typical life cycle, by quantifying (within the current scientific limitations) the likely emissions produced, and resources consumed. Hence, environmental impacts calculated through LCA should not be interpreted as absolute, but rather relative values within the framework of the study. Ultimately, this is not a limitation of the methodology, since LCA is generally used to compare different systems performing the same function, where it's the relative differences in environmental impacts which are key for identifying the solution which performs best.

Among other uses, LCA can identify opportunities to improve the environmental performance of products, inform decision-making, and support marketing, communication, and educational efforts. The importance of the life cycle view in sustainability decision-making is sufficiently strong that over the past several decades it has become the principal approach to evaluate a broad range of environmental problems, identify social risks and to help make decisions within the complex arena of socio-environmental sustainability.

The importance of the life cycle view in sustainability decision-making is sufficiently strong that over the past several decades it has become the principal approach to evaluate a broad range of environmental problems, identify social risks and to help make decisions within the complex arena of socio-environmental sustainability. LCA is a methodology commonly used that is accepted worldwide. Some of the applications of an LCA are:

- Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the objective of prioritizing improving on products or processes.
- Comparison between products for internal or external communication, and as a basis for environmental product declarations.
- The basis for standardized metrics and the identification of Ley Performance Indicators used in companies for life cycle management and decision support.
- LCA provides the quantitative and scientific basis for all these activities. In many cases, LCA feeds the internal and external discussions and communications. Being active in LCA means being able to communicate the environmental impacts of products and business processes.

## 3.2. LCA APPROACH

LCA is a tool to evaluate the environmental impacts (EI) of products. LCA is best practiced as an iterative process, where the findings at each stage influence changes and improvements in the others to arrive at a study design that is of adequate quality to meet the defined goals. The principles, framework, requirements and guidelines to perform an LCA are described by the international standard ISO 14040, which defined the 4 main phases (Figures 4,5) of an LCA [6]:

- Goal and scope definition: defining the purposes of the study, determining the boundaries of the system life cycle in question and identifying important assumptions that will be made.
- Life Cycle Inventory (LCI): compiling a complete record of the list of the materials and energy flows throughout the life-cycle.
- Life Impact Assessment (LCIA): using the inventory compiled in the prior stage to create a clear and concise picture of environmental impacts among a limited set of understandable impact categories.
- Interpretation: identifying the meaning of the results of the inventory and impact assessment relative to the goals of the study. The interpretation phase of an LCA comprises several elements includes:

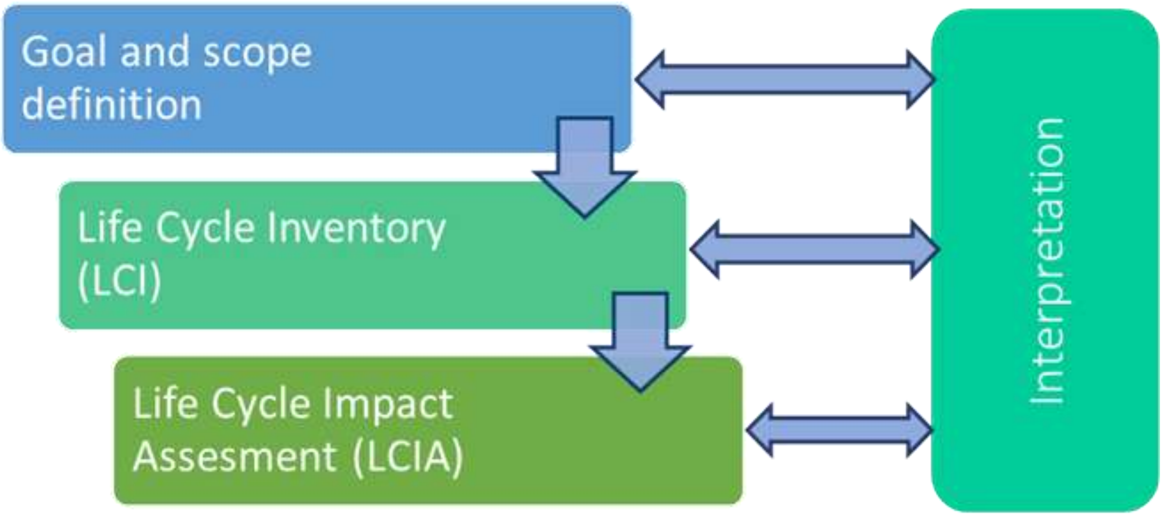



*Figure 4. LCA Framework by International Reference Life Cycle Data System (ILCD) Handbook, 2010.*

a. the identification of the significant issues based on the results of the LCI and LCIA phases of LCA.
b. an evaluation that considers completeness, sensitivity and
c. conclusions, limitations, and recommendations.

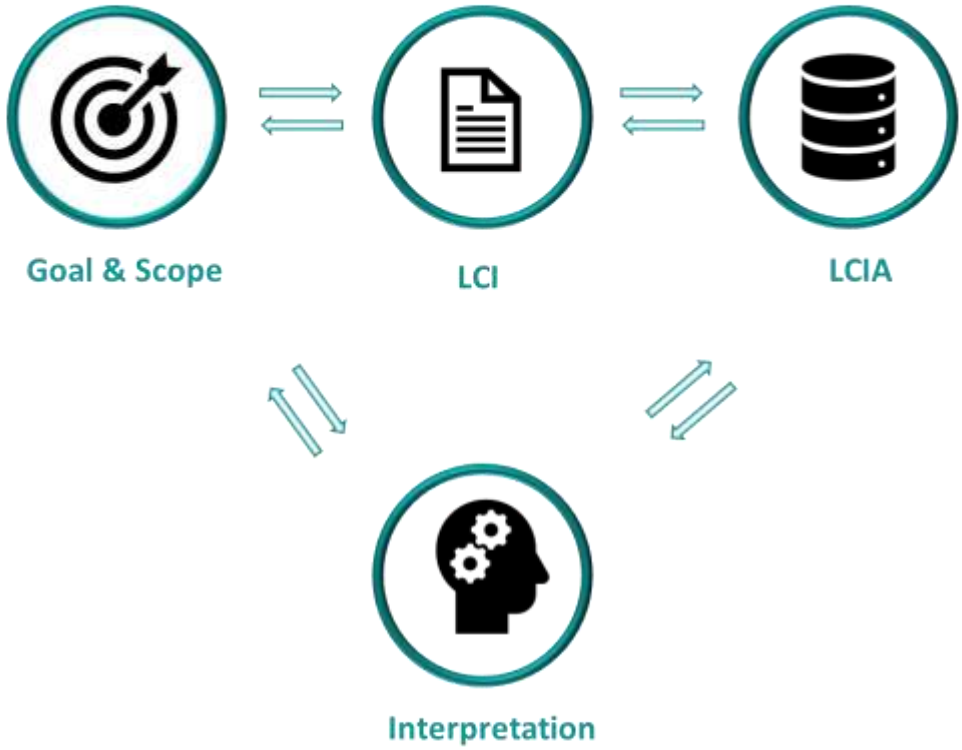



*Figure 5. The 4 phases of the LCA approach.*

Generally, the product/ process Lifecycle consists of five steps (Figure 6):

1. Raw Material Extraction
2. Manufacturing & Processing
3. Transportation
4. Usage & Retail
5. Waste Disposal

**Cradle-to-gate:** Assesses a product until it leaves the factory gates before it is transported to the consumer [7].

**Cradle-to-grave:** Includes all the 5 life phases in the measurements. “Cradle” is the inception of the product with the sourcing of the raw materials. “Grave” is the disposal of the product. It shows a full footprint from start to end.

**Cradle-to-cradle:** It is a variation of cradle-to-grave, exchanging the waste stage with a recycling process that makes it reusable for another product, essentially “closing the loop”. This is why it is also referred to as closed-loop recycling/upcycling process that makes it reusable for another product. Essentially” closing the loop”.


*Figure 6. Product/Process Lifecycle routes in LCA*

Considering the main goal of the analysis, a cradle-to-gate approach was selected in this study. This approach implies considering the production of the raw material and energy consumed, the atmosphere, soil and water emissions generated and the waste treatment and disposal required during the application of PASSENGER's technologies.

LCA methodology creates data and facilitates decisions. In the context of PASSENGER project, a methodology/approach was created and will be followed as it is depicted in Figure 7. Regarding the four steps of the LCA the Goal.

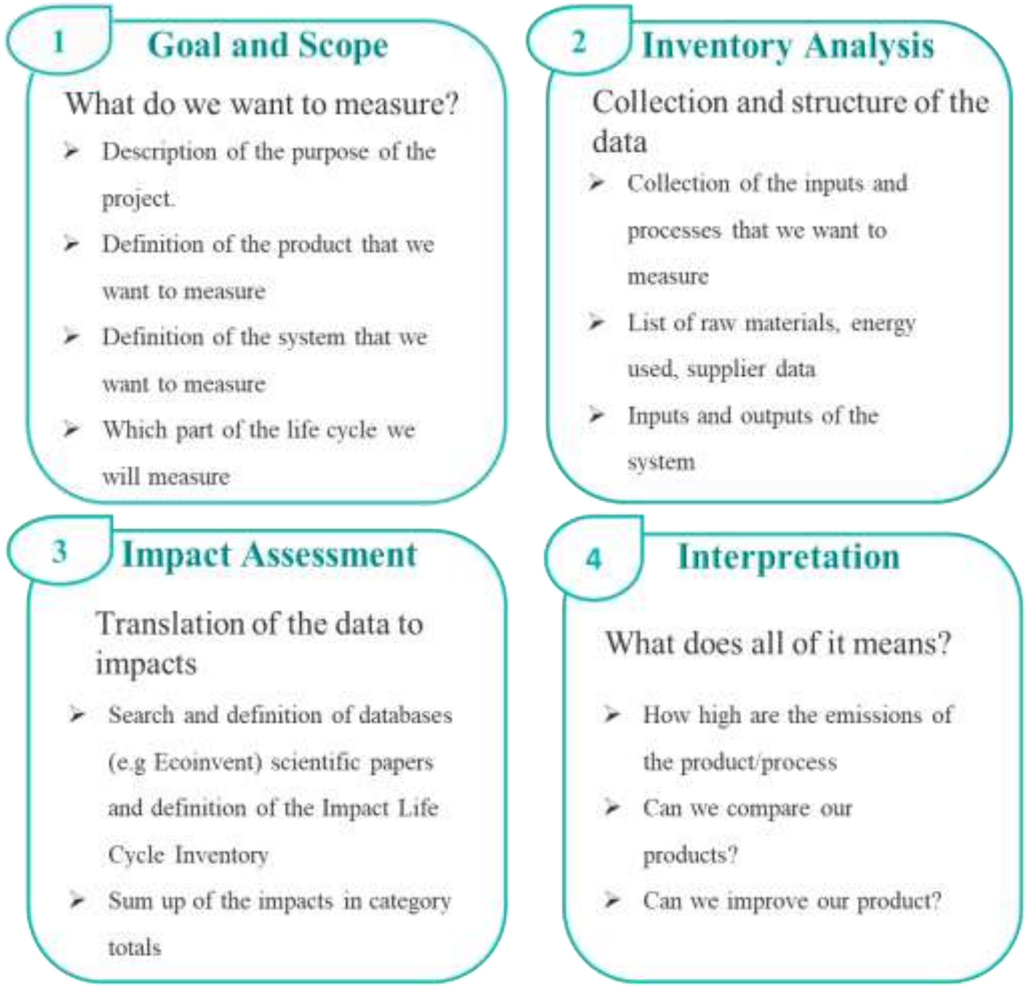



*Figure 7 LCA Methodology / 4 steps for the LCA assessment.*

## 3.3. GOAL & SCOPE

### 3.3.1 Description

In the Goal and Scope Section we define what we want to measure: In this section a description of the purpose of the project is required, a definition of the product that we want to measure, a definition of the system that we want to measure and also which part of the life cycle we are intended to measure. Definition of the goal and scope helps to ensure that the LCA was performed consistently. The goal and scope are not set in stone and can be adjusted if, during the next steps of the LCA, the initial choices reveal themselves not to be optimal or practical. Any adjustments to the goal and scope should be described. A baseline LCA study regarding the production of sintered NdFeB magnets was conducted for comparative purposes and identification of the environmental benefit of the developed non-

CRM magnets within the PASSENGER project. The baseline assessment and the related data that are presented are based on literature reviews [8] and further assumptions. An update LCA study on the sintered/bonded MnAlC magnets and bonded ferrite magnets production was conducted based on the latest LCI data provided by the partners involved in technical WPs.

A comparative LCA of the benchmarking technology using CRMs (NdFeB magnets) and the proposed non-CRM magnets (MnAlC and ferrite magnets) production followed in accordance with the international standards - ISO 14040 and ISO 14044. The comparison was based on the production of 1kg of NdFeB, 1kg of MnAlC and 1 kg of ferrite magnets. SimaPro version 9.4 software was used as well as the Ecoinvent 3.0 database to perform the LCA.

ReCiPe 1.13 Midpoint was selected as the assessment method. ReCiPe is one of the most recent and updated impact assessment methods available to LCA. The mandatory elements of life cycle impact assessment (LCIA) (Organization, 2006) were included: i) selection of impact categories, category indicators, and characterization models, ii) assignment of LCI results (classification), and iii) calculation of category indicator results (characterization). Eighteen impact categories from the ReCiPe 1.13 Midpoint (H) method are selected for LCIA: Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Metal depletion, Fossil depletion. The detailed description of the impact categories and their units are presented in Annexes 1 and 2.

### 3.3.2 System Boundaries

The system boundaries delimit the inputs of materials and energy, and the outputs of wastes and emissions that are considered for the impact calculations of the PASSENGER technology. The life cycle of the PASSENGER's permanent magnets can be divided into five life cycle stages:

- **Materials:** This stage involves the extraction, processing, and sourcing of raw materials needed to produce permanent magnets. Raw materials such as neodymium, iron, boron, and other elements are mined, refined, and processed to obtain the necessary components for the magnets. Environmental impacts associated with this stage include, water and soil pollution, energy consumption, and greenhouse gas emissions from mining, refining, and transportation of raw materials.
- **Production:** The production stage involves manufacturing permanent magnets from the processed raw materials. This includes processes such as mixing raw materials, forming them into shapes (e.g., through casting or pressing), and sintering them at high temperatures to achieve the desired magnetic properties. Energy consumption, emissions, and waste generation occur during production, which should be minimized through efficient manufacturing processes and use of renewable energy sources.

- **Transportation:** Transportation encompasses the movement of materials and products between different stages of the life cycle. This includes transporting raw materials to processing facilities, moving semi-finished and finished products between production facilities, and distributing the final product to customers. Environmental impacts of transportation include fuel consumption, emissions, and pollution associated with various transportation modes such as trucks, ships, trains, and airplanes.
- **Use:** The use stage involves the incorporation of permanent magnets into various applications such as electric motors, generators etc. During this stage, the magnets contribute to the functionality of the end products. Environmental impacts during the use stage depend on the specific application and the efficiency of the devices utilizing permanent magnets.
- **End of Life (EoL):** The end-of-life stage involves the disposal or recycling of products containing permanent magnets once they reach the end of their useful life. Depending on the disposal method, permanent magnets may end up in landfills, be incinerated, or recycled. Recycling permanent magnets can help recover valuable materials and reduce the need for new raw materials extraction.

Considering the main goal of the analysis, a cradle-to-gate approach was selected in this study. This approach implies considering the production of the raw material and energy consumed, the atmosphere, soil and water emissions generated and the waste treatment and disposal required during the production of PASSENGER's permanent magnets. Distribution and use phase of PASSENGER's permanent magnets are not considered in this study. Additionally, the production of the industrial equipment used in the installation has been excluded, as well as possible manufacturing failures (Figure 8).


*Figure 8. Simplified overview of system boundaries.*

It should be highlighted that the recycling or reuse of PASSENGER's permanent magnets for both the production and use phases is excluded from this particular LCA study. These life cycle aspects will be incorporated into the final version of the deliverable once the initial outcomes of the pilot experiments become accessible and more accurate LCI data becomes obtainable on the EoL aspects of the proposed technology.

All in all, in this LCA study, an environmental life cycle assessment was conducted regarding the production phase of PASSENGER's permanent magnets and the conventional production of NdFeB permanent magnets. More specifically, the assessed stages included the production phase of a) PASSENGER's bonded MnAlC and Sr-ferrite magnets and sintered MnAlC magnets and b) the conventional sintered NdFeB magnets as the baseline scenario.

### 3.3.3 Cut-off

Cut-off criteria is used to simplify the system's boundaries while minimizing the loss of accuracy of the results. However, no systematic cut-off criteria (either by mass, energy or impact importance) are to be considered in this study.

### 3.3.4 Allocation rules

Certain product systems can result in several co-products. That being the case, clearly identify which environmental and economic burdens corresponds to each product is necessary. According to ISO 14044 [3,4,5], several allocation methods can be used to resolve this issue:

- Whenever possible, allocation must be avoided by dividing the unit process into two or more sub-processes.
- If the studied unit process cannot be divided, allocation must be avoided by expanding the product system, identifying the sub-products with alternative production methods.
- Whenever these two previous points cannot be applied to LCA study, the environmental impact of the sub-products can be allocated using physical relationships between them. If physical relations cannot be established, other relations can be used.

In this analysis, not all the co-products achieved can be directly employed in a new life-cycle, thus making difficult the expansion of the system boundaries. Therefore, an allocation applying physical relationships will be applied.

### 3.3.5 Functional Unit

The Functional Unit (FU) quantifies the performance of a product system and is used as a reference unit for which the LCA study is performed and the results are presented. For the production of NdFeB, MnAlC and ferrite magnets the functional unit is "1 kg".

## 3.4 Life Cycle Inventory (LCI)

LCI is an inventory of input/output data that relates to the functional unit of the system being studied.

Data sources *for foreground data*

This section regards the input data (or foreground data) that describe the life cycle of both the PASSENGER and the reference product value chains. The approach of this phase will be conducted through two steps:

1. Data collection through the partners of the PASSENGER project.

The detailed set of collected data will be reported in a manner that respects any confidentiality concerns.

2. Data collection through available scientific publications, public reports, existing LCA databases such as Urban Mining Company, Sprecher, own internal database of the consortium members, or through information provided through expert judgment and assumptions.

3. LCI is the collection and the structure of the data. In this context the inventory analysis contains the collection of the inputs and processes that we want to measure. The LCI includes a list of the raw materials that are used, the energy as well as the supplier data. An excel file (Figure 9, 10, 11, 12) was sent to consortium partners in order to fill it out with all the necessary data for the completion of the inventory. The detailed set of collected data is reported and presented in the deliverable D4.4 Collect all required life cycle inventory data at material, process and prototype level, in a manner that respects any confidentiality concern.

| Plant information | | | |
|---|---|---|---|
| | Amount | Units | Comments |
| Total CAPEX (€) | | € | |
| Equipment type and cost (e.g mills, spray dryers, magnetic separators etc.) | | € | |
| Equipment type and cost (e.g mills, spray dryers, magnetic separators etc.) | | € | |
| Equipment type and cost (e.g mills, spray dryers, magnetic separators etc.) | | € | |
| Equipment type and cost (e.g mills, spray dryers, magnetic separators etc.) | | € | |
| Equipment type and cost (e.g mills, spray dryers, magnetic separators etc.) | | € | |
| Useful life | | years | |
| Interest rate | | % | |
| Depreciation | | €/years | |
| Depreciation rate | | % per year | |
| Tax rate | | % per year | |
| Insurances | | €/year | |
| Maintenance | | €/year | |
| Overall utility costs (not directly related with the production process, e.g.: electricity, water, telephone-internet, paper etc.) | | €/year | |
| Overall management cost (not directly related with the production process, e.g. marketing, legal or client service expense) | | €/year | |
| Renting | | €/year | |
| Licenses | | €/year | |
| Disposal cost (for the plant) | | €/year | |

*Figure 9. Excel file: Sheet regarding the inventory of plant and production related costs*

**Assumptions / Annual Production: ___ tons /year**

*Please provide the data based on the annual production*

| | Amount | Comments | |
|---|---|---|---|
| Shifts per day | | plant operation | |
| Operation hours per shift | | plant operation | |
| Operation hours per day | | plant operation | all shifts |
| Operation days per week | | plant operation | |
| Operation hours per week | | plant operation | all shifts |
| Operation hours per month | | plant operation | all shifts |
| Operation hours per year | | plant operation | all shifts |
| Operation days per year | | plant operation | |
| Operation days per month | | plant operation | |
| Number of employees per day | | number of employees | |
| Total Salary per month | | per total nr employees | |
| Salary per month | | per employee | |
| Total Salary per year | | per total nr employees | |
| Salary per per hour per employee | | per employee | |
| Salary per per hour | | per total nr employees | |
| Working hours per year per employee | | per employee | |
| Working hours per month per employee | | per employee | |
| Estimated time to produce 1 kg of the final product | | | |

*Figure 10. Excel file: Sheet regarding TEA assumptions.*

**PASSENGER**

**Process(es) description**

*Please provide a brief description of the process(es). Include the extraction of resources, the production of materials, product parts, management after its disposal, either reuse, recycling and final disposal.*

**Flow diagram of the process(es)**

*Please, provide a flow diagram of the process of interest, including the inputs and outputs.*

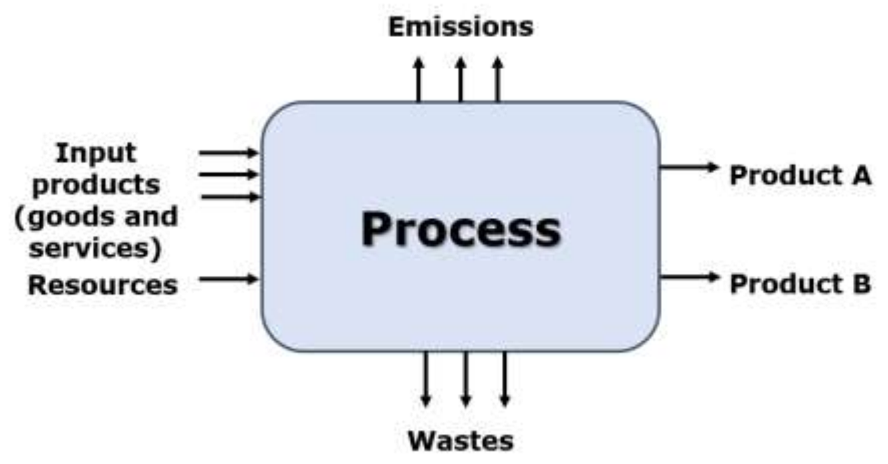



*Figure 11. Excel file: Sheet regarding the General information of for the LCA.*

| Life Cycle Inventory (LCI) | Quantity (Raw Data) | Unit | Comments |
|---|---|---|---|
| **PASSENGER** | | | |
| | | | |
| **Partner Name** | **LCM** | | |
| **Date:** | ________________ | | |
| *For chemicals and raw materials please also provide the safety data sheet and source* | | | |
| **Final product (name)** | **MnAlC alloy** | | |
| **Pilot production (kg or tons per day or year)** | ________________ | | |
| **Duration of the process** | ________________ | | |
| | | | |
| **Unit process 1 (casting)** | *Add this lines for each process defined in the system definition* | | |
| | *Please provide the data based on the pilot production* | | |
| | **Quantity (Raw Data)** | **Unit** | **Comments** |
| **Inputs** | | | |
| Manganese Flake 99.8% | | kg or tons | *If some material is reused, please specify for how many cycles* |
| Aluminium ingot 99.8% | | kg or tons | |
| Carbon | | kg or tons | |
| Electricity | | kWh | |
| Argon | | kg or tons | |
| Other inputs (raw materials/reagents/electricity sources) | | | |
| **Outputs** | | | |
| $CO_2$ emissions | | kg or tons | |
| $NO_2$ emissions | | kg or tons | |
| $CH_4$ emissions | | kg or tons | |
| Wastes (please specify if wastes are disposed, treated or recycled) | | kg or tons | *Please specify if it's a hazardous waste or not and the treatment (Recycling - Disposal - Incineration)* |
| Other outputs (type of emissions/wastes/particulate matter/heat etc.) | | | |
| **Product (name of the product)** | | kg or tons | |
| | | | |
| **Unit process 2 (name of the unit process)** | *Add this lines for each process defined in the system definition* | | |
| | *Please provide the data based on the pilot production* | | |
| | **Quantity (Raw Data)** | **Unit** | |
| **Inputs** | | | |
| Product from unit process 1 | | | |
| Ancillary | | | |
| Electricity | | | |
| **Outputs** | | | |
| $CO_2$ emissions | | | |
| $NO_2$ emissions | | | |
| $CH_4$ emissions | | | |
| Wastes (please specify if wastes are | | | |

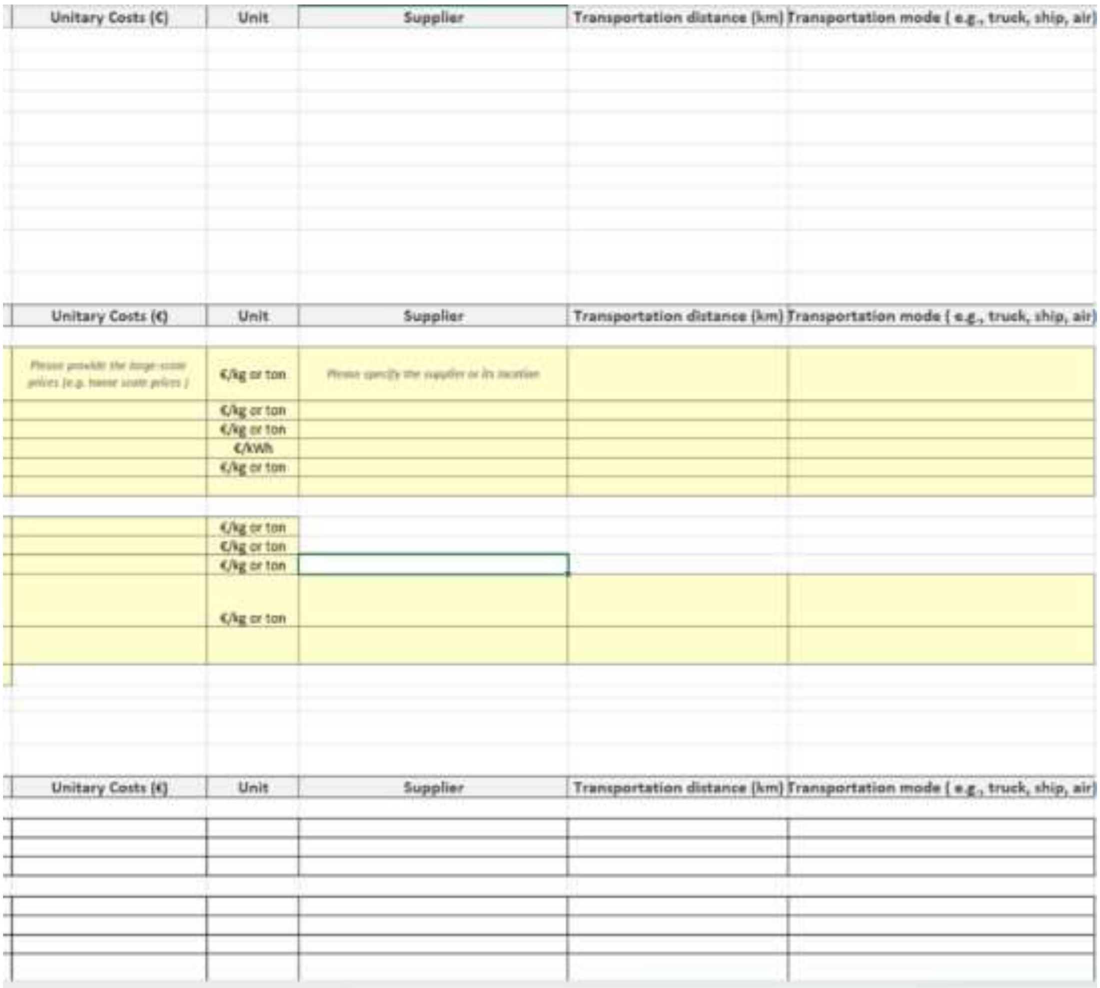



*Figure 12. Excel file: Sheet regarding the Inventory of Inputs and Outputs of the system.*

## 3.5 Impact assessment method

The life cycle impact assessment (LCIA) method provides the basis for analyzing the potential contributions of resource extractions and emissions in a life cycle inventory (LCI) to a number of potential impact indicators (midpoint or endpoint indicators) [1]. The impacts are calculated using characterization factors recommended in internationally recognized impact assessment methods. Life cycle impact assessment is defined as the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. In the Life cycle impact assessment, the inventory data are aggregated and converted to environmental impact/load for each impact category. SimaPro contains a number of impact assessment methods, which are used to calculate impact assessment results.

The LCIA phase includes the collection of indicator results for the different impact categories, which together represent the LCIA profile for the product system. The LCIA consists of mandatory and optional elements. The LCIA phase shall include the following mandatory elements:

Selection of impact categories, category indicators and characterization models;

- Assignment of LCI results to the selected impact categories (classification);
- Calculation of category indicator results (characterization)
- Resulting data: the inputs and outputs of the product system are represented by a discrete compilation of the LCIA category indicator results for the different impact categories referred to as an LCIA profile; a set of inventory results that are elementary flows but have not been assigned to impact categories e.g. due to lack of environmental relevance, and a set of data that does not represent elementary flows.

ReCiPe is a method for the impact assessment (LCIA) in an LCA. Life Cycle Impact Assessment (LCIA) translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterisation factors [1].

The quantification for assessing the environmental impact (LCI) is modelled in SimaPro software version 9.4 the used database/ library is the Ecoinvent 3, from which background data were provided when necessary. The chosen LCA methodology is the ReCiPe methodology [1]. It was created by the RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft. In this methodology, the SimaPro practitioner has the option of using 18 midpoint and 3 endpoint indicators (Annexes). The midpoint indicators concentrate on single environmental problems, such as climate change or ecotoxicity, while endpoint-oriented indicators focus on the environmental impact of three higher aggregation levels as the Figure 13 illustrates: 1) effect on human health, 2) ecosystems and 3) resource scarcity.

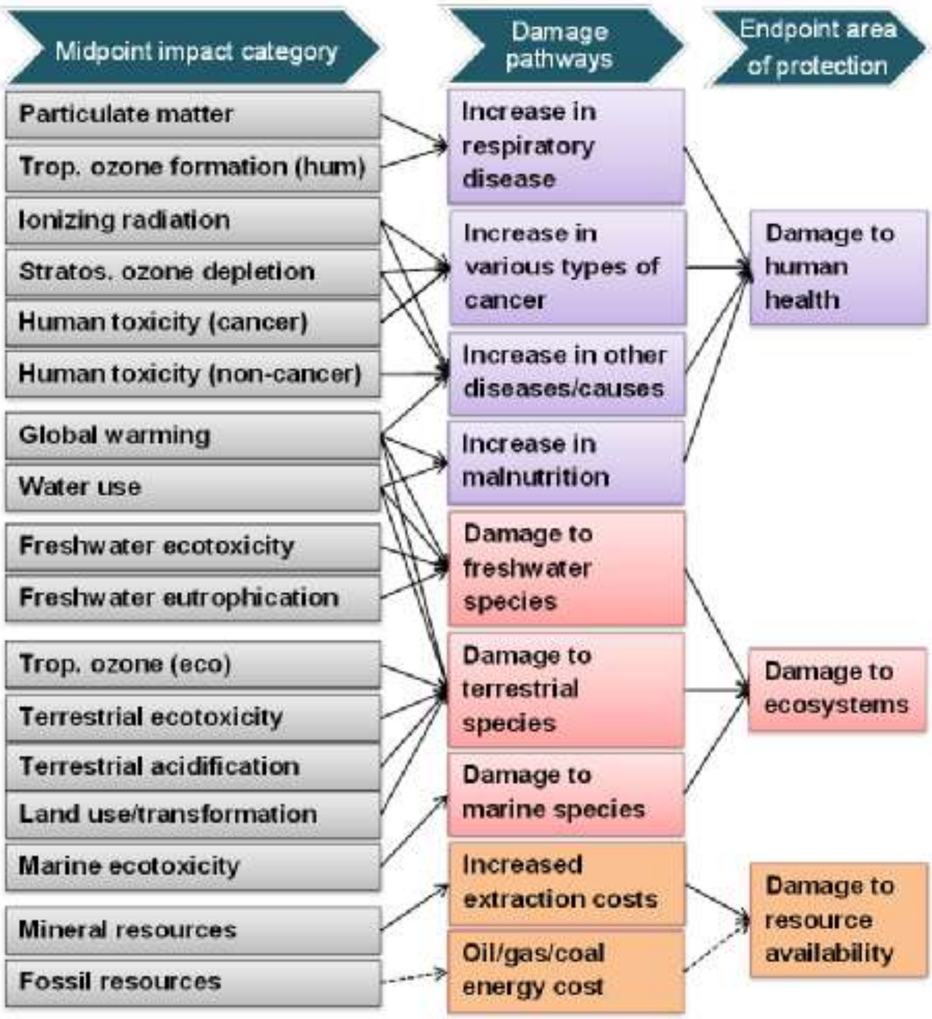



*Figure 13. Relations between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe methodology.*

# 4. LIFE CYCLE ASSESSMENT STUDIES

## 4.1. BENCHMARK LCA ON NdFeB PERMANENT MAGNET PRODUCTION

### 4.1.1. LCI of NdFeB magnets production

A benchmark LCA of the conventional technologies was performed as a baseline LCA for the existing current technology and value chain for comparison purposes. The benchmarking LCA study was conducted using LCI data of the sintered NdFeB magnets production process available in the literature. Literature review revealed that limited data are available as the vast majority of the production is carried out in China. The case study employed in this baseline LCA, evaluated the environmental impact of recycling NdFeB magnets, crucial for applications like electric vehicle motors, as rare earth elements REEs face supply uncertainties [8]. The research employed life cycle assessments to directly measure environmental inputs and outputs, comparing recycling to traditional production from "virgin" materials. The LCI data on sintered NdFeB magnets production from virgin materials were extracted to conduct the baseline LCA of the PASSENGER technology. The electricity consumption from China's electric grid was considered in this LCA study. Figure 14 below illustrates the outline for a typical NdFeB magnet production process [8].

The **system boundary** of the sintered NdFeB magnet production process included all the steps up-to electroplating:

- **Strip casting** to form magnetically anisotropic NdFeB alloy (distinctive step of virgin production).
- **Hydrogen decrepitation** to form a coarse powder of around 4-7 microns average particle size.
- **Jet mill** to form fine powders of around 3-4 microns average particle size.
- **Aligning and Pressing.**
- **Sintering** at 1000◦C to form sintered magnet blocks (5-15% material loss).
- **Slicing** and **Dicing** into two shapes (rectangular and cylindrical).
- **Coating and Magnetizing** using anticorrosion layers (organic or a metallic).

The above life cycle of the producing 1 kg of sintered NdFeB permanent magnets is depicted in the following flowchart (Figure 15). The process simulation in SimaPro software is presented in Figure 16.

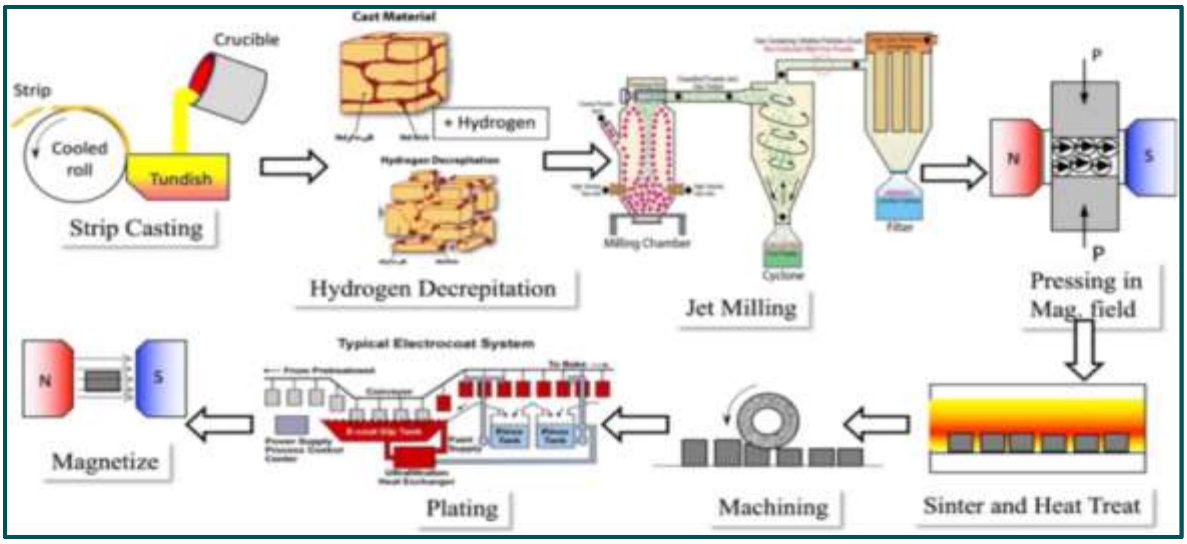



*Figure 14. Basic process steps for the NdFeB-based magnets.*

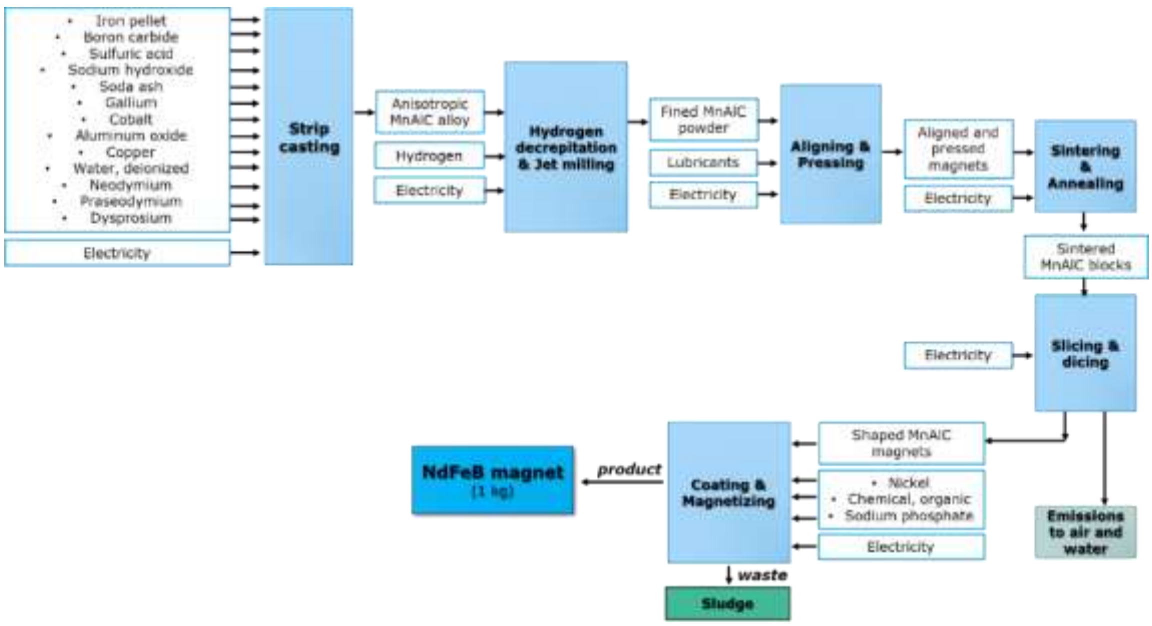



*Figure 15. Flow chart of producing 1 kg NdFeB magnets.*

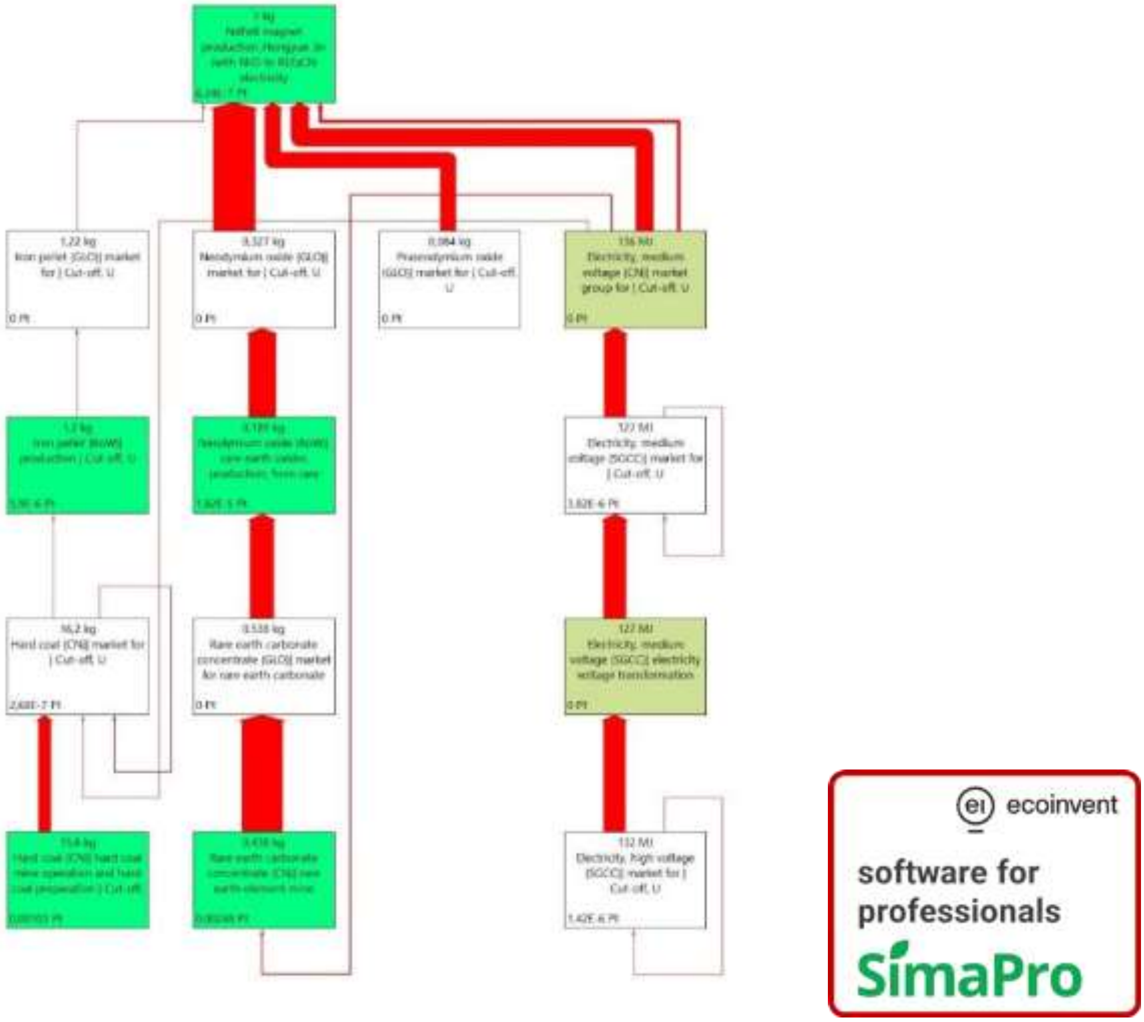



*Figure 16. Process simulation of 1 kg NdFeB magnets production in SimaPro software.*

### 4.1.2 LCI of Neodymium and Praseodymium (Light REEs)

In order to provide more representative estimations on the environmental footprint of NdFeB magnets production, the mining of Nd, Pr and Dy were also included in the system boundary of this LCA study using the available inventory data from the literature [9,10]. These LCI data were combined with the abovementioned LCI data on NdFeB magnets production process to provide a precise estimation of the environmental impact considering the whole life cycle of the NdFeB magnets. In this context, the study from which data were extracted for developing the inventory of the mining and Nd metal production aimed to conduct a comparative LCA of the environmental impacts associated with producing 1 kg of NdFeB magnets, for high-performance applications like direct-drive wind generators. Three major rare earth element production pathways, involving neodymium, praseodymium, and dysprosium from Mount Weld, Mountain Pass, and Bayan Obo deposits, were examined under consistent frame conditions. For light REEs such as Nd and Pr, Bayan Obo deposit is the world's largest production site. This section mainly focusses on the LCI data representing the process from mining stage to Nd metal production taking place in Bayan Obo deposit. The production of rare earth elements involves six key stages: mining, beneficiation, acid roasting, leaching, solvent extraction, and electrolysis. The detailed process is depicted in Figure 17 below. The process simulation of Nd mining in SimaPro software is presented in Figure 18. The same LCI inventory was employed for the mining process of Pr and Pr metal production.

The **system boundary** of the mining process and Nd metal production included the below steps:

- **Mining** for the production of the raw ore
- **Crushing** and **milling** for the production of the ore pulp
- **Flotation** for the production of the RE concentrate
- **Roasting** for the production of the roasted concentrate
- **Leaching** for the production of the RE chloride solution
- **Solvent extraction** and **precipitation** for the production of $Nd_2(C_2O_4)_3$
- **Calcination** for the production of the $Nd_2O_3$
- **Neodymium(III) fluoride production**
- **Nd metal production.**

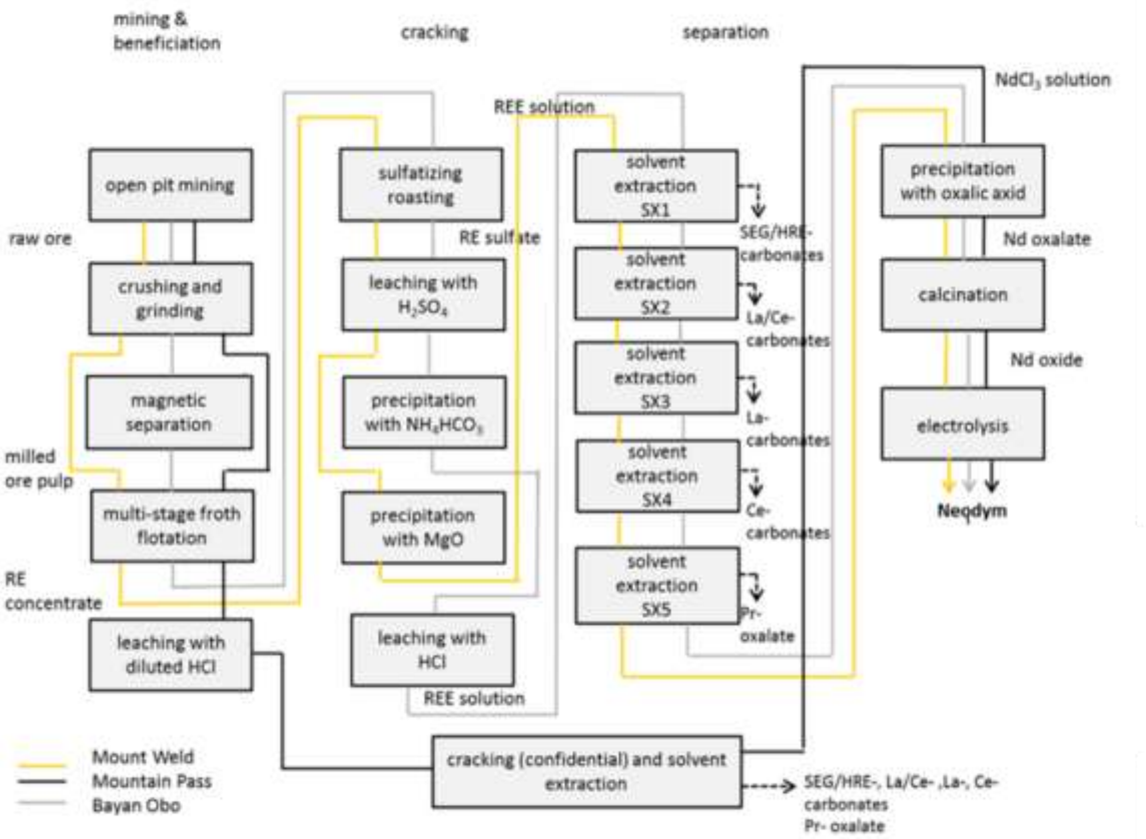



*Figure 17. Exemplary process chain of the three supply chains for the production of Nd.*

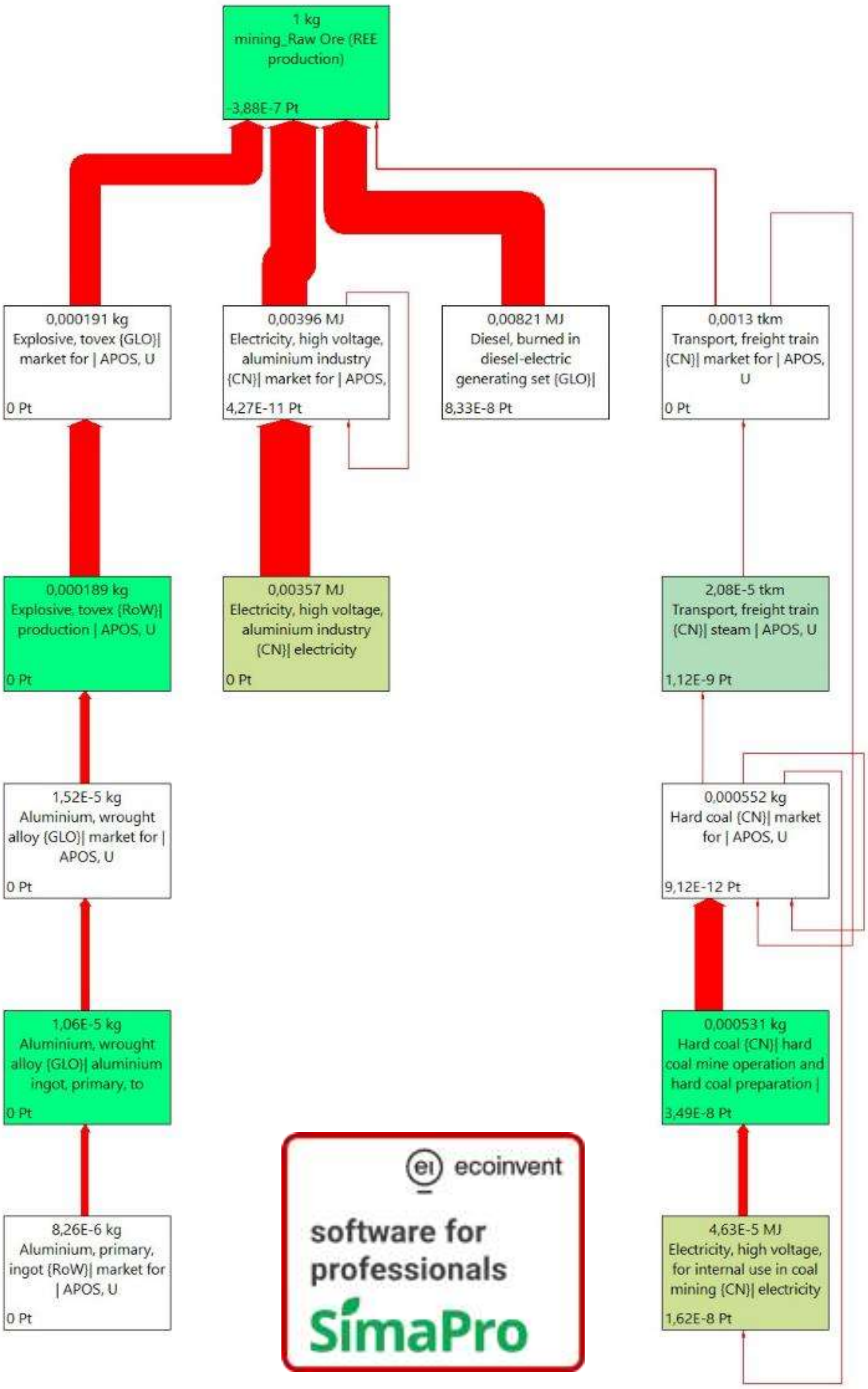



*Figure 18. Process simulation of Nd mining in SimaPro software.*

### 4.1.3. LCI of Dysprosium (Heavy REEs)

The development of the inventory for the mining of Dysprosium was based on LCI data reported in the literature [10]. The paper focused on the Life Cycle Assessment LCA of in-situ leach mining for Rare Earth Elements (REEs) from ion adsorption clays in southern China, with a specific focus on heavy rare earths (HREEs). The detailed process is depicted in Figure 19 below. The process simulation of Dy oxide production in SimaPro software presented in Figure 20.

The **system boundary** of included all the processes up-to Dysprosium oxide production.

- Site preparation which includes soil removal and drilling of holes
- Liquids injection (Leaching)
- Precipitation
- Filtration
- Mechanical Pressing
- Calcination
- Further refining and processing.

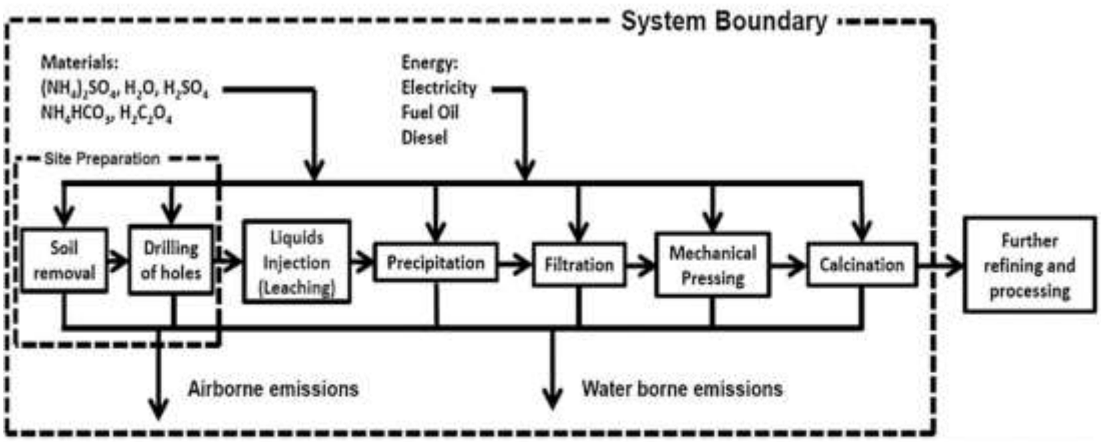



*Figure 19. Exemplary process chain of the Dysprosium oxide production.*

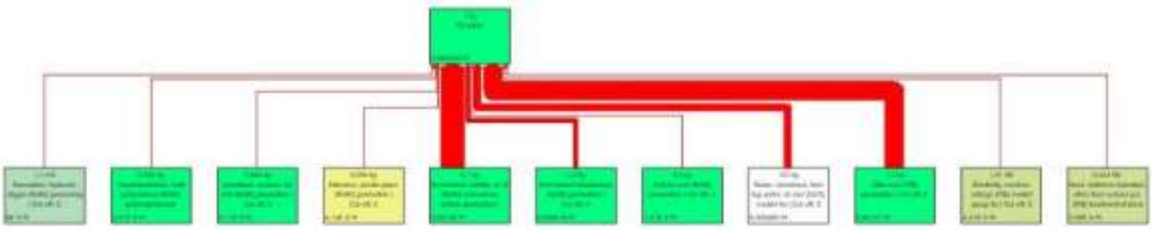


*Figure 20. Process simulation of Dy oxide production in SimaPro software.*

### 4.1.4. LCIA of NdFeB magnets production

Table 1 presents the LCIA results of producing 1 kg of sintered NdFeB magnets. After observing the results, it can be concluded that the most affected impact categories are Global warming (76,41 kg $CO_2$ eq), Ionising radiation (2,86 kBq Co-60 eq), Terrestrial ecotoxicity (423,32 kg 1,4-DCB), Human non-carcinogenic toxicity (38,67 kg 1,4-DCB), Land use (8,12 m2a crop eq), Mineral resource scarcity (16,12 kg Cu eq) and Fossil resource scarcity (17,48 kg oil eq).

**Table 1**. LCIA results of producing 1 kg of NdFeB magnets.

| **Impact category** | **Total Impact** | **Unit** |
|---|---|---|
| Global warming | **76,41** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | kg CFC11 eq |
| Ionizing radiation | **2,86** | kBq Co-60 eq |
| Ozone formation, Human health | **0,22** | kg NOx eq |
| Fine particulate matter formation | **0,18** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,22** | kg NOx eq |
| Terrestrial acidification | **0,47** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | kg P eq |
| Marine eutrophication | **0,32** | kg N eq |
| Terrestrial ecotoxicity | **423,32** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | kg 1,4-DCB |
| Marine ecotoxicity | **0,43** | kg 1,4-DCB |
| Human carcinogenic toxicity | **1,03** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **38,67** | kg 1,4-DCB |
| Land use | **8,12** | m2a crop eq |

| | | |
|---|---|---|
| Mineral resource scarcity | **16,12** | kg Cu eq |
| Fossil resource scarcity | **17,48** | kg oil eq |
| Water consumption | **1,32** | m3 |

Table 2 summarises the impact results in four main categories (Nd, Pr, Dy and magnet production). It should be mentioned that the impact of auxiliary materials, electricity consumption and waste generation for producing 1 kg of sintered NdFeB magnets has been integrated in the magnet production category in the Table 2 below. Tables 3 presents a more detailed environmental impact assessment arising from Nd, Pr, Dy, Fe, B, Cu, and magnet production the production of 1 kg of sintered NdFeB magnets.

**Table 2**. Contributions from Nd, Pr, Dy and magnet production in the environmental impact of producing 1 kg of NdFeB magnets.

| **Impact category** | **Global warming (kg CO2 eq)** | **Ionizing radiation (kBq Co-60 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** |
|---|---|---|---|---|
| **Nd** | 24,77 | 1,93 | 126,15 | 15,21 |
| **Pr** | 8,36 | 0,74 | 47,28 | 5,39 |
| **Dy** | 2,49 | 0,03 | 6,78 | 0,79 |
| **Magnet Production** | 40,8 | 0,16 | 242,27 | 18,31 |
| **Sum** | **76,41** | **2,86** | **423,32** | **39,71** |
| **Impact category** | **Land use (m2a crop eq)** | **Mineral resource scarcity (kg Cu eq)** | **Fossil resource scarcity (kg oil eq)** | **Marine eutrophication (kg N eq)** |
| **Nd** | 5,45 | 10,30 | 6,43 | 0,22 |
| **Pr** | 2,23 | 3,99 | 2,15 | 0,10 |
| **Dy** | 0,07 | 0,09 | 0,61 | 0,00 |
| **Magnet Production** | 0,36 | 1,72 | 8,28 | 0,00 |
| **Sum** | **8,12** | **1,66** | **17,48** | **0,32** |

| *Table 3. Contributions from Nd, Pr, Dy, Fe, B, Cu, and magnet production in the environmental impact of producing 1 kg of NdFeB magnets.* | | | | |
|---|---|---|---|---|
| **Impact category** | **Global warming (kg CO2 eq)** | **Ionizing radiation (kBq Co-60 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** |
| **Nd** | 24,77 | 1,93 | 126,15 | 15,21 |
| **Pr** | 8,36 | 0,74 | 47,28 | 5,39 |
| **Dy** | 2,49 | 0,03 | 6,78 | 0,79 |
| **Fe** | 0,11 | 0,00 | 0,32 | 0,05 |
| **B** | 0,30 | 0,00 | 2,55 | 0,19 |
| **Cu** | 0,01 | 0,00 | 9,37 | 0,51 |
| **Other Auxiliary Materials/Energy/Wastes (Magnet Production*)** | 40,38 | 0,16 | 230,03 | 17,56 |
| **Sum** | **76,41** | **2,86** | **423,32** | **39,71** |
| **Impact category** | **Land use (m2a crop eq)** | **Mineral resource scarcity (kg Cu eq)** | **Fossil resource scarcity (kg oil eq)** | **Marine eutrophication (kg N eq)** |
| **Nd** | 5,45 | 10,30 | 6,43 | 0,22 |
| **Pr** | 2,23 | 3,99 | 2,15 | 0,10 |
| **Dy** | 0,07 | 0,09 | 0,61 | 0,00 |
| **Fe** | 0,00 | 0,06 | 0,03 | 0,00 |
| **B** | 0,00 | 0,00 | 0,06 | 0,00 |
| **Cu** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Other Auxiliary Materials/Energy/Wastes (Magnet Production*)** | 0,36 | 1,66 | 8,19 | 0,00 |
| **Sum** | **8,12** | **1,66** | **17,48** | **0,32** |

**Impact of other auxiliary materials, electricity consumption and waste generation for producing 1 kg of sintered NdFeB magnets.*

Figure 21 presents the percentage contribution of all raw materials, the electricity consumption and waste generation to the total environmental footprint observed in all impact categories during the production of 1 kg of sintered NdFeB magnets. Neodymium is the main contributor to the environmental footprint observed in all impact categories with 44,02 % contribution on average and total emissions of 24,76 kg $CO_2$ eq. More specifically, Neodymium shares the highest impact in almost all impact categories with significant impact in the Ionizing radiation category (67%, 1,93 kBq Co-60 eq), Marine eutrophication (69%, 0,22 kg N eq), Land use (67%, 5,45 m2a crop eq) and Mineral resource scarcity (63%, 10,3 kg Cu eq). Nd has also the highest impact in Human toxicity category (38,5% contribution, 14,81 kg 1,4-DCB).

The electricity which is required for the NdFeB magnets production follows with 17,97% average contribution to the total environmental impact of the process and total emissions of 36,02 kg $CO_2$ eq. Electricity consumption is also the main contributor in the GW impact category with 47 % contribution, the Ozone formation, Human health (44,4% contribution, 0,09 kg NOx eq), Ozone formation, the Terrestrial ecosystems (44,1% contribution, 0,09 kg NOx eq) and the Fossil resource scarcity (39,8% contribution, 6,96 kg oil eq).

Praseodymium follows with 16,9 % average contribution and total emissions of 8,36 kg $CO_2$ eq. Praseodymium has also significant contribution to the impact observed in the Marine eutrophication category (30% contribution, 0,09 kg N eq), the Land use (27,5% contribution, 2,23 m2a crop eq) and the Ionizing radiation category (25,9% contribution, 0,74 kBq Co-60 eq).

Cobalt follows with 3,13% average contribution in all impact categories and total emissions of 2,03 kg $CO_2$ eq. Cobalt is the main contributor to the impact observed in the Water consumption impact category (35,9 % contribution, 0,47 m3). Cobalt also poses a high contribution to the impact observed in the Terrestrial ecotoxicity category (26,4% contribution, 111,96 kg 1,4-DCB) and the Human carcinogenic toxicity (19,6% contribution, 0,20 kg 1,4-DCB).

Nickel follows with 7,21 % average contribution in all impact categories and emissions of 1,39 kg $CO_2$ eq. Nickel is the main contributor to the total impact observed in the Terrestrial acidification category (33,1% contribution, 0,15 kg $SO_2$ eq) and poses a high contribution also in the Fine particulate matter formation category (26,5% contribution, 0,04 kg PM2.5 eq) and the Terrestrial ecotoxicity category (24% contribution, 101,8 kg 1,4-DCB).

Dysprosium follows with 2,05% average contribution in all impact categories and emissions of 2,48 kg $CO_2$ eq.  Wastes, Ga and Iron follow with 1,1%, 0,65% and 0,18% average contribution in all impact categories and emissions of 0,25, 0,65 and 0,10 kg $CO_2$ eq respectively. Waste production poses a significant contribution to the impact observed in the Human non-carcinogenic toxicity category (11,65% contribution, 4,5 kg 1,4-DCB). The rest of the auxiliary material used for the magnet production have less than 0,18% average contribution in all impact categories.

Figure 22 below presents the contribution of Nd, Pr, Dy and magnet production to the total environmental impact observed in all impact categories. After observing the results, it can be concluded that the processes involved in the mining, metal production, transportation and use of the Nd for the sintered NdFeB magnets is the main contributor to the total impact of the process with 44% average contribution and total emissions of 24,76 kg $CO_2$ eq. The production process follows with 36,6% average contribution and total emissions of 24,76 kg $CO_2$ eq. The production phase of NdFeB magnets appears to have the most significant impact on the GW impact category due to the high electricity consumption involved (Figure 23). However, when considering the overall impact of NdFeB magnets, the greatest contribution comes from Nd mining, metal production, transportation, and usage.

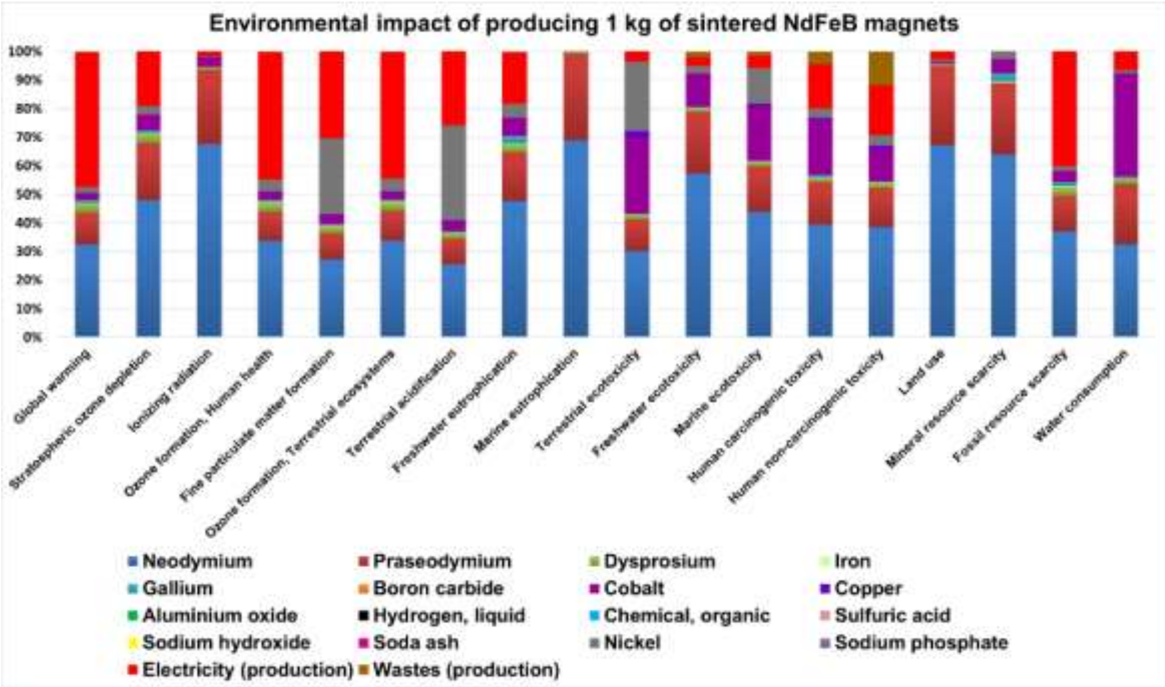



*Figure 21. Environmental impact of producing 1 kg of NdFeB magnets.*

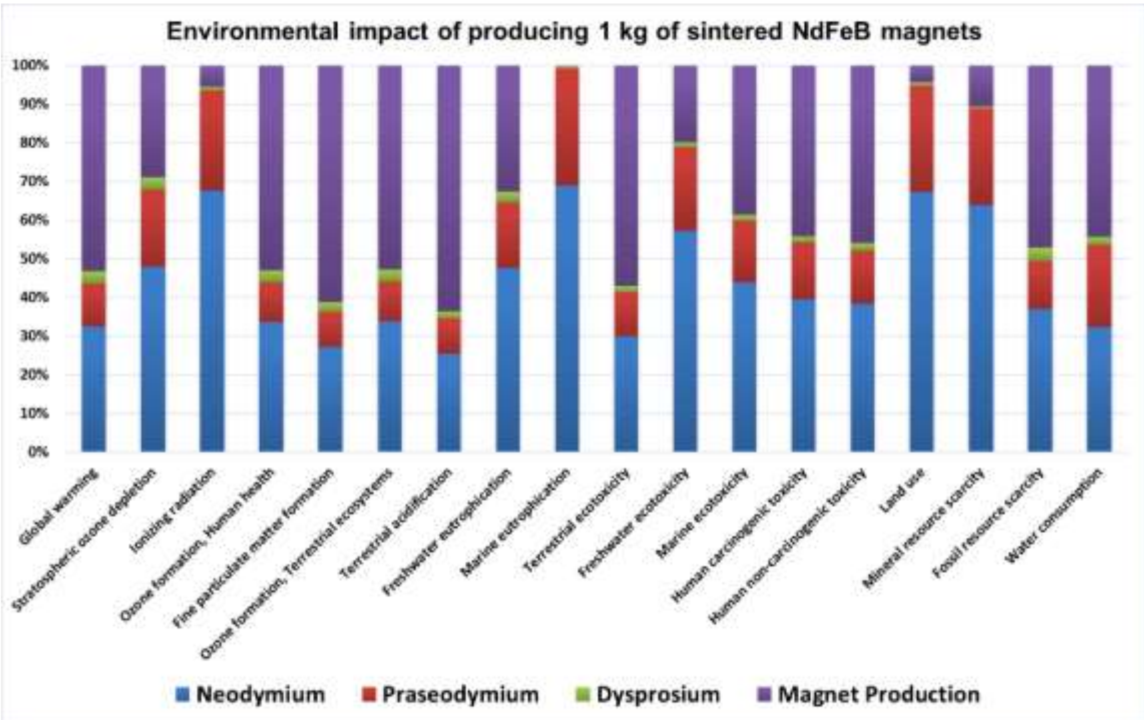



*Figure 22. Environmental impact of producing 1 kg of NdFeB magnets.*

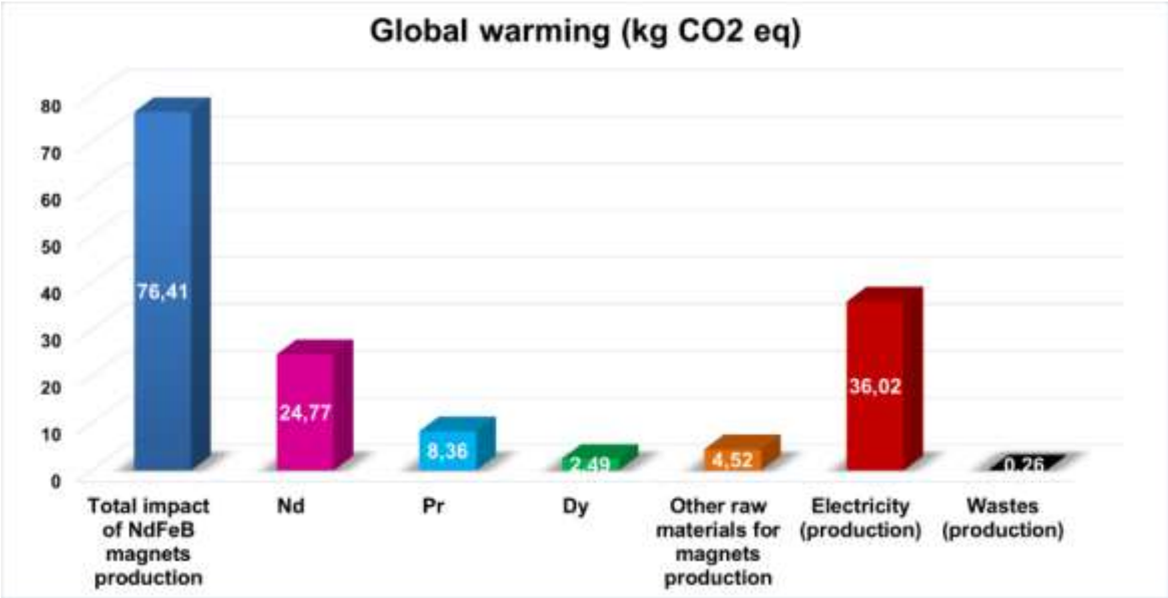



*Figure 23. Environmental impact of producing 1 kg of NdFeB magnets in GW impact category.*

The PASSENGER project aims to foster the independency in EU in the REEs supply. The extraction and refinement of Rare Earth Elements (REEs), predominantly carried out in China, pose significant environmental challenges. There are growing concerns regarding the potential health impacts on local populations and, given the substantial scale of extraction and production globally, implications for people worldwide. The PASSENGER project aims to alleviate the demand for REEs in magnet production, providing an opportunity for regions involved in this activity to implement measures to mitigate pollution effectively. The origin of the electricity grid used for energy consumption during the production of the NdFeB magnets plays a vital role to the total impact of the process. To this end, a comparative LCA study was also conducted to investigate the effect of the electricity origin on the NdFeB magnets environmental footprint. Table 4 below presents the comparative LCIA results using the Chinese and European electricity grids. The use of the European electricity grid leads to reduced environmental impact in almost all impact categories and 30,04 % reduction in CO2 emissions.

*Table 4. Comparative LCIA results using the Chinese and European electricity grids for producing 1 kg of NdFeB magnets.*

| Impact category | Total Impact (Chinese grid) | Total Impact (European Electricity grid) | Unit |
|---|---|---|---|
| Global warming | 76,41 | 53,45 | kg CO2 eq |
| Stratospheric ozone depletion | 0,00 | 0,00 | kg CFC11 eq |
| Ionizing radiation | 2,86 | 3,31 | kBq Co-60 eq |

| | | | |
|---|---|---|---|
| Ozone formation, Human health | 0,22 | 0,15 | kg NOx eq |
| Fine particulate matter formation | 0,18 | 0,15 | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | 0,22 | 0,15 | kg NOx eq |
| Terrestrial acidification | 0,47 | 0,40 | kg SO2 eq |
| Freshwater eutrophication | 0,00 | 0,01 | kg P eq |
| Marine eutrophication | 0,32 | 0,32 | kg N eq |
| Terrestrial ecotoxicity | 423,32 | 414,03 | kg 1,4-DCB |
| Freshwater ecotoxicity | 0,23 | 0,23 | kg 1,4-DCB |
| Marine ecotoxicity | 0,43 | 0,42 | kg 1,4-DCB |
| Human carcinogenic toxicity | 1,03 | 0,92 | kg 1,4-DCB |
| Human non-carcinogenic toxicity | 38,67 | 34,22 | kg 1,4-DCB |
| Land use | 8,12 | 8,19 | m2a crop eq |
| Mineral resource scarcity | 16,12 | 16,12 | kg Cu eq |
| Fossil resource scarcity | 17,48 | 14,01 | kg oil eq |
| Water consumption | 1,32 | 1,47 | m3 |

## 4.2. LCA ON THE MnAlC PERMANENT MAGNET PRODUCTION

### 4.2.1. LCI of bonded MnAlC magnets production

The production chain of the bonded MnAlC magnets developed within the PASSENGER project follows the path outlined below, encompassing the steps of casting, atomization, compounding, and plastic injection (Figure 24). In the following sections, the LCI of each partner's process is analysed.


*Figure 24. Production chain of PASSENGER's bonded MnAlC magnets.*

#### *4.2.1.1 LCM process (casting)*

In the context of data collection, the development of the LCI inventory of the MnAlC alloy by casting was based on data provided by the LCM partner. The detailed inventory including all the input and outputs of the process is presented in the deliverable D4.4 Collect all required life cycle inventory data at material, process and prototype level. The electricity consumption from Europe's electric grid was considered in this LCA study and the production of 7 kg of MnAlC alloy was employed as reference unit.

LCM's process simulation in SimaPro software is presented in Figure 25.

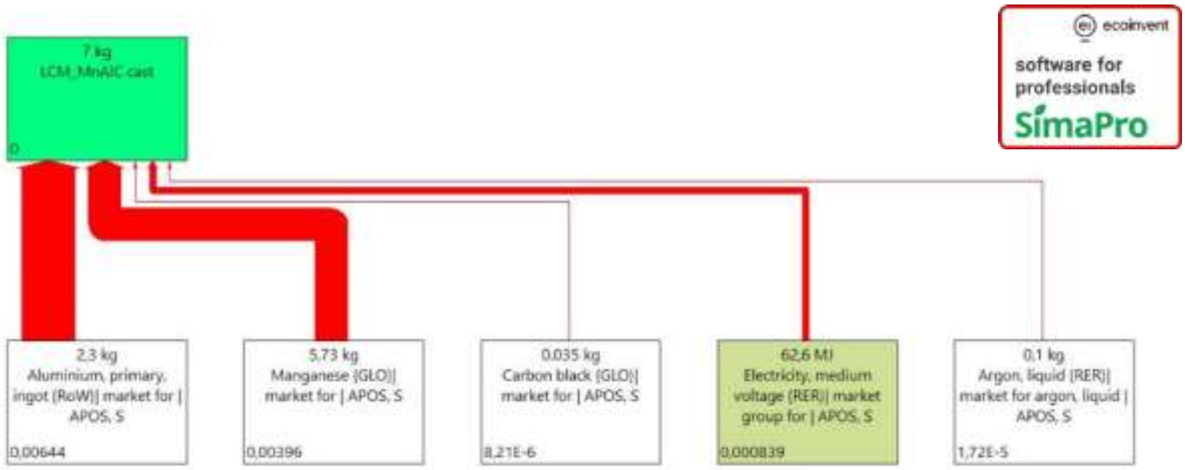



*Figure 25. Process simulation of MnAlC alloy production by casting in SimaPro software (LCM process).*

#### *4.2.1.2 METALPINE process (atomizing)*

In the context of data collection, the development of the LCI inventory of the atomized MnAlC metal powder was based on data provided by the METALPINE partner. The detailed inventory including all the input and outputs of the process is presented in the deliverable D4.4 Collect all required life cycle inventory data at material, process and prototype level. The electricity consumption from Europe's electric grid was considered in this LCA study and the production of 9 kg of atomized MnAlC metal powder was employed as reference unit. METALPINE received the MnAlC alloy from LCM (GB) through shipping from UK to AUT and within EU to De and ES in containers and trucks. The production process took place in the METALPINE's Crucible atomising plant. The production of the atomized MnAlC metal powder is part of the following supply and production chain: The raw material (ingots) are produced from LCM (UK) and then shipped to the production plant of METALPINE (AUT). Atomizing of the material to powder and powder classification follows and then the materials are shipped to IMDEA (ES) and TUDA (DE) for characterization and finally to WILO (DE) for producing fully dense magnets by hot-deformation and to BARLOG (DE) for composites production: (MnAlC / polymer PPS).

Regarding the process details as provided by the METALPINE partner in the LCI questionnaire, for the project, the existing pilot production line was modified to atomize lumpy material. The pieces obtained were melted in a crucible by induction and atomized with argon as a carrier medium. The resulting powder was collected and classified in-house by sieving and sifting. Particle size and sphericity were measured in house and the chemical composition was measured contractors. The process preparation involves conversion to required melting module, setting up the remaining machine parts for the required melting module, installing the required safety measures (shielding, contact protection), pressure and gas tests, connect induction device, gas pipes, water, cleaning each clamp and cleaning steel body. The metal extraction / atomizing process involves meting by induction, atomizing with an argon-stream, collecting with cyclon, sieving, sifting and camsizer analysing.   METALPINE's process simulation in SimaPro software is presented in Figure 26.

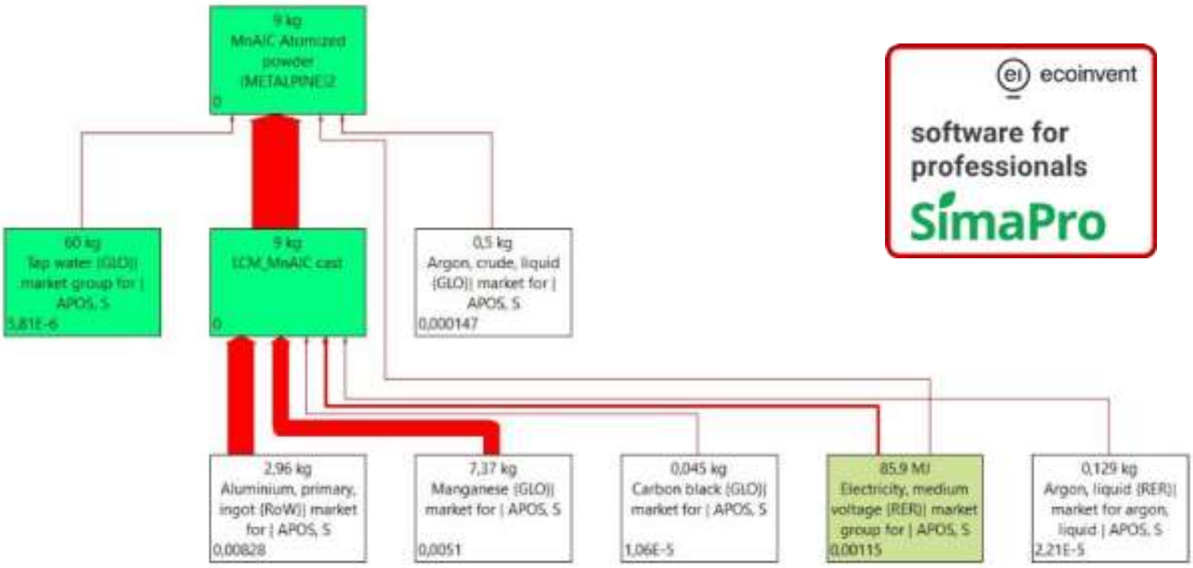



*Figure 26. Process simulation of atomized MnAlC metal powder production in SimaPro software (METALPINE process).*

#### *4.2.1.3 MBN process (High Energy Ball Milling)*

MBN (IT) perform High Energy Ball Milling (HEBM) on MnAlC loose powder produced by LCM (UK) or Metalpine (AT), delivered through shipping. HEBM is a solid state process, performed at inert gas conditions (Argon), with a close loop gas recycling operating at low pressure (max 5bar). A cooling close circuit is installed to control process temperature. The existing pilot production line was modified to process coarse powder and to reduce process time. The processed powder is collected and classified in subsequent pilot-scale sieving systems. The overall process' energy consumption is about 0.22KWh/kg. The yield in fraction <106µm (considering recycling steps of coarser fractions) is 95%. Heat treatment at 550 °C in inert atmosphere can be optionally performed on loose powder (still under investigation).

The process output, i.e. MnAlC loose powder <106µm with increased coercivity is delivered to Barlog (DE) for compounding process. MBN's process simulation in SimaPro software is presented in Figure 27 below.

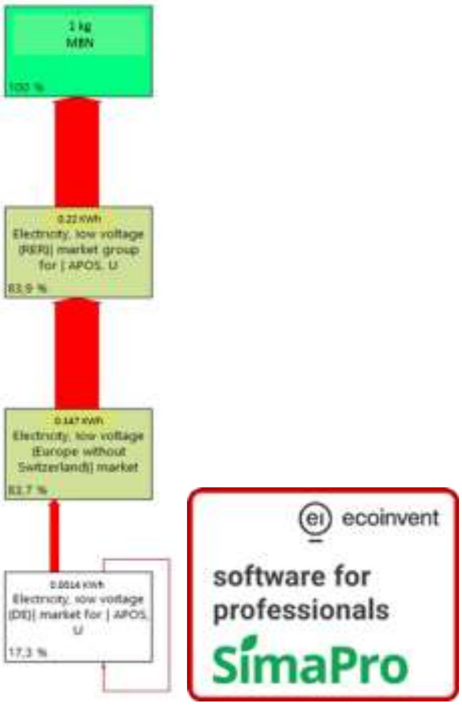



*Figure 27. High Energy Ball Milling process flow sheets (MBN process).*

Specifically, MnAlC powder with a particle size of less than 250 µm, sourced from LCM, serves as the raw material. The process has an energy consumption of approximately 0.22 kWh/kg, and the yield for particles smaller than 106 µm, considering the recycling of coarser fractions, is 95%. The temperature and pressure of the HEBM process are not significant factors. The process requires an inert atmosphere, which is maintained by a closed inert circuit filled with argon gas. There are no wastewater or emissions associated with the process, as the reactor's cooling system operates in a closed circuit. Coarser MnAlC powder is recycled within the process. Finally, a vibratory sieving machine is employed for the sieving step.

#### *4.2.1.4 BARLOG process (compounding)*

In the context of data collection, the development of the LCI inventory of the polymer bonded MnAlC magnet compound was based on data provided by the BARLOG partner. The detailed inventory including all the input and outputs of the process is presented in the deliverable D4.4 Collect all required life cycle inventory data at material, process and prototype level. The assumption of using 1 kg of atomized MnAlC metal powder and the electricity consumption from Europe's electric grid were considered for this LCA study. The production of 1 kg of polymer bonded MnAlC magnet compound was employed as reference unit.

Regarding the process details as provided by the BARLOG partner in the LCI questionnaire, raw materials were stored in a non-heated warehouse and transported within the company by electric forklifts. The raw materials were compounded with a twin-screw extruder and processed into a homogeneous material. After cooling on air at room temperature granules were packed into bags in a manual process. The transport to the customer depends on the quantity of material. Larger quantities were transported by a forwarding agent.

BARLOG's process simulation in SimaPro software is presented in Figure 28.

ecoinvent
software for professionals
SimaPro

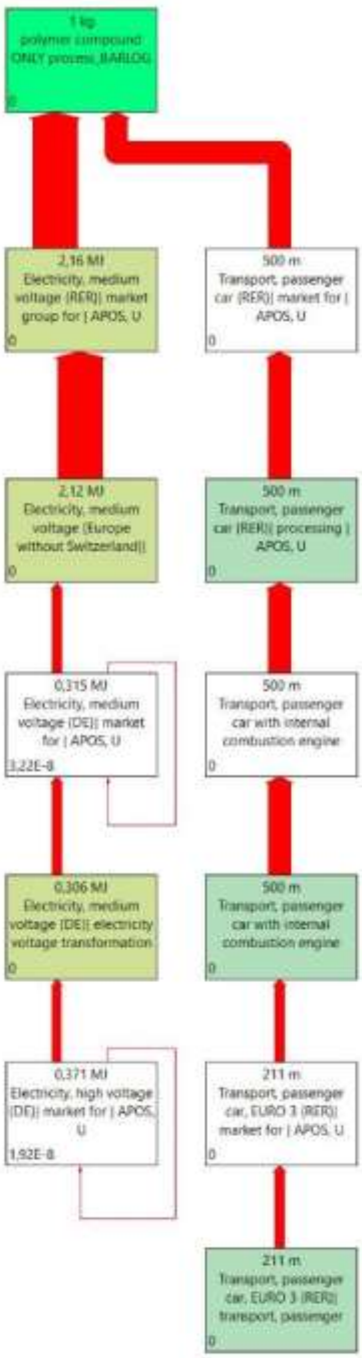


*Figure 28. Process simulation of polymer bonded MnAlC magnet compound production in SimaPro software (BARLOG process).*

#### *4.2.1.5 IMA process (plastic injection)*

In the context of data collection, the development of the LCI inventory of the bonded MnAlC magnets production was based on data provided by the IMA partner. The detailed inventory including all the input and outputs of the process is presented in the deliverable D4.4 Collect all required life cycle inventory data at material, process and prototype level. The assumption of using 1 kg of polymer bonded MnAlC magnet compound and the electricity consumption from Europe's electric grid were considered in this LCA study.

Regarding the process details as provided by the IMA partner in the LCI questionnaire, the plastic-compounds (final product), were produced by pressing bonded magnetic material and injecting magnetic compounds with the wastes being recyclable. IMA's process simulation in SimaPro software is presented in Figure 29. In this flowchart the use of polymer bonded MnAlC magnet compound synthesized in the previous step (BARLOG process) is not depicted. The environmental footprint of the final bonded MnAlC magnet was calculated by using the product stages tool in the SimaPro software. To this end, BARLOG's and IMA's processes were summed and combined to provide the environmental impact of the final magnet product.

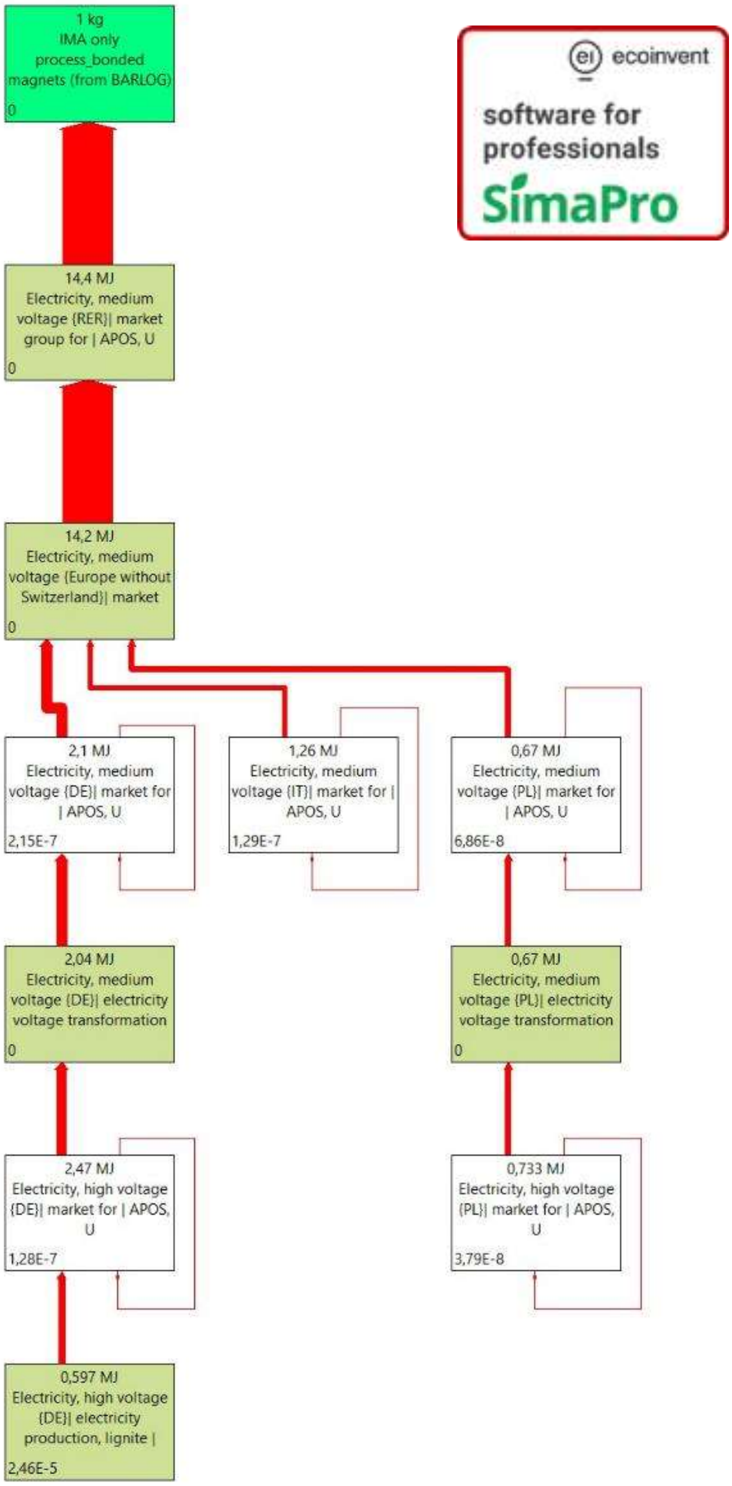



*Figure 29. Process simulation of bonded MnAlC magnets production in SimaPro software (IMA process).*

### 4.2.2 LCI of sintered MnAlC magnets production

The production chain of the sintered MnAlC magnets developed within the PASSENGER project follows the path outlined below, encompassing the steps of casting and metal injection moulding (Figure 30). In the following section, the LCI of KOLEKTOR's process is analysed. The LCI of LCM's process is the same as in the case of bonded MnAlC magnets and has been presented in section 4.2.1.1.


*Figure 30. Production chain of PASSENGER's sintered MnAlC magnets.*

#### *4.2.2.1 KOLEKTOR's process (metal injection moulding)*

In the context of data collection, the development of the LCI inventory of the sintered MnAlC magnets was based on data provided by the KOLEKTOR partner. The detailed inventory including all the input and outputs of the process is presented in the deliverable D4.4 Collect all required life cycle inventory data at material, process and prototype level. The electricity consumption from Europe's electric grid was considered in this LCA study and the production of 100 tons of sintered MnAlC magnets per year was employed as reference unit.

Regarding the process details as provided by the KOLEKTOR partner in the LCI questionnaire, the supply and production chain of the sintered MnAlC magnets followed the route: the MnAlC powder was provided by the LCM partner and the tested polymers were supplied by manufacturing sites located in EU, UK, USA, Japan and China. The product is injection molded magnet intended for motor, actuator or sensor applications and the costumers mainly automotives (80% EU based) for motors, actuators and sensors. KOLEKTOR's process simulation in SimaPro software is presented in Figure 31.

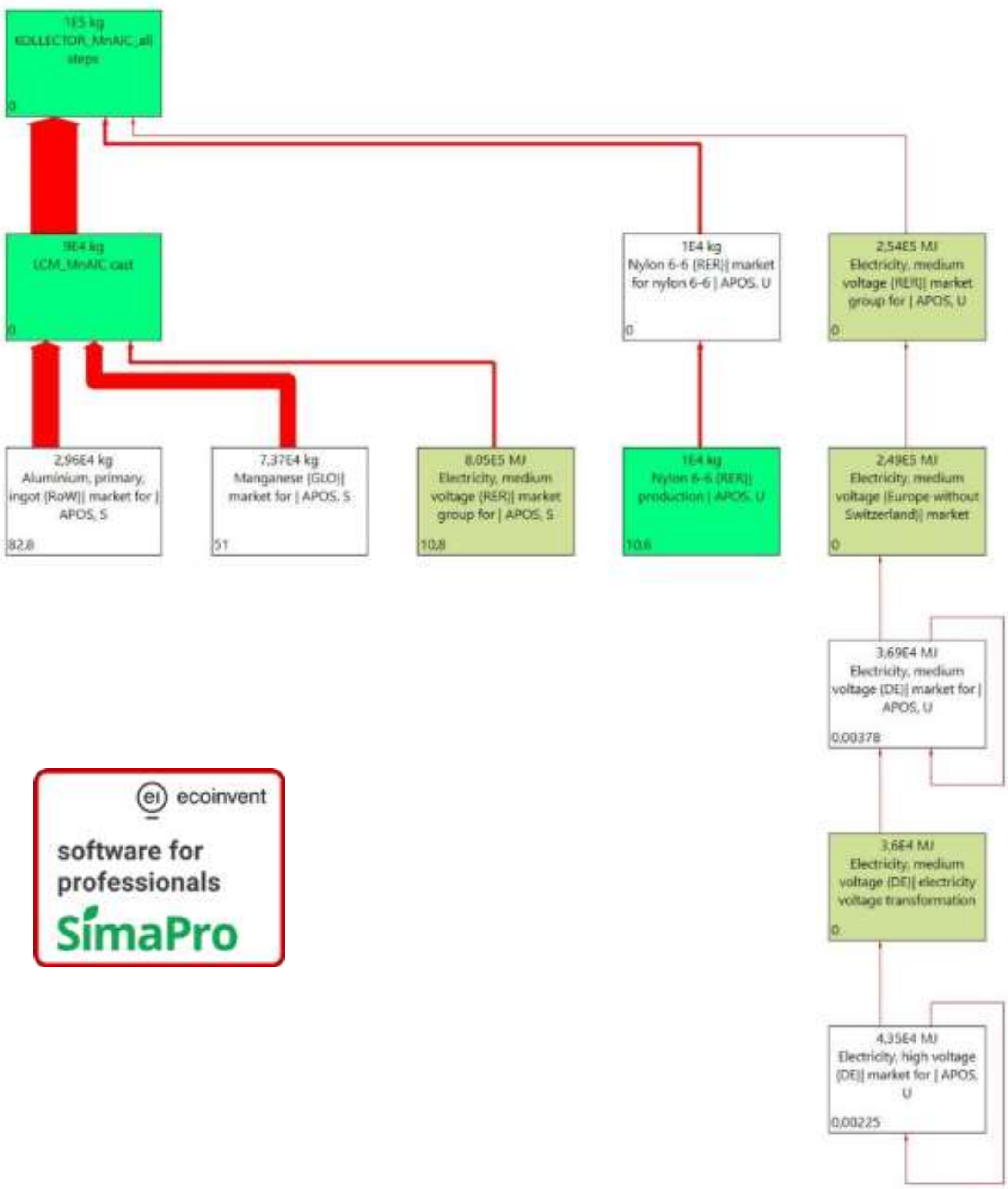



*Figure 31. Process simulation of sintered MnAlC magnets production in SimaPro software (KOLEKTOR process).*

## 4.2.3 LCIA results of PASSENGER's bonded MnAlC magnets production

### *4.2.3.1 MnAlC alloy production*

Table 5 presents the LCIA results of producing 1 kg of MnAlC alloy by casting. After observing the results, it can be concluded that the most affected impact categories are

Global warming (12,87 kg $CO_2$ eq), Terrestrial ecotoxicity (14,59 kg 1,4-DCB), Human toxicity (23,83 kg 1,4-DCB), and Fossil resource scarcity (2,77 kg oil eq).

***Table 5***. *LCIA results of producing 1 kg of MnAlC alloy by casting.*

| **Impact category** | **Total Impact** | **Unit** |
|---|---|---|
| Global warming | **12,87** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | kg CFC11 eq |
| Ionizing radiation | **0,08** | kBq Co-60 eq |
| Ozone formation, Human health | **0,04** | kg NOx eq |
| Fine particulate matter formation | **0,03** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,04** | kg NOx eq |
| Terrestrial acidification | **0,06** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | kg P eq |
| Marine eutrophication | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **14,59** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | kg 1,4-DCB |
| Marine ecotoxicity | **0,35** | kg 1,4-DCB |
| Human carcinogenic toxicity | **18,99** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **4,84** | kg 1,4-DCB |
| Land use | **0,27** | m2a crop eq |
| Mineral resource scarcity | **0,26** | kg Cu eq |
| Fossil resource scarcity | **2,77** | kg oil eq |
| Water consumption | **0,07** | m3 |

Table 6 below summarises the impact results in five main categories (Aluminium, Manganese, Carbon, Argon and Electricity consumption).

***Table 6**. Contributions from Aluminium, Manganese, Carbon, Argon and Electricity consumption in the environmental footprint of producing 1 kg of MnAlC alloy by casting.*

| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
|---|---|---|---|---|
| **Aluminium** | 7,36 | 5,38 | 3,51 | 1,51 |
| **Manganese** | 4,53 | 8,04 | 20,10 | 0,98 |
| **Carbon** | 0,01 | 0,02 | 0,00 | 0,01 |
| **Argon** | 0,02 | 0,02 | 0,00 | 0,01 |
| **Electricity** | 0,96 | 1,12 | 0,22 | 0,26 |
| **Sum** | **12,87** | **14,59** | **23,83** | **2,77** |

Figure 32 presents the percentage contribution of all raw materials, the electricity consumption and waste generation to the total environmental footprint observed in all impact categories during the production of 1 kg of MnAlC alloy by casting. Manganese is the main contributor to the environmental footprint observed in all impact categories with 53,14 % contribution on average and total emissions of 4,53 kg CO2 eq. Manganese has also high impact in the Freshwater ecotoxicity category (97,2% contribution, 0,22 kg 1,4-DCB), the Marine ecotoxicity category (96,1% contribution, 0,33 kg 1,4-DCB) and the Human carcinogenic toxicity category (98,2% contribution, 18,66 kg 1,4-DCB). Aluminium follows with 36% average contribution in all impact categories and total emissions of 7,36 kg CO2 eq. Aluminium is the main contributor to the total impact observed in the GW impact category (Figure 33). Electricity consumption follows with 10,4% average contribution and total emissions of 0,96 kg CO2 eq. The rest raw materials and waste production present less than 1% average contribution to the total impact of the casting process for producing 1 kg of MnAlC alloy.

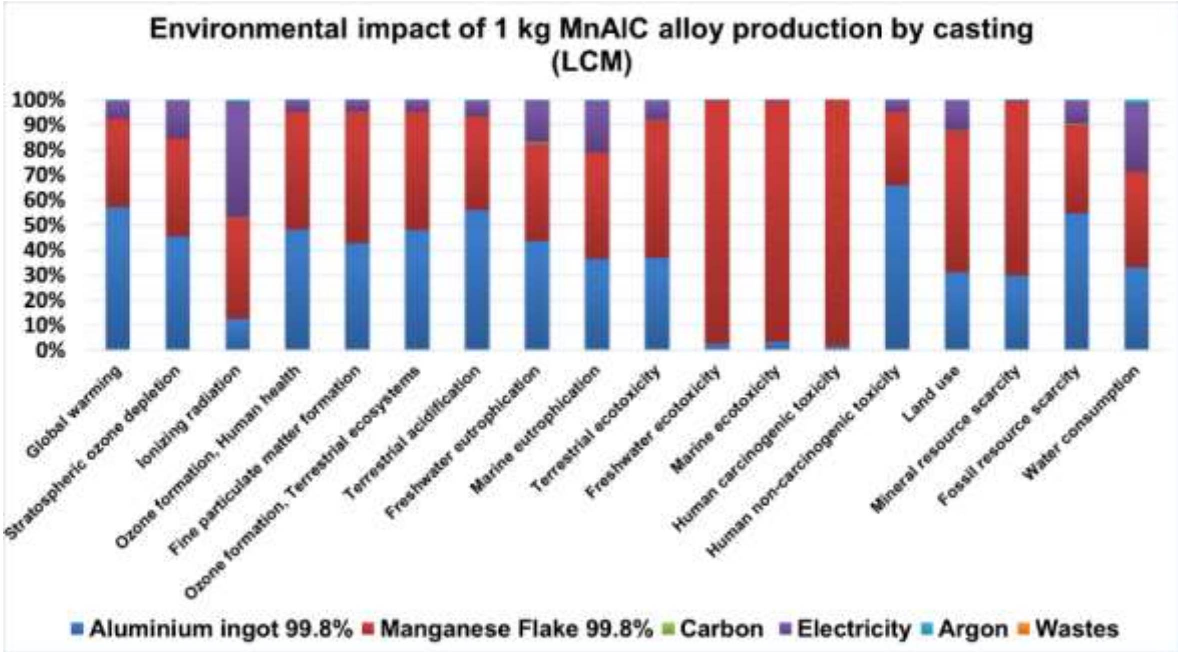



*Figure 32. Environmental impact of 1 kg of MnAlC alloy production by casting.*

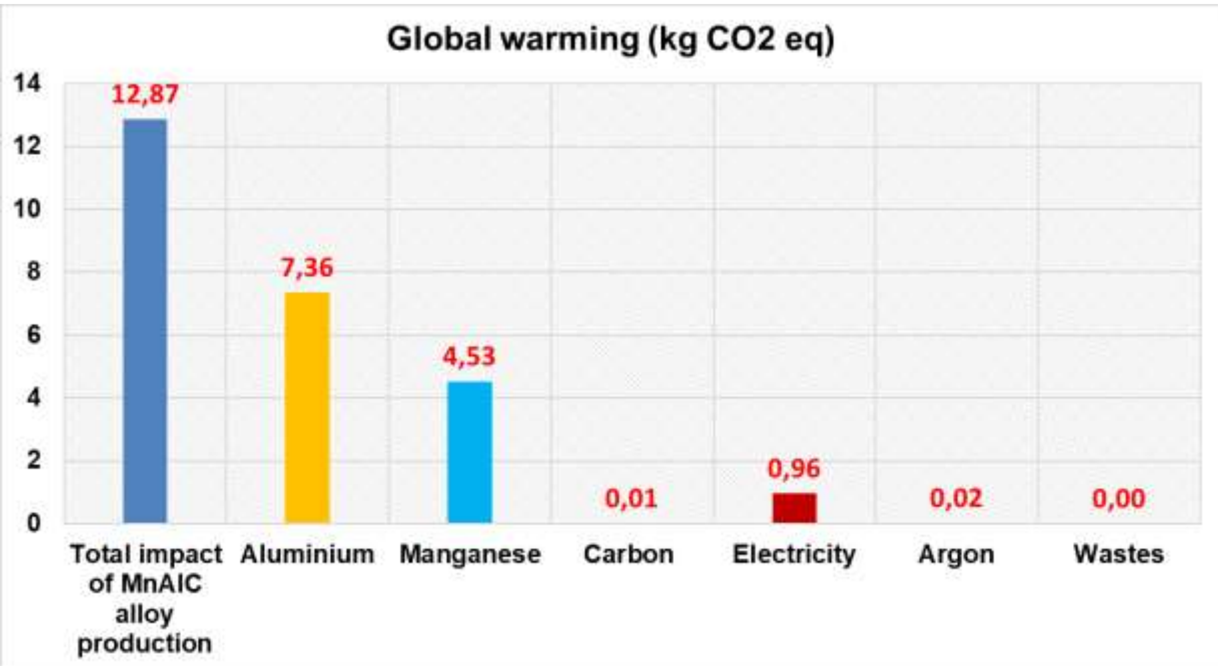



*Figure 33. Carbon dioxide emissions related to 1 kg MnAlC alloy production.*

### *4.2.3.2 MnAlC metal powder production*

Table 7 presents the LCIA results of producing 1 kg of atomized MnAlC metal powder. After observing the results, it can be concluded that the most affected impact categories are Global warming (13,07 kg CO2 eq), Terrestrial ecotoxicity (14,79 kg 1,4-DCB), Human toxicity (23,87 kg 1,4-DCB), and Fossil resource scarcity (2,82 kg oil eq).

***Table 7**. LCIA results of producing 1 kg of atomized MnAlC metal powder.*

| Impact category | Total Impact | Unit |
|---|---|---|
| Global warming | **13,07** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | kg CFC11 eq |
| Ionizing radiation | **0,08** | kBq Co-60 eq |
| Ozone formation, Human health | **0,04** | kg NOx eq |
| Fine particulate matter formation | **0,03** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,04** | kg NOx eq |
| Terrestrial acidification | **0,06** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | kg P eq |
| Marine eutrophication | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **14,79** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | kg 1,4-DCB |
| Marine ecotoxicity | **0,35** | kg 1,4-DCB |
| Human carcinogenic toxicity | **19,00** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **4,88** | kg 1,4-DCB |
| Land use | **0,28** | m2a crop eq |
| Mineral resource scarcity | **0,26** | kg Cu eq |
| Fossil resource scarcity | **2,82** | kg oil eq |
| Water consumption | **0,08** | m3 |

Table 8 below summarises the impact results in six main categories (Aluminium, Manganese, Carbon, Water, Argon and Electricity consumption).

| *Table 8. Contributions from Aluminium, Manganese, Carbon, Water, Argon and Electricity consumption in the environmental footprint of producing 1 kg of MnAlC alloy by casting.* | | | | |
|---|---|---|---|---|
| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
| **Aluminium** | 7,35 | 5,38 | 3,5 | 1,51 |
| **Manganese** | 4,52 | 8,04 | 20,09 | 0,98 |
| **Carbon** | 0,009 | 0,01 | 0,001 | 0,008 |
| **Water** | 0,005 | 0,01 | 0,002 | 0,001 |
| **Argon** | 0,15 | 0,13 | 0,02 | 0,03 |
| **Electricity** | 1,02 | 1,19 | 0,23 | 0,28 |
| **Sum** | **13,07** | **14,79** | **23,87** | **2,82** |

Figure 34 presents the percentage contribution of all raw materials, the electricity consumption and waste generation to the total environmental footprint observed in all impact categories during the production of 1 kg of atomized MnAlC metal powder. As it can be observed, aluminium is the main contributor to the total impact of the production process (52,26% average contribution in all impact categories and emissions of 4,52 kg CO2 eq).

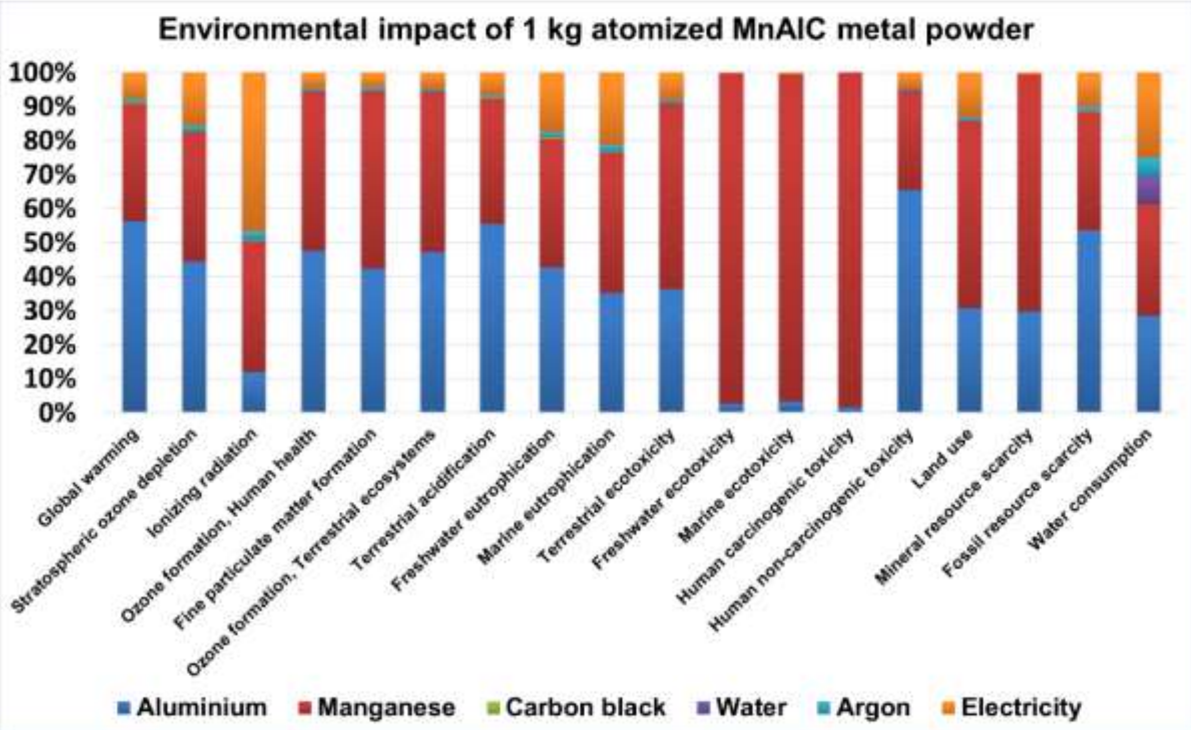



*Figure 34. Environmental impact of 1 kg atomized MnAlC metal powder.*

Figure 35 below presents the environmental impact of METALPINE's gas atomization process. Based on the results, the use of argon is the main contributor to the total impact of the gas atomization process as well as in the GW impact category (54,69% average contribution in all impact categories and emissions of 0,13 kg CO2 eq, Figure 36). The impact category Ozone formation, Human health is also highly affected by the use of argon (68% contribution). Electricity consumption follows with 35,8% average contribution and emissions of 0,06 kg CO2 eq. Finally, water use and waste production present 9,4% and 0% average contribution to the total observed impact of the atomization process.

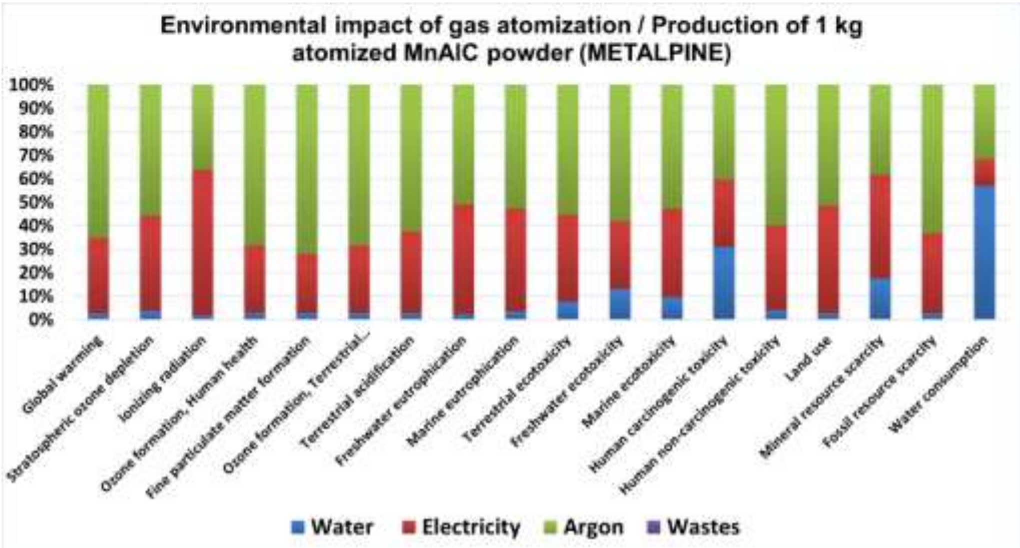



*Figure 35. Environmental impact of METALPINE's gas atomization process.*

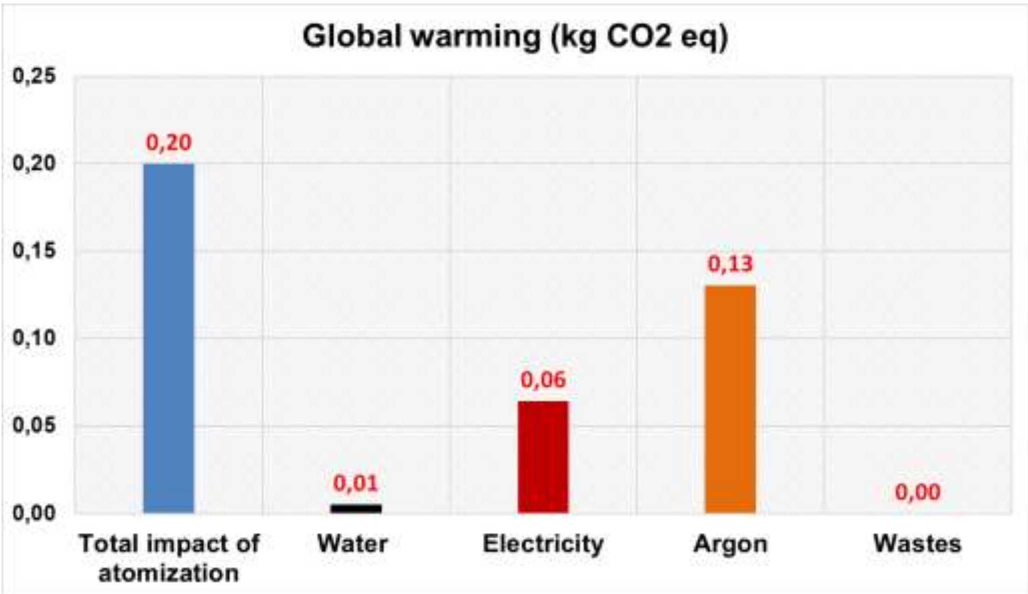



*Figure 36. Carbon dioxide emissions of METALPINE's gas atomization process.*

#### *4.2.3.3 Polymer bonded MnAlC magnet compound*

Table 9 presents the LCIA results of producing 1 kg of polymer bonded MnAlC magnet compound. After observing the results, it can be concluded that the most affected impact categories are Global warming (13,42 kg CO2 eq), Terrestrial ecotoxicity (15,51 kg 1,4-DCB), Human toxicity (23,93 kg 1,4-DCB), and Fossil resource scarcity (2,92 kg oil eq).

***Table 9**. LCIA results of producing 1 kg of polymer bonded MnAlC magnet compound.*

| **Impact category** | **Total Impact** | **Unit** |
|---|---|---|
| Global warming | **13,42** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | kg CFC11 eq |
| Ionizing radiation | **0,09** | kBq Co-60 eq |
| Ozone formation, Human health | **0,04** | kg NOx eq |
| Fine particulate matter formation | **0,03** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,04** | kg NOx eq |
| Terrestrial acidification | **0,06** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | kg P eq |
| Marine eutrophication | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **15,51** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | kg 1,4-DCB |
| Marine ecotoxicity | **0,35** | kg 1,4-DCB |
| Human carcinogenic toxicity | **19,00** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **4,94** | kg 1,4-DCB |
| Land use | **0,28** | m2a crop eq |
| Mineral resource scarcity | **0,26** | kg Cu eq |
| Fossil resource scarcity | **2,92** | kg oil eq |
| Water consumption | **0,09** | m3 |

Table 10 below summarises the impact results in seven main categories (Aluminium, Manganese, Carbon, Water, Argon and Electricity consumption).

***Table 10**. Contributions from Aluminium, Manganese, Carbon, Water, Argon and Electricity consumption in the environmental footprint of producing 1 kg of MnAlC alloy by casting.*

| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
|---|---|---|---|---|
| **Aluminium** | 7,35 | 5,38 | 3,5 | 1,51 |
| **Manganese** | 4,52 | 8,04 | 20,09 | 0,98 |
| **Carbon** | 0,009 | 0,01 | 0,00 | 0,00 |
| **Water** | 0,005 | 0,01 | 0,00 | 0,00 |
| **Argon** | 0,15 | 0,13 | 0,02 | 0,03 |
| **Transportation** | 0,11 | 0,59 | 0,01 | 0,03 |
| **Electricity** | 1,24 | 1,32 | 0,28 | 0,34 |
| **Sum** | **13,42** | **15,51** | **23,93** | **2,92** |

Figure 37 presents the percentage contribution of all raw materials, the electricity consumption, transportation and waste generation to the total environmental footprint observed in all impact categories during the production of 1 kg of polymer bonded MnAlC magnet compound. As it can be observed, manganese is the main contributor to the total impact of the production process (51,11% average contribution in all impact categories and emissions of 4,52 kg CO2 eq).

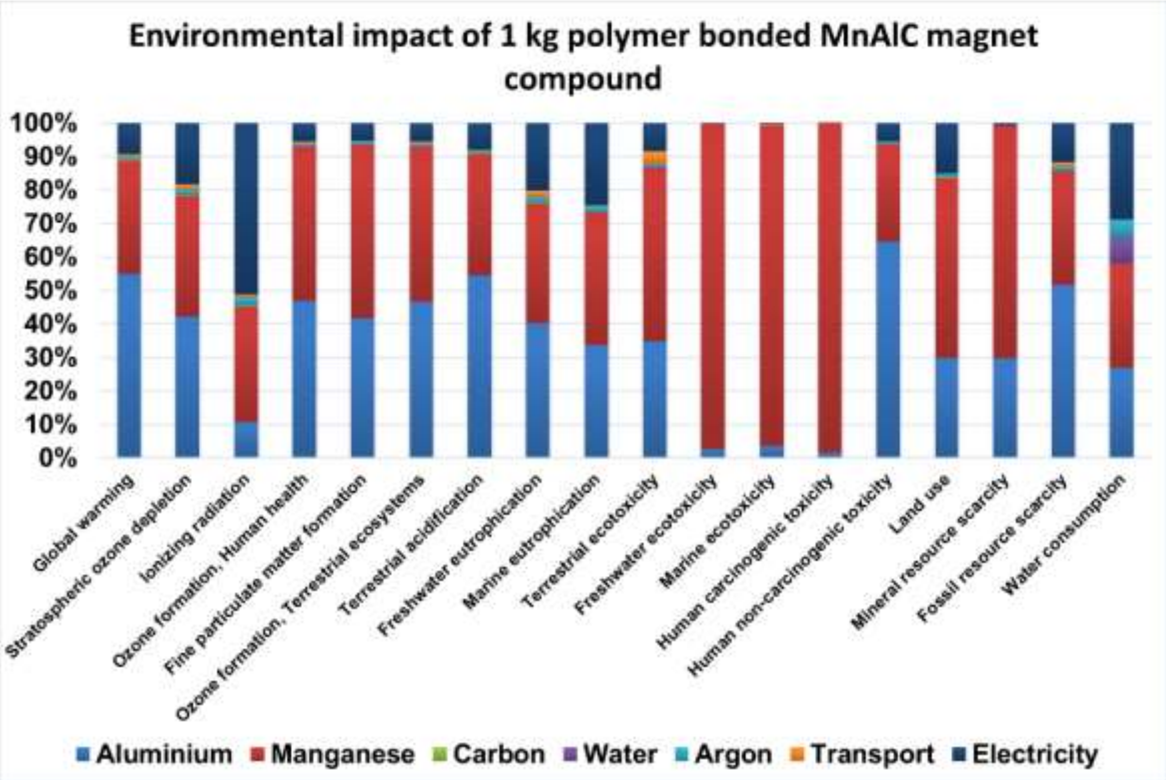



*Figure 37. Environmental impact of 1 kg polymer bonded MnAlC magnet compound.*

Figure 38 below presents the environmental impact of BARLOG's polymer compounding process. Based on the results, the consumption of electricity is the main contributor to the total impact of the polymer compounding process as well as in the GW impact category (70,8% average contribution in all impact categories and emissions of 0,23 kg CO2 eq, Figure 39). The impact category Land use is also highly affected by the electricity consumption (99,3% contribution). The impact of transportation follows with 29,11% average contribution and emissions of 0,12 kg CO2 eq. Considerably, transportation presents high contribution to the total impact observed in the Terrestrial ecotoxicity impact category with 82,3% contribution.

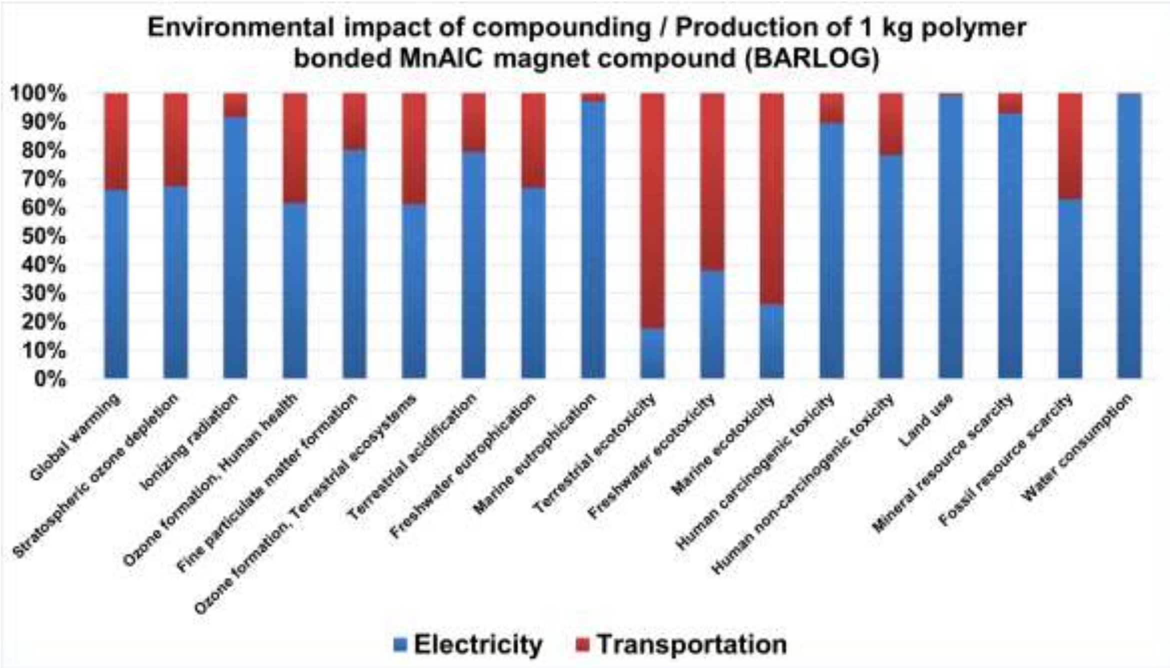



*Figure 38. Environmental impact of BARLOG's polymer compounding process.*

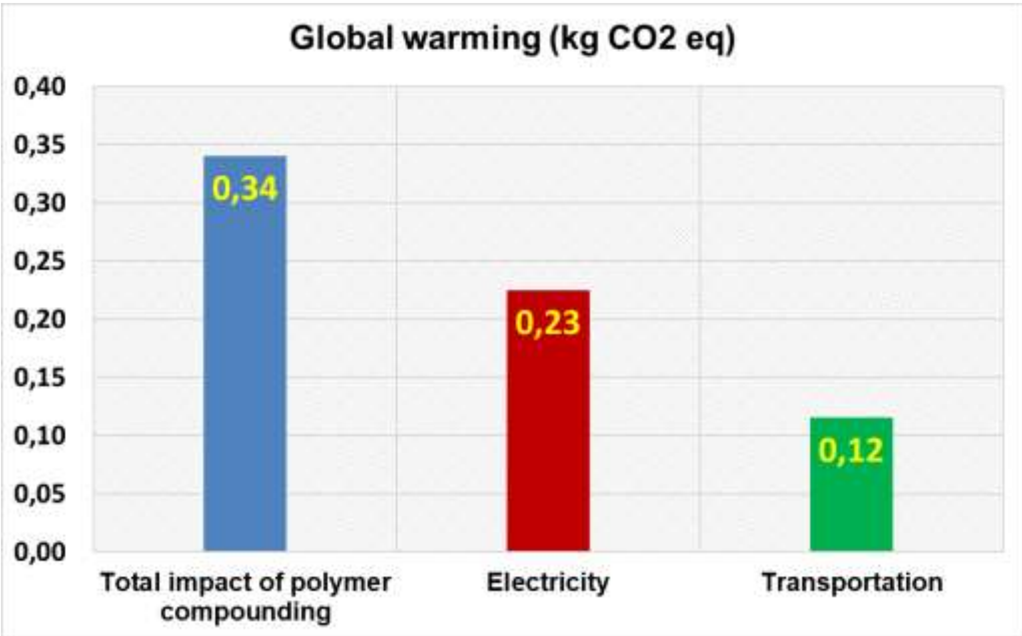



*Figure 39. Carbon dioxide emissions of BARLOG's polymer compounding process.*

#### *4.2.3.4 Bonded MnAlC magnet production*

Table 11 presents the LCIA results of producing 1 kg of bonded MnAlC magnets. After observing the results, it can be concluded that the most affected impact categories are

Global warming (14,92 kg $CO_2$ eq), Terrestrial ecotoxicity (16,35 kg 1,4-DCB), Human toxicity (24,22 kg 1,4-DCB), and Fossil resource scarcity (3,33 kg oil eq).

***Table 11**. LCIA results of producing 1 kg of bonded MnAlC magnets.*

| **Impact category** | **Total Impact** | **Unit** |
|---|---|---|
| Global warming | **14,92** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | kg CFC11 eq |
| Ionizing radiation | **0,15** | kBq Co-60 eq |
| Ozone formation, Human health | **0,04** | kg NOx eq |
| Fine particulate matter formation | **0,04** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,04** | kg NOx eq |
| Terrestrial acidification | **0,06** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | kg P eq |
| Marine eutrophication | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **16,35** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | kg 1,4-DCB |
| Marine ecotoxicity | **0,35** | kg 1,4-DCB |
| Human carcinogenic toxicity | **19,00** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **5,22** | kg 1,4-DCB |
| Land use | **0,33** | m2a crop eq |
| Mineral resource scarcity | **0,27** | kg Cu eq |
| Fossil resource scarcity | **3,33** | kg oil eq |
| Water consumption | **0,12** | m3 |

Table 12 below summarises the impact results in seven main categories (Aluminium, Manganese, Carbon, Water, Argon and Electricity consumption). Figure 40 presents the percentage contribution of all raw materials, the electricity consumption, transportation and waste generation to the total environmental footprint observed in all impact categories during the production of 1 kg of bonded MnAlC magnets. As it can be observed, the use of manganese is the main contributor to the total impact of the production process with 46,9% average contribution in all impact categories and emissions of 4,52 kg $CO_2$ eq. The use of manganese presents also significant contribution to the impact observed in the Human carcinogenic toxicity (98,2% contribution, 18,66 kg 1,4-DCB), the Freshwater ecotoxicity (96,8% contribution, 0,22 kg 1,4-DCB) and the Marine ecotoxicity category (65,6% contribution, 0,33 kg 1,4-DCB). Mineral resource scarcity category is also highly affected by the manganese use (69,1% contribution).

Aluminium use follows with 30,4% average contribution in all impact categories and total emissions of 7,35 kg $CO_2$ eq. Aluminium is the main contributor to the total impact observed the GW impact category (Figure 41). Apart from the GW, the use of aluminium presents high contribution in the Terrestrial acidification category (49,7% contribution, 5,38 kg 1,4-DCB) the Fossil resource scarcity category (45,38% contribution, 1,51 kg oil eq) and the Ozone formation, Human health (44% contribution, 0,019 kg NOx eq).

Electricity consumption follows with 20,6% average contribution in all impact categories and total emissions of 2,74 kg $CO_2$ eq. The use of electricity also highly contributes to the impact observed in the Ionizing radiation (70% contribution, 0,10 kBq Co-60 eq) and Water consumption categories (47,2% contribution, 0,056 $m^3$).

Finally, argon use, transportation, water consumption and carbon use present less than 1% average contribution in all impact categories (0,95%, 0,61%, 0,34% and 0,08% respectively.

***Table 12**. Contributions from Aluminium, Manganese, Carbon, Water, Argon and Electricity consumption in the environmental footprint of producing 1 kg of bonded MnAlC magnets.*

| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
|---|---|---|---|---|
| **Aluminium** | 7,35 | 5,38 | 3,5 | 1,51 |
| **Manganese** | 4,52 | 8,04 | 20,09 | 0,98 |
| **Carbon** | 0,009 | 0,01 | 0,00 | 0,008 |
| **Water** | 0,005 | 0,01 | 0,00 | 0,001 |
| **Argon** | 0,15 | 0,13 | 0,02 | 0,03 |
| **Transportation** | 0,11 | 0,59 | 0,01 | 0,03 |
| **Electricity** | 2,74 | 2,16 | 0,57 | 0,75 |
| **Wastes** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Sum** | **14,91** | **16,35** | **24,22** | **3,33** |

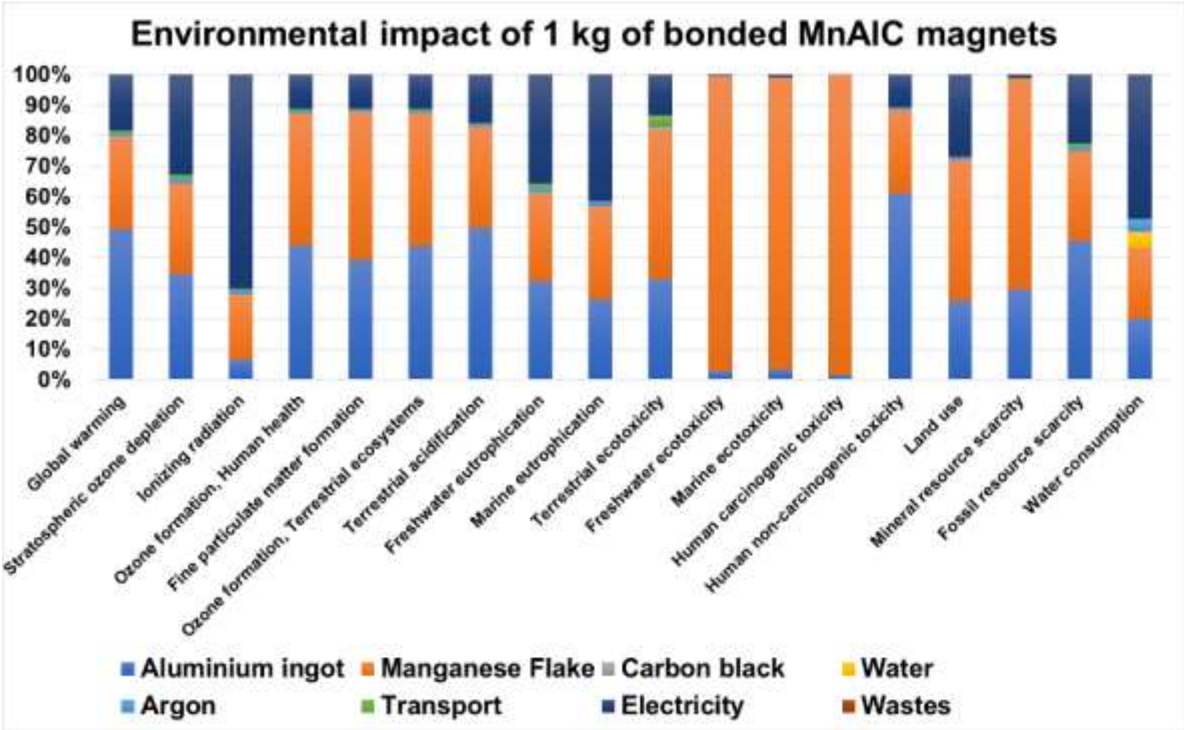



*Figure 40. Environmental impact of 1 kg bonded MnAlC magnets.*

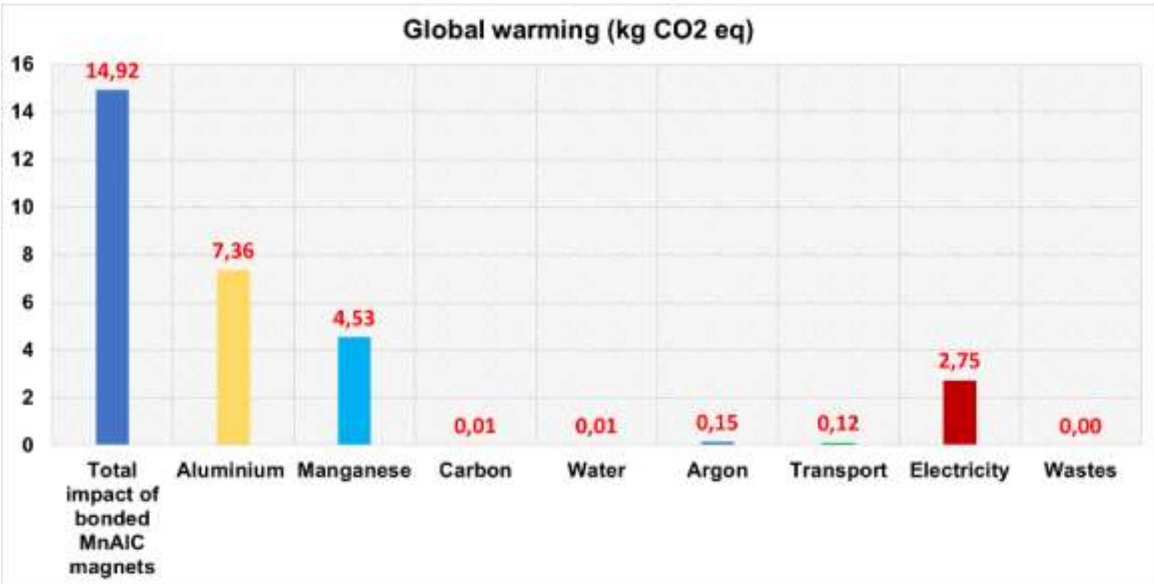



*Figure 41. Carbon dioxide emissions related to 1 kg bonded MnAlC magnets production.*

Table 13 below summarises the impact results in three main categories (Raw Materials, Transportation, Electricity consumption and Waste production).

| *Table 13. Contributions from Raw Materials, Transportation, Electricity consumption and Waste production in the environmental footprint of producing 1 kg of bonded MnAlC magnets.* | | | | |
|---|---|---|---|---|
| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
| **Raw Materials** | 12,05 | 13,59 | 23,63 | 2,54 |
| **Transportation** | 0,11 | 0,59 | 0,01 | 0,03 |
| **Electricity** | 2,74 | 2,16 | 0,57 | 0,75 |
| **Wastes** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Sum** | **14,91** | **16,35** | **24,22** | **3,33** |

Figure 42 below depicts the percentage contribution of the raw materials, the electricity consumption, transportation and waste generation to the total environmental footprint of producing 1 kg of bonded MnAlC magnets. Raw materials use is the main contributor to the environmental footprint of the bonded MnAlC magnets production with 78,7% average contribution and total emissions of 12,05 kg CO2 eq. Raw materials use is also the main contributor to the total impact observed in the GW impact category (Figure 43). Electricity consumption follows with 20,63% average contribution in all impact categories and emissions of 2,74 kg CO2 eq. Finally, transportation and waste production present less than 1% contribution to the total environmental impact of the production process.

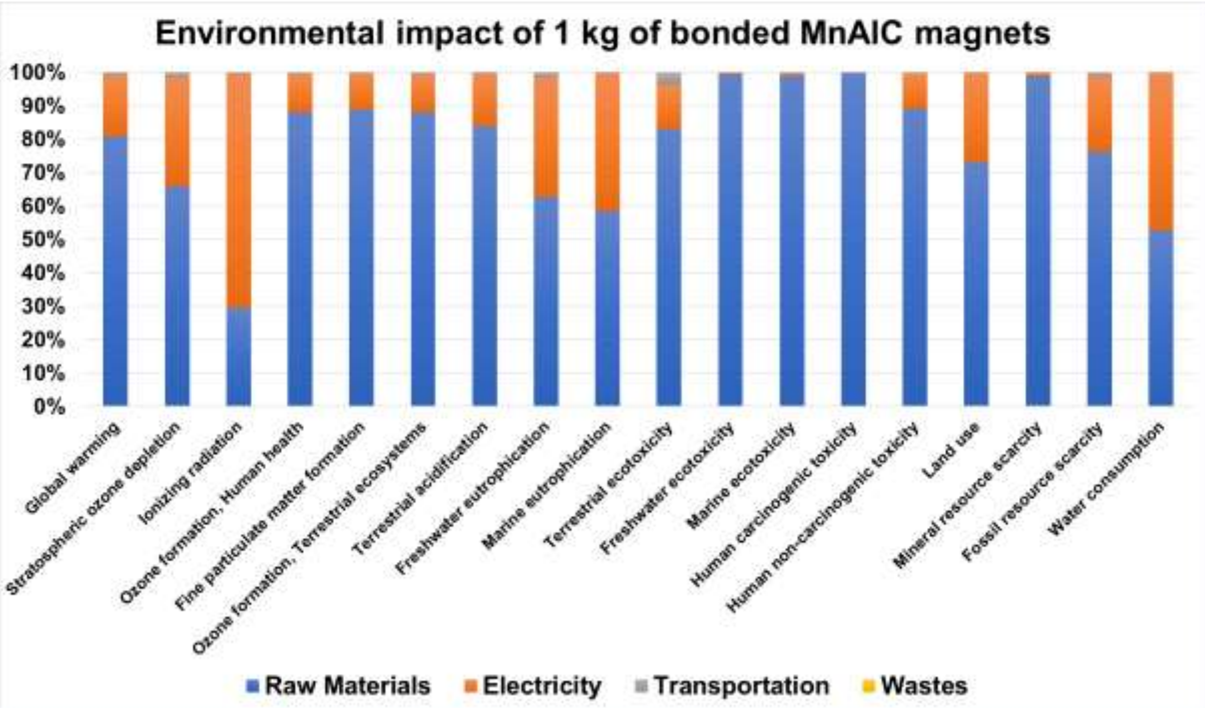



*Figure 42. Environmental impact of 1 kg bonded MnAlC magnets.*

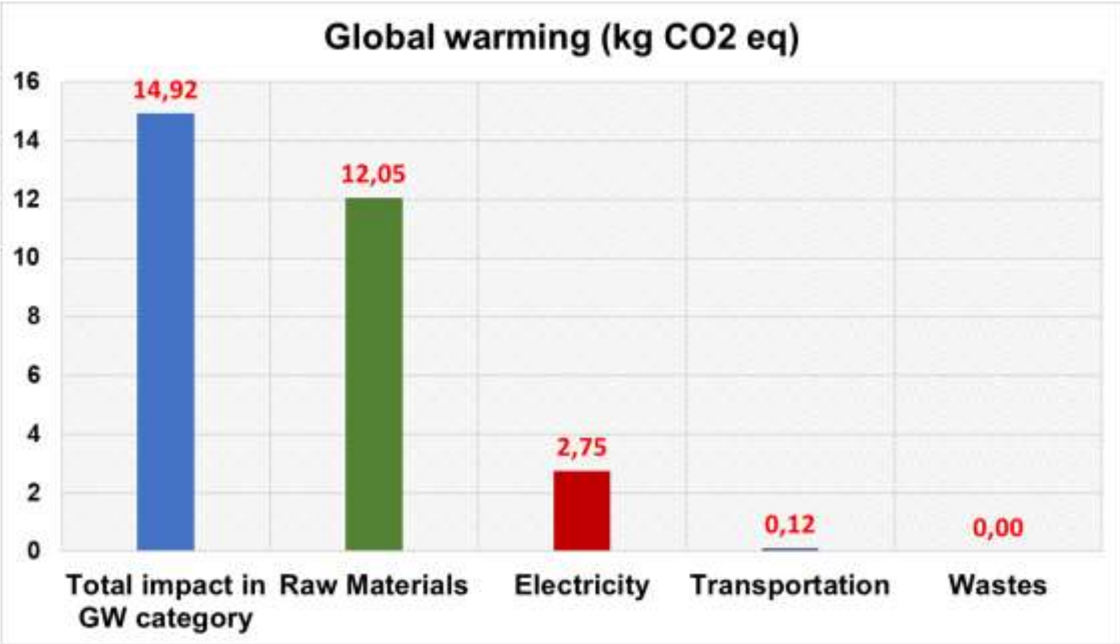



*Figure 43. Carbon dioxide emissions related 1 kg bonded MnAlC magnets.*

#### *4.2.3.5 Comparative LCIA results of PASSENGER's bonded MnAlC magnet production with the benchmark NdFeB magnet production*

Table 14 presents the direct comparison of the environmental footprint of PASSENGER's bonded MnAlC magnet production with the benchmark NdFeB magnet production from virgin raw materials. The use of the electricity grid from China is considered for the NdFeB magnets production and the LCA results are compared against to the PASSENGER's bonded MnAlC magnets production. The direct comparison of the LCIA results in Global warming, Terrestrial ecotoxicity, Human toxicity, Fossil resource scarcity, Ionizing radiation and Mineral resource scarcity categories is depicted in Figure 44.  Based on the LCA results, it can be concluded that the production of the bonded MnAlC magnets within the PASSENGER project results in significant decrease in the environmental impact observed in almost all impact categories. More specifically, an impact reduction of 80,47% is observed in GW impact category, 96,13% reduction of impact in the Terrestrial ecotoxicity category, 38,96% reduction in the Human toxicity category (carcinogenic and non-carcinogenic), 80,94% reduction in the Fossil resource scarcity category, 94,75% reduction in the Ionizing radiation category and 98,38% reduction in the Mineral resource scarcity category. However, it should be noted that regarding the Human carcinogenic toxicity subcategory there is an increase in the observed impact which is attributed to the manganese use.

| ***Table 14***. *Comparative LCIA results of producing 1 kg of NdFeB magnets vs. PASSENGER's bonded MnAlC magnets.* | | | |
|---|---|---|---|
| **Impact category** | **Benchmark NdFeB magnets production** | **PASSENGER's bonded MnAlC magnets production** | **Unit** |
| Global warming | **76,41** | **14,92** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | **0,00** | kg CFC11 eq |
| Ionizing radiation | **2,86** | **0,15** | kBq Co-60 eq |
| Ozone formation, Human health | **0,22** | **0,04** | kg NOx eq |
| Fine particulate matter formation | **0,18** | **0,04** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,22** | **0,04** | kg NOx eq |
| Terrestrial acidification | **0,47** | **0,06** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | **0,00** | kg P eq |
| Marine eutrophication | **0,32** | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **423,32** | **16,35** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | **0,23** | kg 1,4-DCB |
| Marine ecotoxicity | **0,43** | **0,35** | kg 1,4-DCB |
| Human carcinogenic toxicity | **1,03** | **19,00** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **38,67** | **5,22** | kg 1,4-DCB |
| Land use | **8,12** | **0,33** | m2a crop eq |
| Mineral resource scarcity | **16,12** | **0,27** | kg Cu eq |
| Fossil resource scarcity | **17,48** | **3,33** | kg oil eq |
| Water consumption | **1,32** | **0,12** | m3 |

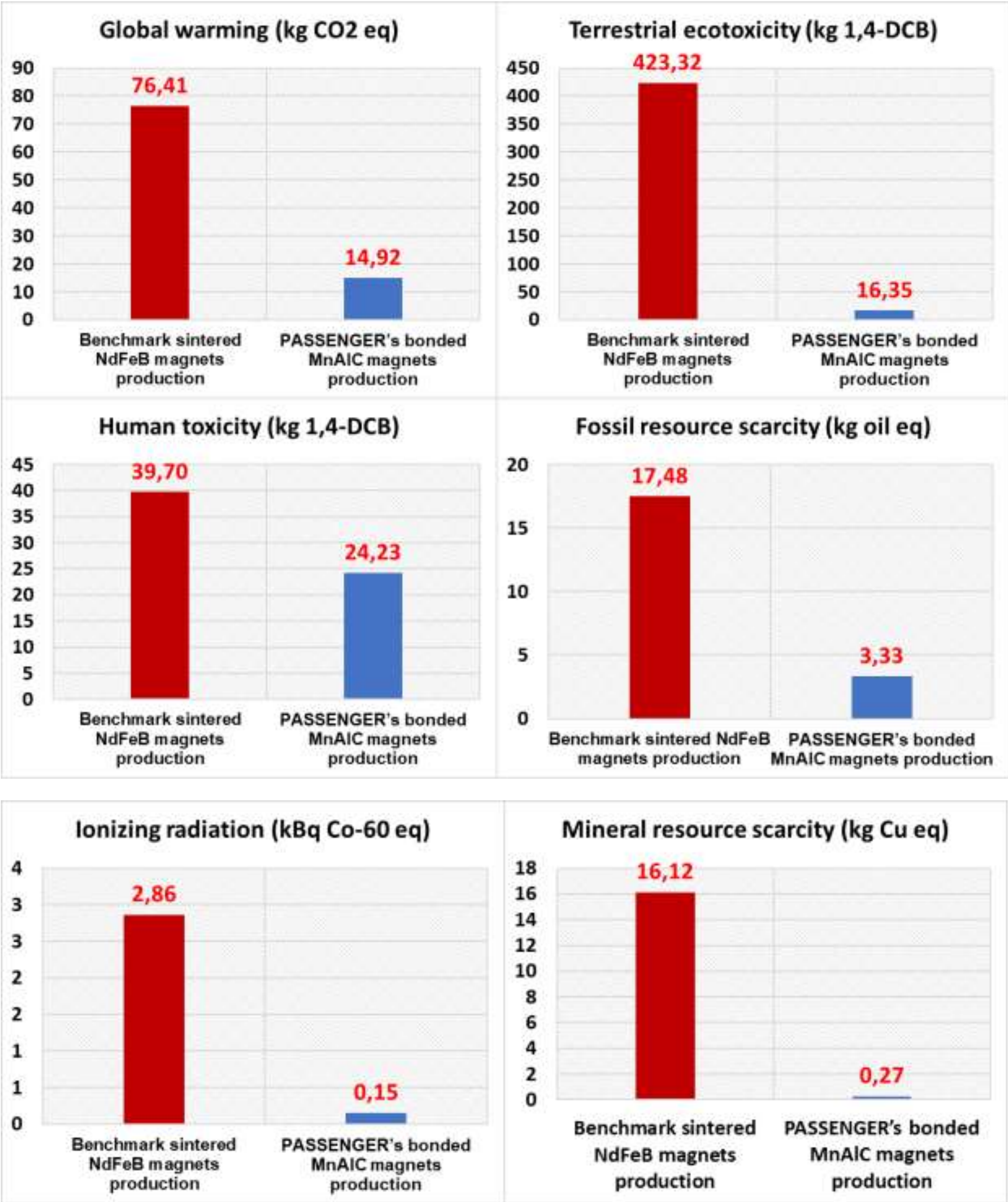



*Figure 44. Comparative LCIA results – NdFeB magnets production vs. PASSENGER's bonded MnAlC magnets production.*

### 4.2.4 LCIA results of PASSENGER's sintered MnAlC magnets production

In the following section, the LCIA results of producing PASSENGER's sintered MnAlC magnets are presented. The results represent the environmental impact of LCM's and KOLEKTOR's processes (casting and metal injection moulding, respectively). The LCIA results of LCM's process (casting for MnAlC alloy production) have been extensively discussed in section 4.2.3.1.

Table 15 presents the LCIA results of producing 1 kg of sintered MnAlC magnets. After observing the results, it can be concluded that the most affected impact categories are Global warming (12,72 kg CO2 eq), Terrestrial ecotoxicity (13,44 kg 1,4-DCB), Human toxicity (21,52 kg 1,4-DCB), and Fossil resource scarcity (2,84 kg oil eq).

***Table 15**. LCIA results of producing 1 kg of sintered MnAlC magnets.*

| Impact category | Total Impact | Unit |
|---|---|---|
| Global warming | 12,72 | kg CO2 eq |
| Stratospheric ozone depletion | 0,00 | kg CFC11 eq |
| Ionizing radiation | 0,08 | kBq Co-60 eq |
| Ozone formation, Human health | 0,04 | kg NOx eq |
| Fine particulate matter formation | 0,03 | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | 0,04 | kg NOx eq |
| Terrestrial acidification | 0,06 | kg SO2 eq |
| Freshwater eutrophication | 0,00 | kg P eq |
| Marine eutrophication | 0,00 | kg N eq |
| Terrestrial ecotoxicity | 13,44 | kg 1,4-DCB |
| Freshwater ecotoxicity | 0,21 | kg 1,4-DCB |
| Marine ecotoxicity | 0,31 | kg 1,4-DCB |
| Human carcinogenic toxicity | 17.1 | kg 1,4-DCB |
| Human non-carcinogenic toxicity | 4,42 | kg 1,4-DCB |
| Land use | 0,25 | m2a crop eq |
| Mineral resource scarcity | 0,24 | kg Cu eq |
| Fossil resource scarcity | 2,84 | kg oil eq |
| Water consumption | 0,09 | m3 |

Table 16 below summarises the LCIA results in the following categories (Aluminium, Manganese, Carbon, Argon, Polymer, Water, Electricity consumption, Transportation and Waste production) while Figure 45 presents the percentage contribution of all the previously mentioned categories to the total environmental footprint of the production process of 1 kg sintered MnAlC magnets. As it can be observed, manganese is the main contributor to the total impact of the production process with 48,17% average contribution in all impact categories and emissions of 4,07 kg CO2 eq. Manganese presents also significant contribution to the impact observed in the Human carcinogenic toxicity (98,2% contribution, 0,28 kg 1,4-DCB), the Freshwater ecotoxicity (96,9% contribution, 0,19 kg 1,4-DCB) and the Marine ecotoxicity category (95,8% contribution, 0,30 kg 1,4-DCB). Mineral resource scarcity category is also highly affected by the manganese use (69,4% contribution).

Aluminium follows with 31,3% average contribution in all impact categories and total emissions of 6,62 kg CO2 eq. Aluminium is the main contributor to the total impact observed the GW impact category (Figure 46). Apart from the GW, the use of aluminium presents high contribution in the Terrestrial acidification (52,5% contribution, 0,029 kg SO2 eq), and the Human non-carcinogenic toxicity category (64,9% contribution, 2,87 kg 1,4-DCB).

Electricity consumption follows with 10,48 % average contribution in all impact categories and total emissions of 1,12 kg CO2 eq. The use of electricity also highly contributes to the impact observed in the Ionizing radiation (52,6% contribution, 0,042 kBq Co-60 eq) and Water consumption categories (24,43% contribution, 0,023 m3).

Polymer use follows with 9,55% average contribution in all impact categories and total emissions of 0,85 kg CO2 eq. The use of polymer also presents high contribution to the impact observed in the Marine eutrophication category with 85,8% contribution.

Finally, argon use, water consumption and carbon use, transportation and wastes present less than 1% average contribution in all impact categories (0,21%, 0,09%, 0,09%, 0,08% and 0% respectively).

***Table 16**. Contributions from Aluminium, Manganese, Carbon, Argon, Polymer, Water, Electricity consumption, Transportation and Waste production in the environmental footprint of producing 1 kg of sintered MnAlC magnets.*

| Impact category | Global warming (kg CO2 eq) | Terrestrial ecotoxicity (kg 1,4-DCB) | Human toxicity (kg 1,4-DCB) | Fossil resource scarcity (kg oil eq) |
|---|---|---|---|---|
| **Aluminium** | 6,62 | 4,85 | 3,16 | 1,36 |
| **Manganese** | 4,08 | 7,24 | 18,09 | 0,88 |
| **Carbon** | 0,01 | 0,02 | 0,00 | 0,01 |
| **Argon** | 0,02 | 0,02 | 0,00 | 0,00 |
| **Polymer** | 0,86 | 0,09 | 0,01 | 0,27 |
| **Water** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Electricity** | 1,13 | 1,16 | 0,25 | 0,31 |
| **Transportation** | 0,01 | 0,06 | 0,00 | 0,00 |
| **Wastes** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Sum** | **12,72** | **13,44** | **21,52** | **2,84** |

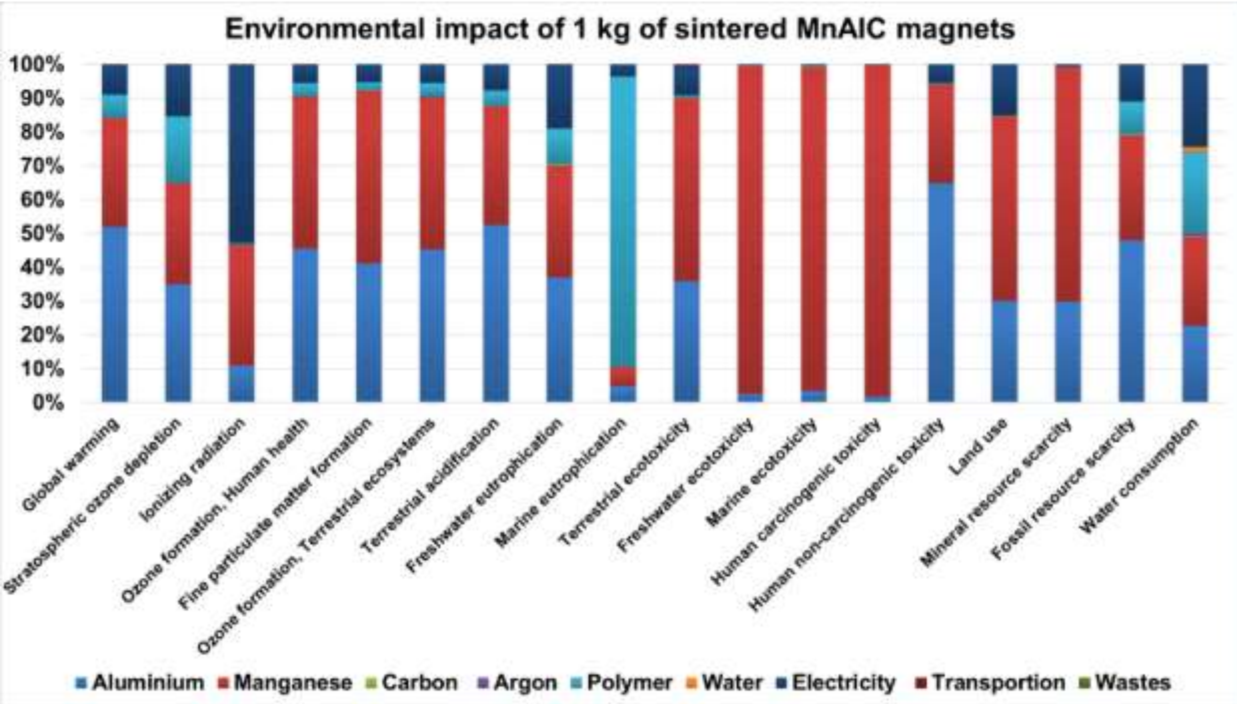



*Figure 45. Environmental impact of 1 kg sintered MnAlC magnets.*

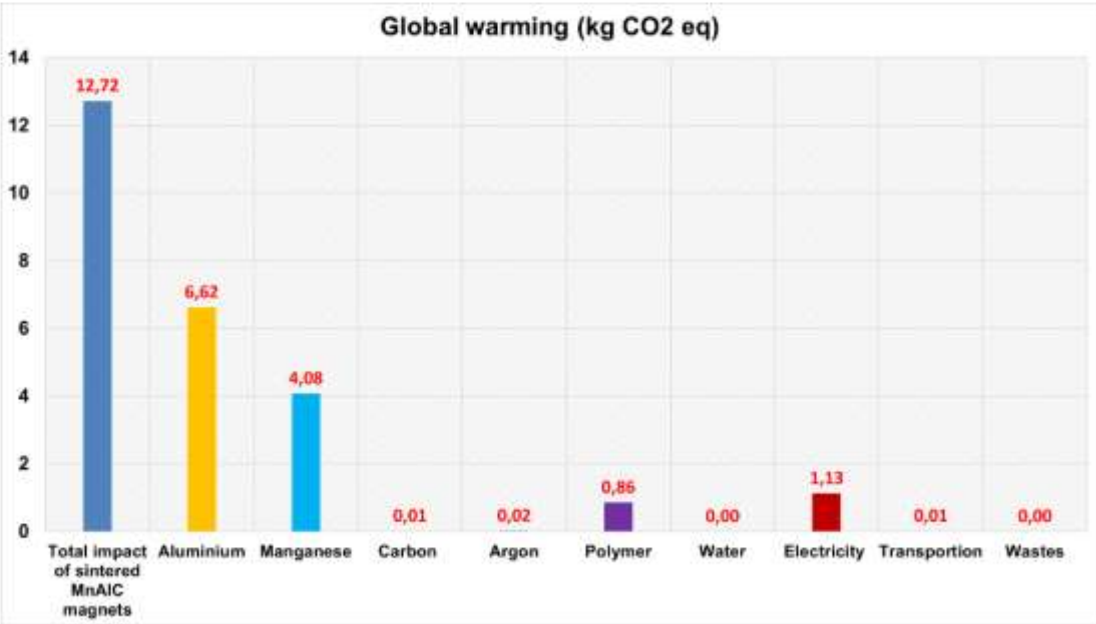



*Figure 46. Carbon dioxide emissions related to 1 kg sintered MnAlC magnets production.*

Table 17 below summarises the impact results in three main categories (Raw Materials, Electricity consumption, Transportation and Waste production).

| ***Table 17**. Contributions from Raw Materials, Electricity consumption, Transportation and Waste production in the environmental footprint of producing 1 kg of sintered MnAlC magnets.* | | | | |
|---|---|---|---|---|
| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
| **Raw Materials** | 11,58 | 12,22 | 21,26 | 2,52 |
| **Electricity** | 1,13 | 1,16 | 0,25 | 0,31 |
| **Transportation** | 0,01 | 0,06 | 0,00 | 0,00 |
| **Wastes** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Sum** | **12,72** | **13,43** | **21,51** | **2,83** |

Figure 47 below depicts the percentage contribution of the raw materials, the electricity consumption, transportation and waste generation to the total environmental footprint of producing 1 kg of sintered MnAlC magnets. Raw materials use is the main contributor to the environmental footprint of the sintered MnAlC magnets production with 89,4% average contribution and total emissions of 11,58 kg CO2 eq. Raw materials use is also the main contributor to the total impact observed in the GW impact category (Figure 48). Electricity consumption follows with 10,47% average contribution in all impact categories and emissions of 1,13 kg CO2 eq. Finally, transportation and waste production present less than 1% contribution to the total environmental impact of the production process.

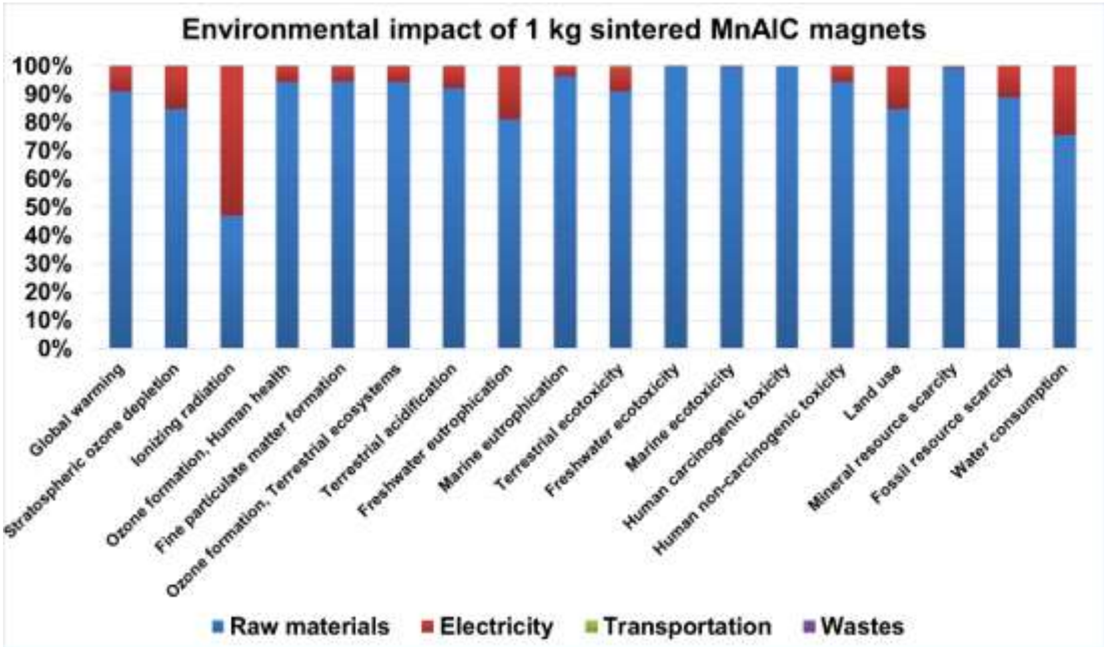



*Figure 47. Environmental impact of 1 kg sintered MnAlC magnets.*

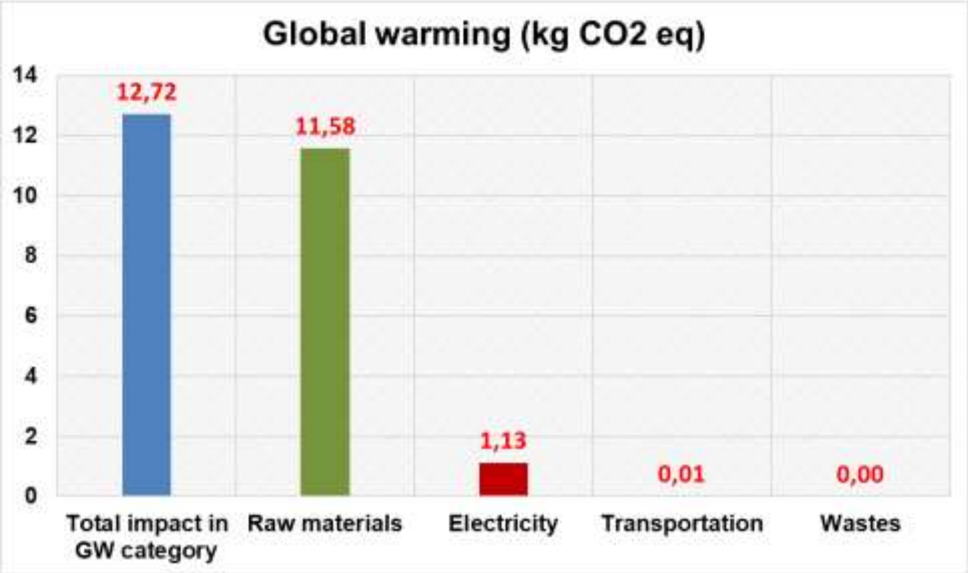



*Figure 48. Carbon dioxide emissions related 1 kg sintered MnAlC magnets.*

Figure 49 below presents the environmental impact of KOLEKTOR's metal injection moulding process. Based on the results, the use of argon is the main contributor to the total impact of the gas atomization process as well as in the GW impact category (54,69% average contribution in all impact categories and emissions of 0,13 kg CO2 eq, Figure 50). The impact category Ozone formation, Human health is also highly affected by the use of argon (68% contribution). Electricity consumption follows with 35,8% average contribution and emissions of 0,06 kg CO2 eq. Finally, water use and waste production present 9,4% and 0% average contribution to the total observed impact of the atomization process.

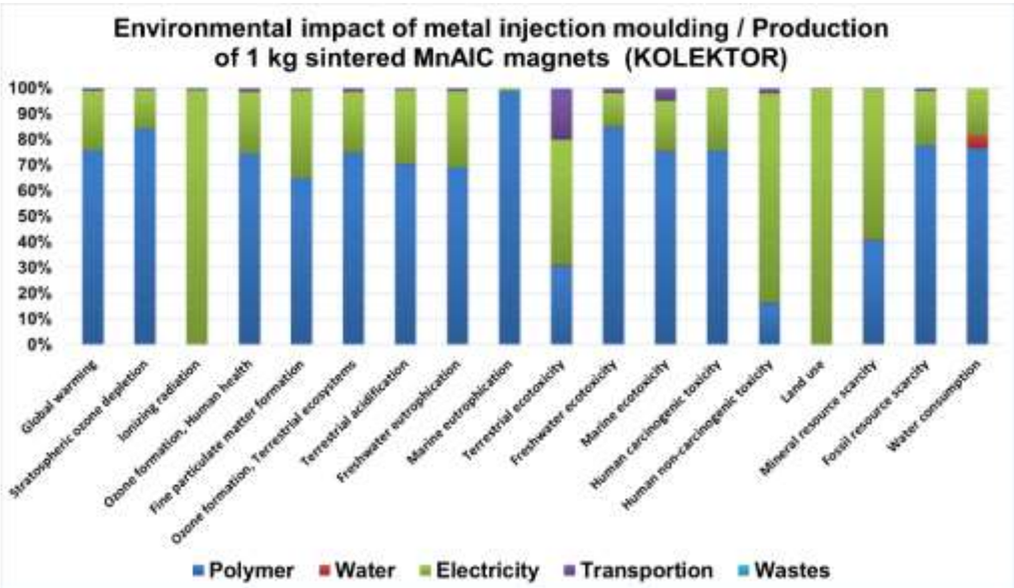



*Figure 49. Environmental impact of KOLEKTOR's metal injection moulding process.*

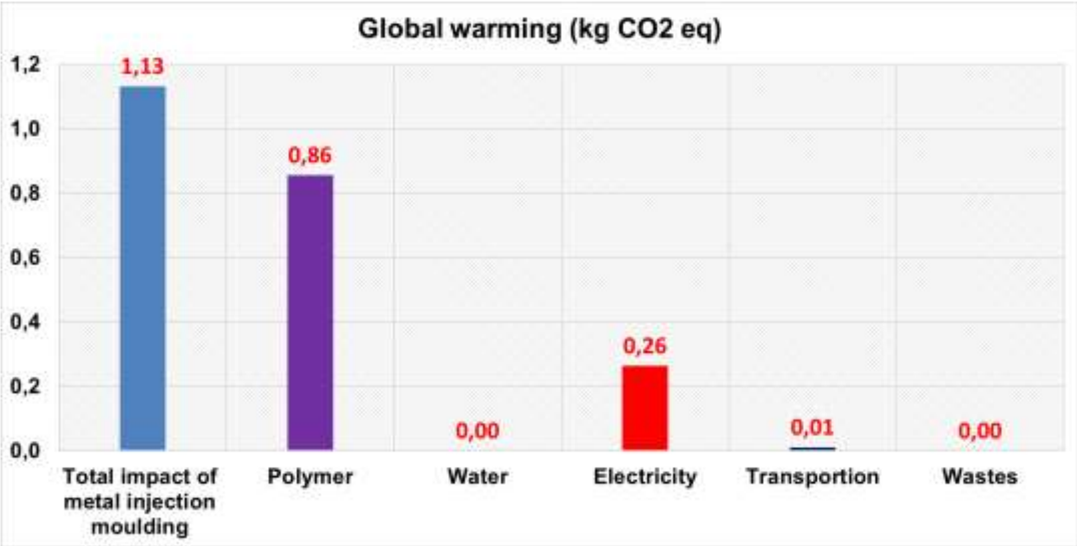



*Figure 50. Carbon dioxide emissions of KOLEKTOR's metal injection moulding process.*

#### *4.2.4.1 Comparative LCIA results of PASSENGER's sintered MnAlC magnet production with the benchmark NdFeB magnet production*

Table 18 presents the direct comparison of the environmental footprint of PASSENGER's sintered MnAlC magnet production with the benchmark NdFeB magnet production from virgin raw materials. The use of the electricity grid from China is considered for the NdFeB magnets production and the LCA results are compared against to the PASSENGER's sintered MnAlC magnets production. The direct comparison of the LCIA results in Global warming, Terrestrial ecotoxicity, Human toxicity, Fossil resource scarcity, Ionizing radiation and Mineral resource scarcity categories is depicted in Figure 51. Based on the LCA results, it can be concluded that the production of the bonded MnAlC magnets within the PASSENGER project results in significant decrease in the environmental impact observed in almost all impact categories. More specifically, an impact reduction of 83,35% is observed in GW impact category, 96,82% reduction of impact in the Terrestrial ecotoxicity category, 45,83% reduction in the Human toxicity category (carcinogenic and non-carcinogenic), 83,75% reduction in the Fossil resource scarcity category, 97,2% reduction in the Ionizing radiation category and 98,5% reduction in the Mineral resource scarcity category. However, it should be noted that regarding the Human carcinogenic toxicity subcategory there is an increase in the observed impact (66% increase of the impact) which is attributed to the manganese use.

*Table 18*. *Comparative LCIA results of producing 1 kg of NdFeB magnets vs. PASSENGER's sintered MnAlC magnets.*

| **Impact category** | **Benchmark NdFeB magnets production** | **PASSENGER's sintered MnAlC magnets production** | **Unit** |
|---|---|---|---|
| Global warming | **76,41** | **12,72** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | **0,00** | kg CFC11 eq |
| Ionizing radiation | **2,86** | **0,08** | kBq Co-60 eq |
| Ozone formation, Human health | **0,22** | **0,04** | kg NOx eq |
| Fine particulate matter formation | **0,18** | **0,03** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,22** | **0,04** | kg NOx eq |
| Terrestrial acidification | **0,47** | **0,06** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | **0,00** | kg P eq |
| Marine eutrophication | **0,32** | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **423,32** | **13,44** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | **0,21** | kg 1,4-DCB |
| Marine ecotoxicity | **0,43** | **0,31** | kg 1,4-DCB |
| Human carcinogenic toxicity | **1,03** | **17.1** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **38,67** | **4,42** | kg 1,4-DCB |
| Land use | **8,12** | **0,25** | m2a crop eq |
| Mineral resource scarcity | **16,12** | **0,24** | kg Cu eq |
| Fossil resource scarcity | **17,48** | **2,84** | kg oil eq |
| Water consumption | **1,32** | **0,09** | m3 |

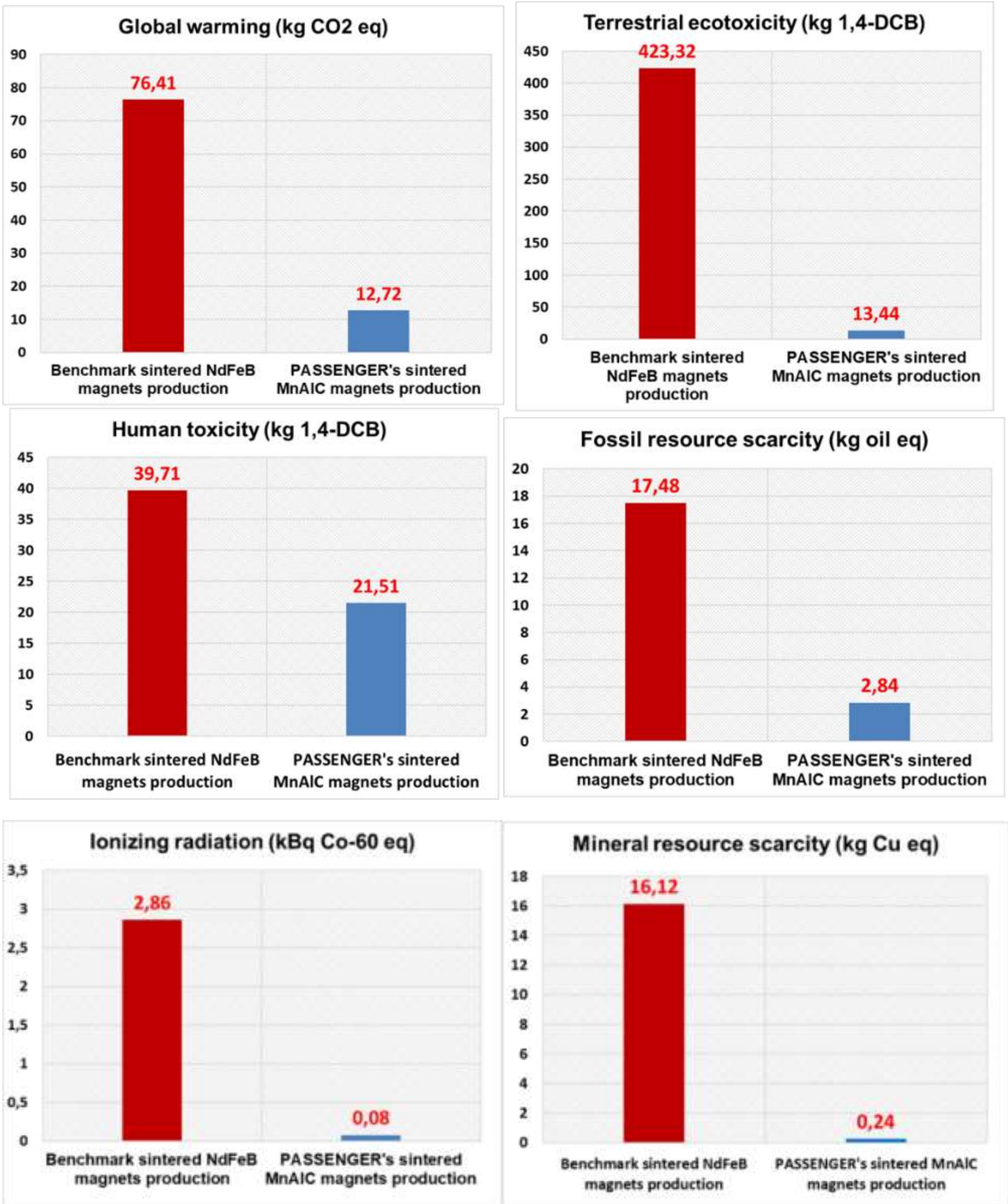



*Figure 51. Comparative LCIA results – NdFeB magnets production vs. PASSENGER's sintered MnAlC magnets production.*

## 4.3. LCA ON THE SR-FERRITE PERMANENT MAGNET PRODUCTION

### 4.3.1. LCI of bonded Sr-ferrite magnets production

The production chain of the bonded Sr-ferrite magnets developed within the PASSENGER project follows the path outlined below, encompassing the steps of calcination, compounding and plastic injection (Figure 52). In the following section, the LCI of ILPEAS's process is analysed. The LCI of BARLOG's and IMA's process are considered to the same as in the case of bonded MnAlC magnets and have been discussed in sections 4.2.1.3 and 4.2.1.4.


*Figure 52. Production chain of PASSENGER's bonded Sr-ferrite magnets.*

#### *4.3.1.1 LCI of ILPEA's process (calcination)*

In the context of data collection, the development of the LCI inventory of the enhanced Sr-ferrite powder ($SrFe_{12}O_{19}$) was based on data provided by the ILPEA partner. The detailed inventory including all the input and outputs of the process is presented in the deliverable D4.4 Collect all required life cycle inventory data at material, process and prototype level. The electricity consumption from Europe's electric grid was considered in this LCA study and the production of 100 kg of enhanced Sr-ferrite powder was employed as reference unit.

Regarding the process details as provided by the ILPEA partner in the LCI questionnaire, the production chain of the enhanced Sr-ferrite powder included: mixing, calcination and milling. Regarding the supply chain, the iron oxide came from several place in UE and Sr carbonate came from Spain or Germany.

ILPEA's process simulation in SimaPro software is presented below in Figure 53.

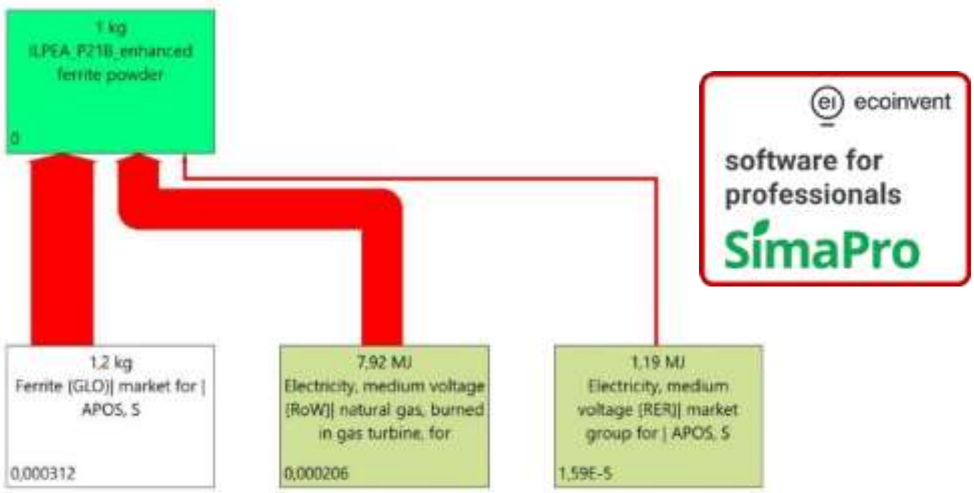



*Figure 53. Process simulation of enhanced Sr-ferrite powder in SimaPro software (ILPEA process).*

## 4.3.2 LCIA results of PASSENGER's bonded Sr-ferrite magnets production

### *4.3.2.1 Enhanced Sr-ferrite powder production*

Table 19 presents the LCIA results of producing 1 kg of enhanced Sr-ferrite powder by calcination. After observing the results, it can be concluded that the most affected impact categories are Global warming (4,27 kg CO2 eq), Terrestrial ecotoxicity (16,34 kg 1,4-DCB), Human toxicity (9,69 kg 1,4-DCB), and Fossil resource scarcity (1,20 kg oil eq).

***Table 19**. LCIA results of producing 1 kg of enhanced Sr-ferrite powder by calcination.*

| **Impact category** | **Total Impact** | **Unit** |
|---|---|---|
| Global warming | **4,27** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | kg CFC11 eq |
| Ionizing radiation | **0,02** | kBq Co-60 eq |
| Ozone formation, Human health | **0,02** | kg NOx eq |
| Fine particulate matter formation | **0,01** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,02** | kg NOx eq |
| Terrestrial acidification | **0,01** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | kg P eq |
| Marine eutrophication | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **16,34** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,10** | kg 1,4-DCB |

| | | |
|---|---|---|
| Marine ecotoxicity | **0,16** | kg 1,4-DCB |
| Human carcinogenic toxicity | **8,22** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **1,48** | kg 1,4-DCB |
| Land use | **0,10** | m2a crop eq |
| Mineral resource scarcity | **0,13** | kg Cu eq |
| Fossil resource scarcity | **1,20** | kg oil eq |
| Water consumption | **0,00** | m3 |

Table 20 below summarises the LCIA results of the enhanced Sr-ferrite powder production in four main categories (Ferrite, Natural gas, Electricity, and Wastes).

***Table 20**. Contributions from Ferrite, Natural gas, Electricity, and Wastes in the environmental footprint of producing 1 kg enhanced Sr-ferrite powder by calcination.*

| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
|---|---|---|---|---|
| **Ferrite** | 2,50 | 16,06 | 9,61 | 0,56 |
| **Natural gas** | 1,65 | 0,13 | 0,05 | 0,61 |
| **Electricity** | 0,13 | 0,15 | 0,02 | 0,03 |
| **Wastes** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Sum** | **4,27** | **16,34** | **9,69** | **1,20** |

Figure 54 presents the percentage contribution of raw materials, energy consumption and waste generation to the total environmental footprint observed in all impact categories during the production of 1 kg of enhanced Sr-ferrite powder by calcination. The use of ferrite is the main contributor to the environmental footprint observed in all impact categories with 80,7 % contribution on average and total emissions of 2,5 kg CO2 eq. Ferrite use has also high impact in the Human carcinogenic toxicity category (99,9% contribution, 8,21 kg 1,4-DCB), the Mineral resource scarcity category (99,5% contribution, 0,12 kg Cu eq), the Marine ecotoxicity category (98,4% contribution, 0,15 kg 1,4-DCB), the Freshwater ecotoxicity category (98,6 % contribution, 0,10 kg 1,4-DCB) and the Terrestrial ecotoxicity category (98,3 % contribution, 16,06 kg 1,4-DCB). Ferrite use is the main contributor to the total impact observed in the GW impact category (Figure 55).

Natural gas use follows with 15,3% average contribution in all impact categories and total emissions of 1,64 kg CO2 eq. Natural gas consumption has also presents also high contribution to the total impact observed in the Fossil resource scarcity category (50,7%

contribution, 0,61 kg oil eq) and in the Ozone formation, Human health category (33,7% contribution, 0,005 kg NOx eq).

Finally, electricity consumption follows with 3,89% average contribution to the total impact observed in all impact categories and total emissions of 0,12 kg CO2 eq. Waste production has insignificant contribution to the total environmental footprint of the calcination process.

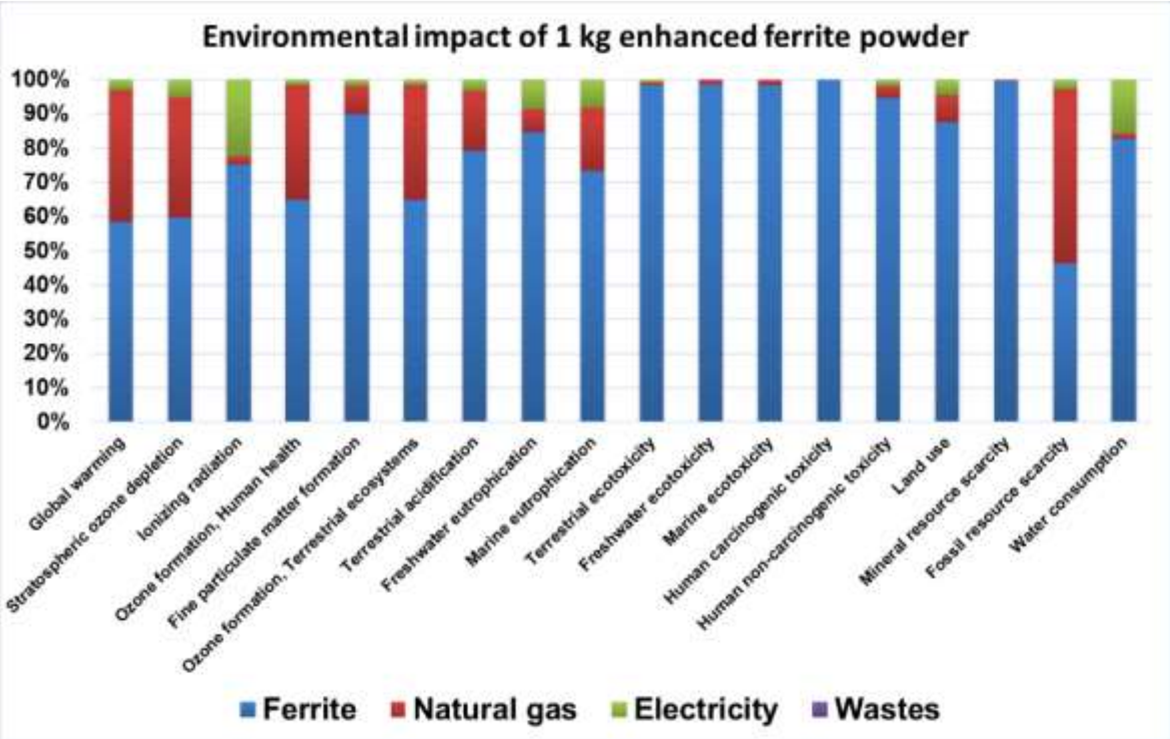



*Figure 54. Environmental impact of 1 kg enhanced Sr-ferrite powder.*

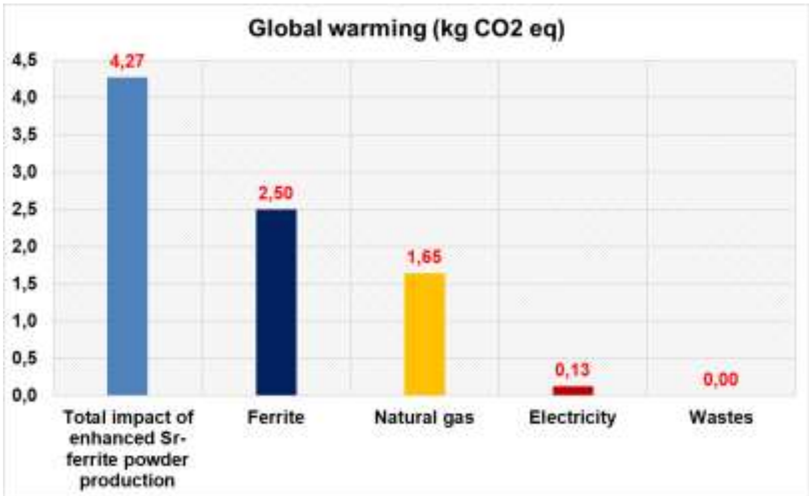



*Figure 55. Carbon dioxide emissions related to 1 kg enhanced Sr-ferrite powder production.*

#### 4.3.2.2 Bonded Sr-ferrite magnets production

In the following section, the LCIA results of producing PASSENGER's bonded Sr-ferrite magnets are presented. The results represent the environmental impact of ILPEA's, BARLOG's and IMA's processes (calcination, compounding and plastic injection, respectively).

Table 21 presents the LCIA results of producing 1 kg of bonded Sr-ferrite magnets. After observing the results, it can be concluded that the most affected impact categories are Global warming (6,11 kg CO2 eq), Terrestrial ecotoxicity (17,90 kg 1,4-DCB), Human toxicity (10,04 kg 1,4-DCB), and Fossil resource scarcity (1,71 kg oil eq).

***Table 21**. LCIA results of producing 1 kg of bonded Sr-ferrite magnets.*

| **Impact category** | **Total Impact** | **Unit** |
|---|---|---|
| Global warming | **6,11** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | kg CFC11 eq |
| Ionizing radiation | **0,09** | kBq Co-60 eq |
| Ozone formation, Human health | **0,02** | kg NOx eq |
| Fine particulate matter formation | **0,01** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,02** | kg NOx eq |
| Terrestrial acidification | **0,02** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | kg P eq |
| Marine eutrophication | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **17,90** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,10** | kg 1,4-DCB |
| Marine ecotoxicity | **0,16** | kg 1,4-DCB |
| Human carcinogenic toxicity | **8,23** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **1,82** | kg 1,4-DCB |
| Land use | **0,15** | m2a crop eq |
| Mineral resource scarcity | **0,13** | kg Cu eq |
| Fossil resource scarcity | **1,71** | kg oil eq |
| Water consumption | **0,03** | m3 |

Table 22 below summarises the LCIA results in the following categories (Ferrite, Natural gas, Electricity, Transportation and Wastes) while Figure 56 presents the percentage contribution of all the previously mentioned categories to the total environmental footprint of the production process of 1 kg bonded Sr-ferrite magnets. As it can be observed, the use of ferrite is the main contributor to the total impact of the production process with 60,3% average contribution in all impact categories and emissions of 2,49 kg CO2 eq. Ferrite is also the main contributor to the total impact observed in the GW impact category (Figure 57). The use of ferrite presents also significant contribution to the impact observed in the Mineral resource scarcity category (98,4% contribution, 0,12 kg kg Cu eq), the Human carcinogenic toxicity (99,8% contribution, 8,21 kg 1,4-DCB), the Freshwater ecotoxicity (97,8% contribution, 0,09 kg 1,4-DCB) and the Terrestrial ecotoxicity category (89,7 % contribution, 16,06 kg kg 1,4-DCB).

Electricity consumption follows with 31,26 % average contribution in all impact categories and total emissions of 1,85 kg CO2 eq. The use of electricity also highly contributes to the impact observed in the Ionizing radiation category (80,3 % contribution, 0,071 kBq Co-60 eq).

Natural gas consumption follows with 10% average contribution in all impact categories and total emissions of 1,64 kg CO2 eq. The use of natural gas also highly contributes to the impact observed in the Fossil resource scarcity category (35,6% contribution, 0,61 kg oil eq).

Finally, transportation follows with 1,1% average contribution in all impact categories and total emissions of 0,11 kg CO2 eq while the average contribution of the waste generation is less than 1%.

***Table 22**. Contributions from Ferrite, Natural gas, Electricity, Transportation and Wastes in the environmental footprint of producing 1 kg bonded Sr-ferrite magnets.*

| **Impact category** | **Global warming (kg CO2 eq)** | **Terrestrial ecotoxicity (kg 1,4-DCB)** | **Human toxicity (kg 1,4-DCB)** | **Fossil resource scarcity (kg oil eq)** |
|---|---|---|---|---|
| **Ferrite** | 2,49 | 16,06 | 9,61 | 0,55 |
| **Natural gas** | 1,64 | 0,12 | 0,05 | 0,61 |
| **Electricity** | 1,85 | 1,11 | 0,36 | 0,50 |
| **Transportation** | 0,11 | 0,59 | 0,01 | 0,03 |
| **Wastes** | 0,00 | 0,00 | 0,00 | 0,00 |
| **Sum** | **6,10** | **17,89** | **10,04** | **1,71** |

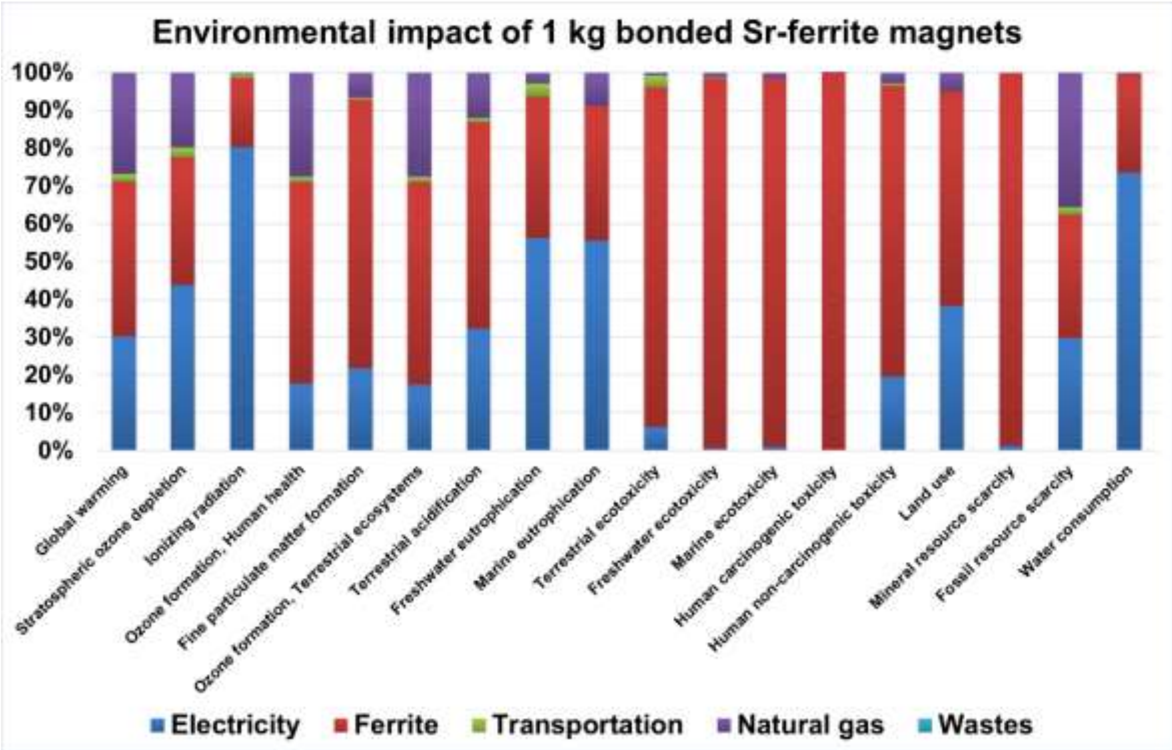



*Figure 56. Environmental impact of 1 kg bonded Sr-ferrite magnets.*

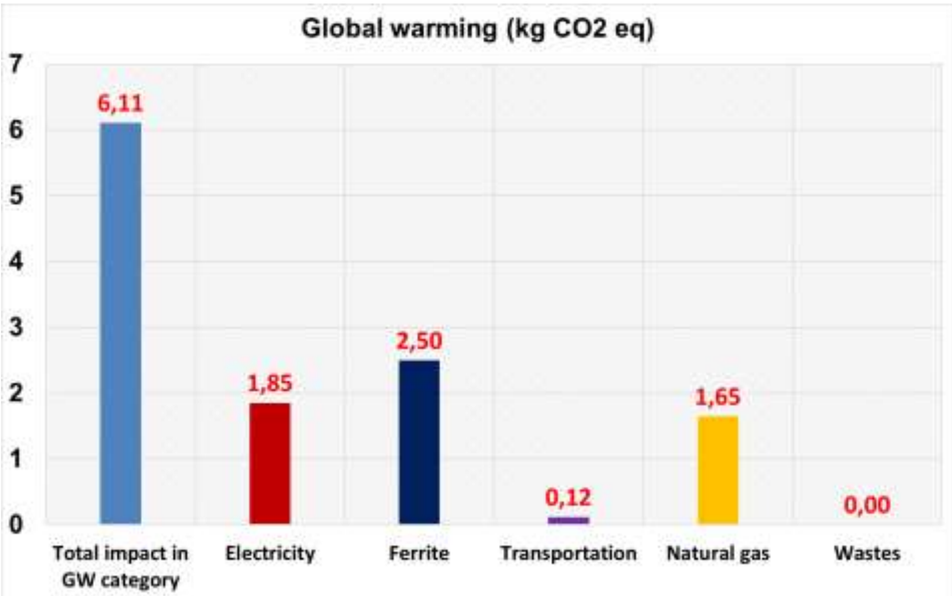



*Figure 57. Carbon dioxide emissions related to 1 kg bonded Sr-ferrite magnets.*

Figure 58 below presents the percentage contribution of four main categories (raw materials, energy consumption, transportation and waste production) in the environmental impact of producing 1 kg bonded Sr-ferrite magnets. Based on the results, raw materials consumption (ferrite) is the main contributor to the total impact with a 60,38% average contribution in all impact categories and emissions of 2,49 kg CO2 eq. Raw materials use also presents a high contribution to the impact observed in the Human carcinogenic toxicity (99,8% contribution, 8,21 kg 1,4-DCB), the Mineral resource scarcity category (98,4% contribution, 0,12 kg Cu eq), the Freshwater ecotoxicity category (97,9% contribution, 0,09 kg 1,4-DCB) and the Marine ecotoxicity category (97,4% contribution, 0,15 kg 1,4-DCB).

Energy consumption, including the electricity from the grid as well as the natural gas consumption, follows with 41,3% average contribution to the total environmental footprint of the production process. Energy appears as the main contributor to the total impact observed in the GW category with total emissions of 3,49 kg CO2 eq (57,25% contribution to the GW impact category, Figure 59). Notably, energy poses high contribution (80,93% contribution) to the impact observed in the Ionizing radiation category (0,07 kBq Co-60 eq).

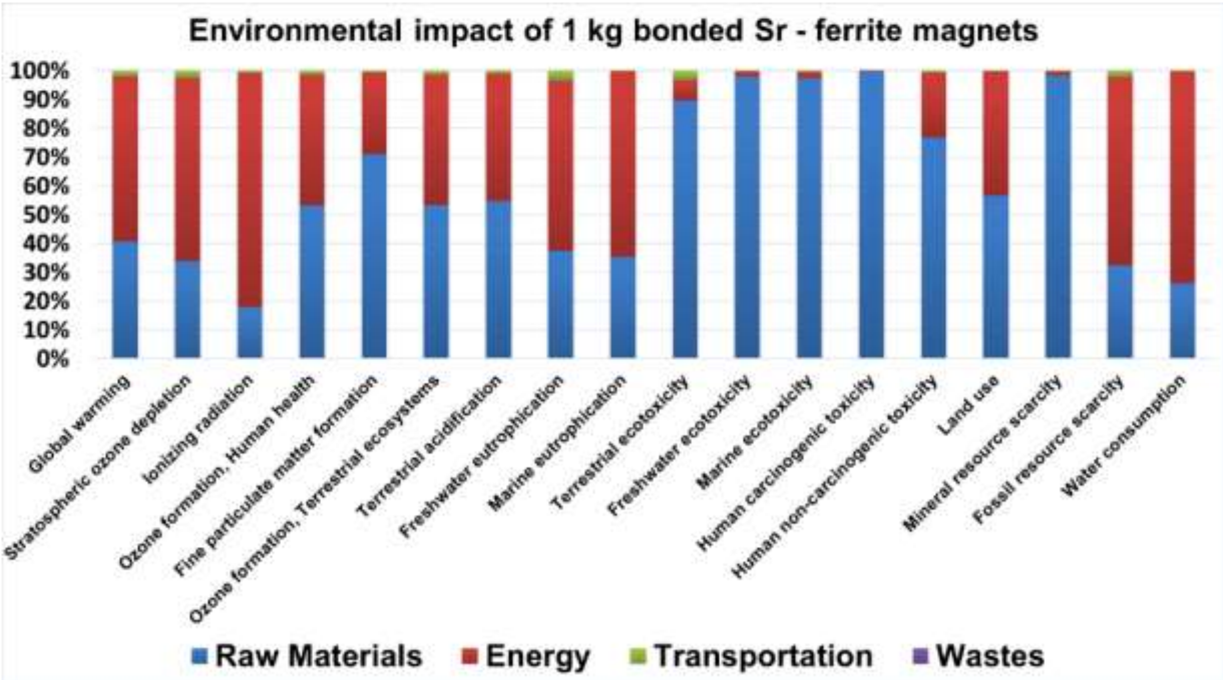



*Figure 58. Environmental impact of 1 kg bonded Sr-ferrite magnets.*

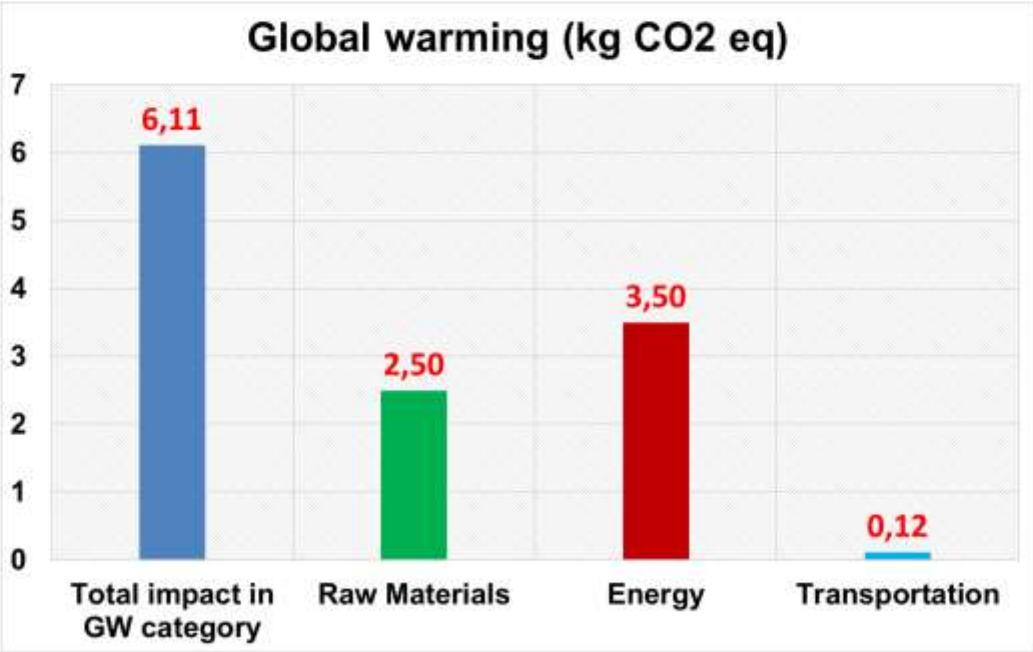



*Figure 59. Carbon dioxide emissions related to 1 kg bonded Sr-ferrite magnets.*

#### *4.3.2.3 Comparative LCIA results of PASSENGER's bonded Sr-ferrite magnets production with the benchmark NdFeB magnet production*

Table 23 presents the direct comparison of the environmental footprint of PASSENGER's bonded Sr-ferrite magnets production with the benchmark NdFeB magnet production from virgin raw materials. The use of the electricity grid from China is considered for the NdFeB magnets production and the LCA results are compared against to the PASSENGER's bonded Sr-ferrite magnets production. The direct comparison of the LCIA results in Global warming, Terrestrial ecotoxicity, Human toxicity, Fossil resource scarcity, Ionizing radiation and Mineral resource scarcity categories is depicted in Figure 60. Based on the LCA results, it can be concluded that the production of the bonded Sr-ferrite magnets within the PASSENGER project results in significant decrease in the environmental impact observed in almost all impact categories. More specifically, an impact reduction of 92% is observed in GW impact category, 95,7% reduction of impact in the Terrestrial ecotoxicity category, 74,71% reduction in the Human toxicity category (carcinogenic and non-carcinogenic), 90,2% reduction in the Fossil resource scarcity category, 97,296,8% reduction in the Ionizing radiation category and 99,1% reduction in the Mineral resource scarcity category. However, it should be noted that regarding the Human carcinogenic toxicity subcategory there is an increase in the observed impact (7,2 times higher impact) which is attributed to the ferrite use.

***Table 23**. Comparative LCIA results of producing 1 kg of NdFeB magnets vs. PASSENGER's bonded Sr-ferrite magnets.*

| **Impact category** | **Benchmark NdFeB magnets production** | **PASSENGER's bonded Sr-ferrite magnets production** | **Unit** |
|---|---|---|---|
| Global warming | **76,41** | **6,11** | kg CO2 eq |
| Stratospheric ozone depletion | **0,00** | **0,00** | kg CFC11 eq |
| Ionizing radiation | **2,86** | **0,09** | kBq Co-60 eq |
| Ozone formation, Human health | **0,22** | **0,02** | kg NOx eq |
| Fine particulate matter formation | **0,18** | **0,01** | kg PM2.5 eq |
| Ozone formation, Terrestrial ecosystems | **0,22** | **0,02** | kg NOx eq |
| Terrestrial acidification | **0,47** | **0,02** | kg SO2 eq |
| Freshwater eutrophication | **0,00** | **0,00** | kg P eq |
| Marine eutrophication | **0,32** | **0,00** | kg N eq |
| Terrestrial ecotoxicity | **423,32** | **17,90** | kg 1,4-DCB |
| Freshwater ecotoxicity | **0,23** | **0,10** | kg 1,4-DCB |
| Marine ecotoxicity | **0,43** | **0,16** | kg 1,4-DCB |
| Human carcinogenic toxicity | **1,03** | **8,23** | kg 1,4-DCB |
| Human non-carcinogenic toxicity | **38,67** | **1,82** | kg 1,4-DCB |
| Land use | **8,12** | **0,15** | m2a crop eq |
| Mineral resource scarcity | **16,12** | **0,13** | kg Cu eq |
| Fossil resource scarcity | **17,48** | **1,71** | kg oil eq |
| Water consumption | **1,32** | **0,03** | m3 |

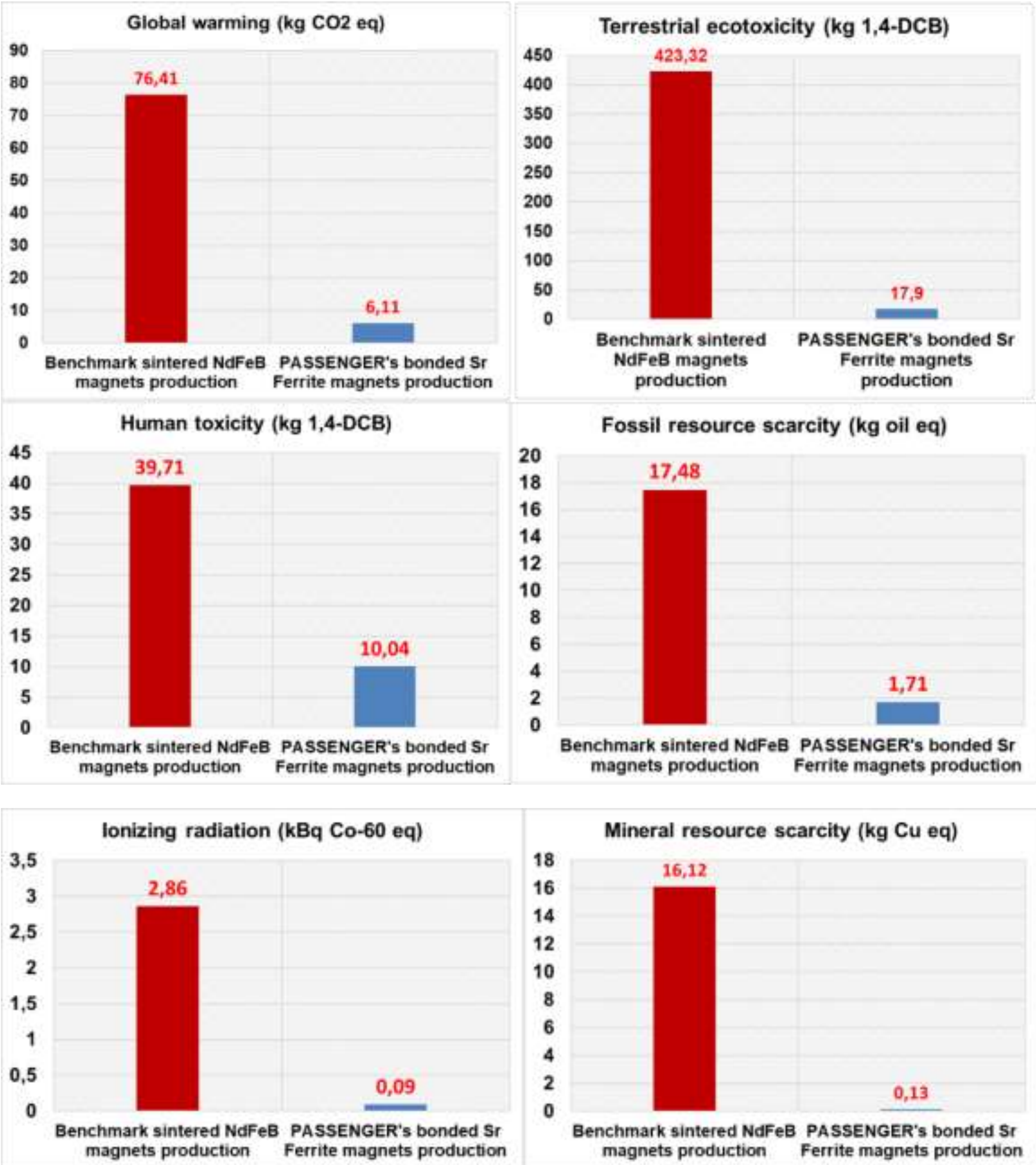



*Figure 60. Comparative LCIA results – NdFeB production vs. PASSENGER's bonded Sr-ferrite production.*

#### *4.3.2.4. Environmental benefit of PASSENGER's permanent magnets*

The LCA results presented in Tables 14, 18, and 23 clearly indicate the environmental benefits of PASSENGER's innovative RE-free permanent magnets, which can achieve up to a 90% reduction in CO2 emissions compared to the commercial NdFeB magnets developed by conventional technologies. More specifically, in the Global Warming impact category, PASSENGER's bonded MnAlC magnets present an 80,47 % reduction in CO2 emissions, the sintered MnAlC magnets exhibit an 83,35 % reduction while the bonded Sr-ferrite magnets demonstrate a 92% reduction compared to the benchmarking production of

NdFeB permanent magnets. The environmental benefit of PASSENGER's solution is also evidenced in other significant impact categories namely, the Terrestrial ecotoxicity, Human toxicity and Fossil resource scarcity categories.

In terms of the environmental benefits of utilizing REE-free permanent magnets as proposed in the PASSENGER project compared to conventional technologies, several key advantages emerge. Firstly, traditional NdFeB magnets heavily rely on rare earth elements, which are associated with environmental concerns related to extraction, processing, and supply chain vulnerabilities. By eliminating the need for rare earth elements, PASSENGER's REE-free magnets mitigate these environmental risks and reduce dependency on potentially environmentally damaging materials. Secondly, as demonstrated by the LCA results, PASSENGER's REE-free permanent magnets offer significant reductions in CO2 emissions compared to conventional NdFeB magnets. This reduction contributes to mitigating climate change and aligns with global efforts to reduce greenhouse gas emissions.

The environmental benefits extend further with the mitigation of environmental impact associated with magnet production and use. The use of REE-free permanent magnets reduces the environmental footprint, encompassing impacts such as energy consumption, water usage, and waste generation. This mitigation supports sustainable development goals and fosters environmentally responsible manufacturing practices. Additionally, by developing magnets that do not rely on rare earth elements, PASSENGER's solution promotes resource efficiency and circular economy principles. It reduces the need for virgin resource extraction and encourages the recycling and reuse of materials, thereby minimizing waste and conserving valuable resources. In summary, these advantages align with broader sustainability objectives and contribute to a more environmentally friendly approach to magnet production and utilization.

## 4.4. LIFE CYCLE COSTING

Life cycle cost (LCC) is the sum of the costs throughout the whole life cycle of a product (Figure 61). Theoretically, an LCC covers the entire life cycle of a product or an engineering project. It means the total cost ownership of an asset. Life Cycle Cost assessment consists of the Initial Costs the Recuring costs that includes operating and maintenance cost, disposal cost and residual value. Recurring costs are those that continue to occur after the purchase, like operations costs, maintenance, and upgrades. Operations costs are recurring costs that are associated with the use of the product. Maintenance costs are costs affiliated with the upkeep of the product. Disposal costs are the costs associated with the disposal of the product once its useful life ends. Finally, residual value is considered which represents the value of the product after it reaches its useful life.

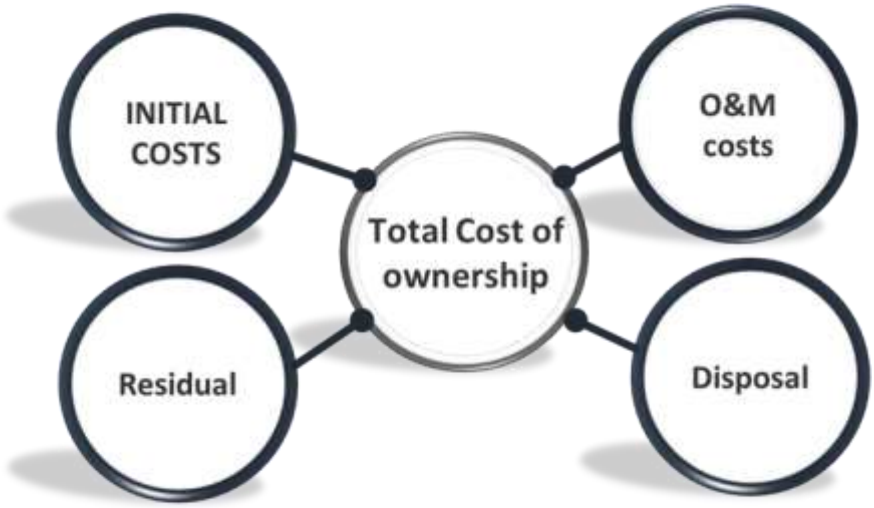



*Figure 61. Representative scheme of the LCC definition*

This document reports about the LCC done in the framework of the PASSENGER project in order to detect the main economic hotspots of the PASSENGER technologies that easy their scaling up. The LCC is normally employed in conjunction with the LCA to estimate the total cost of ownership and help determine the viability of technologies.

The objective of this section of the deliverable D4.3 - Report on preliminary Life Cycle Assessment and Material Flow analysis-R2 is to present the preliminary LCC of the PASSENGER's permanent magnets production phase developed in the framework of the PASSENGER project considering the status of development in the moment this deliverable is submitted.

### 4.4.1 System Boundaries and Functional Unit

The system boundaries and the functional unit of the Life Cycle Cost analysis of PASSENGER's technology are defined the same as in the case of the Life Cycle Assessment described above in Section 4.3.2.

### 4.4.2 LCC Inventory (LCI) - Production of sintered MnAlC magnets

In order to perform the Life Cycle Costing of the production of PASSENGER's sintered MnAlC magnets, data provided by partners were employed. The reference unit used for the LCC calculations is the production of 100 tons/year of sintered MnAlC magnets. The prices represent raw materials at industrial scale amounts from commercial sites.

Table 24 below provides the LCC inventory, assumptions and calculations based on the data provided.

***Table 24**. LCC data and assumptions - Producing 100 tons of PASSENGER's sintered MnAlC magnets per year.*

| **Category** | **Quantity** | **Comments** |
|---|---|---|
| Shifts per day | 2 | plant operation |
| Operation hours per shift | 8 | plant operation |
| Operation hours per day | 16 | plant operation, 2 shifts |
| Operation days per week | 5 | plant operation, 2 shifts |
| Operation hours per week | 80 | plant operation |
| Operation hours per month | 347,6 | plant operation, 4,345 weeks /month, 2 shifts |
| Operation hours per year | 4171,2 | plant operation, 4,345 weeks /month, 2 shifts |
| Total Salary per month | 24000 | per 4 employees |
| Salary per month | 6000 | per employee |
| Total Salary per year | 288000 | per 4 employees |
| Salary per per hour per employee | 34,5 | per employee |
| Salary per per hour | 138 | per 4 employees |
| Number of employees per day | 4 | number of employees |
| Working hours per year per employee | 2000 | per employee |
| Operation days per year | 260,7 | plant operation |
| Operation days per month | 21,725 | plant operation |
| Working hours per month per employee | 173,8 | per employee |
| CAPEX (€) | 750000 | € |
| Useful life | 15 | years |
| Interest rate | 2% | %, CAPEX |
| Depreciation | 50000 | €/years, CAPEX |
| Depreciation rate | 10 | % per year, CAPEX |
| Tax rate | 20 | % per year, CAPEX |
| Insurances | 2000 | €/years, OPEX |
| Maintenance | 50000 | €/years, OPEX |
| Overall utility costs (not directly related with the production process, e.g.: electricity, water, telephone-internet, paper etc.) | 50000 | €/years, OPEX |

| | | |
|---|---|---|
| Overall management cost (not directly related with the production process, e.g. marketing, legal or client service expense) | 50000 | €/years, OPEX |
| Disposal cost (for the plant) | 1000 | €, OPEX |
| Time to produce 1 kg of magnets | 0,004 | h |
| Estimated daily production | 383,5 | kg magnet/d |
| Total magnet production | 1499,67 | tn magnet |
| Total CAPEX | 750000 | € |
| **CAPEX (per 1 kg)** | **0,50** | **€/kg magnet** |

Table 25 below presents the costs related to the production of PASSENGER's sintered MnAlC magnets including the costs for compounding and injection moulding.

***Table 25**. Unitary costs and LCI inventory of LCC - Producing 1 kg of PASSENGER's sintered MnAlC magnets.*

| **Unit process 1 - Compounding** | | | | | |
|---|---|---|---|---|---|
| **Inputs** | **Quantity per 1 kg** | **Unit** | **Unitary cost** | **Unit** | **Total cost (€ per 1kg)** |
| MnAlC alloy (cast) | 0,9 | kg | 5 | **€** | 4,5 |
| PA12 | 0,1 | kg | 10 | **€** | 1 |
| Water, deionised {Europe without Switzerland}\| market for water, deionised \| APOS, U | 0,002 | m3 | 0,92 | **€** | 0,00184 |
| Electricity, medium voltage {RER}\| market group for \| APOS, U | 0,352 | kwh | 0,136 | **€** | 0,047872 |
| Packing | 0,0002 | pcs | 2,45 | **€** | 0,00049 |
| Transport, passenger car {RER}\| market for \| APOS, U | 5050 | km | - | - | - |
| **Outputs** | **Quantity per 1 kg** | **Unit** | **Unitary cost** | **Unit** | **Total cost (€ per 1kg)** |
| Waste to treatment: Inert waste {Europe without Switzerland}\| market for inert waste \| APOS, U | 0,03 | kg | free disposal | **€** | - |
| **Product:** Compound | 1 | kg | - | - | - |
| **Unit process 2 - Injection moulding** | | | | | |

| **Inputs** | **Quantity** | **Unit** | **Unitary cost** | **Unit** | **Total cost per category (€)** |
|---|---|---|---|---|---|
| Compound | 1 | kg | Not internally charged | - | - |
| Electricity, medium voltage {RER}\| market group for \| APOS, U | 0,352 | kwh | 0,136 | € | 0,047872 |
| Packing | 0,01 | pcs | 5 | € | 0,05 |
| Transport, passenger car {RER}\| market for \| APOS, U | 45 | km | - | - | - |
| **Outputs** | **Quantity per 1 kg** | **Unit** | **Unitary cost** | **Unit** | **Total cost (€ per 1kg)** |
| **Product: Sintered MnAlC magnets** | 1 | kg | - | - | - |
| Personnel | - | - | - | - | 0,552 |
| Maintenance | - | - | - | - | 0,048 |
| Insurances | - | - | - | - | 0,0019 |
| Other utility costs | - | - | - | - | 0,048 |
| Management costs | - | - | - | - | 0,048 |
| Disposal cost | - | - | - | - | 0,001 |
| **OPEX (per 1 kg)** | - | - | - | - | **6,35** |
| **CAPEX (per 1 kg)** | - | - | - | - | **0,50** |
| **Manufacturing cost (per 1 kg)** | **-** | **-** | **-** | **-** | **6,85** |

## 4.4.3 LCC results - Production of sintered MnAlC magnets

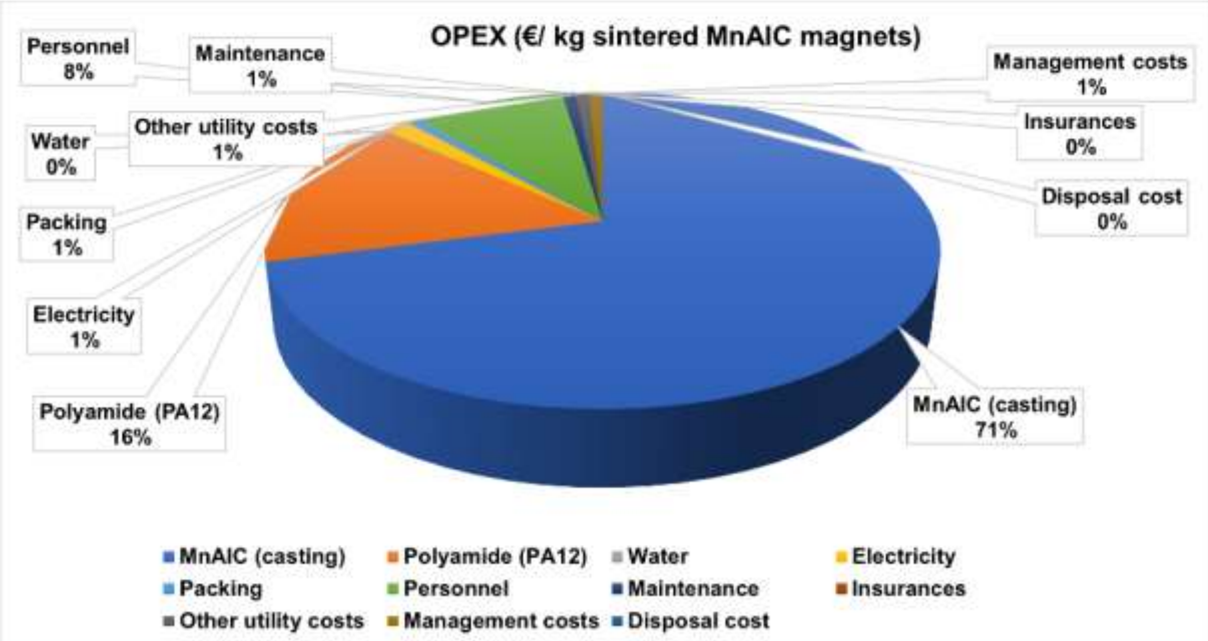
### *4.4.3.1 OPEX*

The detailed OPEX cost breakdown of PASSENGER's sintered MnAlC magnets production is presented in Table 26 while the summary of the OPEX cost breakdown is presented in Table 27.

| Table 26. OPEX cost breakdown of PASSENGER's sintered MnAlC magnets production. | | |
|---|---|---|
| **Category** | **Cost (€)** | **% over OPEX** |
| MnAlC (casting) | 4,500 | 70,90 |
| Polyamide (PA12) | 1,000 | 15,76 |
| Water | 0,002 | 0,03 |
| Electricity | 0,096 | 1,51 |
| Packing | 0,050 | 0,80 |
| Personnel | 0,552 | 8,70 |
| Maintenance | 0,048 | 0,76 |
| Insurances | 0,002 | 0,03 |
| Other utility costs | 0,048 | 0,76 |
| Management costs | 0,048 | 0,76 |
| Disposal cost | 0,001 | 0,02 |
| **OPEX (per 1 kg)** | **6,35** | **100** |

| Table 27. Summary of OPEX cost breakdown - PASSENGER's sintered MnAlC magnets production. | | |
|---|---|---|
| **Category** | **Cost (€)** | **% over OPEX** |
| Raw material | 4,500 | 70,90 |
| Ancillary | 1,052 | 16,58 |
| Energy | 0,096 | 1,51 |
| Personnel | 0,552 | 8,70 |
| Maintenance | 0,048 | 0,76 |
| Insurances | 0,002 | 0,03 |
| Other utility costs | 0,048 | 0,76 |
| Management costs | 0,048 | 0,76 |
| Disposal cost | 0,001 | 0,02 |
| **OPEX (per 1 kg)** | **6,35** | **100** |

The above LCC results are graphically presented in Figure 62.



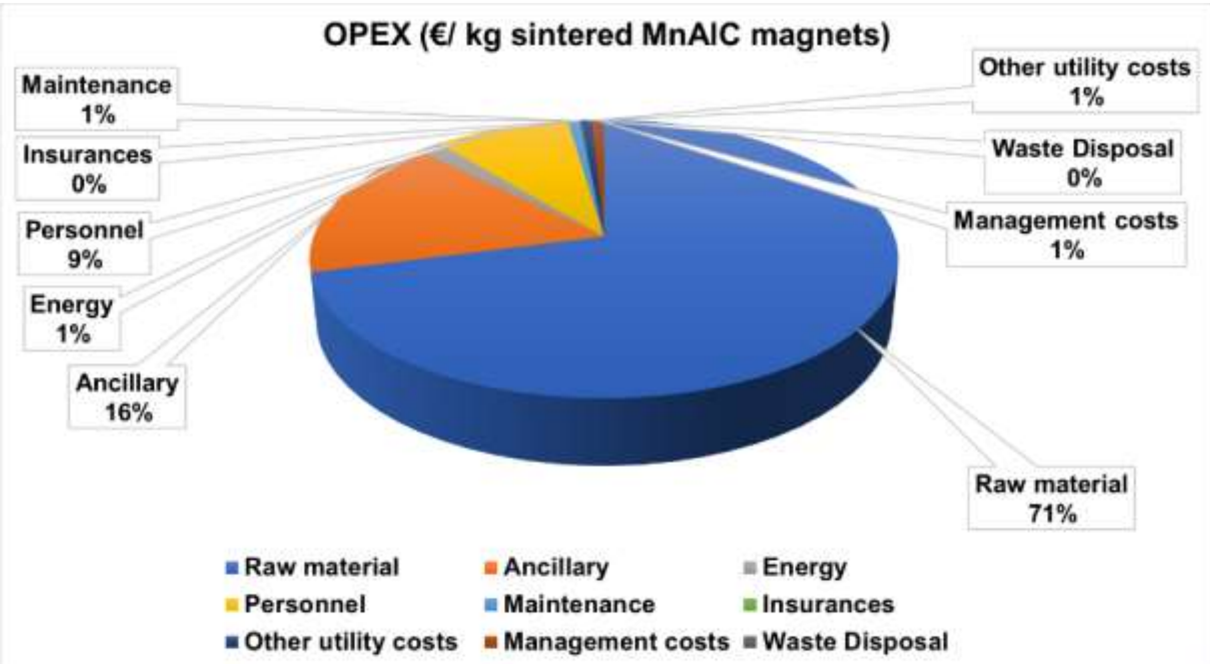




*Figure 62. OPEX cost breakdown of PASSENGER's sintered MnAlC magnets production.*

The calculated total **OPEX** for PASSENGER's **sintered MnAlC magnets production** is **6,35 €/kg**. According to the LCC results, the purchase of the raw material MnAlC alloy which is produced by casting is the main contributor to the total OPEX of the magnet production process (70,9 % contribution). The use of ancillary materials follows with 16,58 % contribution to the OPEX. Among the ancillary materials, polyamide PA12 is the main contributor to the total OPEX with 15,76 % contribution. Personnel costs follow with 8,7% contribution to the OPEX. Energy consumption contributes at 1,51% to the total OPEX of the magnet production process. Maintenance, management costs, insurances, disposal costs and other utility costs have less than 1% contribution to the total OPEX of the sintered MnAlC magnets production.

#### *4.4.3.2 CAPEX*

The following calculations provided the CAPEX for producing 1kg of sintered MnAlC magnets within the PASSENGER project.

- **Estimated daily production** = 383,5 kg sintered MnAlC magnets per day
- **Plant capacity (tons/year)** = [383,5 kg /d * 260,7 days/year]/1000 = 100 tons / year
- **Total magnet production (tons)** = Yearly (tons/year) x Expected lifetime (years)= 100 tons / year * 15 years plant capacity = 1499,6 tons
- **Total CAPEX = 750000 €**
- **CAPEX (€/kg)**= Total plant investment (€)(equipment purchasing cost + Installation) / Total production (kg MnAlC magnets produced) = 750000/ 1499676,75 kg = **0,5 €/kg** sintered MnAlC magnets

#### *4.4.3.3 Comparison of the estimated cost of 1 kg sintered MnAlC magnets to magnets containing CRMs*

Table 28 below provides the market prices for sintered NdFeB magnets, SmCo magnets, Alnico magnets, Alnico magnets and ferrite magnets for comparison purposes. In Figure 63, the **manufacturing cost of PASSENGER's sintered MnAlC magnets** (**6,85 €/kg**) is compared against the current market prices of other state-of-the-art containing and non-containing CRMs permeant magnets. Obviously, the market price of PASSENGER MnAlC magnets will be higher than the manufacturing price but the economic nature of the PASSENGER solution would still be substantial.

***Table 28****. Market prices of state-of-the-art containing and non-containing CRMs permeant magnets.*

| Permanent magnet category | Price | Unit |
|---|---|---|
| Sintered NdFeB | 71,17 | €/kg |
| Bonded NdFeB | 85,4 | €/kg |
| Ferrite | 6,74 | €/kg |
| SmCo | 94,89 | €/kg |
| Alnico | 55,004 | €/kg |


*Figure 63. Comparison of the estimated manufacturing cost of 1 kg sintered MnAlC magnets with the market price of magnets containing CRMs.*


*Figure 64. Comparison of the estimated manufacturing cost of 1 kg sintered MnAlC magnets with the market price of sintered NdFeB permanent magnets.*

As depicted in the Figure 64, the produced RE-free magnets result in a reduction of 90,37 % in magnet price. When comparing the manufacturing price of PASSENGER's sintered MnAlC magnets with the current market prices of conventional permanent magnets, the magnets performance should be taken into consideration. The maximum energy product

$(BH)_{max}$ is a key parameter used to evaluate the performance of permanent magnets (Figure 65). More specifically, when comparing two types of permanent magnets, the one with a higher $(BH)_{max}$ is considered better in terms of performance. This implies that the magnet can generate a stronger magnetic field and store more magnetic energy.

- The reported **$(BH)_{max}$** for **sintered NdFeB** magnets is **33 MGOe to 51 MGOe**.
- The **targeted $(BH)_{max}$** for **sintered MnAlC** magnets of the **PASSENGER** project is $(BH)_{max}$=**10–15 MGOe**.

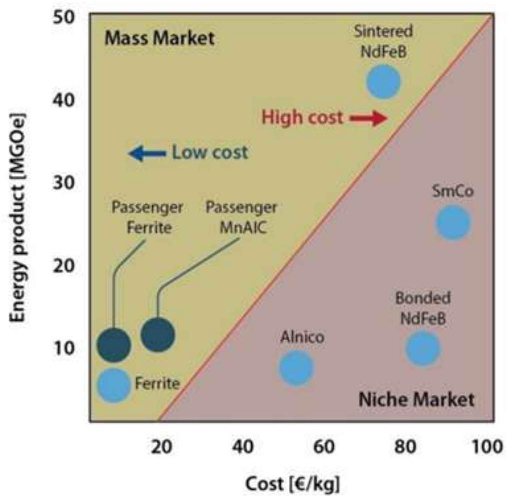



*Figure 65. (BH)max vs cost per kg for PASSENGER's magnets (improved ferrite and Mn-Al-C – dark blue) and magnets containing CRMs (Nd, Dy and Co)).*

- Based on the maximum energy product $(BH)_{max}$ values, **the sintered NdFeB magnets have almost 2,8 times higher performance than the sintered MnAlC magnets**.
- The comparison of the NdFeB and MnAlC magnets price should take into consideration the magnet performance.
- To achieve similar properties and magnet performance with the conventional RE magnets, **2,8 kg of sintered MnAlC magnets can substitute 1 kg of sintered NdFeB magnets with a total cost reduction of 73 %.**
- When comparing magnet prices for a specific application, factors such as appropriate durability, shape, and weight should also be taken into consideration, along with possible redesign of the component that may be required.

Thus, considering the same magnet performance, **the produced RE-free magnets result in significant reduction in magnet cost** (Figure 66).


*Figure 66. Comparison of the estimated manufacturing cost of sintered MnAlC magnets with the market price of sintered NdFeB permanent magnets based on magnet performance.*

## 4.5. SOCIAL LIFE CYCLE

(S-LCA) is a method that can be used to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle. S-LCA is still in a preliminary stage. S-LCA: addresses social impacts, i.e. impacts on human beings and the society. Social aspects relate to the impacts on different stakeholder groups throughout the life cycle of the product. The stakeholders that are most directly affected are employees, consumers, and local communities (Figure 67). Social aspects include issues like wages, health and safety, and access to education. The problem with assessing social issues is that the issues at stake are wide-ranging and often difficult to quantify in a meaningful way. Social indicators are very hard to quantify and their impact changes with the behaviour of the company.


*Figure 67. S-LCA representative scheme*

### 4.5.1 Social Implications of PASSENGER technology

The PASSENGER project, focusing on the production of Rare Earth Element (REE)-free permanent magnets, carries several social implications that extend beyond technological advancements:

- **Reducing Environmental Impact:** By developing REE-free permanent magnets, the project aims to decrease the reliance on REEs, which are often associated with environmentally harmful extraction and refining processes. This reduction in environmental impact aligns with broader societal concerns about sustainability and responsible resource management.
- **Mitigating Health Risks:** The project addresses health concerns related to REE extraction, particularly in regions where mining and refining take place. The reduction in demand for REEs contributes to mitigating potential health risks for local populations and, by extension, the global community.
- **Global Supply Chain Diversification**: The current concentration of REE production, primarily in China, raises concerns about supply chain vulnerabilities. The PASSENGER project, by promoting the use of alternative materials, contributes to diversifying the global supply chain for permanent magnets. This diversification can enhance geopolitical stability and reduce the risk of supply chain disruptions.
- **Socially Responsible Innovation**: The development of REE-free permanent magnets demonstrates a commitment to socially responsible innovation. By actively seeking alternatives that address environmental and social concerns, the project sets a precedent for responsible research and development practices.

- **Employment Opportunities:** The establishment of innovative pilot plants at TRL 7 as part of the project may create new employment opportunities in industries related to the production of REE-free permanent magnets. This has potential positive impacts on local economies and job markets.
- **Social Acceptance and Inclusivity**: The social life cycle assessment (LCA) conducted within the project ensures that the new permanent magnets meet social acceptability standards. Additionally, by engaging with end-user groups and addressing barriers to deployment (psychological, financial, organizational, technical, etc.), the project aims to make the technology accessible and inclusive. This inclusivity can benefit individuals who may be currently excluded from personal mobility due to financial constraints.
- **Economic Benefits:** The project contributes to economic sustainability by promoting alternatives that reduce dependence on potentially scarce or geopolitically sensitive resources. This, in turn, may have positive economic implications for industries involved in the production and application of permanent magnets.
- **Education and Awareness**: The PASSENGER project, by addressing the social implications of its innovations, has the potential to raise awareness about the environmental and social impacts of technology. It contributes to education and dialogue around sustainable practices in materials and manufacturing.

The PASSENGER project's shift towards REE-free permanent magnets carries social implications that align with sustainability goals, health considerations, economic development, and inclusivity, thereby contributing to a more socially responsible and environmentally conscious technological landscape.

### 4.5.2 Social - LCA for rare earth NdFeB permanent magnets – Literature review

The following section focuses on literature review regarding the social life cycle aspects of rare earth NdFeB permanent magnets. While the environmental and economic impacts of permanent magnets production have been studied, social perspectives remain under-researched.

***Social LCA for rare earth NdFeB permanent magnets***

In a specific case study, the Product Social Impact Life Cycle Assessment (PSILCA) 2.0 database is used to assess social implications, focusing on value chain actors in three production chains from different rare earth ore locations: China, Australia/Malaysia, and United States/Japan [11]. The analysis aims to identify differences in social risks along the supply chain, emphasizing fair competition and corruption as key factors. The US value chain emerges with the lowest social risk, but a sectoral and geographical analysis reveals challenges in mineral, fossil fuel, and chemical sectors.

The goal of the S-LCA study is to assess whether social risks vary among the three process chains. The functional unit of this study is defined as 1 kg of NdFeB magnet. The PSILCA database provides 49 quantitative and semi-quantitative impact categories. Value chain actors, a critical stakeholder group, are examined for their social responsibility, fair competition, and corruption risks. The study reveals that the US value chain has the lowest social risk along the supply chain, with a sectoral and geographical analysis highlighting challenges in the mineral, fossil fuel, and chemical sectors across all three cases. Value chain actors are identified as the most vulnerable group, experiencing the highest average indicator values among stakeholders.

Social hotspots are identified through a detailed analysis of impact categories, including public sector corruption, social responsibility along the supply chain, active involvement of enterprises in corruption and bribery, and anti-competitive behaviour. The study emphasizes the significance of value chain actors in influencing social impacts and recommends further investigations to enhance social sustainability. It suggests targeted measures to address specific social risks in different sectors and production phases. The potential for local improvements is highlighted in the literature while acknowledging the need for a holistic approach to social sustainability to minimize adverse effects on local communities.

The main social hotspots identified during the magnets production in the study are associated with public sector corruption, social responsibility along the supply chain, active involvement of enterprises in corruption and bribery, and anti-competitive behaviour or violation of anti-trust and monopoly legislation. These hotspots vary across different process chains and geographical locations. Public sector corruption is highlighted as a significant risk, particularly in Chinese sectors across all three chains. Social responsibility along the supply chain is a concern, with the Bayan Obo and Mount Weld chains performing worst in this category. Active involvement of enterprises in corruption and bribery exhibits notable risks, with the Mountain Pass chain showing the highest risks in this aspect. Anti-competitive behaviour or violation of anti-trust and monopoly legislation is also identified as a significant social hotspot, with risks associated with different phases of magnet production, such as beneficiation and separation, particularly in China. Overall, these social hotspots provide targeted areas for improvement to enhance the social sustainability of rare earth magnet production.

The social hotspots during magnet production, as identified in the study, reveal specific areas of concern within the supply chains. Public sector corruption emerges as a critical issue, particularly in Chinese sectors across all three chains (Bayan Obo, Mount Weld, and Mountain Pass). This hotspot is indicated by high medium risk hours and is based on data from the Transparency International Corruption Index. The involvement of the public sector in corruption is a complex challenge that affects the overall social sustainability of magnet production.

Social responsibility along the supply chain is another significant hotspot, with distinct patterns observed in different process chains. The Bayan Obo and Mount Weld chains show higher risks in this category, reflecting challenges related to how companies in these chains address social responsibility issues throughout the production process. This category focuses on the extent to which companies in specific sectors align their strategies with principles addressing human rights, labour standards, the environment, and corruption.

Active involvement of enterprises in corruption is highlighted as a notable hotspot, with the Mountain Pass chain exhibiting the highest risks in this aspect. This category signifies the risk associated with companies engaging in corrupt practices, which can have far-reaching implications for fair competition and overall business ethics.

Anti-competitive behaviour or violation of anti-trust and monopoly legislation is another identified hotspot. Risks associated with price-fixing and other anti-competitive practices are particularly significant during the beneficiation and separation phase, notably in Chinese sectors. This finding underscores the need for addressing fair competition issues within the magnet production supply chains.

These social hotspots collectively emphasize the importance of addressing corruption, ensuring social responsibility, preventing unfair business practices, and promoting fair competition in the rare earth magnet production process. By focusing on these specific areas, stakeholders can work towards improving the social sustainability of the production chains and mitigating the identified risks.

In conclusion, the study contributes valuable insights into the social implications of rare earth magnet production, supporting ongoing efforts to enhance social sustainability in the industry. The findings offer a valuable understanding of social risks, emphasizing the importance of fair competition, corruption, and social responsibility along the supply chain. The results provide a basis for targeted interventions and improvements in specific sectors and production phases to address social hotspots and promote a more sustainable rare earth magnet production process.

***Designing, prototyping and testing of a ferrite permanent magnet assisted synchronous reluctance machine for hybrid and electric vehicles applications.***

Another study, within the context of the paper titled "Designing, Prototyping, and Testing of a Ferrite Permanent Magnet Assisted Synchronous Reluctance Machine for Hybrid and Electric Vehicles Applications" centres on the development and assessment of a permanent magnet-assisted synchronous reluctance machine (PMaSYRM) tailored for A/B-segment electric vehicles [12]. With a focus on sustainability, the study attempts to eliminate rare-earth materials in the magnets, compensating for potential performance loss through innovative design elements such as ferrite magnets, a novel hairpin winding for the stator, and a lightweight modular rotor design. The research extends to the entire drive system, encompassing integrated power electronics and an air-cooled housing. As part of the life cycle assessment (LCA) and sustainability evaluation, a comprehensive social assessment was conducted. The goal was to identify positive and negative social "hotspots" that may impact labour conditions, human rights, health and safety, governance, and community infrastructure. Using a matrix of 113 countries and 57 sectors, the study calculated work hours invested in each life cycle stage to gauge positive social impacts, revealing significant benefits in Austria and specific regions involved in materials mining, early processing, and fossil fuel extraction and distribution.

The focus shifted to the manufacturing stage, where detailed worker-hours during the production of the PMaSYRM were analysed. Notably, social hotspots were identified in Southern Africa (mainly Mozambique) and Uzbekistan, with risks related to conflict areas, child labour, low-wage employment, and health and safety concerns. Mozambique and Uzbekistan emerged as countries significantly impacted by negative social outcomes in the manufacturing of the PMaSYRM. The assessment further compared the social risk associated with a benchmark motor, revealing a 40% higher risk despite similarities between the two machines. This heightened risk is attributed to increased demand for materials and resources per kilowatt, translating into elevated instances of child and forced labour, restricted freedom of association, and engagement in conflict areas across the supply chain.

The social life cycle assessment (S-LCA) in the paper identified significant social hotspots during the manufacturing stage of the presented PMaSYRM. These hotspots were associated with regions such as Southern Africa, predominantly Mozambique, and Uzbekistan. The analysis focused on various impact categories, including conflict areas, child labour, employment of labour at low wages, human health, and safety issues. The identified risks were linked to the extraction and early processing of metals in Mozambique and the extraction and distribution of energy sources in Uzbekistan.

In Mozambique, the extraction and early processing of metals were found to present the highest risk of social issues across multiple impact categories. Specific concerns included the risk of conflict areas, child labour, employment of labour at low wages, and human health and safety issues. These challenges were particularly associated with the extraction of raw materials.

Similarly, in Uzbekistan, where energy sources are extracted and distributed to Western Europe, the study highlighted elevated social risks. Issues included poor work conditions, lack of freedom of association, long work hours, and special cases of forced labour. These findings underscored the importance of considering social aspects in the evaluation of the technology's life cycle, beyond its technical and environmental dimensions. The assessment was based on a matrix involving 113 countries and 57 sectors. The analysis calculated work hours invested in each life cycle stage to determine positive social impacts, particularly in terms of increased employment. The study aimed to identify potential positive or negative social "hotspots" influencing labor conditions, human rights, health and safety, governance, and community infrastructure.

***The energy-mineral-society nexus – A social LCA model***

In another study, the goal was to analyse the complex interactions within the energy-mineral-society nexus (EMS nexus), focusing on the social life cycle assessment of rare earth elements used in direct-drive wind turbines. The paper utilised an extended S-LCA model and a scenario approach, employing the Social Hotspots Database (SHDB) to scrutinize the social footprint of rare earth production in Australia, Malaysia, the USA, and China [13]. The analysis encompassed various production stages, including mining, beneficiation, separation, metal, and magnet production. The study monetised social risks for three rare earth production chains and introduced a novel approach incorporating the Human Development Index (HDI) for estimating the social footprint and risk intensity.

The findings revealed distinct social footprints across production sites, with notable differences in the marginal social costs associated with mining, processing, electrolysis, separation, and magnet production. The study identified significant variations in social risks, emphasizing the importance of considering societal impacts alongside ecological effects. Notably, the social footprint was framed as analogous to the ecological footprint, indicating the negative effects of rare earth-based permanent magnet production on social capital. The results underscored that renewable energy technologies, while crucial for sustainable energy systems, are not immune to social risks.

The study identified social hotspots by applying an extended social life cycle assessment (S-LCA) model, focusing on the production of rare earth elements for wind turbine magnets. To conduct the S-LCA, the researchers utilised the Social Hotspots Database (SHDB). The SHDB was particularly employed to investigate rare earth production in specific locations, namely Australia, Malaysia (Mount Weld process), the USA (Mountain Pass process II), and China (Bayan Obo process).

The identified social hotspots encompassed various stages of the rare earth production chain, including mining, beneficiation, separation, metal, and magnet production. By employing a scenario approach, the study monetised social risks associated with these production stages, allowing for a quantitative assessment of the social footprint. The use of the Human Development Index (HDI) added an additional layer to the analysis, providing insights into the social risk intensity associated with each production site.

Key social hotspots were revealed through the calculated marginal social footprints, which represent the negative social effects of production and consumption patterns. The results demonstrated considerable variations in social costs among different production processes and locations. For instance, the study found that the Bayan Obo process in China exhibits the highest marginal social footprint, indicating elevated social risks. This includes implications for uncontrolled fabrication conditions, highlighting the need for attention to the social implications of renewable energy technologies.

In summary, the social hotspots identified in the study are rooted in the diverse social impacts associated with rare earth production for wind turbine magnets. The use of the SHDB and a comprehensive S-LCA model allows for a systematic and quantitative analysis of social risks, providing valuable insights into the societal implications of renewable energy technologies. The study employed an innovative S-LCA model to assess the social impacts of rare earth production for wind turbine magnets. The research highlights the necessity of addressing social risks in tandem with ecological considerations in the pursuit of sustainable energy solutions.

# 5. MATERIALS FLOW ANALYSIS (MFA)

## 5.1. INTRODUCTION

The Material Flow Analysis (MFA) performed within the Task 4.9 has the target to investigate the flows of valuable elements though the life of permanent magnets (PM). More in detail, the selected elements are supplied for the PM manufacturing, they are stocked within PM for a variable times (based on PM lifetime) and they are recovered from PM waste to be supplied on the market as secondary raw materials, in agreement with the circular economy principles [14].

In this context, the MFA is an important data provider for the identification of effective strategies of secondary raw material supply and the development of specific policies. The possibility to follow the element flows is essential to support the economy conversion with the emergence of new realities of industrial symbiosis, where the resulting flow from a facility becomes the raw materials from another one. Considering its characteristics, the MFA results are suitable to be integrated to economic and environmental sustainability analysis [15].

## 5.2. GOAL AND SCOPE

The present report aims at showing the state of play of the MFA within PASSENGER project, Task 4.9. The data resulting from the MFA study for elements selected from PM will provide an important base of background information from which future materials criticality, in the PM field, can be better addressed, and sustainable development pathways, on European level. Considering the PASSENGER goals, the present Deliverable mainly focuses on both ferrite magnets and NdFeB ones, with the aim to have a picture of the current situation. The consequent step will be the estimation of the effect of PASSENGER technologies and products on the decrease of REE consumption, thanks to the substitution with ferrite and MnAlC technologies.

## 5.3. MFA METHODOLOGY

The analysis will include four main phases that will be developed during the Project progress:

1. Definition of scenarios
2. Collection of information about PM (production, use, recycling)
3. Numerical MFA performing
4. Data processing

Currently, we have worked on scenario definitions and data collection. The outcome is a deepened state of the art of PM manufacturing and recycling by different options resulting in mass balances, suitable to perform the final steps of MFA.

## 5.4. IDENTIFICATION OF SCENARIOS

The first phase of MFA aimed at the identification of the scenarios to study, including the choices of:

- The target elements to consider;
- The PM life steps to include in the system boundaries;
- The temporal geographical boundaries to include.

The choice of metals has been driven by the study of the state-of-the-art of magnet technologies. More in detail, we selected **Sr and Fe**, for ferrite PM, **Nd Dy, Pr** for **NdFeB PM**. As concerns the time, we will start from the reference **year 2021**, with the intention of a further integration with future perspectives **up to 2030**. We considered the European and global limits.

## 5.5. DATA COLLECTION

Figure 68 reports the list of data chosen for the implementation of analysis. Data currently included in the analysis comes from both scientific literature and technical reports. The final step of MFA will include the information of project stakeholders to assess the potential enhancements achieved by PASSENGER within the circular economy strategy. The paragraphs below aim at explaining the information collected for each block included within the MFA related to Ferrite PM (Section 5.6) and NdFeB PM (Section 5.7). MnAlC PM are excluded from the current stage of MFA since they represent innovative technologies in PM field and not relevant flows were detected at the moment.

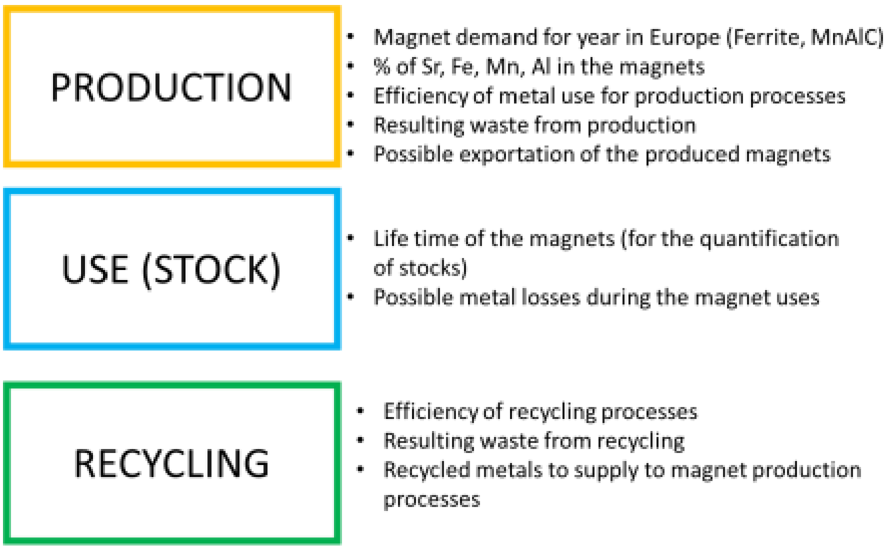



*Figure 68. Summary of necessary data to perform the numerical MFA*

## 5.6. FERRITE MAGNETS

Ferrite magnets represents the oldest application in the PM field. Nevertheless, the long-lasting interest for this technology is connected to the relatively good magnetic properties and low price which make it a promising substitute of high-cost rare earth elements (REE) magnets (for applications in which it is possible).

### 5.6.1 Production

*Demand for year*

Currently, the worldwide market of hexagonal ferrites has been estimated around $1.13*10^6$ tons per year [16-18]. Asia Pacific dominates the ferrite market (with a 40% share), followed by North America and Europe, in agreement with the industrialization and urbanization level of the countries [19]. As reported in Table 29, over 65% of the total ferrite magnets in 2020 were used in motor applications, mainly automotive motors (18%), appliance motors (14%), HVAC motors (13%), and industrial and commercial motors (12%). Furthermore, they are also utilized in loudspeakers, separation equipment, Magnetic Resonance Imaging (MRI), relays and switches, and holding and lifting application [20]. According to a new report written by Expert Market Research, it is expected an increase of ferrite demand up to 1.44 $*10^6$ by 2026 [18]. The report on the future market insights describes an expected global market increase up to 5.2% by 2031 [19,21].

*Table 29. Application of ferrite magnets (Average lifetimes adapted from [22])*

| Product category | Product | Average lifetime |
|---|---|---|
| **Automotive motors** | Starter motors | 16 |
| **($1.3*10^5$ tons)** | Small electric motors | 16 |
| | Actuators and sensors | 16 |
| | Dynamos | 16 |
| **Appliance motors** | Microphones | 4 |
| **($1.0*10^5$ tons)** | Loudspeakers | 4 |
| | Holding magnets | 4 |
| | Toys | 4 |
| **HVAC motors** | Washing machines | 11 |
| **($9.6*10^4$ tons)** | Refrigerators | 12 |
| | Magnetron in microwave ovens | 8 |
| | Air conditioner | 10 |
| **Industrial & commercial motors** | Machines tools | 20 |
| **($8.8*10^4$ tons)** | | |
| | Small electric motors | 20 |
| | Transformers | 20 |

| | | |
|---|---|---|
| | Actuators and sensors | 20 |
| | Magnetic separators | 20 |
| **Others (2.5*10$^5$ tons)** | - | - |

*Manufacture details*

The literature is rich in technologies aimed at the PM manufacturing, as summarized in Table 30 which reports the most common techniques and the related magnetic properties (Figure 69).

*Table 30. Magnetic properties of ferrite magnet processed by different techniques.*

| Reference | Composition | Sintering technique | Ms [emu $g^{-1}$] | Mr [emu $g^{-1}$] | Hc [kOe] | $(BH)_{max}$ [MGOe] |
|---|---|---|---|---|---|---|
| [23] | $SrFe_{12}O_{19}$ | Conventional (Thermal sintering) | | 0.38 T | 3.4 | 4.21 |
| [24] | $SrFe_{12}O_{19}$ · SiO2 | Conventional (Thermal sintering) | | 54 | 1.70 | |
| [25] | $SrFe_{12}O_{19}$· 0,2%PVA·0,6%SiO2 | Ceramic processing route with two-step sintering | 58 | 46 | 2.05 | |
| [26] | $SrFe_{12}O_{19}$ | Microwave-assisted calcination route | 54,8 | 29,52 | 5.3 | |
| [27] | $SrFe_{12}O_{19}$ | Microwave sintering | 50,43 | | 5.5 | |
| B.Grindi | M- $SrFe_{12}O_{19}$ | Microwave sintering | 64 | | 1.20 | |
| [28] | SrM ferrite fine particles (1.0%$La_2O_3$ .0.1%$Co_3O_4$) | Spark Plasma sintering | | 0.32 T | 4.10 | 2.29 |

| | | | | | | |
|---|---|---|---|---|---|---|
| [29] | $SrFe_{12}O_{19}$ | Spark Plasma sintering | 73,6 | 65,8 | 2.10 | 2.75 |
| [30] | $SrFe_{12}O_{19}$ | Hydrothermal: Sol-gel precursor coating technique | 64,5 | | 4.9 | |
| [31] | $SrFe_{12}O_{19}$ | Hydrothermal | 72,2 | 44,764 | 2.2 | 1.20 |

| Process | Step | Input | Output |
|---|---|---|---|
| Ferrite thermal sintering | Mixing | 0.5 kWh | 102.6 kg mixed powder (13 wt% $SrCO_3$; 86,7 wt% $Fe_2O_3$ 0.1 wt% $SiO_2$; 0.2 wt% $H_3BO_3$) |
| | Pelletizing | 8.8 kWh | 107 kg ball pellet (diameter 6 mm) |
| | Pre-sintering | 195 kWh | 96.2 kg $SrFe_{12}O_{19}$-$SiO_2$<br>2.4 kg $Fe_2O_3$<br>4.0 kg $CO_2$ |
| | Dry crushing | 44 kWh | Pre-sintered powder (<10 μm) |
| | Wet crushing | 33 kWh<br>95.9 kg water<br>1.0 kg $CaCO_3$<br>0.1 kg $SiO_2$<br>0.3 kg dispersant | 195.9 kg slurry |
| | Dehydration | 18.5 kWh | 133.3 kg slurry (75 wt% solid)<br>62.6 kg water |
| | Moulding | 34 kWh | 1400 unit of compact magnet (Diameter 5 cm; heigh 1 cm; ρ 3.8 g cm |
| | Dry | 96 kWh | 1400 unit (=100 kg solid)<br>33.3 kg water |
| | Sintering | 640 kWh | 1400 unit synthetized ferrite magnet |
| | Magnetization | - | 1400 unit ferrite PM (=100 kg)<br>*Br* 4.3kGs; *Hc* 3.9 kOe; $(BH)_{max}$ 4.4 MGOe |

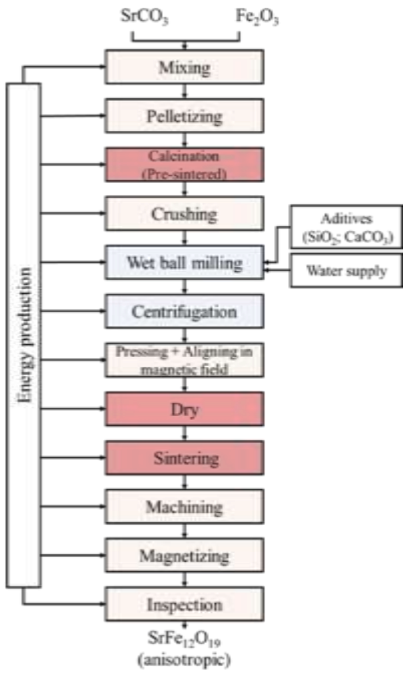



*Figure 69. Ferrite PM sintering route (block diagram and the related mass and energy balances). Functional unit: 100 kg of anisotropic magnets products*

On the literature research basis, a representative schema was built to describe the manufacture of 100 kg of anisotropic magnets products (with the related mass and energy balances) following the patent CN103265277B [32].

The process description reports a content of **Fe and Sr** of about **62 and 7%,** respectively, in agreement with the composition described by the scientific literature [33,34]. The SrO and $Fe_2O_3$ ratio should be 1:5.7. As in most manufacturing processes, the ferrite magnet production results in residues, which vires on the production volume basis [35]. It was assumed a **15% of ferrite scraps** (compared to the input of ferric oxide) due to the mechanical operations of grinding [36]. **Scraps are usually collected and sold for use in new material production, often for lower quality applications** [33]. Therefore, **the manufacturing losses can be considered near-zero.**

As concern the raw material productions, Table 31 summarizes important information to better understand the worldwide situation of both Fe and Sr.

*Table 31. Information about mining and refinery of Fe and Sr.*

| | Fe | Sr |
|---|---|---|
| **Main world reserves** | Brasil 26% [37] | China (around 100%) [38] |
| | Australia 20% | |
| | Canada 14% | |
| **Primary producer** | Australia 39% [37] | Spain 31% [37,39] |
| | Brasil 17% | Iran Islamic Rep. 30% |
| | India 10% | China 19% |
| | China 7% | |
| **Main refinery producer** | China 54% [37] | n.a. |
| **Eu reserves** | 1% [37] | n.a. |
| **Eu primary prod** | 1.8% [37] | 33.4% [37] |
| **Au refinery prod** | 8.1% [37] | n.a. |
| **Main uses** | Construction 35% [37] | Magnets 36% [37] |
| | Automotive 19% | Pyrotechnics 36% |
| | Mech. Engineering 15% | Zn Production 7% |
| | Metalware 15% | Master alloys 7% |
| | Tubes 10% | Pigments 7% |
| | Others 6% | Others 7% |

### 5.6.2 Stocks (uses)

The definition of stock is “The total amount of materials stored in a process” [25]. The characteristic of a stock is strongly correlated to the lifespan of products, which varies on the Ferrite application basis, as showed in Table 29. Considering the ferrite uses, not relevant losses were identified during the product life. The only losses of Fe and Sr could be due to the product wear (with very low percentages); for this reason, they are excluded from the MFA.

### 5.6.3 Recycling

The recycling processes can be developed for both the treatment of **manufacturing scraps** and the end-of-life products. As concerns the first category of scraps, the production section explains as a 15% of ferrite magnets residue can results from a common production process. Usually, this material is re-used for further applications which request lower technical properties than permanent magnets. Nevertheless, a recent study, published by Bollero et al. (2023) explains that **the magnetic properties of these residues are comparable (even higher)** to those of the starting material. The process does not need chemicals and it uses processing conditions comparable to those applied for “primary” ferrite magnet. **A zero-waste production could be assumed for this process.**

As concerns the recycling of end-of-life products, the literature is poor of information about promising processes. Rassõlkin et al. (2020) describe the dismantling and recycling of a waste electrical motor-drive system. They explain that the waste machines are shredded or disassembled (manually or mechanically). In disassembly case, the components are re-used and the resulting fractions are remelted for the production of new materials/alloys. The disassembly efficiency is highly linked to the electrical machine design. The disassembly often damages the magnet, mainly in the case of permanent magnet integrated into the system. For this reason, the re-use can be hypothesized only for easily accessible magnets such as wind turbine and large-scale motors and generators in hybrid and electric vehicles.

The most common recycling way is the shredding option, where the electrical machines are cut into small pieces and separated by specific equipment. This step is characterized by the risk of material mixing resulting in low purity secondary raw materials [40].

It is evident that the recycling effort is mainly implemented in the REE magnet. The reason, explained by a presentation of Arnold Magnetic Technologies (a leading global manufacturer of high-performance permanent magnets), is that ferrite is an inexpensive raw material which should be treated by an expensive, energy-intensive reprocessing to be considered a good secondary raw material. Furthermore, different additives could be mixed during the recycling process, poisoning the formulation. The recycling unsustainability, combined with the mechanical properties (the material is a ceramic in nature), makes the **end-of-life ferrite suitable for structural applications such as roadbed and crushed aggregate fill applications** [41]. Figure 70 summarizes the main data collected about ferrite PM flows.

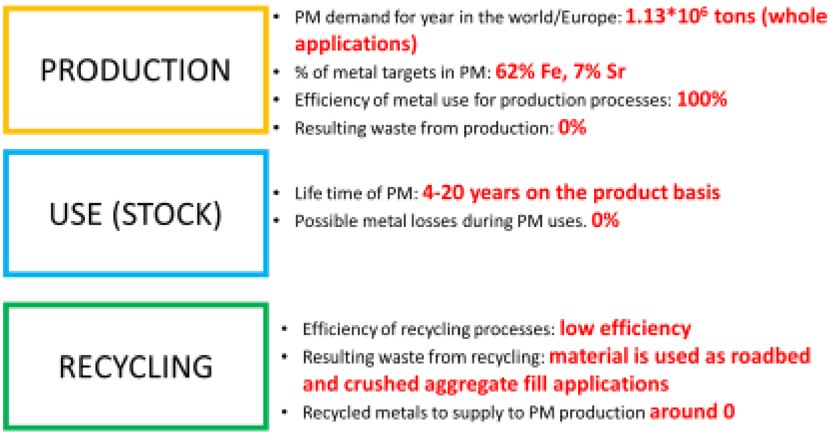



*Figure 70. Summary of ferrite PM data collected (Fe, Sr)*

## 5.7. REE-MAGNETS

PASSENGER focuses on Sr-ferrite and MnAlC to improve their properties, making them suitable to substitute Nd-Fe-B technologies. More in detail, PASSENGER considers three applications in the e-mobility sector: Class 1: e-scooter, Class 2: e-bikes and e-motorbikes, and Class 3: e-cars. Pump motors are also included within the project. On the basis of technical results achieved by Passenger (process efficiencies, product lifespan and recyclability), the Nd, Dy, Pr flows in the selected sectors could be significantly decreased.

### 5.7.1 Production

*Demand for year in e-bikes*

The Confederation of the European bicycle Industry Booming (CONEBI 2021) reports an e-bike number sold in Europe in 2021 around **5 million** [42]. The forecast talks about a possible **market increase between 2021 and 2031 around 60%** [43,44]. Each unit needs around 300 g of permanent magnet [45] with a content of 30% of Nd [46], 4% Dy [47], 7% Pr [48]. Considering these average percentages, the consumptions of metal targets **in 2021** for e-bike production were **450 ton, 60 ton, 105 ton for Nd, Dy Pr, respectively in 2021**.

*Demand for year in e-motorbikes*

The European Association of Motorcycle Manufacturers (ACEM) reported a motorcycle registrations around **16,800 e-motorcycles and 61,200 moped in 2021**, considering only the greatest country in EU [49]. Between 2020 and 2030, the electric motorbike market is projected to have a compound annual growth rate of 7.4%, **with a whole increase around 50% by 2031**. Assuming that each e-motorbike requires 450 g of Nd-Fe-B, and that REE percentages are those reported before, the consumptions of metal targets for e-bike production were **9 tons, 2 tons, 1 ton for Nd, Dy Pr, respectively in 2021.**

*Demand for year in e-cars*

The European Commission reported **2.5 million of e-cars in 2021** (54% hybrid, 24% battery electric and 21% pug in hybrid vehicles) [50]. The forecasts for 2027 reports an estimated vehicles increase around 27%, mainly connected to the full-electric cars (around 14% each year), which should reach a **70% increase** (compared to 2021) **by 2031** [38,39]. The e-car quantity (weight of each NdFeB magnets 1.25 kg [53]) is translated into a consumption of **392 tons of Nd, 181 of Dy** [50] **and 65.8 of Pr, in 2021**. The lowest quantity of Pr consumption is due to its (possible) role as partial substitute of Nd [54] (only in some cases) [55].

*Demand for year in e-scooter*

The estimations reported an e-scooter number on European territory, in 2021, higher **than 20 million** with a **growth forecast of 24.5% between 2022 and 2029** [56]. Assuming an average magnet weight of 300g (comparable with that in e-bikes), the REE consumption has been estimated around **2400 tons of Nd, 320 tons of Dy and 560 tons of Pr.**

*Demand for year in pump drives*

The magnetic drive pump market in 2021 was estimated around **822,540 units,** with an **annual growth rate around 7.6%** (2021-2031) [57,58]. This kind of system has an average weight of **55g with 25% of Nd and 0.05% of Dy** [22], translated into a consumption of about **10 tons of Nd and 20 kg of Dy in 2021**.

On the application basis, Table 32 summarizes the average lifespans that will be considered for the MFA.

*Table 32. Average lifetimes of PASSENGER products (adapted from[9])*

| Product | Average lifetime | Reference |
|---|---|---|
| e-bikes | 5 | [46] |
| e-motorbikes | 16 | [9] |
| e-cars | 16 | [9] |
| e-scooter | 3 | [47,48] |
| pump drives | 20 | [9] |

*Manufacture details*

The manufacture of REE magnets is fully described by scientific literature, starting from REE mining and beneficiation, cracking and separation resulting in NdFeB magnet [62,63]. As concern Nd, Dy and Pr production as raw materials, Table 33 summarizes important information to better understand the worldwide situation. The process chain causes relevant REE losses, mainly during the ore treatment (30-50% during the flotation, 1-5% during the roasting 6-10% during the hydrometallurgical treatment and 3-5% for the final electrolysis). On the other hand, the losses resulting from the **magnet manufacturing are in the range of 10-15%** of the input flow [62]. Overall, the REE recovery from minerals to magnet production ranges from 50-84% [64].

*Table 33. Information about mining and refinery of Nd, Dy and Pr.*

| | Nd | Dy | Pr |
|---|---|---|---|
| **Main world reserves** | China 34%<br>Vietnam 17%<br>Russia 16%<br>Brazil 16% [65] | China 34%<br>Vietnam 17%<br>Russia 16%<br>Brazil 16% [65] | China 34%<br>Vietnam 17%<br>Russia 16%<br>Brazil 16% [65] |
| **Primary producer** | China 93% [37]<br>UK 3% | China 68%<br>Japan 18%<br>UK 6% [36] | China 93% [37]<br>UK 3% |
| **Main refinery producer** | China 99% [37] | China 99% [37] | China 99% [37] |
| **Eu reserves** | - | - | - |
| **Eu primary prod** | - | - | - |
| **Eu refinery prod** | - | - | - |
| **Main uses** | Magnet 71%<br>Ceramics 12%<br>Catalysts 10%<br>Batteries 3%<br>Others 4% [37] | Magnets 99% [37] | Magnet 24%<br>Ceramics 15%<br>Batteries 12%<br>Metal alloys 11%<br>Autocatalysts 10%<br>Others 28% [37] |
| **Worldwide production 2019** | 35,000 tons | 2,500 tons | 11,000 ktons |

## 5.7.2 Stock (uses)

As better explained before, the characteristic of a stock is strongly correlated to the lifespan of products, which varies on the ferrite application basis, as reported in Table 29. Considering the NdFeB uses not relevant losses were identified during the product life. The only losses can be due to the product wear (with very low percentages), for this reason they are excluded from the MFA.

## 5.7.3 Recycling

As concerns the recycling of end-of-life products, there is not a relevant contribution of secondary Nd, Dy, Pr on the current market. Only 1% from secondary resources has been reported for Nd supply [37]. Furthermore, the considered applications of these magnets are mainly found in very recent products, most products containing NdFeB magnets do not yet appear in the current scraps, but they will represent the waste of future. The growing attention for the development of efficient recycling methods is confirmed by Kumari and Sahu (2023) which reported 300,000 tons of REE stockpiled worldwide (considering all the magnet applications). Overall, the preliminary issue of spent magnet enhancement chain is the dismantling, before crushing [53,66], since the recycling operations could cause the REE loss within ferrous or nonferrous scraps. The experimental approaches for REE recovery from magnets can be classified in: direct recycling of magnets, metal extraction from waste (pyrometallurgy, hydrometallurgy, electrometallurgy) [66], with different efficiencies based on waste, selected technique and metal target. Considering the innovative products included within the present MFA, it could be considered a current lack of full-scale recycling processes. Figure 71 summarizes the main data collected about NdFeB PM flows.

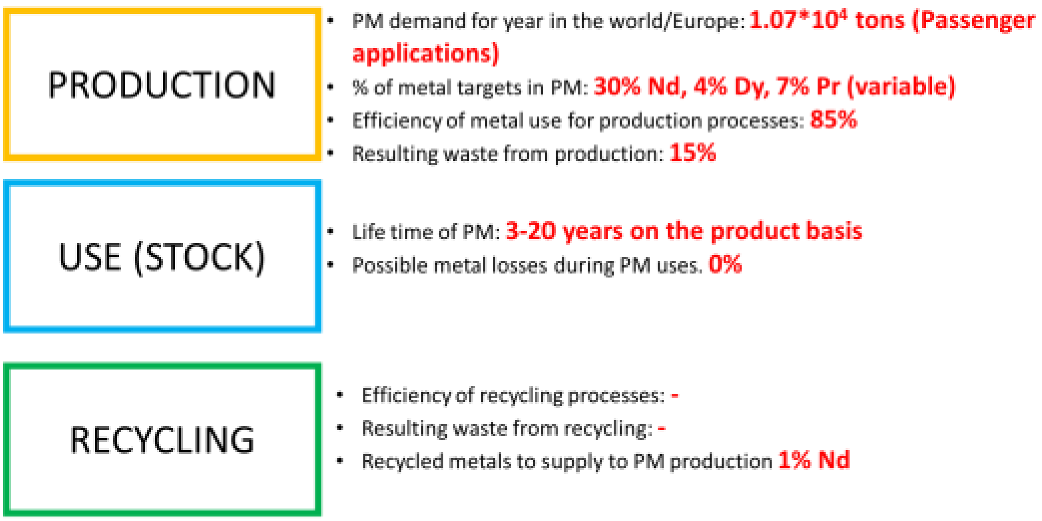



*Figure 71. Summary of NdFeB PM data collected (Nd, Dy, Pr)*

## 5.8. IMPLEMENTATION OF SANKEY DIAGRAMS

### 5.8.1. Key terms and assumptions

This paragraph presents the core of MFA analysis. To better understand the analysis output some key terms were explained below.

- Good describes merchandise and wares (the REE-magnets in each considered product, in the present case);
- Process, represented by blocks, describes something is changing in its quality (feedstocks become products and waste);
- Stock, represented by a little block inside the process block, is the total amount of materials stored in a process;
- Data collected in the paragraph 3.3 were essential to build the Sankey diagrams showed in the present paragraph.

A period of 10 years between 2021 and 2030 was considered.

Some assumptions were performed for the analysis:

- The market increase reported in section 5.7.1 for each product was considered equally distributed among the considered ten-years period.
- The output flows were determined considering the average lifetime values reported in Table 10
- Considering the key aspects of the young market and the longest lifetime of e-motorbikes, e-cars and pump drives (between 16 and 20 years), no output flows were reported up to 2027 for e-cars and 2030 for both motorbikes and pumps.
- No magnet material losses were considered in product production processes.
- A data error of 10% was considered for all the estimated flows, considering the data variability observed on the available market information.
- The stocks in 2021 were estimated based on the references reported in Table 12. As concern the e-scooter, the estimation of the input flows and the stocks was performed considering 12 times the quantities reported in the literature for the Italian market.
- As concern the pump stocks, a constant market in the previous 10 years was considered.

*Table 34. List of references used for the stock estimations.*

| Product | Reference |
|---|---|
| e-bike | [67] |
| e-motorbike | [49] |
| E-car | [50] |
| e-scooter | [68,69] |
| Pump | [57,58] |

### 5.8.2. MFA without the implementation of Passenger results

Figure 72 reports the Sankey diagrams built by the support of the free software Stan 2.7, developed at the Research Unit for Waste and Resource Management at TU Wien. More in detail, STAN allows the building of graphical models by using predefined components (processes, flows, system boundary, text fields).

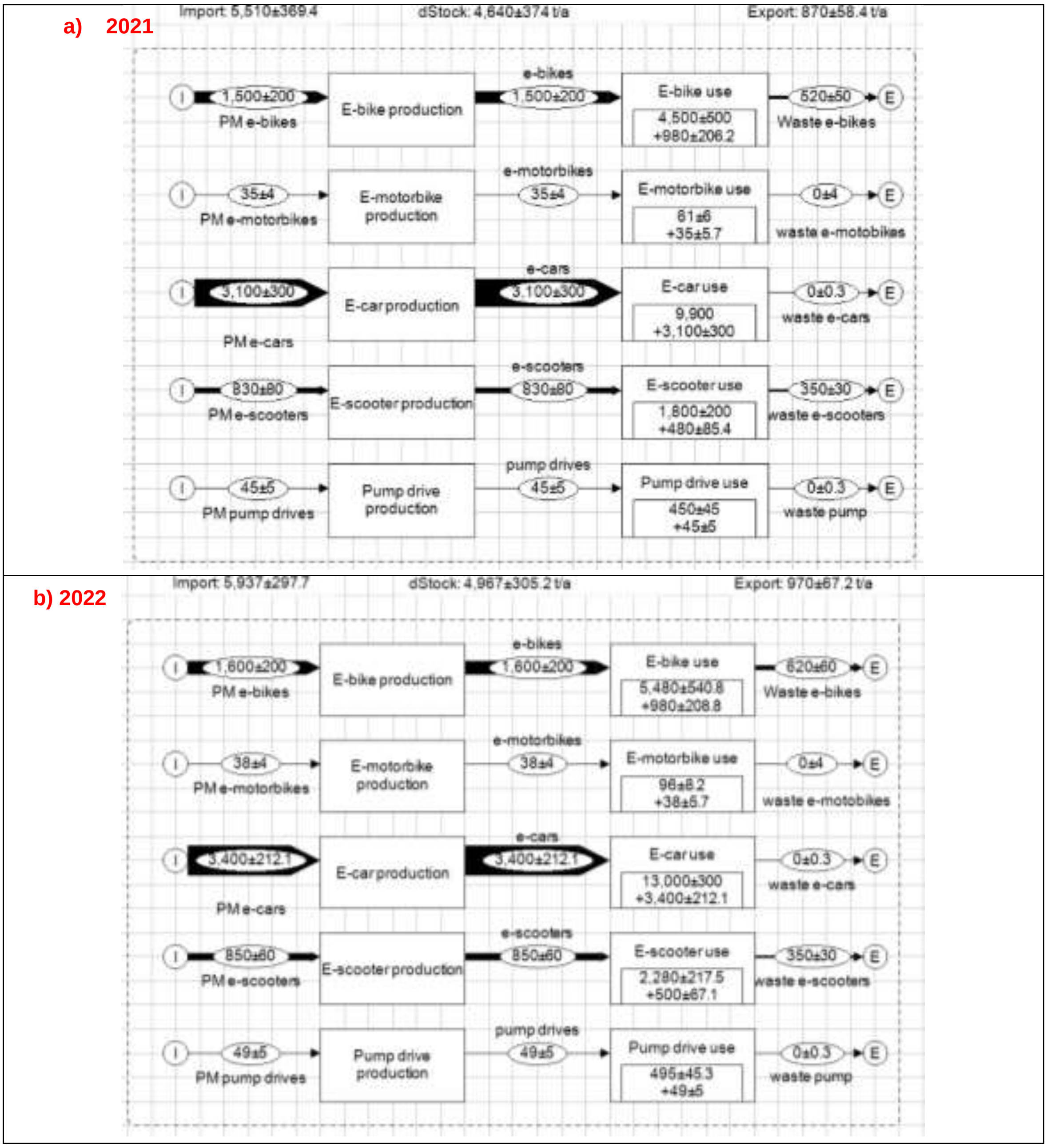
The results showed in the diagrams represent an excellent food of thought to define the most winning strategies.

Following the European estimation, the EU demand of REE-PM in 2030 could reach the 40,000 tons (or 18,800 tons on the basis of ERMA and Eit Raw Materials report on rare earth oxide magnets [70]), including all the possible applications of these components (e.g. the green technologies, such as wind turbines [71]). Following the results in Figure 72j, the demand of REE-permanent magnets for e-bikes, e-motorbikes, e-cars, e-scooters and pump drives will represent more than 20% of this amount, mainly due to the growing market expected for the e-cars. Another important observation is that related to the PM stock, around 6,000 tons in 2030, corresponding to 15% of the expected PM demand.

The evaluation of input/output flows and the stocks trend are important to better understand the relevance of the integration of REE substitution and recycling strategies. Indeed, the observation of the Sankey diagrams Figure 72 suggests that:

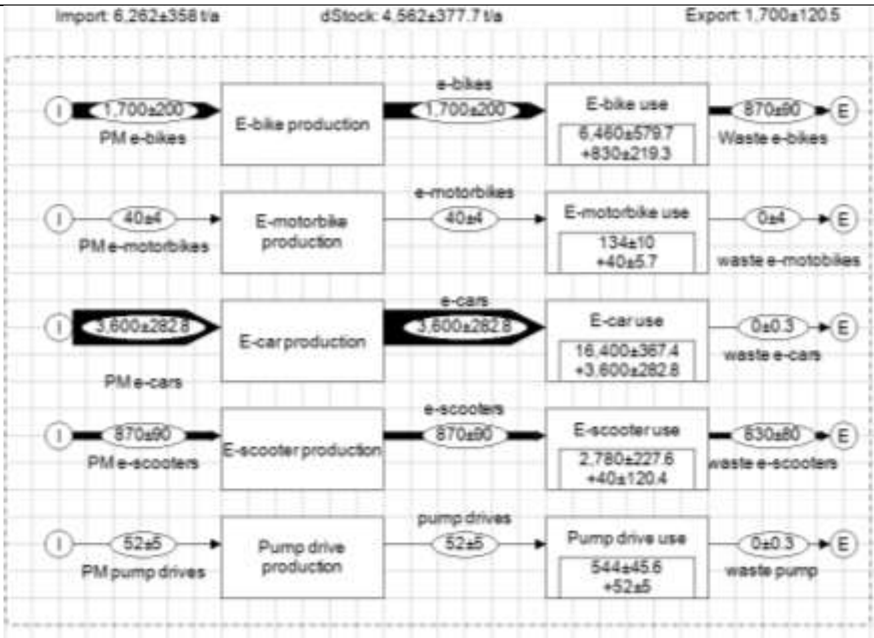
- Among the considered products, the highest PM consumption is due to the manufacturing of both e-cars and e-bikes (followed by e-scooters). Therefore, the possibility to demonstrate the RE-PM substitution in both these products could have the greatest impact on the material demand.
- Currently, low output flows of both e-motorbikes and e-cars were observed mainly due to the young technology, in the first case, and the longest lifetime in the second one.
- The short average lifetime of both e-bikes and e-scooters, suggests constant output flows of these end-of-life products, available to feed recycling processes (not included in the Sankey diagrams).
- Winning strategies should focus on the integration of PM recycling strategy to enhance the future output flows of e-cars, and the at least partial substitution of this kind of PM to reduce the future input flows.

These observations are related to the RE-PM flows with, variable concentrations of Nd, Pr, and Dy, as described in Paragraph 5.7.

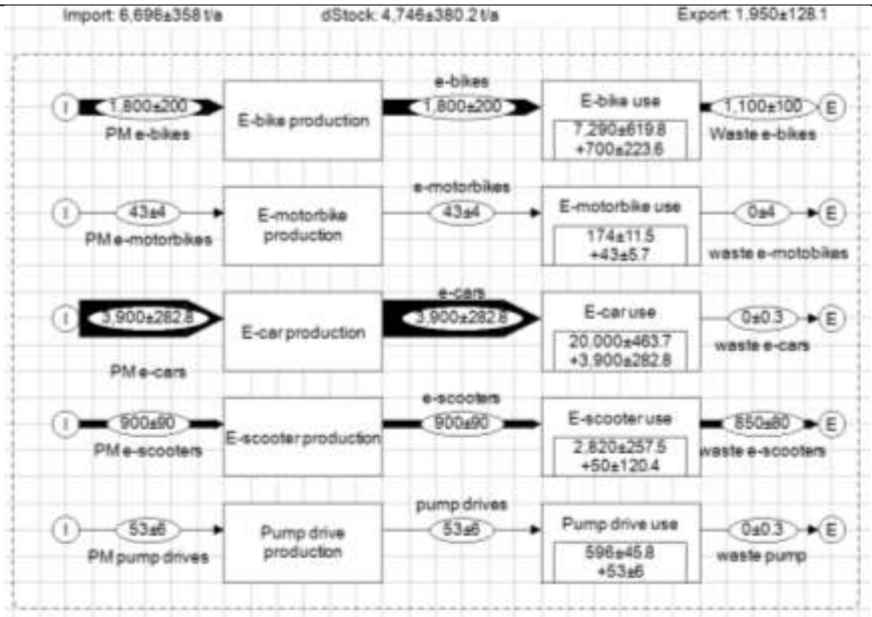


a) 2021
Import: 5,510±369.4
dStock: 4,640±374 t/a
Export: 870±58.4 t/a
1,500±200
PM e-bikes
E-bike production
e-bikes
1,500±200
E-bike use
4,500±500
+980±206.2
520±50
Waste e-bikes
35±4
PM e-motorbikes
E-motorbike production
e-motorbikes
35±4
E-motorbike use
61±6
+35±5.7
0±4
waste e-motobikes
3,100±300
PM e-cars
E-car production
e-cars
3,100±300
E-car use
9,900
+3,100±300
0±0.3
waste e-cars
830±80
PM e-scooters
E-scooter production
e-scooters
830±80
E-scooter use
1,800±200
+480±85.4
350±30
waste e-scooters
45±5
PM pump drives
Pump drive production
pump drives
45±5
Pump drive use
450±45
+45±5
0±0.3
waste pump
b) 2022
Import: 5,937±297.7
dStock: 4,967±305.2 t/a
Export: 970±67.2 t/a
1,600±200
PM e-bikes
E-bike production
e-bikes
1,600±200
E-bike use
5,480±540.8
+980±208.8
620±60
Waste e-bikes
38±4
PM e-motorbikes
E-motorbike production
e-motorbikes
38±4
E-motorbike use
96±8.2
+38±5.7
0±4
waste e-motobikes
3,400±212.1
PM e-cars
E-car production
e-cars
3,400±212.1
E-car use
13,000±300
+3,400±212.1
0±0.3
waste e-cars
850±60
PM e-scooters
E-scooter production
e-scooters
850±60
E-scooter use
2,280±217.5
+500±67.1
350±30
waste e-scooters
49±5
PM pump drives
Pump drive production
pump drives
49±5
Pump drive use
495±45.3
+49±5
0±0.3
waste pump

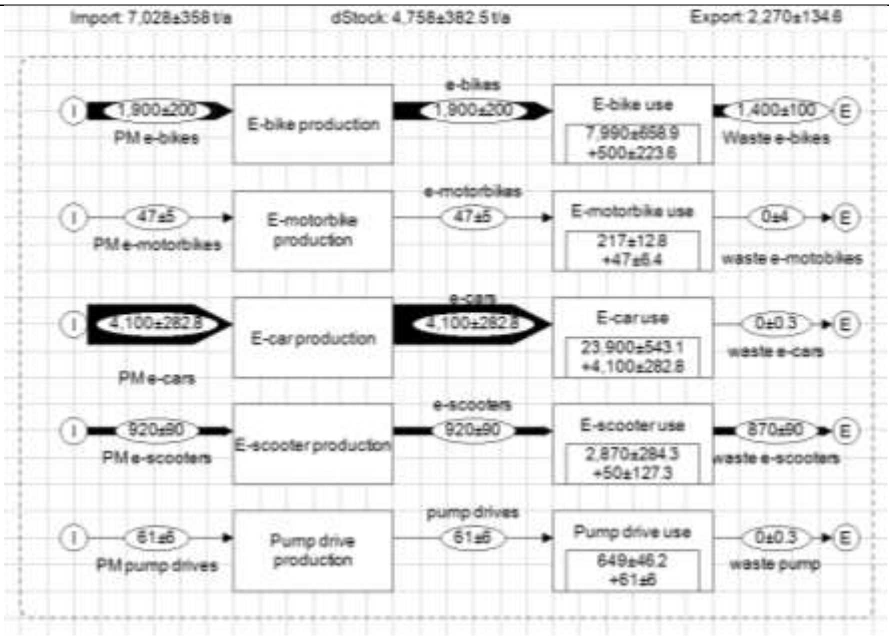
**c) 2023**


Import 6,262±358 t/a
dStock 4,562±377.7 t/a
Export 1,700±120.5
e-bikes
1,700±200
PM e-bikes
E-bike production
1,700±200
E-bike use
6,460±579.7
+830±219.3
870±90
Waste e-bikes
e-motorbikes
40±4
PM e-motorbikes
E-motorbike production
40±4
E-motorbike use
134±10
+40±5.7
0±4
waste e-motobikes
e-cars
3,600±282.8
PM e-cars
E-car production
3,600±282.8
E-car use
16,400±367.4
+3,600±282.8
0±0.3
waste e-cars
e-scooters
870±90
PM e-scooters
E-scooter production
870±90
E-scooter use
2,780±227.6
+40±120.4
830±80
waste e-scooters
pump drives
52±5
PM pump drives
Pump drive production
52±5
Pump drive use
544±45.6
+52±5
0±0.3
waste pump

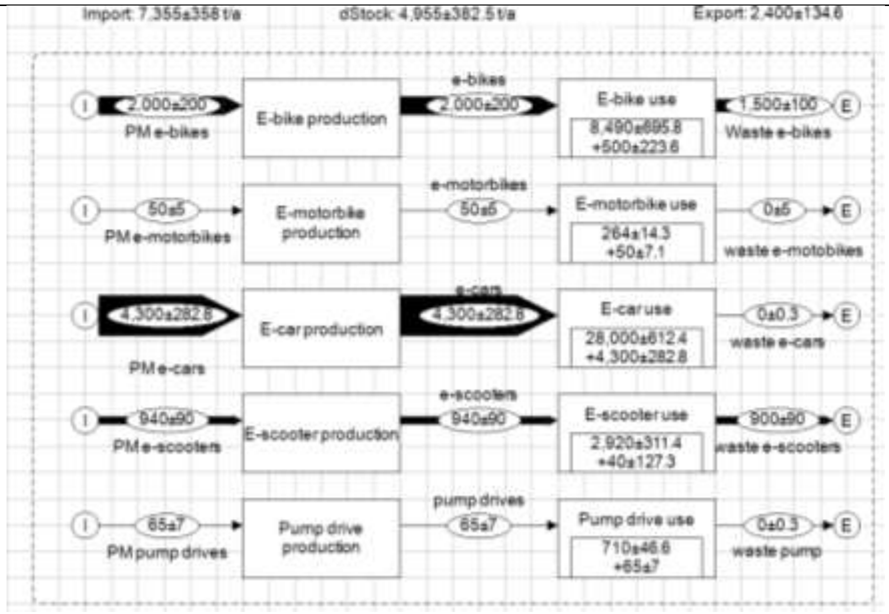
**d) 2024**


Import 6,696±358 t/a
dStock 4,746±380.2 t/a
Export 1,950±128.1
e-bikes
1,800±200
PM e-bikes
E-bike production
1,800±200
E-bike use
7,290±619.8
+700±223.6
1,100±100
Waste e-bikes
e-motorbikes
43±4
PM e-motorbikes
E-motorbike production
43±4
E-motorbike use
174±11.5
+43±5.7
0±4
waste e-motobikes
e-cars
3,900±282.8
PM e-cars
E-car production
3,900±282.8
E-car use
20,000±463.7
+3,900±282.8
0±0.3
waste e-cars
e-scooters
900±90
PM e-scooters
E-scooter production
900±90
E-scooter use
2,820±257.5
+50±120.4
850±80
waste e-scooters
pump drives
53±6
PM pump drives
Pump drive production
53±6
Pump drive use
596±45.8
+53±6
0±0.3
waste pump

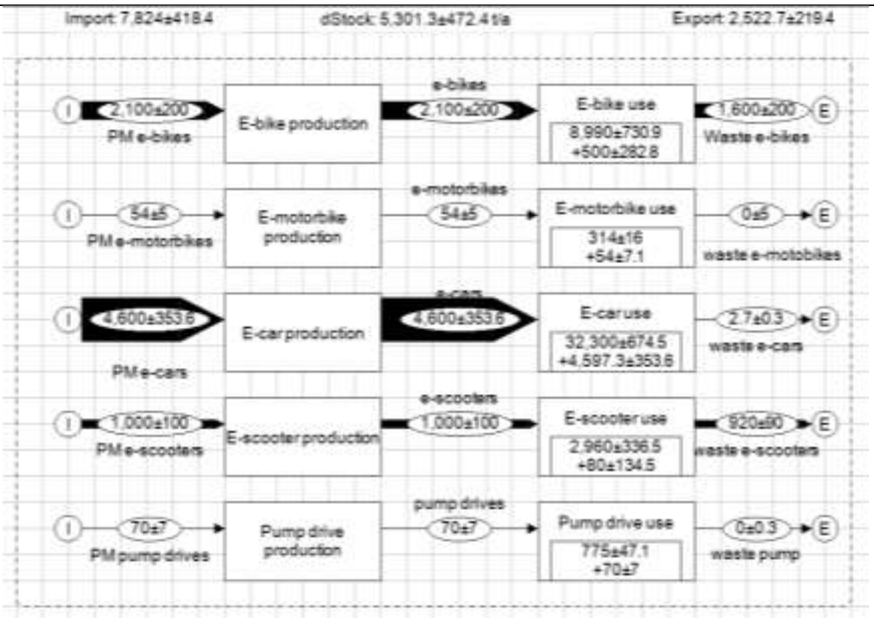
**e) 2025**


Import: 7,028±358 t/a
dStock: 4,758±382.5 t/a
Export: 2,270±134.6
1,900±200
PM e-bikes
E-bike production
e-bikes
1,900±200
E-bike use
7,990±658.9
+500±223.6
1,400±100
Waste e-bikes
47±5
PM e-motorbikes
E-motorbike production
e-motorbikes
47±5
E-motorbike use
217±12.8
+47±6.4
0±4
waste e-motobikes
4,100±282.8
PM e-cars
E-car production
e-cars
4,100±282.8
E-car use
23,900±543.1
+4,100±282.8
0±0.3
waste e-cars
920±90
PM e-scooters
E-scooter production
e-scooters
920±90
E-scooter use
2,870±284.3
+50±127.3
870±90
waste e-scooters
61±6
PM pump drives
Pump drive production
pump drives
61±6
Pump drive use
649±46.2
+61±6
0±0.3
waste pump

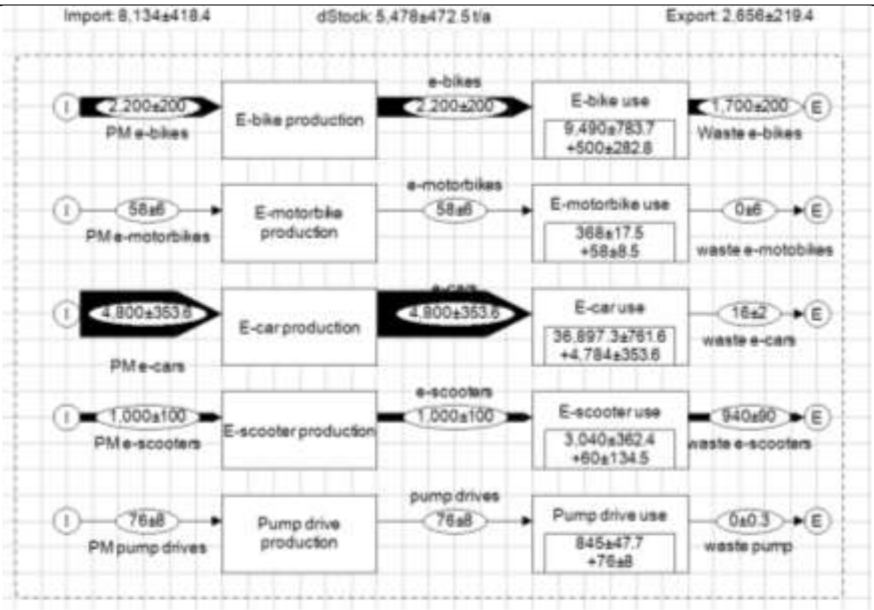
**f) 2026**


Import: 7,355±358 t/a
dStock: 4,955±382.5 t/a
Export: 2,400±134.6
2,000±200
PM e-bikes
E-bike production
e-bikes
2,000±200
E-bike use
8,490±695.8
+500±223.6
1,500±100
Waste e-bikes
50±5
PM e-motorbikes
E-motorbike production
e-motorbikes
50±5
E-motorbike use
264±14.3
+50±7.1
0±5
waste e-motobikes
4,300±282.8
PM e-cars
E-car production
e-cars
4,300±282.8
E-car use
28,000±612.4
+4,300±282.8
0±0.3
waste e-cars
940±90
PM e-scooters
E-scooter production
e-scooters
940±90
E-scooter use
2,920±311.4
+40±127.3
900±90
waste e-scooters
65±7
PM pump drives
Pump drive production
pump drives
65±7
Pump drive use
710±46.8
+65±7
0±0.3
waste pump

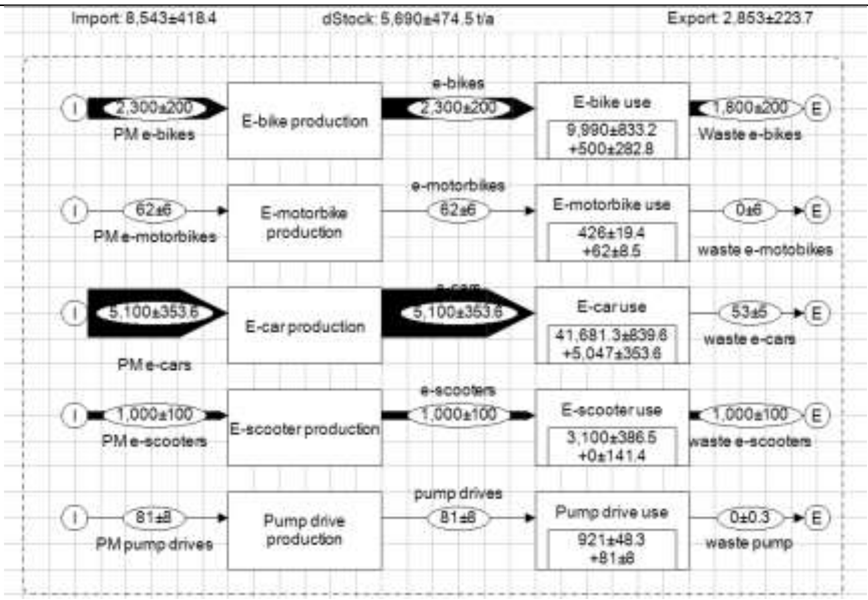
**g) 2027**




**h) 2028**




**i) 2029**




**j) 2030**

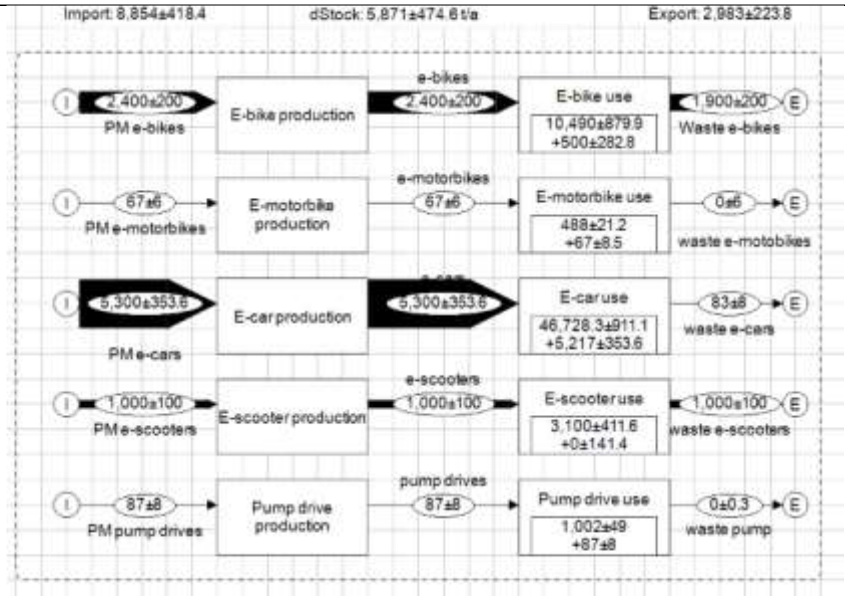



*Figure 72. Sankey diagrams describing the permanent magnets material flows in Europe from 2021 (a) to 2030 (j), including their applications in e-bikes, e-motorbikes, e-cars, e-scooters, pump drives.*

### 5.8.3. Study of the effects of Passenger result implementation, future perspectives

The Material Flow Analysis (MFA) built on literature information data allowed to estimate the flows of RE-magnet in Europe, between 2021 and 2030, considering the applications included in Passenger Project (E-bikes, E-motorbikes, E-Cars, E-scooter, Pump drives). The further step was the estimation of the benefits achieved by Passenger result implementation on the reduction of REE-magnet input flows. With this aim, a survey with seven questions was submitted to Passenger partners to verify the possibility of REE-magnet substitutions in the different products. The goal was to exploit the combination of partner expertise and the technical results achieved within the project. A space for comments was added to the survey to report possible thoughts.

The survey format, reported in Figure 73, aimed at the identification of the partner and the alternative REE-free magnet evaluated (ferrite/Mn-Al-C). The second and the third questions aimed at exploring the efficiency of substitution of RE-magnet, within specific products. Question 4 was relevant to evaluate the possible increase of product weight due to the ferrite/Mn-Al-C use. Another key aspect of MFA is the definition of material stocks (i.e. the total amount of materials stored in a process), based on the product life cycle, and compared to the current technology with RE-magnet (question 5). Questions 6 and 7 were relevant to evaluate the recyclability of the free RE-magnets (at the end of their life) and the possible use of the secondary raw materials within the same value chain.

**Partner name:**

**Date:**

**Questions:**

1. **Which kind of alternative magnet?**
   ☐ Ferrite ☐ Mn-Al-C

2. **Which product?**


3. **Which is the substitution efficiency?**
   ….%

4. **1 kg of RE-magnet can be substitute by …**
   ….kg of ferrite magnet/….kg of Mn-Al-C

5. **Average life cycle of new products**
   …years /the same of RE-magnet products

6. **Recyclability of new magnets**
   Yes/no/yws with efficiency of…./I don't know

7. **Is it possible to use secondary ferrite/Mn-Al-C (from recovery/recycling) for the production of passenger product?**

☐ Yes ☐ No ☐ I don't know

*Figure 73. Survey sent to Passenger partners*

We collected the interest from 5 partners (IMA S.L., MBN Nanomaterialia SpA, GmbH, MTE, CRF). Most of them were able to supply only partial responses, often due to the question specificities which make the answers difficult at this stage of the research, mainly for the Mn-Al-C PM.

Nevertheless, very interesting information was supplied by IMA S.L. and CRF that reported the possible use of ferrite magnet within E-bikes, E-motorbikes, E-scooter, pump drives (IMA) and E-cars (CRF), covering all the passenger products.

Table 35 was built on the IMA and CRF responses, considering the completeness of their supplied information. As concern, questions 3 and 4, the partners considered the best conditions achieved (to be confirmed with further simulations, in IMA case).

*Table 35. Summary of the responses to the Survey*

| | Question N° | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 **Kind of PM** | 2 **Application** | 3 **Substitution eff.** | 4 **Kg free RE PM/kg RE PM** | 5 **Life time** | 6 **Recyclability** | 7 **Possible use of secondary PM** |
| Product | Ferrite | E-bikes | 80% | 1 | 5 (the same of REE-PM) | Yes | Yes |
| | Ferrite | E-motorbikes | 80% | 1 | 16 (the same) | Yes | Yes |
| | Ferrite | E-cars | 10% | 3-5 | 4-6 | n.a. | Yes |
| | Ferrite | E-scooter | 80% | 1 | 3 (the same) | Yes | Yes |
| | Ferrite | Pump drives | 80% | 1 | 20 (the same) | Yes | Yes |

Data supplied by partners were integrated into the Sankey diagrams with the hypothesis of the implementation of PASSENGER results on a large scale. The effect of PASSENGER was assessed from 2026 (considered as a realistic assumption, given the end date of the project). It was set a growing introduction on the market of the innovative products, with a REE PM magnet substitution of 10% in 2026, 20% in 2027, 30% in 2028, 50% in 2029, the maximum value in 2030. The substitution efficiency estimated by the partners, 80% for e-bikes, e-motorbikes, e-scooter, pump drives and 10% for e-cars was considered during the whole period (2026-2030).

The Sankey diagrams in Figure 74 highlights the change of future scenario in 2030 with (a) and without (b) the market entry of PASSENGER technologies. The results are affected by a relevant variability (as also confirmed by the results of survey), nevertheless, it is evident that the PASSENGER benefit could be translated into a decrease of REE PM demand of about 40%, considering the production of the 5 products in Passenger. On the MFA result basis, the market of e-bikes, e-scooter and e-cars, has the key role to the decrease of REE

PM demand, with a contribution of 57%, 23% and 15% respectively on the estimated reduction. The reason is the shortest lifetime of e-bikes and e-scooters (which justifies the quick substitution of these products), combined with the hypothesis of a complete replacement by innovative Passenger products, with an efficiency of 80% (as hypothesized by IMA S.L.). On the other hand, despite the lowest substitution efficiency in e-cars (10%, reported by CRF), their growing demand, in the perspective of the green transition, will play a key role in the decrease of REE demand.

a)

b)

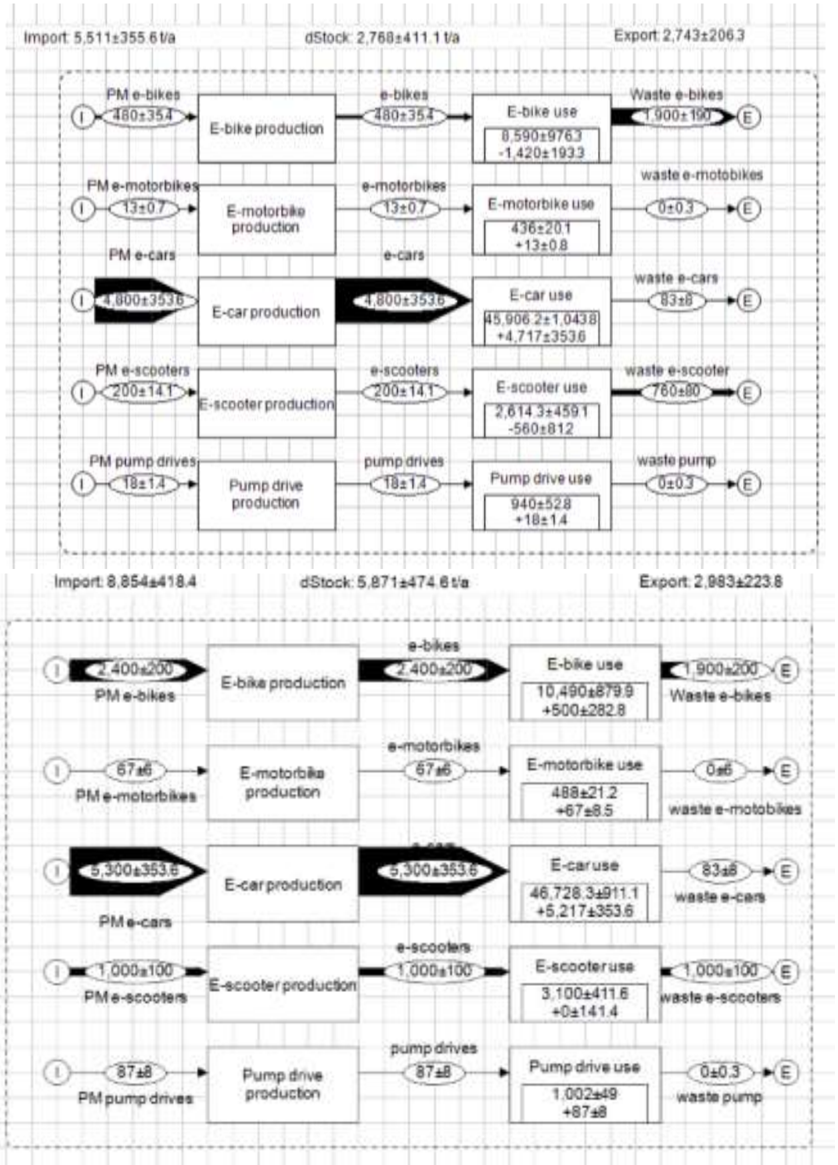



*Figure 74. Sankey diagrams describing the permanent magnets material flows estimated for 2030 a) with b) without the implementation of Passenger results on the European market, considering the Passenger products (i.e. PM e-bikes, PM e-motorbikes, PM e-cars, PM e-scooter, PM pump drives).*

The additional trend of REE PM input flow, showed in Figure 75, better represents the possible effect of Passenger on the European REE PM demand within the considered period between 2021 and 2030, to prodcuce e-bikes, e-motorbikes, e-cars, e-scooters and pump drives. Starting from 2026, the Passenger benefit is gradual, but after 2029, the hypothesis of the fastest market entry of the products will allow the best expected outcome. The difference between the scenarios without and with PASSENGER result implementation is around 3,400 tons of REE PM, which represent around 20% of rare earth oxide PM European demand, estimated by ERMA and EIT Raw Materials for 2030 [70]. Free-RE PM probably, could not replace the RE PM in all the applications due to both the possible reduction in performance and the weight increase of the equipment (as confirmed by CRF response about e-cars). However, their contribution, integrated with the exploitation of RE PM stocks estimated by the present MFA, represents an evident opportunity for the European market.

Furthermore, as highlighted by partners in the survey responds, the end-of-life ferrite PM will be recyclable and suitable to be reused in PM value-chain (aspect relevant to solve the possible decrease of lifetime reported for e-cars), reducing the EU dependence (currently almost complete) from extra-EU for primary raw material supplies.

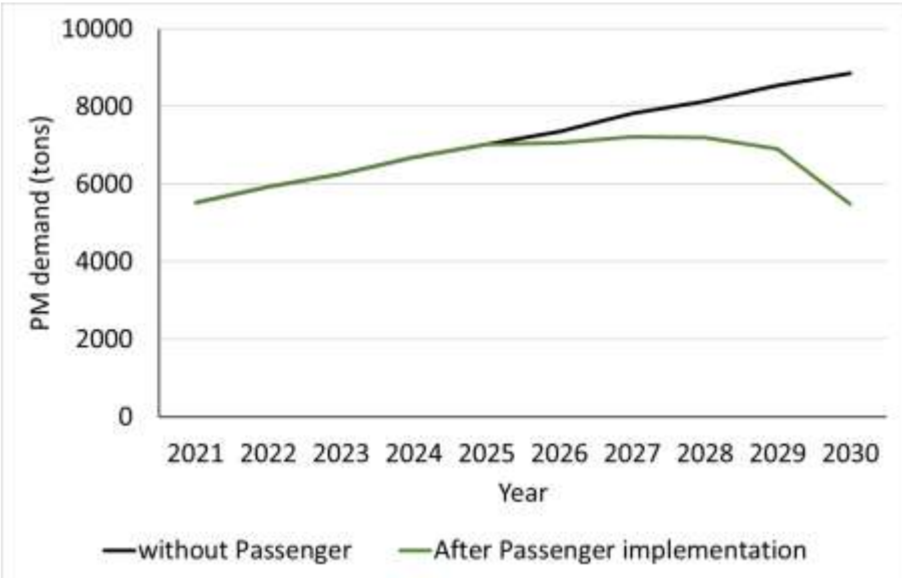



*Figure 75. Comparison of RE PM demand for Passenger products (i.e. PM e-bikes, PM e-motorbikes, PM e-cars, PM e-scooter, PM pump drives), from 2021 to 2030 between a European market with and without the implementation of Passenger results.*

# 6. CONCLUSIONS

PASSENGER project use the LCIA to identify the environmental impacts of current manufacturing processes and products, as well as proposed project developments. The LCA also serves to report on the environmental and health impacts, social and cultural impacts of the materials (including life expectancy, number of cycles and effects of using the modules/raw material used), products (CORE rates and methods), and processes. MFA aims to identify the flows of elements throughout all the PM value chain and integrate the results into the economic and environmental sustainability analysis. These findings will allow to inform about the development strategy of the project and ultimately prove the environmental credentials of the processes and products developed.

The PASSENGER project has conducted a comprehensive analysis comparing the environmental impact related data provided by the PASSENGER partner for this propose. The main conclusions of this analysis are summarized as follows:

- With all the collected and analysed data, PASSENGER REE-free magnets (bonded MnAlC, sintered MnAlC and Sr-Fe magnets) have shown a **notable reduction in environmental impacts in comparison with the conventional NdFeB magnets across various categories.** For instance, MnAlC magnets showed an impressive 80.47% reduction in CO2 emissions compared to traditional alternatives based on NdFeB PMs. Furthermore, sintered MnAlC also exhibited a notable decrease on CO2 emissions, particularly within the Terrestrial category, with a 99.9% decrease. Finally, the Sr-Fe analyses revealed a substantial reduction in CO2 emissions footprint. In this sense, a 74.11% decrease related to the human was found highlighting its commitment to human toxicity.
- While NdFeB magnets can offer excellent magnetic properties, their environmental **impact cost is significantly higher than the PASSENGER' ones**, primarily due to reliance on neodymium as well as the Chinese electricity grid. Therefore, a green energy source alternative might be considered to reduce the overall environmental footprint of these magnets. In this sense, PASSENGER alternatives put faith in the use of renewable medium-voltage electricity as energy source, reducing the environmental impact associated with it.
- LCA and LCIA results confirms that PASSENGER project has demonstrated the **potential of RE-free magnets manufacturing by offering sustainable alternatives** that significantly minimize the permanent magnets environmental impacts within the categories under study (Global warming, terrestrial ecotoxicity, human toxicity, and fossil resource scarcity).
- While these findings are promising and serve as starting point for the proposed solutions, continuous efforts are crucial for further refining and enhancing these novel RE-free solutions. In this direction, future research could be oriented to obtain more information about the processes among the value chain of the novel PMs, such as detailed emissions, waste characterization and its recyclability capacity as well as its valuable accountancy.

- The PASSENGER LCA approach will serve as an instrument for guiding further development and providing environmental credential of the PASSENGER's processes and products.

Overall, the PASSENGER project paves the way for a more sustainable future in permanent magnet manufacturing by showcasing the significant environmental benefits of these permanent magnets.

# 7. REFERENCES

[1] https://www.sustain.ucla.edu/wp-content/uploads/UCLA-Sustainability-Charter.pdf

[2] https://www.un.org/sustainabledevelopment/news/communications-material/

[3] ISO, "ISO 14040:2006(E) Environmental management -- Life cycle assessment -- Principles and framework," ISO, 2006.

[4] ISO, "ISO 14044:2006(E) Environmental management — Life cycle assessment — Requirements and guidelines," ISO, 2006.

[5] ISO, " ISO/TS 14072:2014(E) Environmental management — Life cycle assessment — Requirements and guidelines for organizational life cycle assessment," ISO, 2006.

[6] https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Framework-Requirements-ONLINE-March-2010-ISBN-fin-v1.0-EN.pdf

[7] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/life-cycle-assessment#:~:text=Life%20cycle%20assessment%20is%20a,From%3A%20Environmental%20Management%2C%202017

[8] H. Jin, P. Afiuny, S. Dove, Life Cycle Assessment of Neodymium-Iron-Boron Magnet-to-Magnet Recycling for Electric Vehicle Motors, Acs Publications, (2018) https://doi.org/10.1021/acs.est.7b05442.

[9] Josefine Marx, Andrea Schreiber, Petra Zapp, and Frank Walachowicz ACS Sustainable Chemistry & Engineering 2018 6 (5), 5858-5867 DOI: 10.1021/acssuschemeng.7b04165

[10] Vahidi, E., Navarro, J., & Zhao, F. (2016). An initial life cycle assessment of rare earth oxides production from ion-adsorption clays. Resources, Conservation and Recycling, 113, 1–11. doi:10.1016/j.resconrec.2016.05.0

[11] Holger, S., Petra, Z., Josephine, M., Andrea, S., Sandra, V., & Jürgen-Friedrich, H. (2017). The social footprint of permanent magnet production based on rare earth elements – a social life cycle assessment scenario. Energy Procedia, 142, 984–990. doi:10.1016/j.egypro.2017.12.157

[12] De Gennaro, M., Jürgens, J., Zanon, A., Gragger, J., Schlemmer, E., Fricassè, A., … Messagie, M. (2019). Designing, prototyping and testing of a ferrite permanent magnet assisted synchronous reluctance machine for hybrid and electric vehicles applications. Sustainable Energy Technologies and Assessments, 31, 86–101. doi:10.1016/j.seta.2018.12.002

[13] Schlör, H., Venghaus, S., Zapp, P., Marx, J., Schreiber, A., & Hake, J.-F. (2018). The energy-mineral-society nexus – A social LCA model. Applied Energy, 228, 999–1008. doi:10.1016/j.apenergy.2018.06.048

[14] F. Passarini, L. Ciacci, P. Nuss, S. Manfredi, Material flow analysis of aluminium, copper, and iron in the EU-28, 2018. https://doi.org/10.2760/1079.

[15] P.H. Brunner, H. Rechberger, Handbook of material flow analysis for environemntal, resource and waste engineers, Second edi, 2016.

[16] J.M.D. Coey, Perspective and Prospects for Rare Earth Permanent Magnets, Engineering. 6 (2020) 119–131. https://doi.org/10.1016/j.eng.2018.11.034.

[17] S. Plazzotta, R. Ibarz, L. Manzocco, O. Martín-Belloso, Optimizing the antioxidant biocompound recovery from peach waste extraction assisted by ultrasounds or microwaves, Ultrason. Sonochem. 63 (2020) 104954. https://doi.org/10.1016/j.ultsonch.2019.104954.

[18] Expert market research, Global Ferrite Magnet Market: By Application: Electro-Acoustic Products, Electronics Industry, Power Play Tools, Car Line Industry, Calculating Machines; Regional Analysis; Historical Market and Forecast (2018-2028); Market Dynamics; Project Requirements;, 2022. https://www.expertmarketresearch.com/reports/ferrite-magnet-market.

[19] Future Marchet Insights, Ferrite market, 2022. https://www.futuremarketinsights.com/reports/ferrite-market.

[20] Grand View Research, Permanent Magnets Market Size, Share & Trends Analysis Report By Material (Ferrite, NdFeB), By Application (Consumer Goods & Electronics, Energy), By Region (Europe, Asia Pacific), And Segment Forecasts, 2022 - 2030, 2020. https://www.grandviewresearch.com/industry-analysis/permanent-magnets-industry.

[21] J.U.N. Cui, J. Ormerod, D. Parker, R. Ott, A. Palasyuk, S. Mccall, M.P. Paranthaman, M.S. Kesler, M.A. Mcguire, I.C. Nlebedim, C. Pan, T. Lograsso, Manufacturing Processes for Permanent Magnets : Part I — Sintering and Casting, JOM. 74 (2022) 1279–1295. https://doi.org/10.1007/s11837-022-05156-9.

[22] K. Habib, P.K. Schibye, A.P. Vestbø, O. Dall, H. Wenzel, Material flow analysis of ndfeb magnets for denmark: A comprehensive waste flow sampling and analysis approach, Environ. Sci. Technol. 48 (2014) 12229–12237. https://doi.org/10.1021/es501975y.

[23] E.H. Lalana, Imanes Permanentes y su Producción por Pulvimetalurgia, Rev. Metal. 54 (2018) e121–e121. https://doi.org/10.3989/REVMETALM.121.

[24] J.C. Guzmán-Mínguez, L.M. Vicente-Arche, C. Granados-Miralles, J.F. Fernández, A. Quesada, Improvement of the magnetic properties of SrFe12O19 ceramics by tailored sintering with SiO2 addition, J. Alloys Compd. 860 (2021) 157890. https://doi.org/10.1016/J.JALLCOM.2020.157890.

[25] J.C. Guzmán-Mínguez, V. Fuertes, C. Granados-Miralles, J.F. Fernández, A. Quesada, Greener processing of SrFe12O19 ceramic permanent magnets by two-step sintering, Ceram. Int. (2021). https://doi.org/10.1016/J.CERAMINT.2021.08.058.

[26] Z. Wang, L. Zhong, J. Lv, H. Qian, Y. Zheng, Y. Fang, M. Jin, J. Xu, Microwave-assisted synthesis of SrFe12O19 hexaferrites, J. Magn. Magn. Mater. 322 (2010) 2782–2785. https://doi.org/10.1016/J.JMMM.2010.04.027.

[27] S. Kanagesan, M. Hashim, S. Jesurani, T. Kalaivani, I. Ismail, C.S. Ahmod, Effect of microwave sintering on microstructural and magnetic properties of strontium hexaferrite using sol–gel technique, J. Mater. Sci. Mater. Electron. 2013 2410. 24

(2013) 3881–3884. https://doi.org/10.1007/S10854-013-1333-9.

[28] G. Obara, H. Yamamoto, M. Tani, M. Tokita, Magnetic properties of spark plasma sintering magnets using fine powders prepared by mechanical compounding method, J. Magn. Magn. Mater. 239 (2002) 464–467. https://doi.org/10.1016/S0304-8853(01)00649-7.

[29] P. Jenuš, M. Topole, P. McGuiness, C. Granados-Miralles, M. Stingaciu, M. Christensen, S. Kobe, K.Ž. Rožman, Ferrite-Based Exchange-Coupled Hard–Soft Magnets Fabricated by Spark Plasma Sintering, J. Am. Ceram. Soc. 99 (2016) 1927–1934. https://doi.org/10.1111/JACE.14193.

[30] L. Cong-Ju, X. Guo-Rong, Template preparation of strontium hexaferrite (SrFe12O19) micro/nanostructures: Characterization, synthesis mechanism and magnetic properties, Mater. Res. Bull. 46 (2011) 119–123. https://doi.org/10.1016/J.MATERRESBULL.2010.09.030.

[31] A. Serrano, E. García-Martín, C. Granados-Miralles, G. Gorni, J. López-Sánchez, S. Ruiz-Gómez, L. Pérez, A. Quesada, J.F. Fernández, Hexaferrite-based permanent magnets with upper magnetic properties by cold sintering process via a non-aqueous solvent, Acta Mater. 219 (2021) 117262. https://doi.org/10.1016/J.ACTAMAT.2021.117262.

[32] L. Zhou, Y. Zhou, A. Cheng, Preparation method of permanent magnetic ferrite, CN103265277B, 2013.

[33] A. Nordelöf, E. Grunditz, S. Lundmark, A.M. Tillman, M. Alatalo, T. Thiringer, Life cycle assessment of permanent magnet electric traction motors, Transp. Res. Part D Transp. Environ. 67 (2019) 263–274. https://doi.org/10.1016/j.trd.2018.11.004.

[34] X. Suo, J. Li, W. Zhang, P. Li, Effect of La3+ Substitution on the Structure and Magnetic Properties of M-type Sr Hexaferrites, J. Supercond. Nov. Magn. 36 (2023) 197–206. https://doi.org/10.1007/s10948-022-06450-y.

[35] A. Bollero, J. Rial, M. Villanueva, K.M. Golasinski, A. Seoane, J. Almunia, R. Altimira, Recycling of Strontium Ferrite Waste in a Permanent Magnet Manufacturing Plant, ACS Sustain. Chem. Eng. 5 (2017) 3243–3249. https://doi.org/10.1021/acssuschemeng.6b03053.

[36] B. Sprecher, Y. Xiao, A. Walton, J. Speight, R. Harris, R. Kleijn, G. Visser, G.J. Kramer, Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets, Environ. Sci. Technol. 48 (2014) 3951–3958. https://doi.org/10.1021/es404596q.

[37] European Commission, Raw Materials Profiles, (2020). https://rmis.jrc.ec.europa.eu/rmp#/.

[38] USGS, Strontium, 2020. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-strontium.pdf.

[39] European Commission, Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability, 2020. https://doi.org/10.1007/978-3-030-40268-6_9.

[40] A. Rassõlkin, A. Belahcen, A. Kallaste, T. Vaimann, D. Vyacheslavovich Lukichev, S. Orlova, H. Heidari, B. Asad, J. Pando Acedo, Life cycle analysis of electrical motor drive system based on electrical machine type, Proc. Est. Acad. Sci. 69 (2020) 162–

177. https://doi.org/10.3176/proc.2020.2.07.

[41] Arnold magnetics, The recycling and future selection of permanent magnets and powder cores, Complement. (2017) 1–32. https://www.arnoldmagnetics.com/wp-content/uploads/2017/10/Recycling-and-Future-Selection-of-Magnets-Goodier-2005-psn-lo-res.pdf.

[42] CONEBI, Bicycle And E-Bike Sales Continue To Grow, Reaching Record Levels, (2022). https://www.conebi.eu/bicycle-and-e-bike-sales-continue-to-grow-reaching-record-levels/ (accessed March 16, 2023).

[43] EMR, Europe E-Bike Market Outlook, (2022). https://www.expertmarketresearch.com/reports/europe-e-bike-market#:~:text=The Europe e-bike market attained a value of about,at a CAGR of 18.1%25. (accessed August 16, 2023).

[44] Statista, Projections for the global electric bike market between 2018 and 2030, (2022). https://www.statista.com/statistics/1261084/global-e-bike-market-forecast/ (accessed August 16, 2023).

[45] K. Habib, H. Wenzel, Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling, J. Clean. Prod. 84 (2014) 348–359. https://doi.org/10.1016/j.jclepro.2014.04.035.

[46] V. Zepf, Rare earth elemnta, A new approach to the nexus of supply, demand and Use: exemplified along the use of Neodymium in permanent magnets, 2013. https://doi.org/10.1007/978-3-642-35458-8.

[47] K. Binnemans, P.T. Jones, B. Blanpain, T. Van Gerven, Y. Yang, A. Walton, M. Buchert, Recycling of rare earths: A critical review, J. Clean. Prod. 51 (2013) 1–22. https://doi.org/10.1016/j.jclepro.2012.12.037.

[48] Z. Hua, J. Wang, L. Wang, Z. Zhao, X. Li, Y. Xiao, Y. Yang, Selective extraction of rare earth elements from NdFeB scrap by molten chlorides, ACS Sustain. Chem. Eng. 2 (2014) 2536–2543. https://doi.org/10.1021/sc5004456.

[49] T. motorcycle industry in E. Acem, Registrations of motorcycles and mopeds in largest European markets continue to increase in Q1 2022, (2022). https://acem.eu/registrations-of-motorcycles-and-mopeds-in-largest-european-markets-continue-to-raise-in-the-first-3-months-of-2022 (accessed March 16, 2023).

[50] European Commission, Raw materials information system- Raw materials in vehicles, (2023). https://rmis.jrc.ec.europa.eu/veh#/p/intro (accessed March 17, 2023).

[51] Statista, Electric Vehicles - Europe, (2023). https://www.statista.com/outlook/mmo/electric-vehicles/europe (accessed March 17, 2023).

[52] ACEA Driving mobility for Europe, Electrification trends worldwide, (2022). https://www.acea.auto/news/electrification-trends-worldwide/ (accessed March 22, 2023).

[53] A. Kumari, S. Kumar Sahu, A comprehensive review on recycling of critical raw materials from spent neodymium iron boron (NdFeB) magnet, Sep. Purif. Technol. (2023) 123527. https://doi.org/10.1016/j.seppur.2023.123527.

[54] Statista, Forecasted demand for praseodymium used for electric vehicle transaction motors in the European (EU) in 2015 and 2030, by vehicle type, (2018). https://www.statista.com/statistics/1015502/electric-vehicle-traction-motor-praseodymium-demand-forecast-eu/ (accessed March 17, 2023).

[55] K. Habib, P.K. Schibye, A.P. Vestbø, O. Dall, H. Wenzel, Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach, Environ. Sci. Technol. 48 (2014) 12229−12237.

[56] ISFORT-Italian higher education and research institute for transport, Mobility report 2020, (2020). https://www.isfort.it/wp-content/uploads/2020/12/RapportoMobilita2020.pdf (accessed August 16, 2023).

[57] Future Market Insights, Magnetic drive pump market, (2021). https://www.futuremarketinsights.com/reports/magnetic-drive-pump-market (accessed August 16, 2023).

[58] Straits research, Magnetic drive pump market, (2022). https://straitsresearch.com/report/magnetic-drive-pump-market (accessed August 16, 2023).

[59] ITALMOTO, Come prolungare la durata della batteria al litio della tua e-bike, (2021). https://www.italmoto.com/come-prolungare-durata-della-batteria-al-litio-e-bike/ (accessed March 22, 2023).

[60] AIKE, How Long Do Electric Scooters Last? Plus Tips for a Longer Lifespan, (2022). https://rideaike.com/blog/how-long-do-electric-scooters-last/#:~:text=On average%2C e-scooters in,3 years or even more. (accessed March 20, 2023).

[61] Scooter.guide, HOW LONG DO ELECTRIC SCOOTERS LAST?, (2022). https://scooter.guide/how-long-do-electric-scooters-last/ (accessed March 20, 2023).

[62] J. Marx, A. Schreiber, P. Zapp, F. Walachowicz, Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits, ACS Sustain. Chem. Eng. 6 (2018) 5858–5867. https://doi.org/10.1021/acssuschemeng.7b04165.

[63] P.S. Arshi, E. Vahidi, F. Zhao, Behind the Scenes of Clean Energy: The Environmental Footprint of Rare Earth Products, ACS Sustain. Chem. Eng. 6 (2018) 3311–3320. https://doi.org/10.1021/acssuschemeng.7b03484.

[64] DEPARTMENT OF INDUSTRY AND SECURITY, Publication of a Report on the Effect of Imports of Neodymium-Iron-Boron (NdFeB) Permanent Magnets on the National Security: An Investigation Conducted Under Section 232 of the Trade Expansion Act of 1962, as Amended, 2023. https://doi.org/10.1016/0196-335x(80)90058-8.

[65] USGS, Rare earths, 2023. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-rare-earths.pdf.

[66] Y. Yang, A. Walton, R. Sheridan, K. Güth, R. Gauß, O. Gutfleisch, M. Buchert, B.M. Steenari, T. Van Gerven, P.T. Jones, K. Binnemans, REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review, J. Sustain. Metall. 3 (2017) 122–149. https://doi.org/10.1007/s40831-016-0090-4.

[67] CONEBI-Confederation of the European Bicycle Industry, 2021 European bicycle industry and market profile, 2021. https://www.conebi.eu/wp-

content/uploads/2023/08/2021_BIMP_with_2020_data.pdf.

[68] C. of Commerce, Report of wind mobility, (2022). https://www.camera.it/application/xmanager/projects/leg18/attachments/upload_file_doc_acquisiti/pdfs/000/006/288/19._Memoria_Wind_Mobility.pdf (accessed September 22, 2023).

[69] GfK, Scooter racing: sales at +140% in the first 7 months of 2020, (2020). https://www.gfk.com/it/stampa/corsa-al-monopattino-piu-140-percento-nei-primi-7-mesi-del-2020.

[70] R. Gauß, C. Burkhardt, F. Carencotte, M. Gasparon, O. Gutfleisch, I. Higgins, M. Karajić, A. Klossek, M. Mäkinen, B. Schäfer, R. Schindler, B. Veluri, Rare earth magnets and motors: A European call for action. A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance, Berlin, 2021. https://eit.europa.eu/sites/default/files/2021_09-24_ree_cluster_report2.pdf.

[71] The European Commission, Second in-depth review of strategic areas for Europe's interests, (2022). https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-industrial-strategy/second-depth-review-strategic-areas-europes-interests_en (accessed September 28, 2023).

[72] Carbon dioxide ($CO_2$) equivalent is a measure of how much a gas contributes to global warming, relative to carbon dioxide. $CO_2$e is a term for describing different greenhouse gases in a common unit. For any quantity and type of greenhouse gas, $CO_2$e signifies the amount of $CO_2$ which would have the equivalent global warming impact

# ANNEX 1

| | | |
|---|---|---|
| **1** | Climate change | Global Warming Potential calculating the radiative forcing over a time horizon of 100 years. |
| **2** | Ozone depletion | Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years. |
| **3** | Acidification | Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. European-country dependent. |
| **4** | Freshwater eutrophication | Expression of the degree to which the emitted nutrients reaches the freshwater end compartment (phosphorus considered as limiting factor in freshwater). European validity. Averaged characterization factors from country dependent characterization factors. |
| **5** | Marine eutrophication | Expression of the degree to which the emitted nutrients reaches the marine end compartment (nitrogen considered as limiting factor in marine water). European validity. Averaged characterization factors from country dependent characterization factors. |
| **6** | Human toxicity, cancer effects | Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme). Specific groups of chemicals require further works. |
| **7** | Human toxicity, non-cancer effects | Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme). Specific groups of chemicals require further works. |
| **8** | Photochemical ozone formation | Expression of the potential contribution to photochemical ozone formation. Only for Europe. It includes spatial differentiation. |
| **9** | Particulate matter | Quantification of the impact of premature death or disability that particulates/respiratory inorganics have on the population, in comparison to PM2,5. It includes the assessment of primary (PM10 and PM2,5) and secondary PM (incl. creation of secondary PM due to SOx, NOx and NH3 emissions) and CO. |
| **10** | Ionizing radiation HH (human health) | Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235. |
| **11** | Ionizing radiation E | [note: this method is classified as interim] Comparative |

| | | |
|---|---|---|
| | (ecosystems) | Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a radionucleide emitted (PAF $m^3$ year/kg). Fate of radionucleide based on USEtox consensus model (multimedia model). Relevant for freshwater ecosystems. |
| **12** | Terrestrial eutrophication | Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit. European-country dependent |
| **13** | Freshwater ecotoxicity | Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF $m^3$ year/kg). Specific groups of chemicals requires further works. |
| **14** | Land use | Soil Organic Matter (SOM) based on changes in SOM, measured in (kg C/$m^2$/a). Biodiversity impacts not covered by the data set. |
| **15** | Water resource depletion | Freshwater scarcity: Scarcity-adjusted amount of water used. |
| **16** | Mineral, fossil & renewable resource depletion | Scarcity of mineral resource with the scarcity calculated as 'Reserve base'. It refers to identified resources that meets specified minimum physical and chemical criteria related to current mining practice. The reserve base may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. |

# ANNEX 2

Indicators and Units of each SimaPro methodology.

| Indicators | Methodology ReCiPe (H) Midpoint - Characterization | Description |
|---|---|---|
| **Climate change** | kg $CO_2$ eq [72] | Indicator of potential global warming due to emissions of greenhouse gases to air. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) bio-based resources and (3) land use change. |
| **Ozone depletion** | kg CFC-11 eq | Indicator of emissions to air that cause the destruction of the stratospheric ozone layer |
| **Human toxicity** | kg 1,4-DB eq | The emission of some substances (such as heavy metals) can have impacts on human health: kg 1,4 dichlorobenzene |
| **Freshwater eutrophication** | kg P eq | indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor containing compounds |
| **Particulate matter formation** | kg PM10 eq | Inhalable particles, with diameters that are generally 10 micrometers and smaller. |
| **Ionizing radiation** | kBq U235 eq | Damage to human health and ecosystems linked to the emissions of radionuclides. |
| **Photochemical oxidant formation** | kg NMVOC eq | Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight. |
| **Terrestrial acidification** | kg $SO_2$ eq | |
| **Terrestrial ecotoxicity** | kg 1,4-DB eq | The emission of some substances (such as heavy metals) can have impacts on human health: kg 1,4 dichlorobenzene |
| **Freshwater ecotoxicity** | kg 1,4-DB eq | The emission of some substances (such as heavy metals) can have impacts on human health: kg 1,4 dichlorobenzene |
| **Marine ecotoxicity** | kg 1,4-DB eq | The emission of some substances (such as heavy metals) can have impacts on human health: kg 1,4 dichlorobenzene |
| **Marine eutrophication** | kg N eq | Indicator of the enrichment of the marine |

| | | |
|---|---|---|
| | | ecosystem with nutritional elements, due to the emission of nitrogen containing compounds. |
| **Agricultural land occupation** | $m^2a$ | Occupation, mineral extraction site |
| **Urban land occupation** | $m^2a$ | Occupation construction site |
| **Natural land transformation** | $m^2$ | Transformation |
| **Water depletion** | $m^3$ | |
| **Metal depletion** | kg Fe eq | |
| **Fossil depletion** | kg oil eq | |