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8	05/06/2023	Stylianos Spathariotis	Additional input and corrections.
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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 contains the main results from several tasks of the WP4 of PASSENGER project so far. The document reports about the preliminary Life Cycle Assessment and Material Flow analysis-R1. The purpose of the current report is to present a preliminary assessment of the Life Cycle Assessment based on basic data of the processes that are being developed inside PASSENGER project. D4.2 is the second deliverable of WP4 and the first that include a preliminary Life Cycle Assessment. The scope of D4.2 is to perform several preliminary LCAs in order to incorporate the environmental results in the technologies and products. In the context of D4.2 will be presented the first preliminary studies regarding the Life Cycle Assessment that was conducted on the PASSENGER project.

The Life Cycle Assessment has been performed following the ISO 14040 standards. The goal and scope of the analysis was defined in the context of D4.2 Report on preliminary Life Cycle Assessment and Material Flow analysis-R1. The Life Cycle Inventory was created by asking partners regarding the mass, energy balances or their technologies and processes. Common aspects regarding the general framework of the PASSENGER and (where relevant) the reference system, with a value chain defined.

In a nutshell, deliverable D4.2 defines the scope for each preliminary study on Life Cycle Assessment. In order to conduct the preliminary studies on LCA appropriate excel files were prepared for data collection stage and Life Cycle Inventory completion.

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INTRODUCTION

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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 M24. The following key activities will be considered in this deliverable that are distributed among the different Tasks:

- Life Cycle Inventory (LCI) of the processes. Ensure the complete, timely, and secure process for data sharing with the involvement of all relevant consortium partners.
- 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 will set the frame and familiarize the partners with the main principles of this WP objectives, and secondly will structure 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, and to secure that frequent discussions with partners of the technologies and products will be organized and visits to the sites of pilot plants. Part of these workshops and visits will be the definition of scenarios for the up-scaled PASSENGER technologies for the environmental (LCA) impact assessment. In the context 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 will be 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 will allow 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:

- A preliminary environmental LCA performed over the two years of the project (M12, M24)
- A more detailed final environmental LCA (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.

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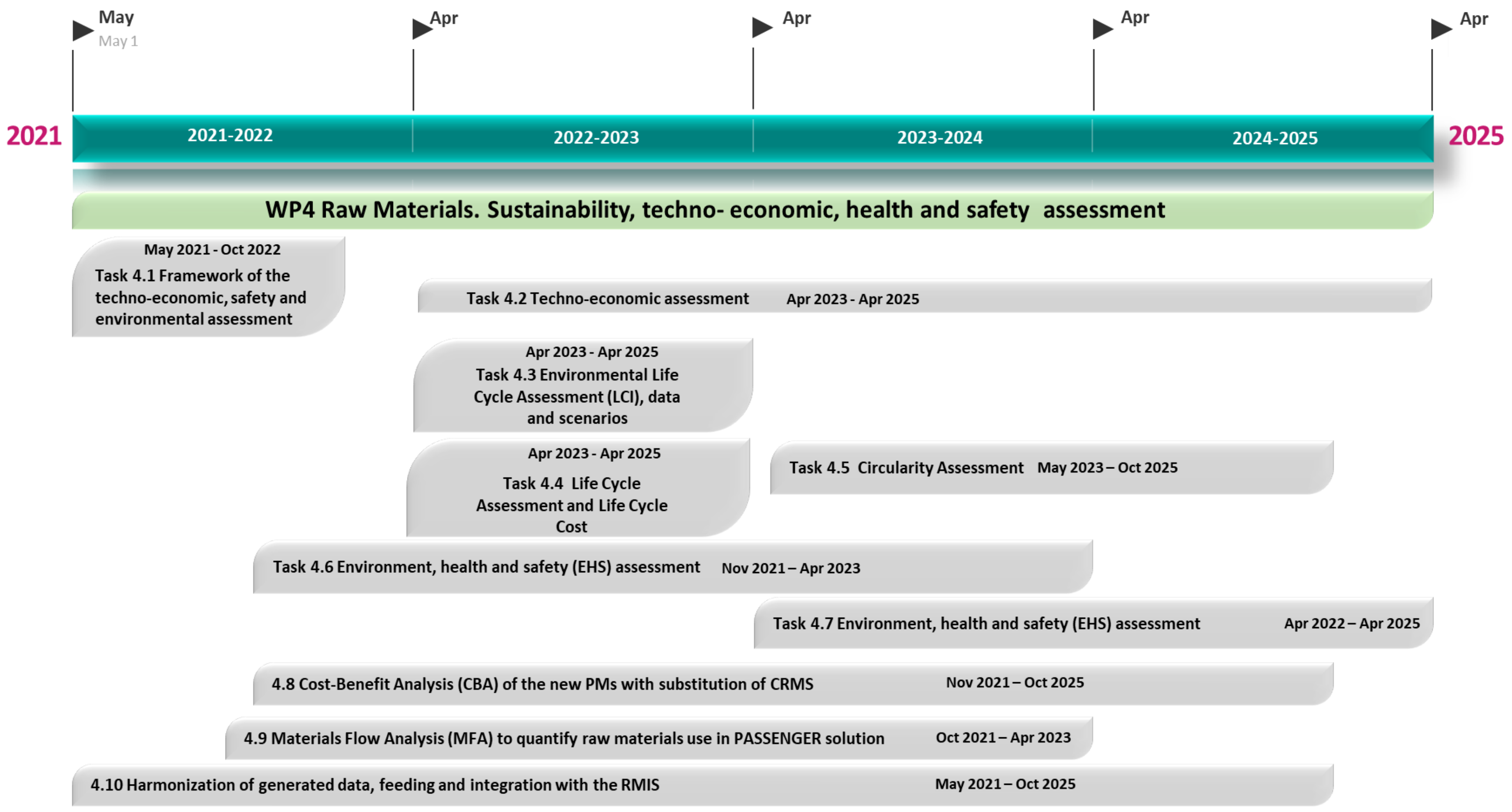

Figure 1 WP4 Timeline

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.

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

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

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Figure 3 Sustainable Development Goals (SDGs)

PASSENGER addresses at least 4 Sustainable Development Goals (Figure 4), 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 labor-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

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[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.

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 (Fig. 5, 6) 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:

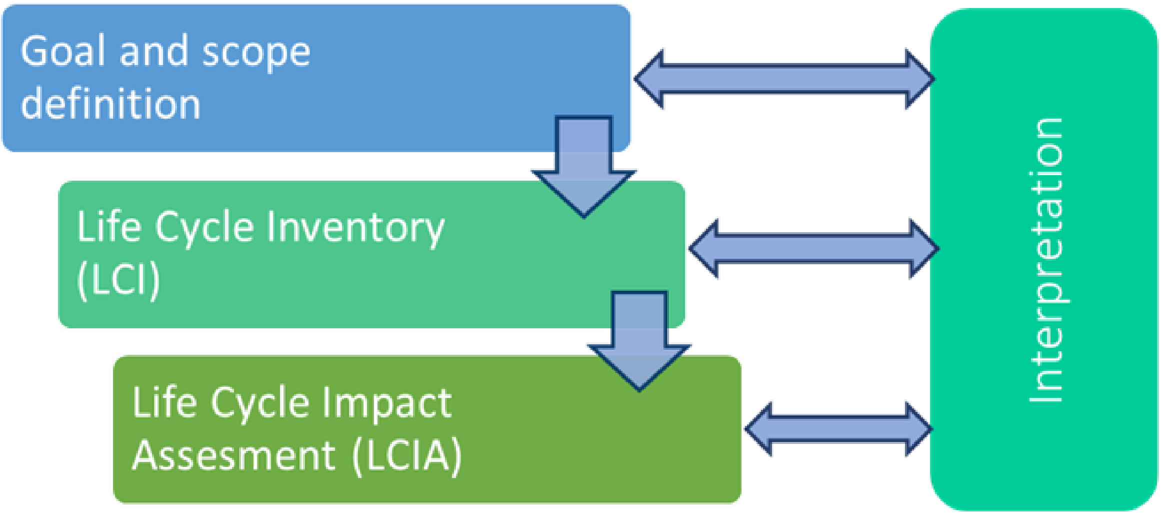

Figure 5 LCA Framework by International Reference Life Cycle Data System (ILCD) Handbook, 2010

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.

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

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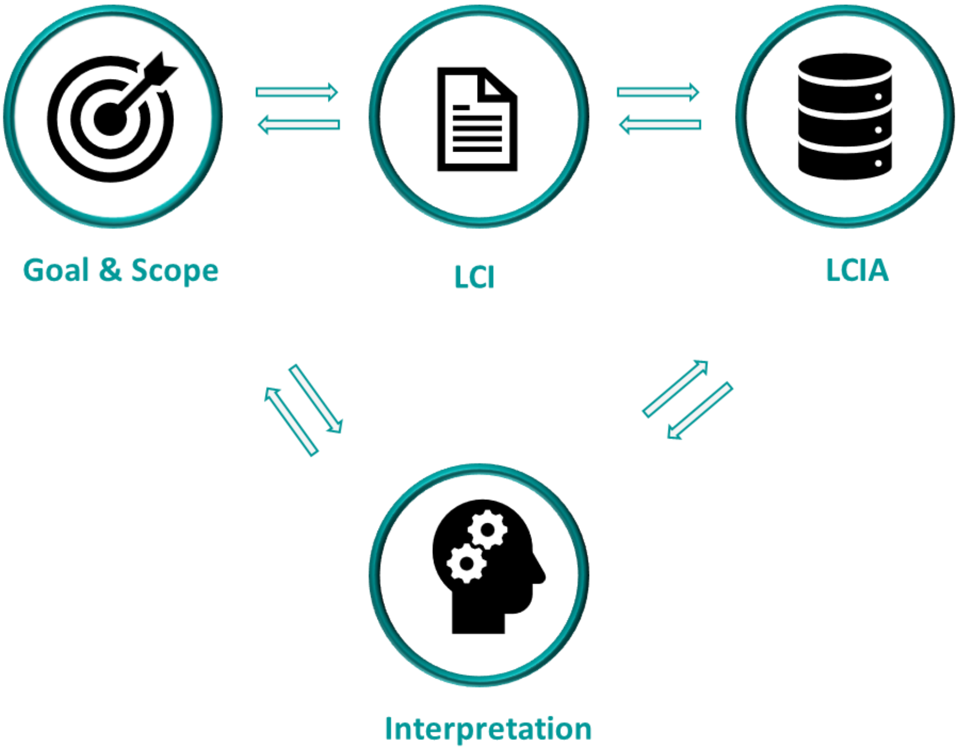

Figure 6 The 4 phases of the LCA approach.

Generally, the product/ process Lifecycle consists of five steps (Figure 7):

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].

Gradle-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”.

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[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

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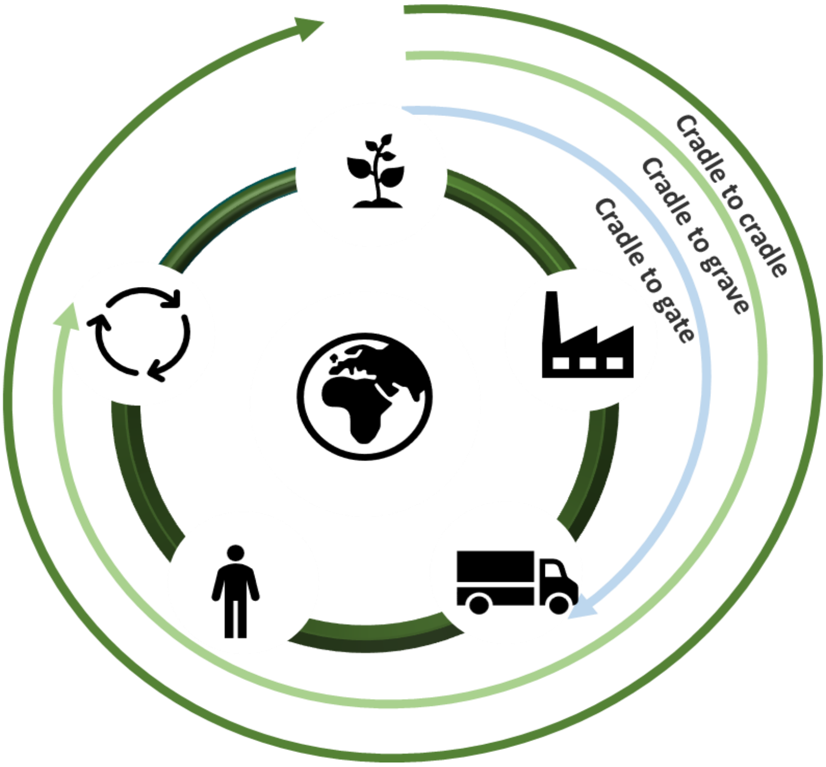

Figure 7 Product/Process Lifecycle routes in LCA

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 8. Regarding the four steps of the LCA the Goal.

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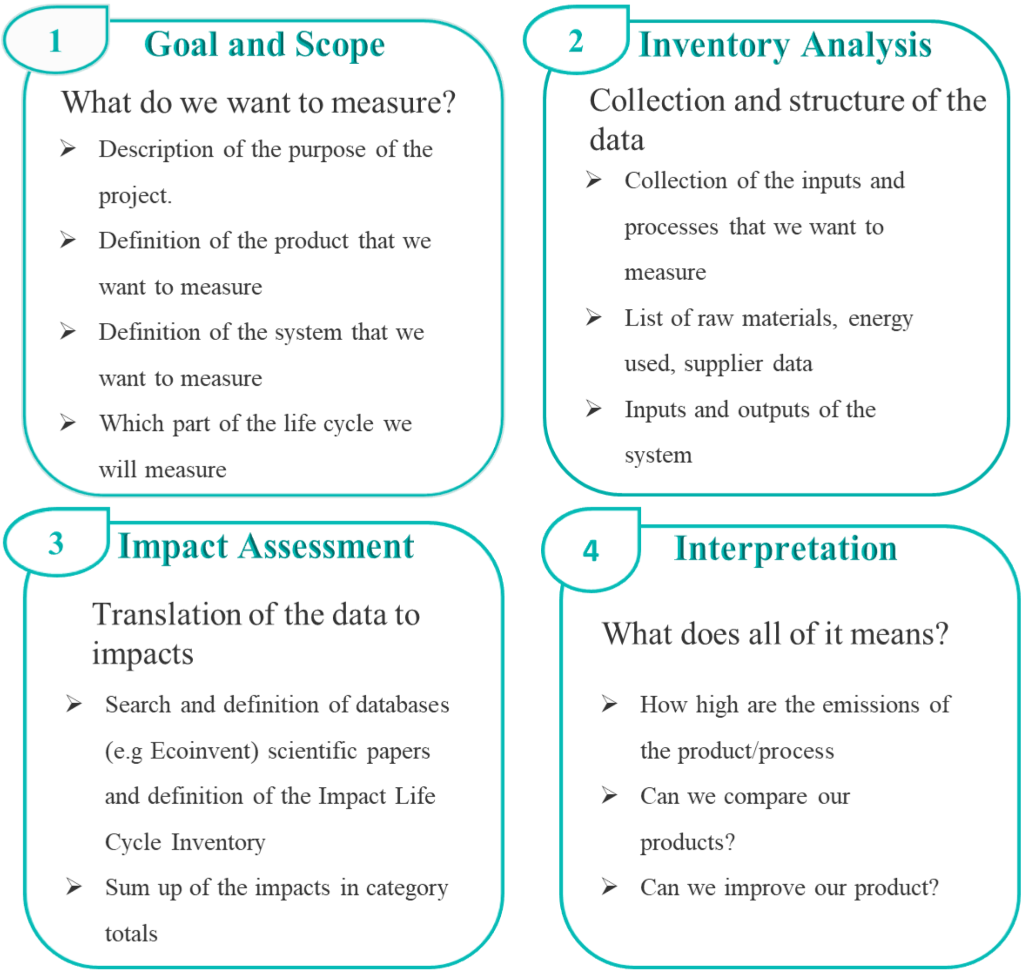

Figure 8 LCA Methodology / 4 steps for the LCA assessment.

3.3 GOAL & SCOPE

3.2.1 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. An initial assessment was conducted regarding the production of NdFeB and MnAlC. In order to evaluate the environmental impact of NdFeB magnet and MnAlC magnet an initial preliminary comparative LCA was performed, in accordance with the international standards - ISO 14040 and ISO 14044. The assessment and the related data that are presented are based on literature reviews [8, 50] and further assumptions. The comparison was based on the production of 1kg of NdFeB and 1kg of MnAlC 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

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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.

3.2.2 Description

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 and MnAlC magnets the functional unit is “1kg”.

3.2.3 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 together with the detailed LCA report, 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 will be reported together with the detailed LCA report, in a manner that respects any confidentiality concern.

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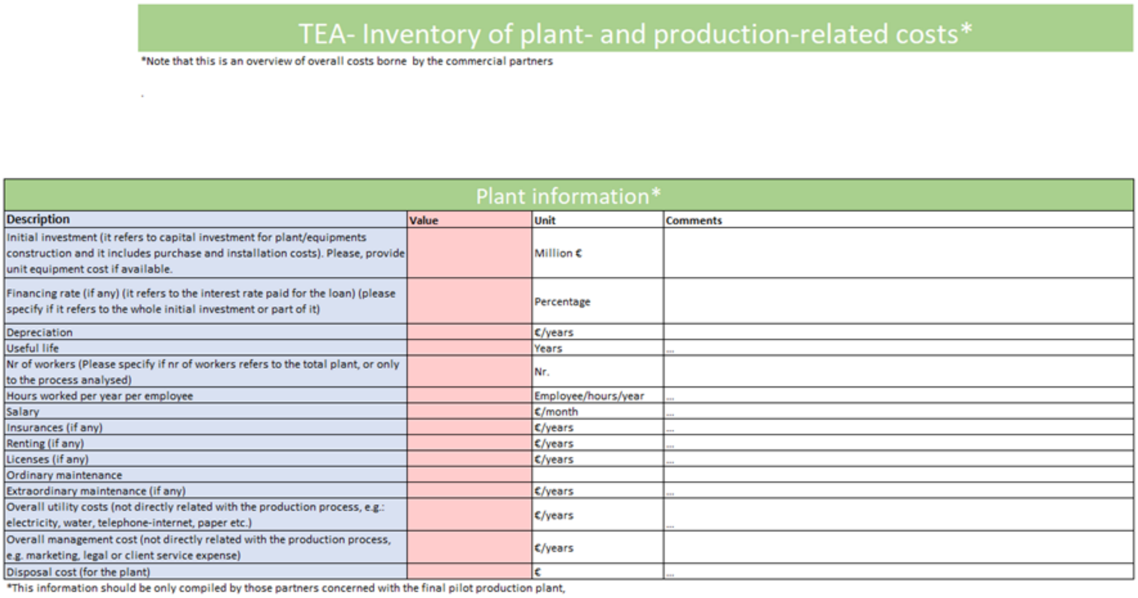

TEA- Inventory of plant- and production-related costs*

*Note that this is an overview of overall costs borne by the commercial partners

Plant information*			
Description	**Value**	**Unit**	**Comments**
Initial investment (it refers to capital investment for plant/equipments construction and it includes purchase and installation costs). Please, provide unit equipment cost if available.		Million €	
Financing rate (if any) (it refers to the interest rate paid for the loan) (please specify if it refers to the whole initial investment or part of it)		Percentage	
Depreciation		€/years	
Useful life		Years	...
Nr of workers (Please specify if nr of workers refers to the total plant, or only to the process analysed)		Nr.	
Hours worked per year per employee		Employee/hours/year	...
Salary		€/month	...
Insurances (if any)		€/years	...
Renting (if any)		€/years	...
Licenses (if any)		€/years	...
Ordinary maintenance			
Extraordinary maintenance (if any)		€/years	...
Overall utility costs (not directly related with the production process, e.g.: electricity, water, telephone-internet, paper etc.)		€/years	...
Overall management cost (not directly related with the production process, e.g. marketing, legal or client service expense)		€/years	
Disposal cost (for the plant)		€	...

*This information should be only compiled by those partners concerned with the final pilot production plant,

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

Figure 10 Excel file: Sheet regarding the system definition

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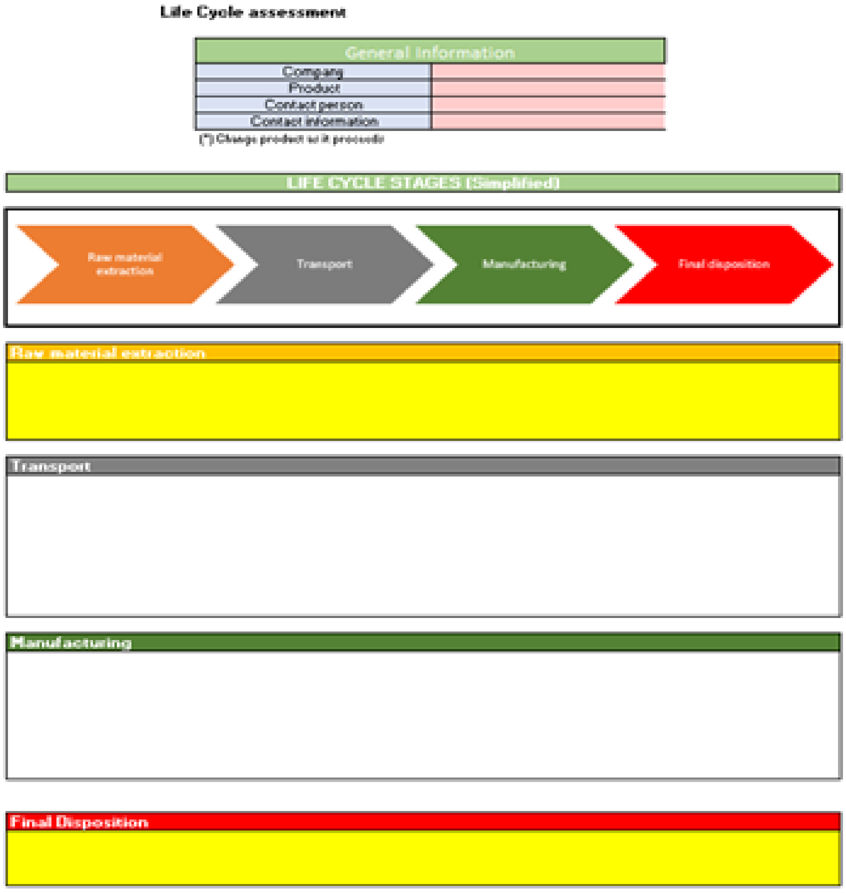


Life Cycle assessment

General Information	
Company	
Product	
Contact person	
Contact information	

(*) Change product w it procedure

LIFE CYCLE STAGES (Simplified)

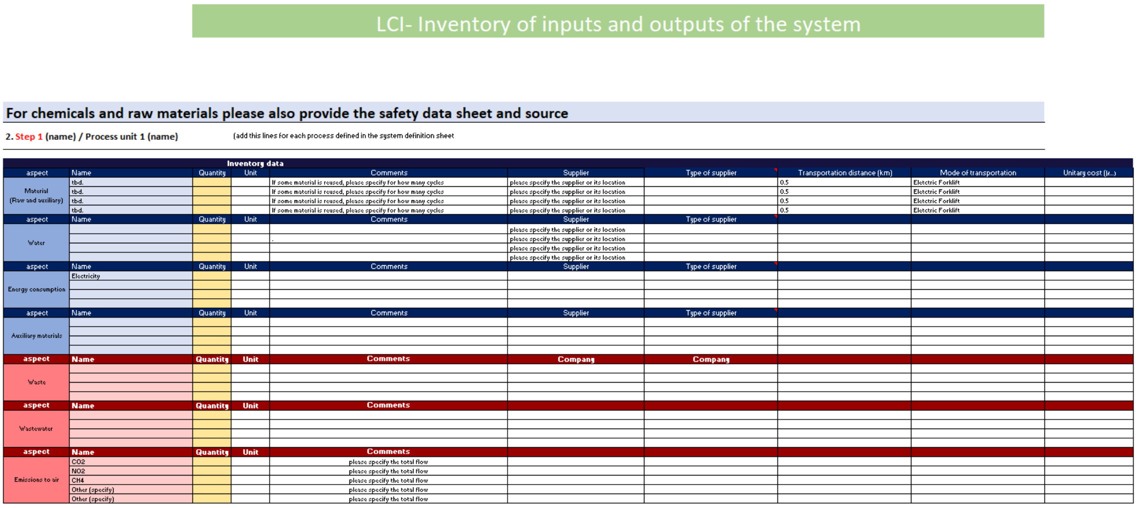
Raw material extraction

Transport

Manufacturing

Final Disposition

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



LCI- Inventory of inputs and outputs of the system

For chemicals and raw materials please also provide the safety data sheet and source

2. Step 1 (name) / Process unit 1 (name) (add this lines for each process defined in the system definition sheet

Inventory data									
aspect	Name	Quantity	Unit	Comments	Supplier	Type of supplier	Transportation distance (km)	Mode of transportation	Unitary cost (k...)
Material (Raw and auxiliary)	tbd.			If some material is reused, please specify for how many cycles	please specify the supplier or its location		0.5	Eletctric Forklift	
	tbd.			If some material is reused, please specify for how many cycles	please specify the supplier or its location		0.5	Eletctric Forklift	
	tbd.			If some material is reused, please specify for how many cycles	please specify the supplier or its location		0.5	Eletctric Forklift	
	tbd.			If some material is reused, please specify for how many cycles	please specify the supplier or its location		0.5	Eletctric Forklift	
aspect	Name	Quantity	Unit	Comments	Supplier	Type of supplier			
Water					please specify the supplier or its location				
				.	please specify the supplier or its location				
					please specify the supplier or its location				
					please specify the supplier or its location				
aspect	Name	Quantity	Unit	Comments	Supplier	Type of supplier			
Energy consumption	Electricity								
aspect	Name	Quantity	Unit	Comments	Supplier	Type of supplier			
Auxiliary materials									
aspect	**Name**	**Quantity**	**Unit**	**Comments**	**Company**	**Company**			
Waste									
aspect	**Name**	**Quantity**	**Unit**	**Comments**					
Wastewater									
aspect	**Name**	**Quantity**	**Unit**	**Comments**					
Emissions to air	CO2			please specify the total flow					
	NO2			please specify the total flow					
	CH4			please specify the total flow					
	Other (specify)			please specify the total flow					
	Other (specify)			please specify the total flow					

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

3.2.4 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)[8]. The impacts

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[8] https://www.sciencedirect.com/topics/engineering/life-cycle-impact-assessment

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[9].

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[10]. 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.

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[9] https://ec.europa.eu/environment/biodiversity/business/assets/pdf/tool-descriptions/RECiPe%20and%20BioScope%20summary%20description.pdf

[10] National Institute for Public Health and the Environment Ministry of Health, Welfare and Sport, “LCIA: The ReCiPe model”, February 2018

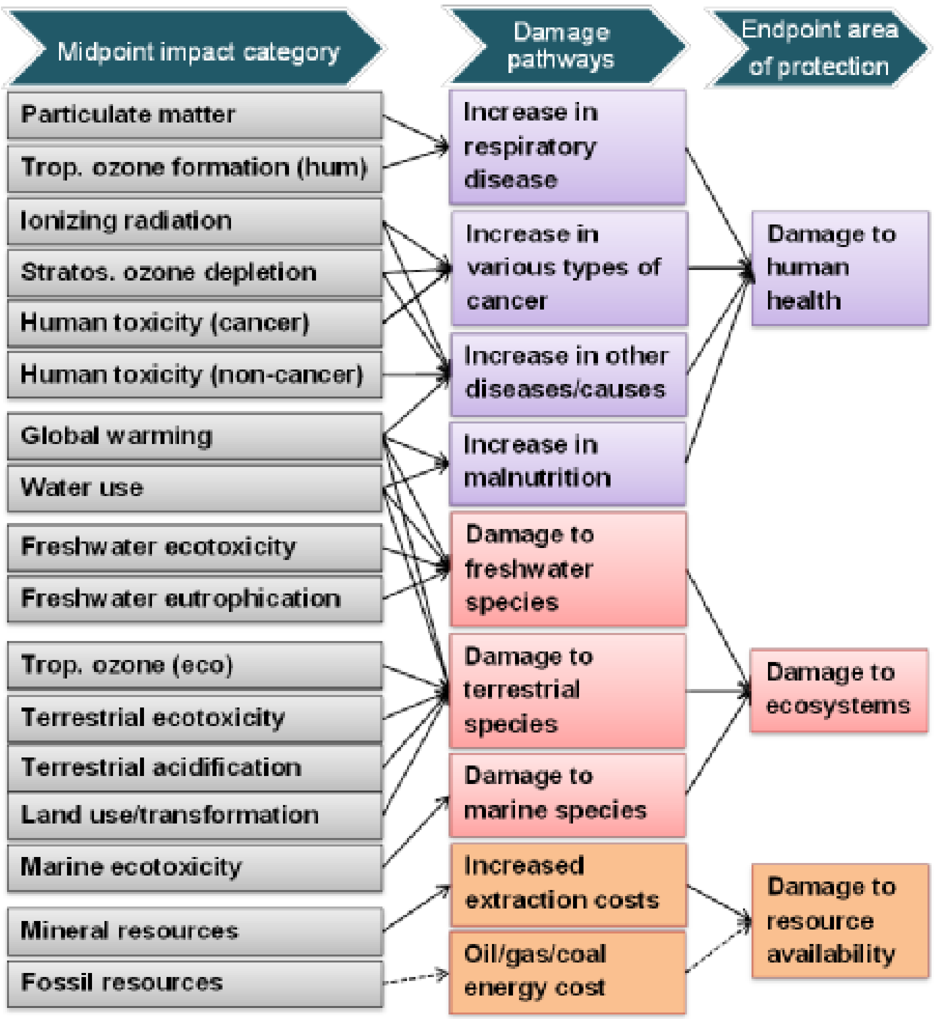

Figure 13. Relations between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe methodology.

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4 LIFE CYCLE ASSESSMENT STUDIES

4.1 LCIA ON THE INITIAL SCENARIO OF THE NdFeB PERMANENT MAGNET PRODUCTION

Regarding the initial scenario of the preliminary assessment (limited data available in the literature as the vast majority of the production is carried out in China) of 1kg NdFeB permanent magnet, Figure 14 illustrates the outline for a typical NdFeB magnet production process [8]. Figure 15 shows the LCA results of producing 1kg of NdFeB magnets, while the obtained data are recorded in Table 1, based on a literature review [50]. Considering the conditions which this study took place and after observing the results of the characterized impact assessment methods of the Recipe (H) Midpoint methodology it can be roughly estimated that for the production of 1 kg of NdFeB, concerning the impact of the metals the Nd has the highest CO2 emissions with 13.95 kgCO2eq as it is also depicted in Table 1. The Nd adds some environmental load to the resources mainly and additionally to human health category.

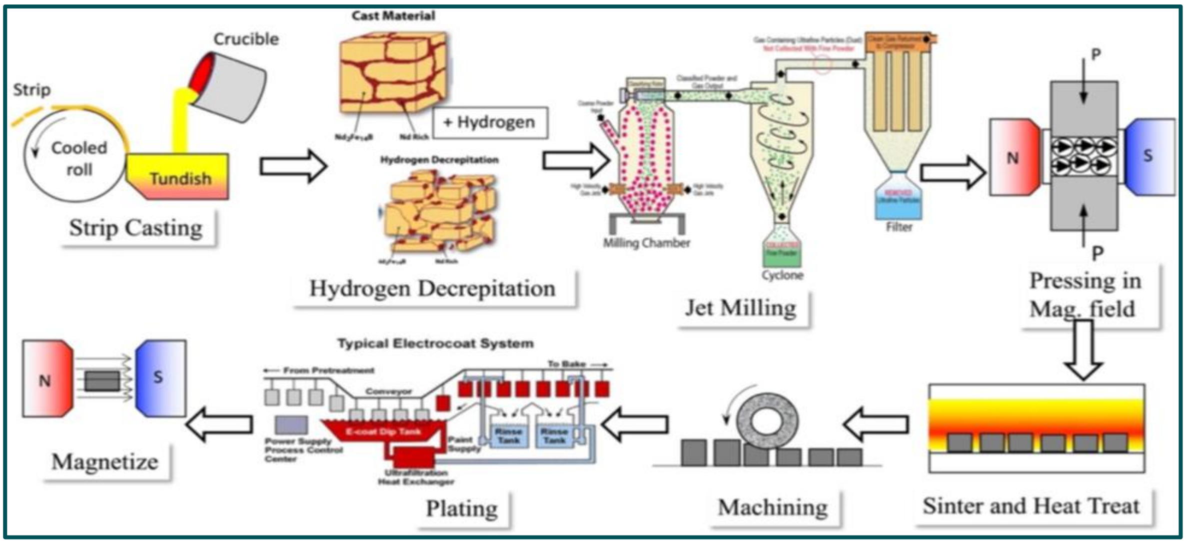

Figure 14. Basic process steps for the NdFeB-based magnets.

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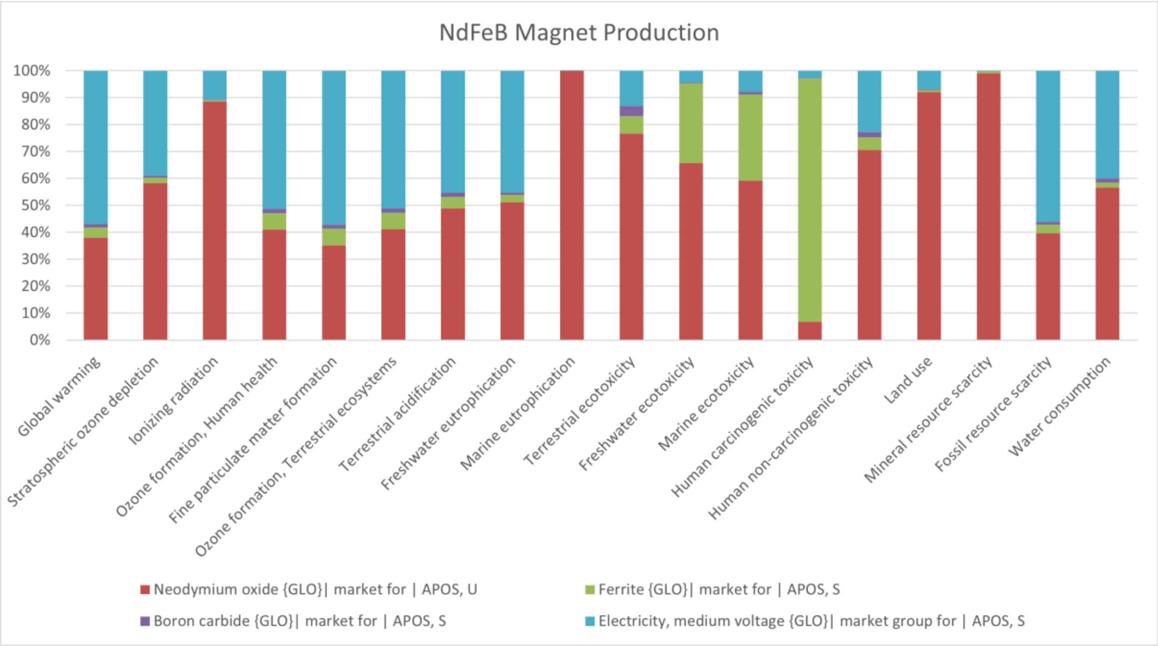

Figure 15. Life cycle impact of producing 1 kg NdFeB magnet.

Table 1 LCA results of producing 1 kg NdFeB magnet.

Impact category	Unit	Total	Neodymium oxide	Ferrite	Boron carbide	Electricity
Global warming	kg CO2 eq	**36,64**	**13,95**	**1,35**	**0,50**	**20,84**
Ionizing radiation	kBq Co-60 eq	**2,05**	1,82	0,01	0,00	0,22
Ozone formation, Human health	kg NOx eq	**0,09**	0,04	0,01	0,00	0,05
Fine particulate matter formation	kg PM2.5 eq	**0,08**	0,03	0,00	0,00	0,05
Ozone formation, Terrestrial ecosystems	kg NOx eq	**0,09**	0,04	0,01	0,00	0,05
Terrestrial acidification	kg SO2 eq	**0,15**	0,08	0,01	0,00	0,07
Marine eutrophication	kg N eq	**0,21**	0,21	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	**132,42**	101,49	8,70	4,95	17,28
Freshwater ecotoxicity	kg 1,4-DCB	**0,18**	0,12	0,05	0,00	0,01
Marine ecotoxicity	kg 1,4-DCB	**0,27**	0,16	0,09	0,00	0,02
Human carcinogenic toxicity	kg 1,4-DCB	**4,92**	0,33	4,45	0,01	0,13
Human non-carcinogenic toxicity	kg 1,4-DCB	**16,39**	11,58	0,76	0,34	3,72
Land use	m2a crop eq	**5,53**	5,09	0,05	0,01	0,38
Mineral resource scarcity	kg Cu eq	**9,79**	9,71	0,07	0,00	0,01
Fossil resource scarcity	kg oil eq	**9,40**	3,73	0,30	0,10	5,26
Water consumption	m3	**0,39**	0,22	0,01	0,01	0,16

4.2 LCIA ON THE INITIAL SCENARIO OF THE MnAlC PERMANENT MAGNET PRODUCTION

Regarding the initial scenario of the preliminary assessment of MnAlC permanent magnet, Figure 16 shows the LCA results of producing 1kg of MnAlC magnets, while the obtained data are recorded in Table 2. Considering the conditions which this study took place and after observing the results of the characterized impact assessment methods of the Recipe (H) Midpoint methodology it can be concluded that from the production of 1 kg of MnAlC the Mn has the highest CO2 emissions with 3.60 kgCO2eq as it is also depicted in Table 2. The Mn adds some environmental load to the resources mainly and additionally to human health category.

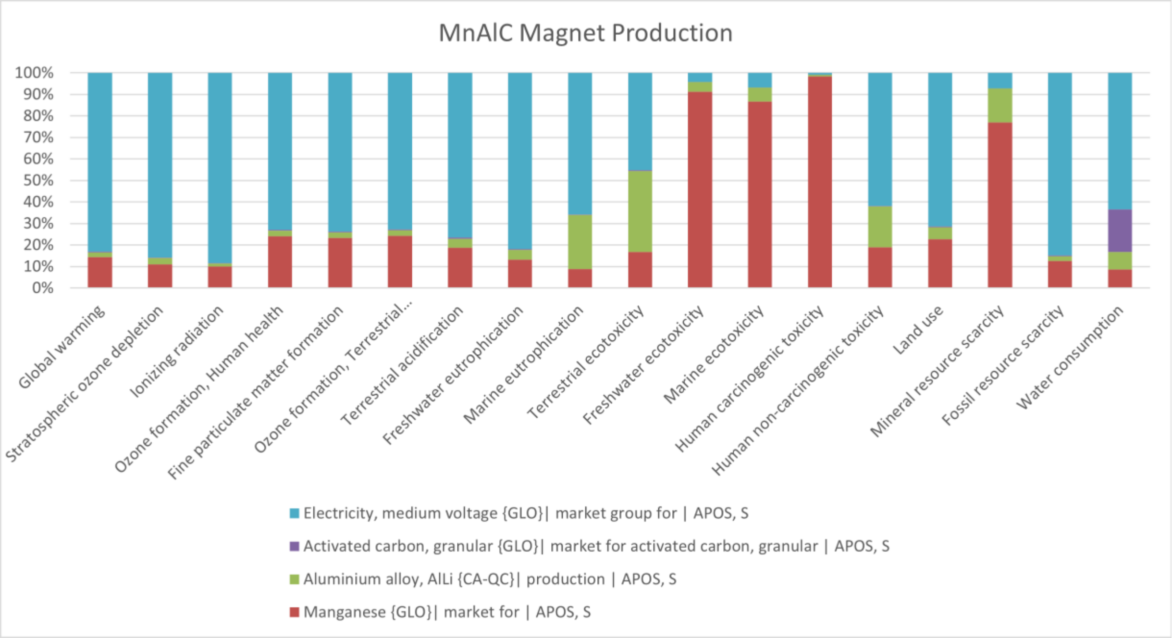

Figure 16. Life cycle impact of producing 1 kg MnAlC magnet.

Table 2 LCA results of producing 1 kg MnAlC magnet.

Impact category	Unit	Total	Manganese	Aluminium alloy	Activated carbon	Electricity
Global warming	kg CO2 eq	**25,09**	**3,60**	**0,56**	**0,09**	**20,84**
Ionizing radiation	kBq Co-60 eq	**0,25**	0,03	0,00	0,00	0,22
Ozone formation, Human health	kg NOx eq	**0,06**	0,01	0,00	0,00	0,05
Fine particulate matter formation	kg PM2.5 eq	**0,06**	0,01	0,00	0,00	0,05
Ozone formation, Terrestrial ecosystems	kg NOx eq	**0,06**	0,02	0,00	0,00	0,05
Terrestrial acidification	kg SO2 eq	**0,09**	0,02	0,00	0,00	0,07
Marine eutrophication	kg N eq	**0,00**	0,00	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	**38,22**	6,38	14,43	0,13	17,28
Freshwater ecotoxicity	kg 1,4-DCB	**0,19**	0,18	0,01	0,00	0,01
Marine ecotoxicity	kg 1,4-DCB	**0,31**	0,27	0,02	0,00	0,02
Human carcinogenic toxicity	kg 1,4-DCB	**15,05**	14,82	0,10	0,00	0,13
Human non-carcinogenic toxicity	kg 1,4-DCB	**6,02**	1,14	1,15	0,02	3,72
Land use	m2a crop eq	**0,53**	0,12	0,03	0,00	0,38
Mineral resource scarcity	kg Cu eq	**0,19**	0,15	0,03	0,00	0,01
Fossil resource scarcity	kg oil eq	**6,21**	0,78	0,14	0,02	5,26
Water consumption	m3	**0,25**	0,02	0,02	0,05	0,16

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2020 research and innovation programme under grant agreement No 101003914

4.3 PRELIMINARY COMPARATIVE ASSESSMENT OF NdFeB AND MnAlC PERMANENT MAGNET PRODUCTION

An initial comparative assessment of the NdFeB and MnAlC magnets was conducted. Figure 17 shows the LCA results comparison from SimaPro in terms of the environmental impact of producing 1 kg NdFeB and 1 kgMnAlC magnets production. As it is evident from the Figure 17, the MnAlC has significantly less environmental impact than the NdFeB magnet production in almost all of the impact categories. As it is depicted in Figure 18, on the impact category of global warming, an indicator of potential global warming due to emissions of greenhouse gases to air, the NdFeB has the highest CO_2 emissions, with 36.64 kg CO_2 equivalent as it is also depicted in Table 3 shows the specific response for each impact category. The biggest difference between the NdFeB and MnAlC magnet appears to be in ionizing radiation impact category (Figure 19) (Table 3) that is an indicator of the damage to human health and ecosystems linked to the emissions of radionuclides based on the raw materials appeared in these two types of magnets.

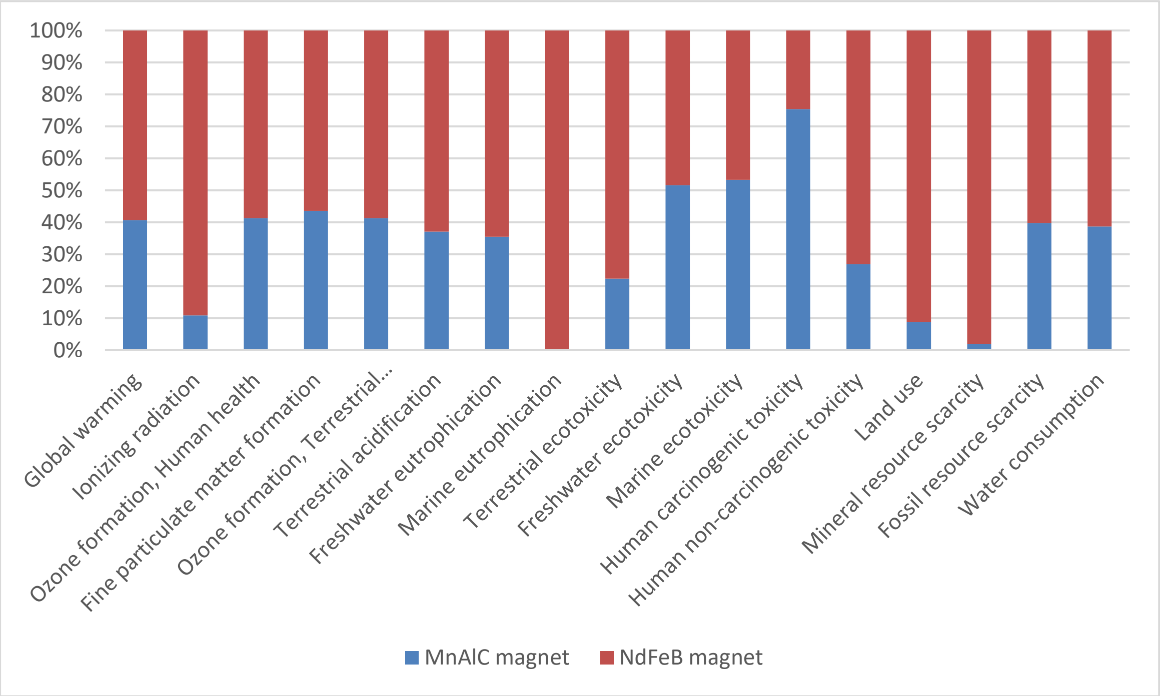

Figure 17. Life cycle impact comparison of producing 1 kg NdFeB magnet versus 1 kg MnAlC magnet.

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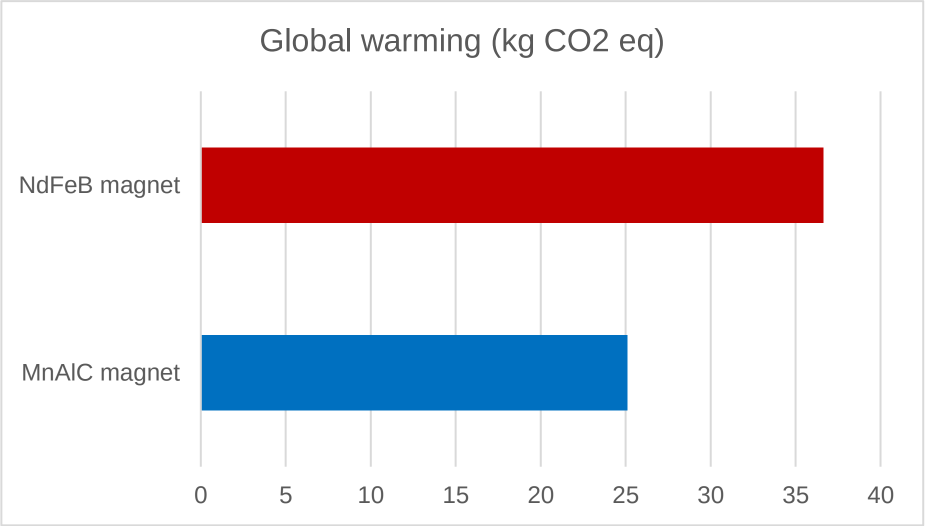

Figure 18. Impact comparison of NdFeB versus MnAlC magnet production in global warming impact category.

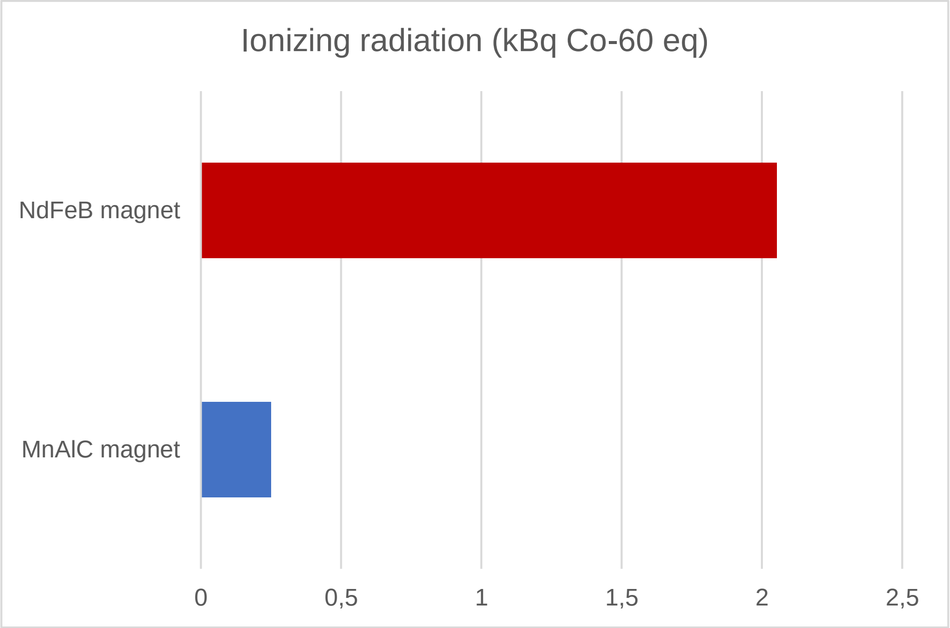

Figure 19. Impact comparison of NdFeB versus MnAlC magnet production in ionizing radiation impact category.

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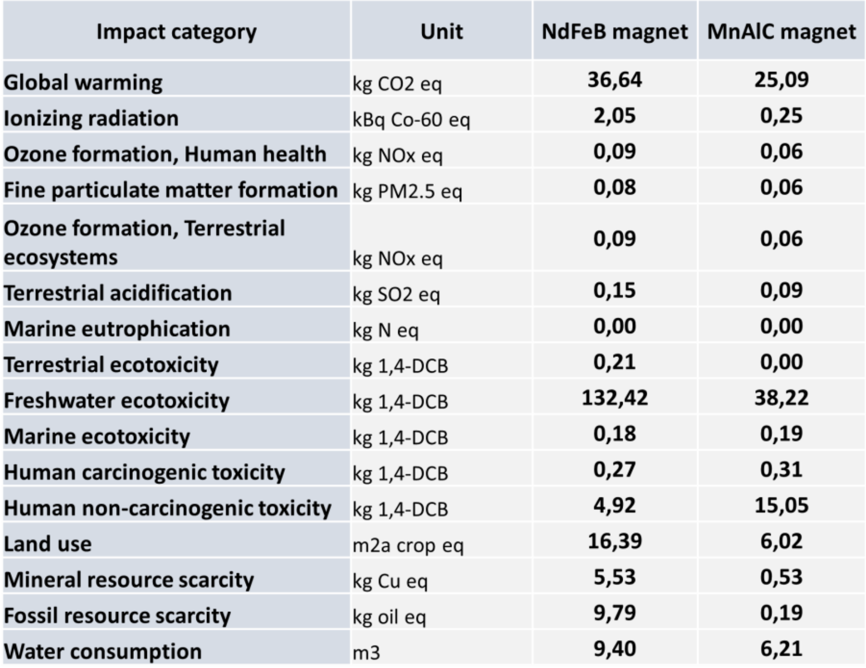
Table 3 Life cycle impacts of producing 1 kg of NdFeB magnet in comparison with 1 kg of MnAlC magnet.



Impact category	Unit	NdFeB magnet	MnAlC magnet
Global warming	kg CO2 eq	**36,64**	**25,09**
Ionizing radiation	kBq Co-60 eq	**2,05**	**0,25**
Ozone formation, Human health	kg NOx eq	**0,09**	**0,06**
Fine particulate matter formation	kg PM2.5 eq	**0,08**	**0,06**
Ozone formation, Terrestrial ecosystems	kg NOx eq	**0,09**	**0,06**
Terrestrial acidification	kg SO2 eq	**0,15**	**0,09**
Marine eutrophication	kg N eq	**0,00**	**0,00**
Terrestrial ecotoxicity	kg 1,4-DCB	**0,21**	**0,00**
Freshwater ecotoxicity	kg 1,4-DCB	**132,42**	**38,22**
Marine ecotoxicity	kg 1,4-DCB	**0,18**	**0,19**
Human carcinogenic toxicity	kg 1,4-DCB	**0,27**	**0,31**
Human non-carcinogenic toxicity	kg 1,4-DCB	**4,92**	**15,05**
Land use	m2a crop eq	**16,39**	**6,02**
Mineral resource scarcity	kg Cu eq	**5,53**	**0,53**
Fossil resource scarcity	kg oil eq	**9,79**	**0,19**
Water consumption	m3	**9,40**	**6,21**

SimaPro software was used as well as the Ecoinvent database to perform the LCA. Eighteen impact categories from the ReCiPe 1.13 Midpoint (H) method were selected for LCIA. The assessment is based in literature review and further assumptions. Although this study provides quantitative measurement of environmental impacts, due to the assumptions and uncertainties inherent to LCA, it delivers a qualitative, ‘relative magnitude’ comparison of environmental impacts for the production of NdFeB and MnAlC magnet. The results represent a preliminary assessment for the development of green magnets able to significantly contribute to an effective sustainability transition.

4.4 LIFE CYCLE ASSESSMENT OF ILPEA PROCESS (Sr-FERRITE)

In the context of data collection ILPEA (production in Europe) provided us a report with several data regarding the synthesis of 100kg of P21B material (enhanced ferrite powder) in order to conduct an initial LCA based on their data. Figure 20 and Table 4 shows the obtained LCA results. Considering the conditions which this study took place and after observing the results of the characterized impact assessment methods of the Recipe (H) Midpoint methodology it can be concluded that from the production of 100kg of P21B material (enhanced ferrite powder) the ferrite has CO_2 emissions of 250 kgCO_2eq.

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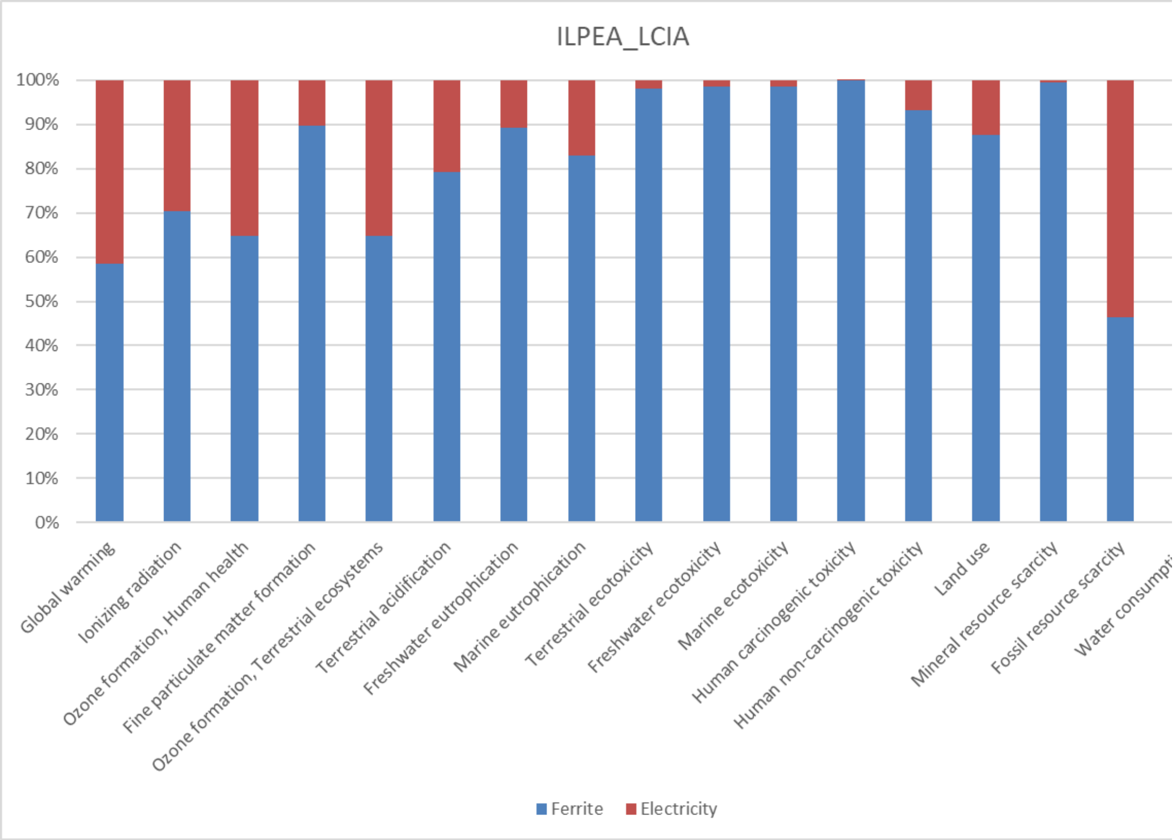

Figure 20 Life cycle impact of 1 kg P21B material production (enhanced ferrite powder).

Table 4 LCA results of 1 kg P21B material production (enhanced ferrite powder).

.

Impact category	Unit	Total	Ferrite	Electricity
Global warming	kg CO2 eq	**4,27**	**2,50**	**1,77**
Ionizing radiation	kBq Co-60 eq	**0,24**	**0,17**	**0,00**
Ozone formation, Human health	kg NOx eq	**0,02**	**0,01**	**0,07**
Fine particulate matter formation	kg PM2.5 eq	**0,01**	**0,01**	**0,01**
Ozone formation, Terrestrial ecosystems	kg NOx eq	**0,02**	**0,01**	**0,00**
Terrestrial acidification	kg SO2 eq	**0,01**	**0,01**	**0,01**
Marine eutrophication	kg N eq	**0,00**	**0,00**	**0,00**
Terrestrial ecotoxicity	kg 1,4-DCB	**0,00**	**0,00**	**0,00**
Freshwater ecotoxicity	kg 1,4-DCB	**16,41**	**16,11**	**0,00**
Marine ecotoxicity	kg 1,4-DCB	**0,57**	**0,56**	**0,30**
Human carcinogenic toxicity	kg 1,4-DCB	**0,84**	**0,83**	**0,01**
Human non-carcinogenic toxicity	kg 1,4-DCB	**34,21**	**34,19**	**0,01**
Land use	m2a crop eq	**3,58**	**3,34**	**0,02**
Mineral resource scarcity	kg Cu eq	**0,10**	**0,09**	**0,25**
Fossil resource scarcity	kg oil eq	**0,13**	**0,13**	**0,01**
Water consumption	m3	**1,20**	**0,56**	**0,00**

4.5 LIFE CYCLE ASSESSMENT OF METALPINE PROCESS (MnAlC)

In the context of data collection METALPINE provided us the data regarding тhe metal powder production by gas atomization of MnAlC in order to conduct an initial LCA based on their data. Figure 21 and Table 5 shows the obtained LCA results. the conditions which this study took place and after observing the results of the characterized impact assessment methods of the Recipe (H) Midpoint methodology it can be concluded that from the production of 10kg metal powder by gas atomization the Aluminium has the highest CO_2 emissions with 53.4 kgCO2eq.

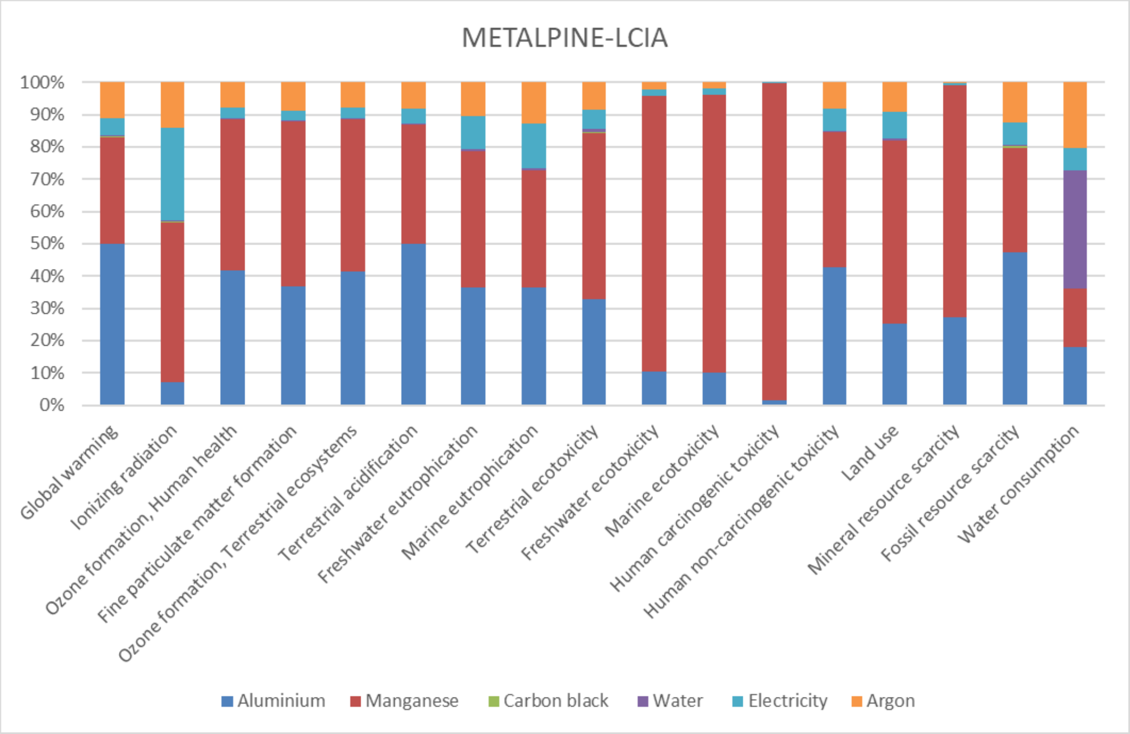

Figure 21 Life cycle impact of 1 kg metal powder production by gas atomization.

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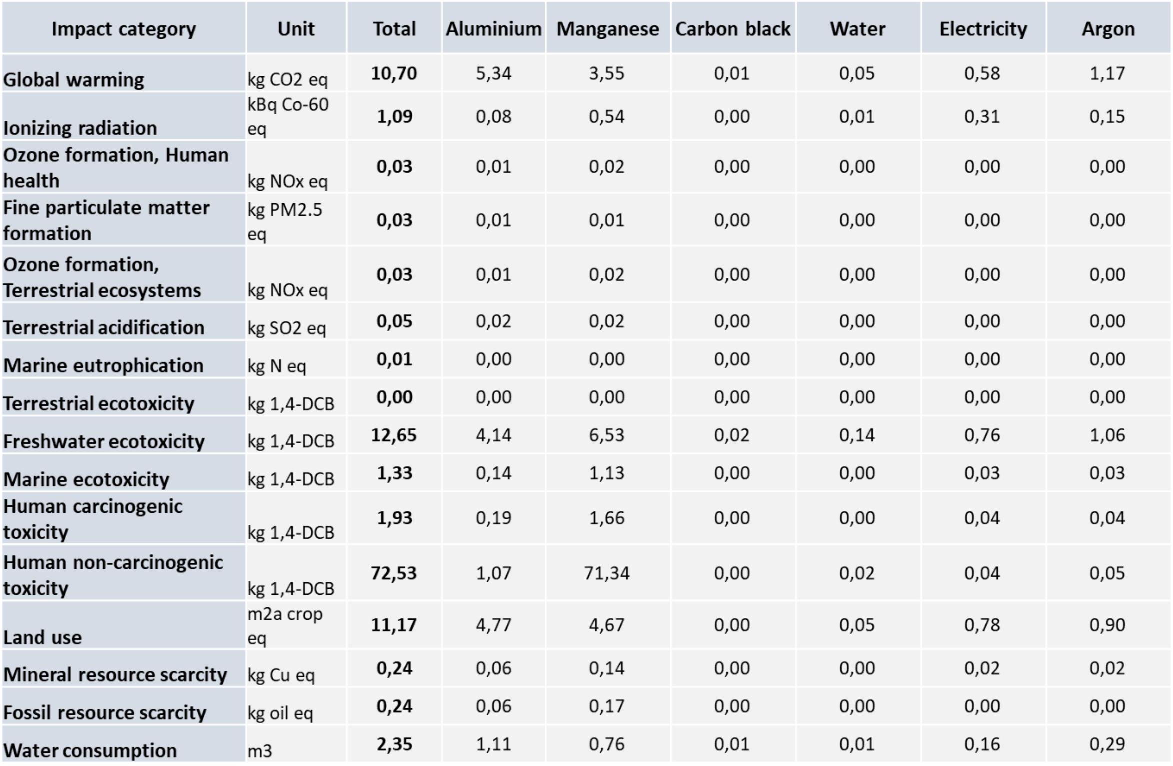
Table 5 LCA results of 1 kg metal powder production by gas atomization.



Impact category	Unit	Total	Aluminium	Manganese	Carbon black	Water	Electricity	Argon
Global warming	kg CO2 eq	**10,70**	5,34	3,55	0,01	0,05	0,58	1,17
Ionizing radiation	kBq Co-60 eq	**1,09**	0,08	0,54	0,00	0,01	0,31	0,15
Ozone formation, Human health	kg NOx eq	**0,03**	0,01	0,02	0,00	0,00	0,00	0,00
Fine particulate matter formation	kg PM2.5 eq	**0,03**	0,01	0,01	0,00	0,00	0,00	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	**0,03**	0,01	0,02	0,00	0,00	0,00	0,00
Terrestrial acidification	kg SO2 eq	**0,05**	0,02	0,02	0,00	0,00	0,00	0,00
Marine eutrophication	kg N eq	**0,01**	0,00	0,00	0,00	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	**0,00**	0,00	0,00	0,00	0,00	0,00	0,00
Freshwater ecotoxicity	kg 1,4-DCB	**12,65**	4,14	6,53	0,02	0,14	0,76	1,06
Marine ecotoxicity	kg 1,4-DCB	**1,33**	0,14	1,13	0,00	0,00	0,03	0,03
Human carcinogenic toxicity	kg 1,4-DCB	**1,93**	0,19	1,66	0,00	0,00	0,04	0,04
Human non-carcinogenic toxicity	kg 1,4-DCB	**72,53**	1,07	71,34	0,00	0,02	0,04	0,05
Land use	m2a crop eq	**11,17**	4,77	4,67	0,00	0,05	0,78	0,90
Mineral resource scarcity	kg Cu eq	**0,24**	0,06	0,14	0,00	0,00	0,02	0,02
Fossil resource scarcity	kg oil eq	**0,24**	0,06	0,17	0,00	0,00	0,00	0,00
Water consumption	m3	**2,35**	1,11	0,76	0,01	0,01	0,16	0,29

4.6 LIFE CYCLE ASSESSMENT OF LCM PROCESS (MnAlC)

In the context of data collection LCM provided us the data regarding the metal powder production by casting in order to conduct an initial LCA based on their data. Figure 22 and Table 6 shows the obtained LCA results. Considering the conditions which this study took place and after observing the results of the characterized impact assessment methods of the Recipe (H) Midpoint methodology it can be concluded that from the production of 7kg metal powder a total of 90.16 kg CO2 are produced.

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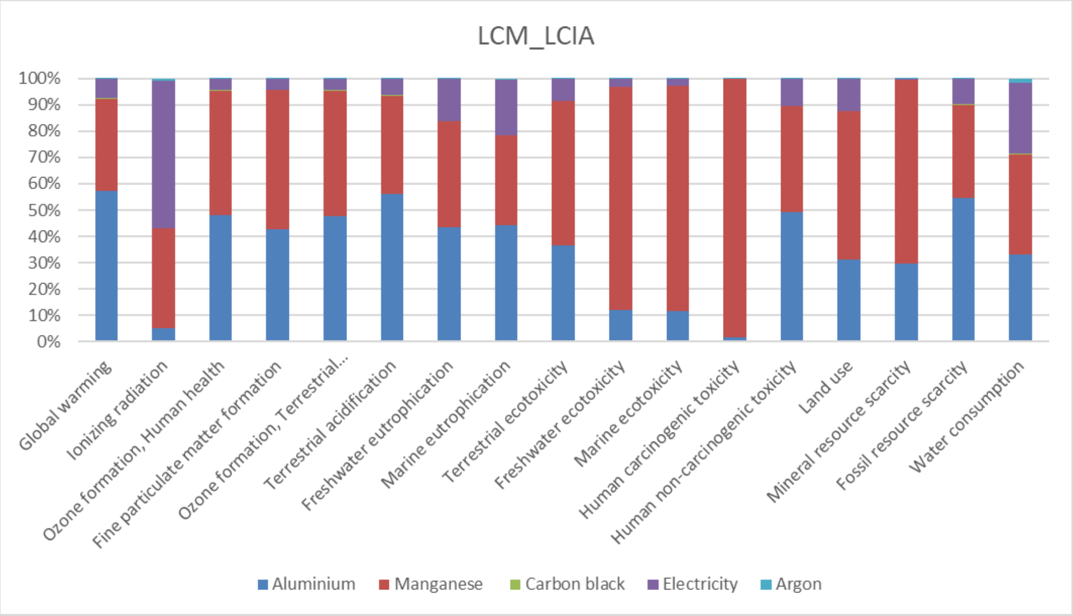

Figure 22 Life cycle impact of 1kg metal powder production by casting.

Table 6 LCA results of 1 kg metal powder production by casting.

Impact category	Unit	Total	Aluminium	Manganese	Carbon black	Electricity	Argon
Global warming	kg CO2 eq	**12,88**	7,36	4,53	0,01	0,96	0,02
Ionizing radiation	kBq Co-60 eq	**0,93**	0,05	0,35	0,00	0,52	0,01
Ozone formation, Human health	kg NOx eq	**0,04**	0,02	0,02	0,00	0,00	0,00
Fine particulate matter formation	kg PM2.5 eq	**0,03**	0,01	0,02	0,00	0,00	0,00
Ozone formation, Terrestrial ecosystems	kg NOx eq	**0,04**	0,02	0,02	0,00	0,00	0,00
Terrestrial acidification	kg SO2 eq	**0,06**	0,03	0,02	0,00	0,00	0,00
Marine eutrophication	kg N eq	**0,01**	0,00	0,00	0,00	0,00	0,00
Terrestrial ecotoxicity	kg 1,4-DCB	**0,00**	0,00	0,00	0,00	0,00	0,00
Freshwater ecotoxicity	kg 1,4-DCB	**14,83**	5,40	8,13	0,02	1,25	0,03
Marine ecotoxicity	kg 1,4-DCB	**1,45**	0,18	1,23	0,00	0,04	0,00
Human carcinogenic toxicity	kg 1,4-DCB	**2,11**	0,25	1,80	0,00	0,06	0,00
Human non-carcinogenic toxicity	kg 1,4-DCB	**79,12**	1,35	77,70	0,00	0,07	0,00
Land use	m2a crop eq	**12,67**	6,22	5,13	0,00	1,30	0,03
Mineral resource scarcity	kg Cu eq	**0,27**	0,08	0,15	0,00	0,03	0,00
Fossil resource scarcity	kg oil eq	**0,26**	0,08	0,18	0,00	0,00	0,00
Water consumption	m3	**2,77**	1,51	0,98	0,01	0,26	0,01

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 [1].

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 [2].

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 2031**. We considered the European and global limits.

5.5 DATA COLLECTION

Figure 23 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.

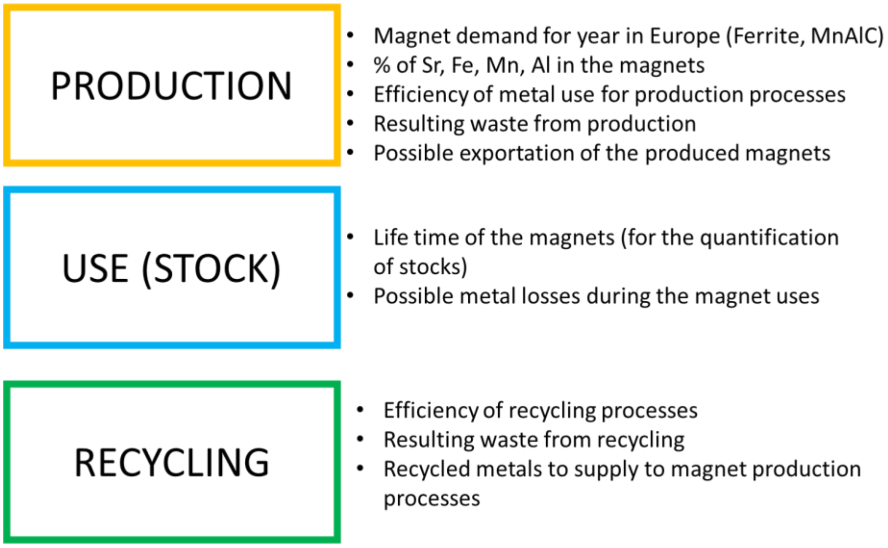

Figure 23 Summary of necessary data to perform the numerical MFA

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*106 tons per year [3–5]. 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 [6]. As reported in Table 7, 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 applications [7]. According to a new report written by Expert Market Research, it is expected an increase of ferrite demand up to 1.44 *106 by 2026 [5]. The report on the future market insights describes an expected global market increase up to 5.2% by 2031 [6,8].

Table 7 Application of ferrite magnets (Average lifetimes adapted from [9])

Product category	Product	Average lifetime
Automotive motors **($1.3*10^5$ tons)**	Starter motors	16
	Small electric motors	16
	Actuators and sensors	16
	Dynamos	16
Appliance motors **($1.0*10^5$ tons)**	Microphones	4
	Loudspeakers	4
	Holding magnets	4
	Toys	4
HVAC motors **($9.6*10^4$ tons)**	Washing machines	11
	Refrigerators	12
	Magnetron in microwave ovens	8
	Air conditioner	10
Industrial & commercial motors **($8.8*10^4$ tons)**	Machines tools	20
	Small electric motors	20
	Transformers	20
	Actuators and sensors	20
	Magnetic separators	20
Others ($2.5*10^5$ tons)	-	-

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Manufacture details

The literature is rich in technologies aim at the PM manufacturing, as summarized in Table 8 which reports the most common techniques and the related magnetic properties (Figure 24).

Table 8. 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]
[10]	$SrFe_{12}O_{19}$	Conventional (Thermal sintering)		0.38 T	3.4	4.21
[11]	$SrFe_{12}O_{19}$ · SiO2	Conventional (Thermal sintering)		54	1.70	
[12]	$SrFe_{12}O_{19}$· 0,2%PVA·0,6%SiO2	Ceramic processing route with two-step sintering	58	46	2.05	
[13]	$SrFe_{12}O_{19}$	Microwave-assisted calcination route	54,8	29,52	5.3	
[14]	$SrFe_{12}O_{19}$	Microwave sintering	50,43		5.5	
B.Grindi	M- $SrFe_{12}O_{19}$	Microwave sintering	64		1.20	
[15]	SrM ferrite fine particles (1.0%La_2O_3 .0.1%Co_3O_4)	Spark Plasma sintering		0.32 T	4.10	2.29
[16]	$SrFe_{12}O_{19}$	Spark Plasma sintering	73,6	65,8	2.10	2.75
[17]	$SrFe_{12}O_{19}$	Hydrothermal: Sol-gel precursor coating technique	64,5		4.9	
[18]	$SrFe_{12}O_{19}$	Hydrothermal	72,2	44,764	2.2	1.20

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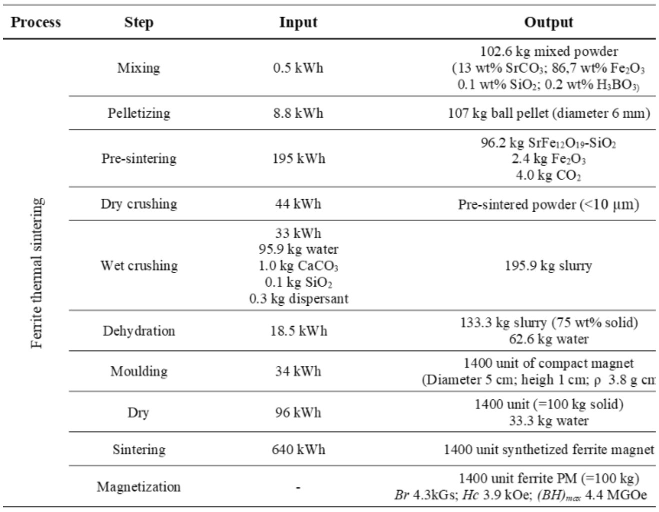

Process	Step	Input	Output
Ferrite thermal sintering	Mixing	0.5 kWh	102.6 kg mixed powder (13 wt% $SrCO_3$; 86,7 wt% Fe_2O_3 0.1 wt% SiO_2; 0.2 wt% H_3BO_3)
	Pelletizing	8.8 kWh	107 kg ball pellet (diameter 6 mm)
	Pre-sintering	195 kWh	96.2 kg $SrFe_{12}O_{19}$-SiO_2 2.4 kg Fe_2O_3 4.0 kg CO_2
	Dry crushing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

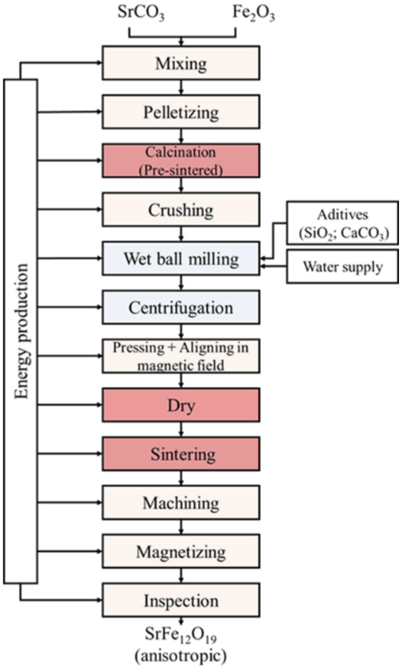

Figure 24 Ferrite PM sintering route (block diagram and the related mass and energy balances). Functional unit: 100 kg of anisotropic magnets products

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 [19].

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 [20,21]. 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 [22]. It was assumed a **15% of ferrite scraps** (compared to the input of ferric oxide) due to the mechanical operations of grinding [23]. **Scraps are usually collected and sold for use in new material production, often for lower quality applications** [20]. Therefore, **the manufacturing losses can be considered near-zero.**

As concern the raw material productions, Table 9 summarizes important information to better understand the worldwide situation of both Fe and Sr.

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Table 9. Information about mining and refinery of Fe and Sr.

	Fe	Sr
Main world reserves	Brasil 26% [24] Australia 20% Canada 14%	China (around 100%) [25]
Primary producer	Australia 39% [24] Brasil 17% India 10% China 7%	Spain 31% [24,26] Iran Islamic Rep. 30% China 19%
Main refinery producer	China 54% [24]	n.a.
Eu reserves	1% [24]	n.a.
Eu primary prod	1.8% [24]	33.4% [24]
Au refinery prod	8.1% [24]	n.a.
Main uses	Construction 35% [24] Automotive 19% Mech. Engineering 15% Metalware 15% Tubes 10% Others 6%	Magnets 36% [24] Pyrotechnics 36% Zn Production 7% Master alloys 7% Pigments 7% Others 7%

5.6.2 Stocks (uses)

The definition of stock is “The total amount of materials sored in a process” [2]. The characteristic of a stock is strongly correlated to the lifespan of products, which varies on the Ferrite application basis, as showed in Table 7. 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

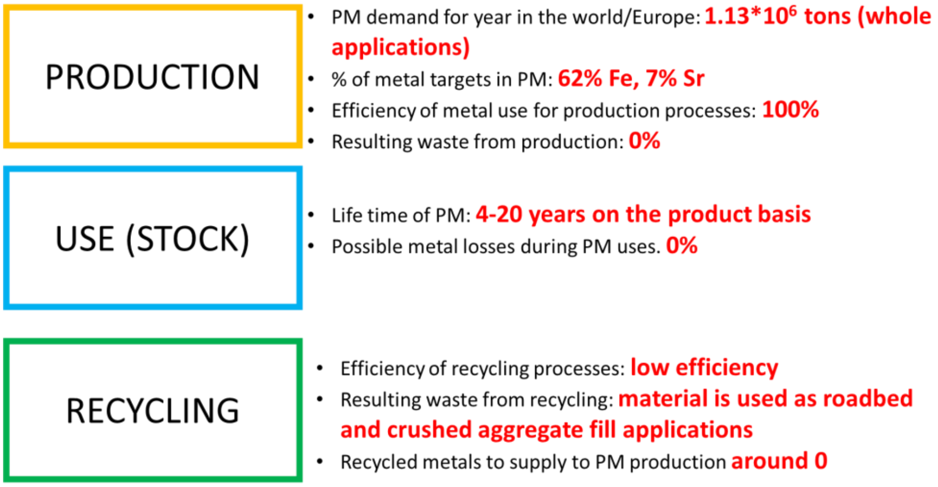
The recycling processes can be developed for both the treatment of **manufacturing scraps** and the end-of-life products. As concerns the first category of scraps, the production section explains as a 15% of ferrite magnets residue can results from a common production process. Usually, this material 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 [27].

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** [28]. Figure 25 summarizes the main data collected about ferrite PM flows.



PRODUCTION

- PM demand for year in the world/Europe: **$1.13*10^{6}$ tons (whole applications)**
- % of metal targets in PM: **62% Fe, 7% Sr**
- Efficiency of metal use for production processes: **100%**
- Resulting waste from production: **0%**

USE (STOCK)

- Life time of PM: **4-20 years on the product basis**
- Possible metal losses during PM uses. **0%**

RECYCLING

- Efficiency of recycling processes: **low efficiency**
- Resulting waste from recycling: **material is used as roadbed and crushed aggregate fill applications**
- Recycled metals to supply to PM production **around 0**

Figure 25 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,

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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** [29]. The forecast talks about a possible **market increase between 2021 and 2031 around 60%** [30,31]. Each unit needs around 300 g of permanent magnet [32] with a content of 30% of Nd [33], 4% Dy [34], 7% Pr [35]. 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 [36]. 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 ton, 2 ton, 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) [37]. 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 [40]) is translated into a consumption of **392 tons of Nd, 181 of Dy** [37] **and 65.8 of Pr, in 2021**. The lowest quantity of Pr consumption is due to its (possible) role as partial substitute of Nd [41] (only in some cases) [42].

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** [43]. 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) [44,45]. This kind of system has an average weight of **55g with 25% of Nd and 0.05% of Dy** [9], translated into a consumption of about **10 tons of Nd and 20 kg of Dy in 2021**.

On the application basis, Table 10 summarizes the average lifespans that will be considered for the MFA.

Table 10 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 [49,50]. As concern Nd, Dy and Pr production as raw materials, Table 11 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 [49]. Overall, the REE recovery from minerals to magnet production ranges from 50-84% [51].

Table 11 Information about mining and refinery of Nd, Dy and Pr.

	Nd	**Dy**	**Pr**
Main world reserves	China 34% Vietnam 17% Russia 16% Brazil 16% [52]	China 34% Vietnam 17% Russia 16% Brazil 16% [52]	China 34% Vietnam 17% Russia 16% Brazil 16% [52]
Primary producer	China 93% [24] UK 3%	China 68% Japan 18% UK 6% [23]	China 93% [24] UK 3%
Main refinery producer	China 99% [24]	China 99% [24]	China 99% [24]
Eu reserves	-	-	-
Eu primary prod	-	-	-
Eu refinery prod	-	-	-
Main uses	Magnet 71% Ceramics 12% Catalysts 10% Batteries 3% Others 4% [24]	Magnets 99% [24]	Magnet 24% Ceramics 15% Batteries 12% Metal alloys 11% Autocatalysts 10% Others 28% [24]
Worldwide production 2019	35,000 tons	2,500 tons	11,000 ktons

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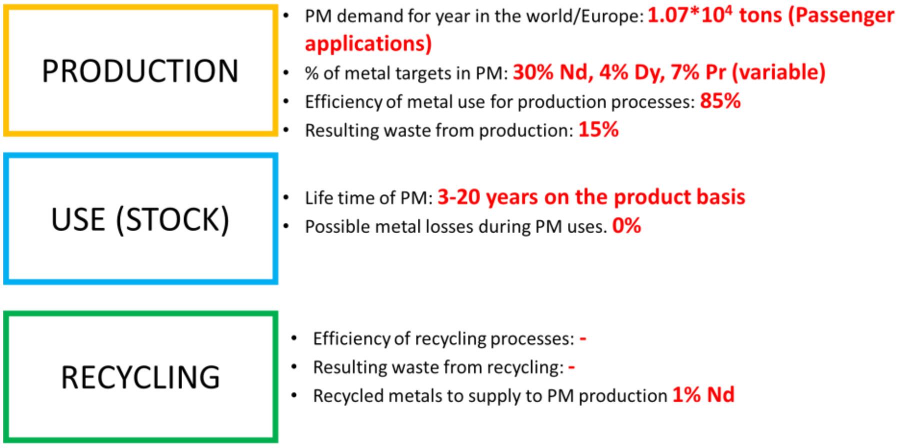
5.7.2 Stock (uses)

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 7. 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 [24]. 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 [40,53], 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) [53], 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 26 summarizes the main data collected about NdFeB PM flows.



- PM demand for year in the world/Europe: **$1.07*10^4$ tons (Passenger applications)**
- % of metal targets in PM: **30% Nd, 4% Dy, 7% Pr (variable)**
- Efficiency of metal use for production processes: **85%**
- Resulting waste from production: **15%**

- Life time of PM: **3-20 years on the product basis**
- Possible metal losses during PM uses. **0%**

- Efficiency of recycling processes: **-**
- Resulting waste from recycling: **-**
- Recycled metals to supply to PM production **1% Nd**

Figure 26 Summary of NdFeB PM data collected (Nd, Dy, Pr)

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6 CONCLUSIONS

Discussions among WP4 partners through physical and remote meetings lead to the definition of key elements to set the basis for the techno-economic, sustainability, health and safety assessments. Several online meetings took place until the D4.2 was issued and have been complemented by email communications. Deliverable D4.2 summarizes the outcome of the internal WP4 meetings together with specific contributions of industrial partners in regard to the scope description of their task(s). In addition, the definition of the needed data for LCI has been identified, as the use of data generated through LCI. It was highlighted during many WP4 meetings that the not provision of figures and data such as costs, mass balances, materials flow required to carry out the LCA/MFA analysis by industrial partners will mean a possible lack of comprehensive information about the framework on techno-economic and environmental assessment. WP1 and WP2 partners were needed to be guided in order to complete the surveys conducted by WP4. As a result of confidentiality reasons, some industrial partners information was not provided and not included in the framework of this deliverable (D4.2), but this fact doesn't comprise the reliability and accuracy of the framework presented. The present Deliverable presented the results of MFA at month 24. The collected data from the literature meet the objectives of the three considered block: production, use and recycling of the considered PM kinds. Further steps will include:

- The elaboration of the collected data by suitable software for MFA

- The creation of MFA forecast, able to integrate the PASSENGER stakeholder results, to quantify the positive effect on the reduction of REE demand. With this aim, we will need information about the possible product substitutions, the life cycle of the innovative products (with hypothesis about lifespan, recyclability level, material losses during their life).

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7 REFERENCES

[1] 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.

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

[3] 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.

[4] 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.

[5] 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.

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

[7] 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.

[8] 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.

[9] 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.

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

[11] 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.

[12] 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.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

[17] 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.

[18] 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.

[19] L. Zhou, Y. Zhou, A. Cheng, Preparation method of permanent magnetic ferrite, CN103265277B, n.d.

[20] 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.

[21] 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.

[22] 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.

[23] 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.

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

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

[26] 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.

[27] 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.

[28] 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.

[29] 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).

[30] 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.

[31] Statista, Projections for the global electric bike market between 2018 and 2030, 2022. https://www.statista.com/statistics/1261084/global-e-bike-market-forecast/.

[32] 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.

[33] 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.

[34] 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.

[35] 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.

[36] 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).

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

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

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

[40] 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.

[41] 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).

[42] 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.

[43] ISFORT-Italian higher education and research institute for transport, Mobility report 2020, 2020. https://www.isfort.it/wp-content/uploads/2020/12/RapportoMobilita2020.pdf.

[44] Future Market Insights, Magnetic drive pump market, 2021. https://www.futuremarketinsights.com/reports/magnetic-drive-pump-market.

[45] Straits research, Magnetic drive pump market, 2022. https://straitsresearch.com/report/magnetic-drive-pump-market.

[46] 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).

[47] 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).

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

[49] 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.

[50] 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.

[51] 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.

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

[53] 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.

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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 (ecosystems)	[note: this method is classified as interim] 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 radionucleide emitted (PAF m^3 year/kg). Fate of

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		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.

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ANNEX 2

Indicators and Units of each SimaPro methodology.

Indicators	Methodology ReCiPe (H) Midpoint - Characterization	Description
Climate change	kg CO_2 eq[11]	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

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[11] Carbon dioxide (CO_2) equivalent is a measure of how much a gas contributes to global warming, relative to carbon dioxide. CO_2e is a term for describing different greenhouse gases in a common unit. For any quantity and type of greenhouse gas, CO_2e signifies the amount of CO_2 which would have the equivalent global warming impact.

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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^{2}a	Occupation, mineral extraction site
Urban land occupation	m^{2}a	Occupation construction site
Natural land transformation	m^2	Transformation
Water depletion	m^3	
Metal depletion	kg Fe eq	
Fossil depletion	kg oil eq	