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Doctoral Dissertation  
Doctoral Program in Energy Engineering (35<sup>th</sup> Cycle)

# **Critical raw materials and strategic technologies. Theoretical and practical approaches towards the green transition**

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A handwritten signature in black ink, enclosed in a thin black rectangular border. The signature is cursive and appears to read 'Umberto Eynard'. Below the signature is a horizontal dotted line.

Umberto Eynard  
Turin, October 24, 2023



# Abstract

The transition towards a climate neutral economy by 2050 and EU's commitments to global climate action under the Paris agreements are determining important changes in the European industrial ecosystems with unprecedented effects to the environment and the society.

The development of strategic technologies towards a green and digital future requires growing quantities of energy and critical raw materials for their deployment at a larger scale.

An additional fact is the particular period in history that has characterized years since 2019. At a short distance in time two important disruptive events struck Europe such as the Covid-19 pandemic and then the conflict inside Ukrainian territories in 2022. Both determined an increased geopolitical instability and scenarios that were previously considered simple possibilities have become the reality. Alongside the sustainability objectives as defined by the United Nations Sustainable Development Goals and the European Green Deal, the concepts of self-sufficiency, resilience and strategic autonomy have gained increasing importance within the policy agendas. This has accelerated the need to produce sound mechanisms to give timely and effective answers and at the same time has posed the question how and to which degree the theoretical approaches proposed in the past can be at the height of present expectancy.

Critical raw materials are one of the fundamental blocks of this transition period and their management at political level is influencing the different dimensions of future technological, environmental and social challenges and geopolitical stability.

The dissertation investigates the role of methodologies, software tools and indicators to obtain results in terms of evaluations, choices, decisions, and actions in the path towards the climate neutrality transition considering the role of critical

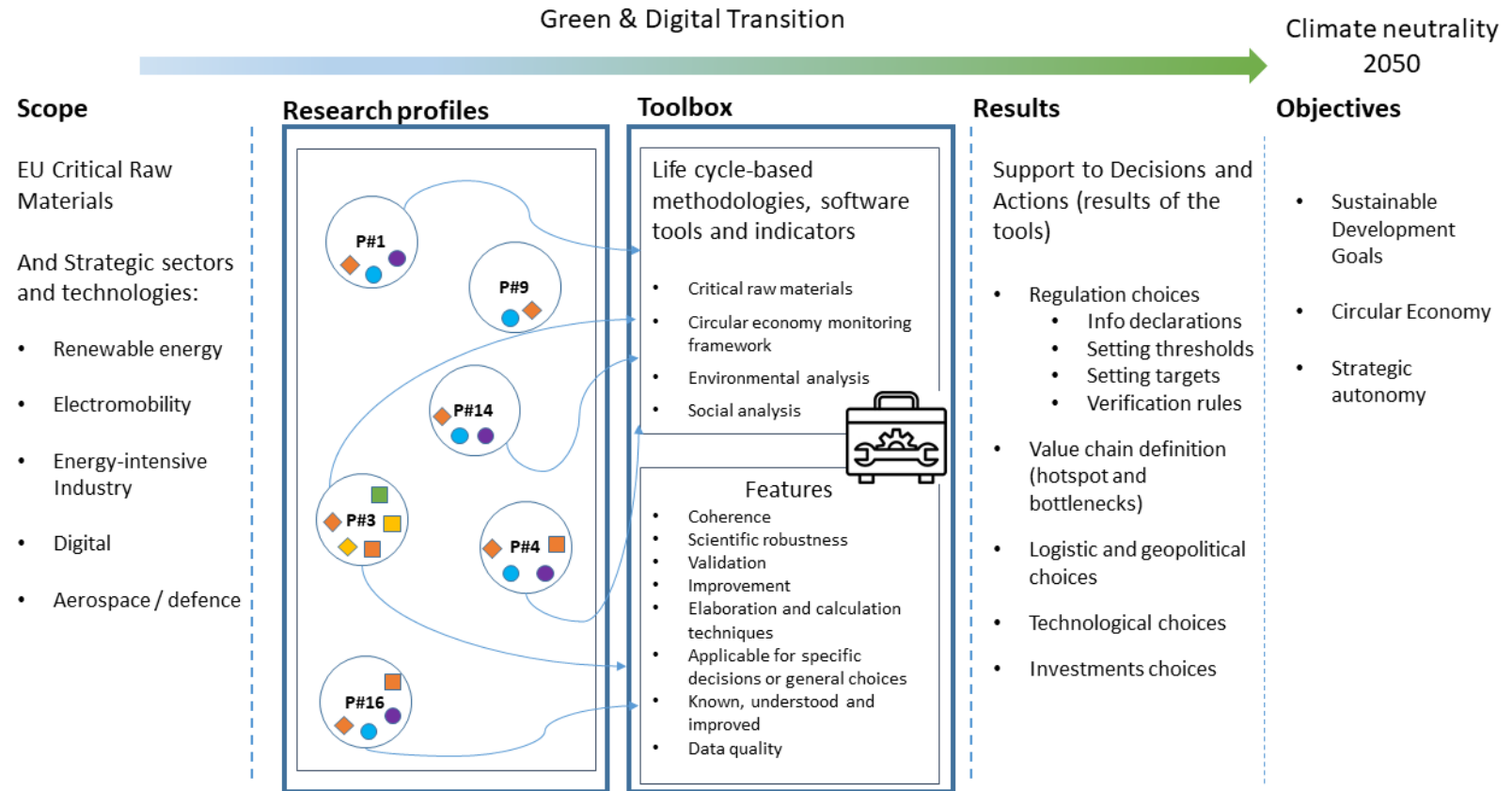
raw materials and strategic technologies in four different dimensions: technological, environmental, social and geopolitical.

Based on several theoretical approaches and practical calculation techniques defined in literature, this work gathers and analyses the methods and software tools and indicators that have been developed or applied in a three years period from 2019-2023. All tools are used to investigate problems of the four considered dimensions related to raw materials supply, such as their environmental compatibility, social impacts and ensure sustainable practises also through innovative technologies and circular economy strategies. Particularly innovative here are the considerations on circular economy mitigation strategy in addition to recycling with the proposal of a circularity index, the development of a bridging tool as a combination of criticality assessment, material flow analysis and life cycle assessment, and the conversion of environmental footprint method into policy requirements for Photovoltaics. A multi-criteria approach is considered as a *conditio sine qua non* to quantitatively understand the complexity of globalised value chains and to provide policy makers with reliable results and solid arguments. This brings us to interpret the various approaches, methodologies, software tools and indicators as components of a toolbox.

Tools can be selected and grouped together in a toolbox with rather homogeneous categories that can help choose which is more adequate to use situation per situation and suggest improvements based on commonalities and differences.

Although improvable in the future, the novelty of this work is the comparative analysis of tools and their application with the identification of profiles and scenarios. This method of analysis and categorization could be reviewed along with the introduction of new tools and the increase in complexity of the problems that shall be faced in relation with green transition. This plethora has stimulated the interest to widen the knowledge and deepen the comparative and integrative analysis, although these are the first hints. In particular the availability and quality of data appears to be considered one of the most critical aspects that influence the reliability and significance of results. The toolbox represents a didactic value, since the analysis of critical raw materials needs to take into account all these views. Finally, further research is required to enlarge the set of tools under study considering future evolutions, applications, their interoperability and integration, especially if a path towards input data standardisation could prove successful.

Figure 1: Graphical abstract





# Acknowledgment

First of all, I want to thank Professor Gian Andrea Blengini for giving me the possibility to devote my research activities in such an interesting and fascinating subject, for involving me in several didactic activities at Politecnico di Torino and for the international connections that represented an important experience for me.

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I am grateful to all the colleagues at the JRC with whom I am always sharing very good discussions, continuous working challenges and enjoying nice moments. Their passion and high professionalism are a continuous source of energies and inspiration.





*Alla mia famiglia,  
A Giulia, Giosuè e Cesare*

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# Chapter 1: Introduction

The historical period (2019-2023) in which this thesis and related research activities have been developed has been characterised by quick and disruptive events within the geopolitical and technological spheres worldwide.

This thesis wants to highlight from different possible perspectives the issue related to critical raw materials in the energy and digital transition. Indeed, one of the aspects that more and more raised the attention is the issue of raw materials being fundamental blocks of the European and global economy and important to deploy the so called strategic technologies and sectors. Critical raw materials started to be increasingly cited in several EU policies in the period 2019-2023. This resulted in an urgent need of methodologies and tools to tackle the different challenges of the sustainable development objectives and definition of circular economy strategies.

The research activities carried out during the doctorate were developed at the Joint Research Centre of the European Commission in Ispra (VA) in the last three years.

In 2019, when I started my PhD studies, critical raw materials were already a high priority policy dossier in the EU and within the international community.

Since 2008, with the Raw Materials Initiative (European Commission 2008) in Europe, theoretical and methodological discussion around critical raw materials increased considerably also around the world. A few of industrialised and resource-rich countries started to compile their lists of critical/strategic materials.

For example in 2017 the European Commission updated its criticality assessment methodology (Blengini, Blagoeva, Dewulf, Torres de Matos, et al. 2017). For the third time after 2010 and 2014 also worldwide some countries such as United States, developed their own criticality assessment methodology to estimate the risk of supply disruptions for those raw materials considered important for their economy.

In some months, many of the theoretical discussions started to face real consequences of supply disruption at international level, such as the Covid-19 pandemic and the conflict within Ukrainian territories. In these difficult periods, methodologies, data and tools developed in the past years showed their effectiveness and reliability in describing the reality, in turn of showing also a need of further tool development to face disruptive events. Not only energy crisis, but raw materials dependence on third countries need policy makers to make important decisions in a limited time. What was perceived as medium-long term planning and investments, started to be an urgency and the concept of resilience and strategic autonomy came to be more important in the political agenda.

To be more precise the decisions regarded the launch by the European Commission of Critical Raw Materials Action Plan (European Commission 2020b) and the Critical Raw Materials Act (European Commission 2023a), the Chips Act (European Commission 2022a) and Strategies such as Hydrogen strategy (European Commission 2020c), Solar energy strategy (Innovation Union 2010), REPOWER EU (European Commission 2022b)). The key point of the green transition are all the initiatives raised from the European Green Deal

(European Commission 2019) having strong impacts of several sectors in the European industrial sectors.

Critical Raw Material Action Plan in 2020 (European Commission 2020b) and the creation of the European Raw Materials Alliance<sup>1</sup> started to pave the way for important investments in the field of critical raw materials and deployment of strategic technologies for the European industry. The same happened for example in the United States with a series of Executive Orders since 2017 with the signature of the “Executive Order 13817 A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals” signed by President Trump. A list of 35 critical raw materials for US was then published (Hammond and Brady 2022). Other Executive Orders were signed, among them the “Executive Order 13953 on Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries” signed by US President Donald Trump in 2020. In 2022 the US Geological Survey published a list of critical minerals. Most probably there will be an updated list in the upcoming years. List or definition of critical/strategic raw materials have been publicly or confidentially identified in the most industrialised countries such as Japan, China, India, Canada, and Australia. China for example established its first official list of 24 strategic minerals in 2016. This list is based on six different criteria to define “strategic materials”, among them importance for strategic sectors, supply risk and substitutability (Andersson 2020).

In 2009 the Ecodesign Directive (European Union 2009) was released with the aim at developing provisions to improve the energy efficiency and environmental performance of the products put in the European Union market. It is also relevant to see how the Ecodesign requirements have often been revised to tackle not only aspects of energy efficiency, but also considering material efficiency, critical raw materials and aiming at identifying strategic autonomy aspects. The Ecodesign requirements are then applied on different product groups and for each product group specific analysis and specific parameters need to be considered. For example it is important to flag some circular economy strategies (such as reuse, recycled content, recyclability, remanufacturing, ability to disassemble, etc.) which might have a more positive impact for some product groups than others.

Built on the Ecodesign Directive, the proposal for a new Ecodesign for Sustainable Products Regulation<sup>2</sup> published on March 30<sup>th</sup> 2022 has the aim to set a framework to more environmentally sustainable and circular products.

It is important then to rely on robust and well established methodologies, software tools and indicators to analyse the value chains and to measure the environmental and social performances along each step. Regarding resource efficiency it is fundamental to set indicators to monitor progress towards circular economy by measuring the effectiveness of the strategies put in place. Material flow analysis and material system analysis are some of the powerful tool to be selected.

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<sup>1</sup> Available at: <https://erma.eu/>

<sup>2</sup> Available at: [https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation\\_en](https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en)

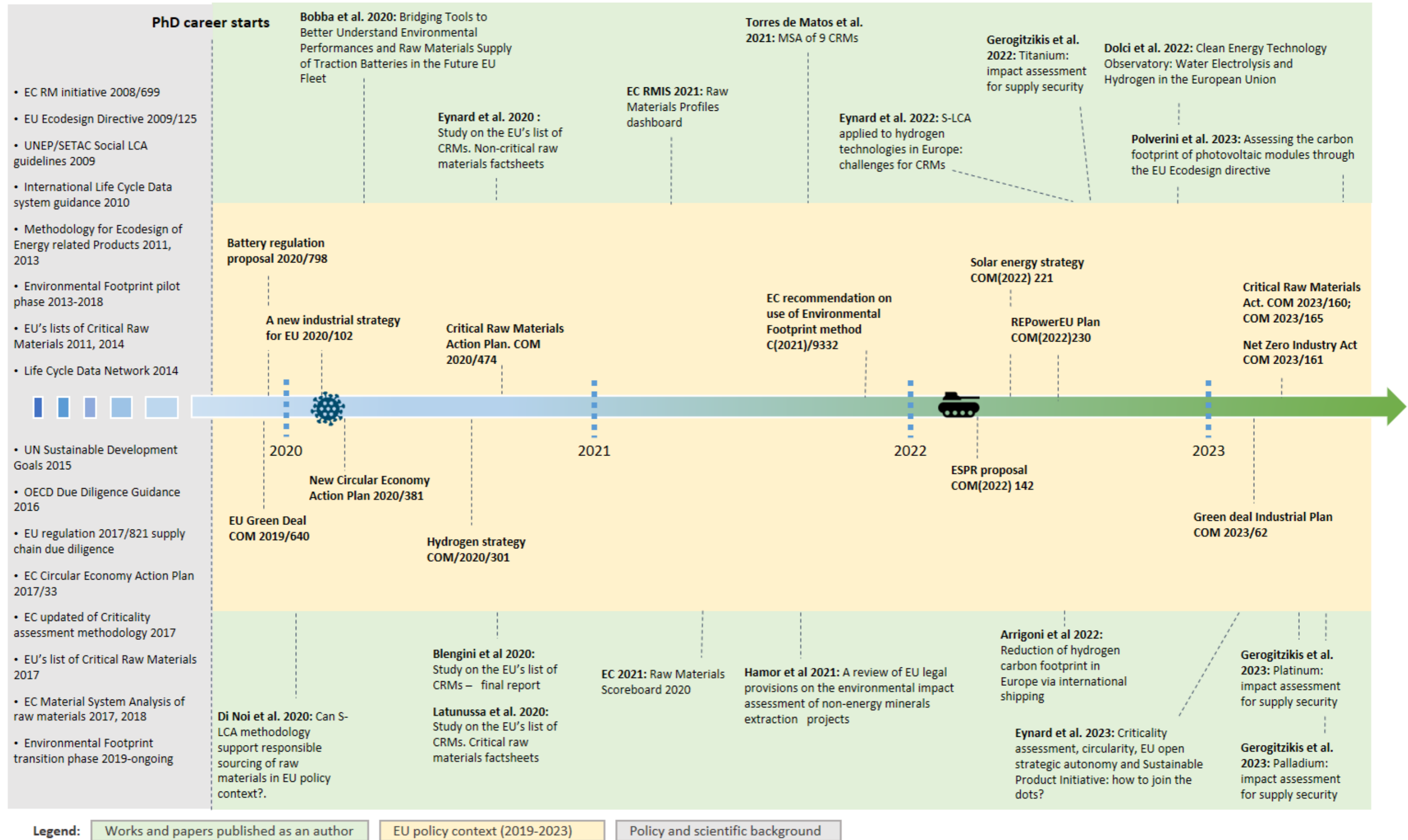
In general, it is clear that life cycle-based approaches in such kind of analysis are the basis to build on further methodological improvements and developments. For what concerns the environmental and social impacts Life Cycle Assessment is a well-established methodology that allows highlighting and measuring impacts along the supply chains. Nonetheless, when these aspects need to be translated into policy requirements, harmonisation and standardisation rules of the approaches and tools are needed.

The contribution of this thesis is an attempt to join the dots of methodological aspects, policy questions and implications around the issue of critical raw materials considering also sustainability aspects and circular economy strategies deployment in the new technologies which is not systematically applied in the criticality assessment methods. An holistic and integrated approach of the different dimensions of the LCA and its application in policies is also analysed in (Serenella Sala et al. 2021). The evolution towards an integrated approach and the life cycle based approaches have been continuously growing, becoming a relevant element in the implementation of future policies.

The wide range of methods and applications brings us to interpret the various approaches, techniques and methodologies as component of a toolbox.

Many of the aspects are related to some of the components of strategic sectors and technologies for the EU (e.g. lithium ion batteries, hydrogen and fuel cells technologies and permanent magnets) which contain critical and strategic raw materials. Nevertheless, the approaches treated throughout this dissertation are also valid and translated for other strategic value chains.

Figure 2: Timeline representation of the policy background in the last years relevant for the work carried out for this dissertation and list of works and scientific publications during the PhD career.



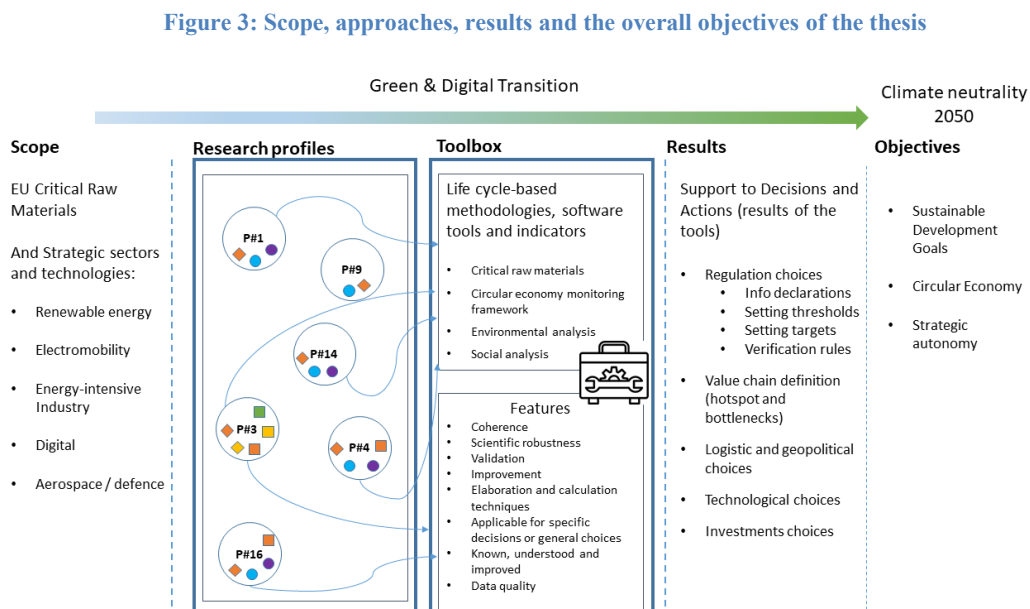
## 1.1. Objectives and outline of the thesis

The main objective of this work is to present the toolbox elaborated during the PhD studies and used to address multiple and interconnected aspects related to the critical raw materials of interest for the EC. This approach has been stimulated by the variety of themes treated in the various papers, and by the analysis of existing literature on this topic such as (Dewulf 2015), (Moraga et al. 2019), (Schrijvers et al. 2020), (Tercero Espinoza et al. 2020) and finally by subsequent reflections I made by the parallel analysis of the different problems. We shall concentrate on the logical steps, value chains, the methods, tools, sources of information and their quality, the strategies and the related policies and actions, their compatibility with circular economy and sustainability towards the green transition.

It is also relevant that the competencies and skills, which are necessary to fulfil the various steps at the basis of the scientific results that stimulate the need for timely action, are put in evidence so that public opinion is stimulated towards these topics instead of being victim of prejudices and hindering the new proposals. Students should be informed and interested in deepening their knowledge in the field, acquire the indicated culture, and develop adequate skills.

It is important that the issue of critical raw materials is well understood and therefore transparency to the steps of the process should be given. The various studies carried on during the three years cover not all but most of the steps in the general picture. Reference is made for each chart to the relevant steps.

In the following figure, we try to give an overall description of the process.



The next sections of this chapter of introduction (chapter 1) will cover:

- a list of publications (in peer-reviewed journal, JRC technical and Science for policy reports and contribution to conferences);
- brief overview of the critical raw materials and strategic technologies, both for the EU and third countries also included in the context of circular economy and sustainability analysis.

Section 1.3.1 deals with the evolution of the legislative provisions and their impacts on the methodological aspects and to face current geopolitical challenges; Section 1.3.2 is an introduction of the concept of circular economy and its possible strategies to improve resource efficiency. How these strategies can impact on the mitigation of critical raw materials and the necessity to measure and monitoring progress; Section 1.3.3 is an overview of the sustainability aspects considered in the dissertation and how environmental and social analysis throughout the life cycle of products and materials are effective when analysing complex value chains such as batteries or hydrogen technologies.

Chapter 2 will deal with the objective of the work, namely methodology, tools and indicators. The logical steps of the narrative of all the activities are then summarised towards the objective of the thesis. All the papers and works in which I contributed during these years and relevant for the development of this dissertation are summarised in research activities profiles (section 2.2) with a defined layout to make the message of the paper more direct and easy to understand for the reader. A graphical abstract has been drawn for all the profiles.

Chapter 3 describes how the different tools (methodologies, techniques and indicators) are interconnected and integrated within the proposed toolbox by with different possible configurations.

Chapter 4 wraps-up the main messages of this work and proposes some of the further analysis that would be important to carry out in the different fields.

Chapter 5 it is a collection of the three most relevant papers published in journals related to the activities performed during my doctoral career.

## **1.2. Terminology and definitions**

In this section, for the sake of clarity the most important terms and definitions used in the dissertation are presented clarify aspects discussed in the following sections. This glossary does not intend to be exhaustive of all relevant terms in the field.

**Critical raw materials (CRMs):** according to the methodology developed by the EC, a material is considered as critical for the EU if it has high economic importance to the economy of the EU and its supply is vulnerable to disruption (Blengini, Blagoeva, Dewulf, and Others 2017).

**Circular economy:** a state in which the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimised (European Commission 2021a).

End-of-life recycling input rate (EOLRIR): it reflects the contribution of recycled materials from end-of-life products to raw materials demand. It is calculated as the input of post-consumer secondary material to the total material input (primary and secondary) in the production system (European Commission 2023d).

Indicators: a key result that may be got as the result of a methodology and helps to define a situation of interest or of danger

Life Cycle Assessment (LCA): compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Material Flow Analysis (MFA): method to quantify flows and stocks of materials or substances in a system.

Methodology: the logical and technical procedure that may comprise one or more algorithms and or tools arranged in such a way adequate to get the solution of a problem

Parameter: a quantity that may have various values and allows a tool to act in different scenarios depending on the value of such quantity

Supply risk: in the EC methodology, it is calculated based on factors that measure the risk of a disruption in supply of a specific material (Blengini, Blagoeva, Dewulf, and Others 2017).

Tool: methodologies, software tools and indicators used to collect and process input data to obtain primary or secondary results useful for the aims of the analysis we want to perform

Toolbox: A set of tools that may be defined at logical and mathematical level or may be implemented in software. The tools in the toolbox may be applied separately or sequentially or alternatively to solve a specific problem. They can be combined in order to solve more complex or general problems

### **1.3. Publications**

The research works developed during the doctorate are listed in this section distinguishing them by their scope: published in scientific journals, JRC technical reports, JRC Science for Policy reports and works presented during conferences.

### 1.3.1. Publications (scientific peer-reviewed journals)

- Bobba, Bianco, **Eynard**, Carrara, Mathieux, Blengini (2020) – Bridging tools to better understand environmental performances and raw materials supply of traction batteries in the future EU fleet. *Energies* <https://doi.org/10.3390/en13102513>
- Di Noi, Cirotto, Mancini, **Eynard**, Pennington, Blengini (2020) – Can S-LCA methodology support responsible sourcing of raw materials in EU policy context?. *International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-019-01678-8>
- Polverini, Espinosa, **Eynard**, Leccisi, Ardente, Mathieux (2023) – Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign directive. *Solar Energy*. <https://doi.org/10.1016/j.solener.2023.04.001>
- Bobba, **Eynard**, Maury, Ardente, Blengini, Mathieux (2023) - Circular Input Rate: Novel indicators to monitor circularity progress in a sector. Application to rare earth elements when remanufacturing e-vehicles motors. *Resources, Conservation & Recycling*. <https://doi.org/10.1016/j.resconrec.2023.107037>

Submitted, forthcoming:

- Arrigoni Marocco, Hurtig, Buffi, **Eynard**, Andreasi Bassi, Scarlat, Dolci (2023) - Life cycle assessments use in hydrogen-related policies: the case for a harmonized methodology addressing multifunctionality

### 1.3.2. Publications (JRC technical reports and JRC Science for Policy reports)

- Georgitzikis, **Eynard**, Bobba, Perpetuo Coelho, Ingoglia, D’Elia, Garbossa (2023) - Palladium: impact assessment for supply security. EC JRC Science for policy brief - Raw materials & the war in Ukraine. JRC133117. <https://publications.jrc.ec.europa.eu/repository/handle/JRC133117>
- Georgitzikis, **Eynard**, Bobba, Perpetuo Coelho, Ingoglia, Garbossa (2023) - Platinum: impact assessment for supply security. EC JRC Science for policy brief - Raw materials & the war in Ukraine. JRC133245 <https://publications.jrc.ec.europa.eu/repository/handle/JRC133245>
- Dolci, Gryc, **Eynard**, Georgakaki, Letout, Kuokkanen, Mountraki, Ince, Shtjefni, Joanny Ordonez, Eulaerts and Grabowska (2022) - Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets. JRC130683. doi: 10.2760/7606

- Georgitzikis, D'Elia, **Eynard** (2022) - Titanium: impact assessment for supply security. EC JRC Science for policy brief - Raw materials & the war in Ukraine. JRC129594. <https://publications.jrc.ec.europa.eu/repository/handle/JRC129594>
- Vidal Legaz, Unguru, Mancini, Latunussa, Hamor, Ardenete, Mathieux, Nita, Torres de Matos, Plazzotta, Bonollo, Blengini, Pasimeni, Wittmer, **Eynard**, Garbossa, Pennington, Ciupagea (2021) - European Commission, Raw Materials Scoreboard 2020. doi: 10.2873/567799
- Torres de Matos, Devauze, Planchon, Wittmer, Ewers, Auberger, Dittrich, Latunussa, **Eynard**, Mathieux (2021) - Material system analysis of nine raw materials: Barytes, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum and Vanadium. JRC technical report. doi:10.2760/677981
- Hamor, Vidal-Legaz, Zampori, **Eynard**, Pennington (2021) – A review of EU legal provisions on the environmental impact assessment of non-energy minerals extraction projects. JRC technical report. doi:10.2760/705726
- **Eynard**, Georgitzikis, Wittmer, Latunussa, Torres de Matos, Mancini, Unguru, Blagoeva, Bobba, Pavel, Carrara, Mathieux, Blengini (2020): Study on the EU's list of CRMs – Non-critical raw materials factsheets. European Commission report. doi: 10.2873/587825
- Latunussa, Georgitzikis, Torres de Matos, Grohol, **Eynard**, Wittmer, Mancini, Unguru, Pavel, Carrara, Mathieux, Blengini (2020): Study on the EU's list of CRMs – Critical raw materials factsheets. European Commission report. doi: 10.2873/92480
- Blengini, Latunussa, **Eynard**, Torres de Matos, Wittmer, Georgitzikis, Mancini, Unguru, Blagoeva, Pavel, Carrara, Mathieux, Blengini (2020): Study on the EU's list of CRMs – final report. European Commission report. . doi: 10.2873/11619

To be submitted:

- Gama Caldas, **Eynard**, Spiliotopoulos, Blengini, Mancini, Mathieux, Ardenete, Alfieri (2023) - Review of the MEErP - Methodology for Ecodesign of Energy-related Products. JRC Technical report. Draft version available at: [https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2022-07/MEErP%20Revision%20Stakeholder%20Meeting%20230622\\_Presentation.pdf](https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2022-07/MEErP%20Revision%20Stakeholder%20Meeting%20230622_Presentation.pdf)
- **Eynard**, Gama Caldas, Spiliotopoulos, Mathieux, Ardenete, Alfieri (2023) - Ecoreport tool - Manual. JRC technical report
- Santucci, **Eynard**, Valente, Mathieux (2023) - Procedure for developing datasets related with hydrogen value chain to be shared in the Life Cycle Data Network. JRC technical report

- **Eynard**, Santucci, Arrigoni Marocco, Weidner, Mathieux (2023) - Life Cycle Assessment checklist for the projects of the Clean Hydrogen Joint Undertaking

### **1.3.3. Presentations in conference/workshops**

- **Eynard**, Maury, Ardente, Mathieux (2023) - Criticality assessment, circularity, EU open strategic autonomy and Sustainable Product Initiative: how to join the dots? International Round Table of Criticality 2023 Feb 17th. (Speaker). Scientific paper under submission on Mineral Economics journal
- Arrigoni, Weidner, Dolci, Ortiz Cebolla, **Eynard**, Mathieux (2022) - Reduction of hydrogen carbon footprint in Europe via international shipping. 23rd World Hydrogen Energy Conference.
- Martin-Gamboa, **Eynard**, Valente, Mancini, Arrigoni-Marocco, Weidner, Mathieux (2022) - Social-LCA applied to hydrogen technologies in Europe: challenges for critical raw materials. Preliminary results presented at social LCA conference Sept 2022 (Speaker) Scientific paper under submission on International Journal of Life Cycle Assessment

## **1.4. State of the Art. Criticality, circular economy and environmental and social sustainability of raw materials and strategic technologies.**

Some of the work described in this chapter was also previously published by the author in:

- (Bobba et al. 2020),
- (European Commission 2020g),
- (European Commission 2020h)
- (European Commission 2020f),
- (European Commission 2021c),
- (Gama Caldas et al. 2023),
- (Torres De Matos et al. 2021),
- (Georgitzikis, D'elia, and Eynard 2022),
- (Georgitzikis, Eynard, Bobba, Perpetuo Coelho, Ingoglia, D'elia, et al. 2023),
- (Georgitzikis, Eynard, Bobba, Perpetuo Coelho, Ingoglia, and Garbossa 2023)
- (Di Noi et al. 2020)
- (Hamor et al. 2021)
- (European Commission 2021a)

The European list of Critical Raw Materials was first issued in 2011 and since then it has been updated every three years (2011, 2014, 2017, 2020 and 2023). Due to the evident fact that conditions may vary in time in relation with availability of data or changes in the international market, some materials that were included in the list in the past may exit the list or materials that were examined in the past and not considered critical may afterwards be re-examined and enter the list (such as Lithium which was considered not critical in 2017, but it entered the list in 2020). Nevertheless, in the past editions, every three years a larger list of candidate materials was analysed and some of these materials were added to the list starting from 41 candidates in 2011 to 83 candidates in 2020.

Another action based upon the list is the stimulation of research and innovation to identify new solutions that can improve the critical situation, with new solutions or materials that may contrast scarcity or reduce costs.

To achieve the objectives of the Action Plan on Critical Raw Materials (European Commission 2020b), the European Commission outlined some actions, among them: the establishment of a European Raw Materials Alliance (ERMA)<sup>3</sup> and the 2020 List of Critical Raw Materials for the European Union that were announced on 3 September 2020. The European Raw Materials Alliance (ERMA) contributes to ensure a reliable, secure and sustainable access to raw materials.

ERMA's vision is to secure access to critical and strategic raw materials, advanced materials, and processing know-how for EU Industrial Ecosystems. Stakeholders engagement, including industrial actors along the value chain, Member States and regions, trade unions, civil society, research and technology organisations, investors and NGOs is of paramount importance (European Commission 2020b).

It is important therefore to devote significant attention to carefully analysing value chains so that bottlenecks and other problems can be identified with greater precision helping to guide research or action to overcome the limitations. In 2020, the European Commission also issued a study "Critical materials for strategic technologies and sectors in the EU - a foresight study" (European Commission 2020d) looking at the supply chains of nine technologies used in three strategic sectors for the EU: renewable energy, e-mobility, defence and aerospace.

In 2020, together with the list of critical raw materials and the EC Communication (European Commission 2020b), EC also released a study on "Critical Raw Materials for Strategic technologies and sectors in the EU". This study shows the importance of some sectors in the EU which are heavily reliant on critical raw materials.

As a consequence of the reports on critical raw materials and the three-yearly updating of the list of CRMs, the EC has issued an Act in March 2023. It is oriented to encourage and suggest action to be urgently taken in order to ensure availability of critical raw materials. Compared to the EC Communication in 2020 on CRMS, the Critical Raw Materials Act is composed of Regulation and

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<sup>3</sup> <https://erma.eu/>

Communication. The supply of critical raw materials must become secure, diversified, affordable and sustainable.

One of the main aspects mentioned in the Act is that Critical raw materials should be subject to declaration of environmental footprint and targets related to circular economy requirements.

It is clear that the European Union cannot be autonomous for such raw materials and shall make use of imports also in the future. But exactly for this reason, it is fundamental that import rules are controlled, that different providers are identified and guaranteed as reliable trading partners. Secondary sources such as from recycling activities should be well organised and both efficient and effective. The CRM Acts is also an important part of a strategy to make European industry competitive again, according to the Green Deal Industrial Plan (European Commission 2023b). Two other pillars of this plan are the Net Zero Industry Act (European Commission 2023c) and the Reform of the EU electricity market design<sup>4</sup>.

Sharp benchmarks are defined to organise strategic raw material supply along the chain in the 2030 perspective: the annual consumption should reserve at least 10% for extraction, 40% for processing, 15% for recycling and mainly not more than 65% of each strategic raw material at any relevant stage of processing from a single country.

The Regulation part of the act is divided in six parts:

1. The first part contains the proposal for a regulation of the European Parliament and of the council establishing a framework for ensuring secure and sustainable supply of critical raw materials.
2. The second part contains six annexes to the Proposal.
3. The third part is a subsidiarity grid that accompanies the proposal.
4. The fourth part is the impact assessment.
5. The fifth part is an executive summary of the impact assessment of the previous part.
6. The sixth and final part contains the EU measures for critical raw materials and the opinion of the regulatory scrutiny board.

A specific chapter of the Regulation proposal is devoted to permanent magnets where it is defined how to set requirements on recycling and recycled content of permanent magnets.

Mining initiatives are encouraged, provided that they are compliant with the environment. In Europe thanks to this Act the bureaucratic complexity should be reduced and procedures to get permission to work on critical materials should be smoothed.

The critical raw material act promises to reduce administrative burden and simplify permitting procedures for critical raw materials. Selected strategic projects on critical raw materials will enjoy a shorter time of not more than 24

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<sup>4</sup> [https://ec.europa.eu/commission/presscorner/detail/%20en/ip\\_23\\_1591](https://ec.europa.eu/commission/presscorner/detail/%20en/ip_23_1591)

months for approval for extraction permits and of not more than 12 months for processing and recycling permits.

Measures will be encouraged in the member states to improve the collection of critical raw materials wastes and ensure recycling into secondary critical raw materials. Recovery of critical raw materials from extractive waste in current mining activities and historical mining waste sites.

Products containing permanent magnets will need to meet circularity requirements and provide information about the recyclability and recycled content.

Beyond the Regulation, the Act contains also a Communication. This part explains the overall strategic vision to strengthen the position of Europe with respect to critical raw materials supply and the actions proposed within and outside the EU.

Apart from the European Commission criticality assessment and EU dossiers there are several groups (governmental and academic entities) dealing with the issue of criticality worldwide.

It is important to mention the role of the International Round Table of Criticality<sup>5</sup> that gathers a community composed by the most prominent experts of raw materials, strategic technologies and sectors and criticality methodologies around the world.

Is an international project that through conferences that involve the world major experts on the theme advancing criticality assessment on a global level. Round table workshops and joint publications encourage research on the various approaches on criticality discussing commonalities and differences. It also examines the progress in industries and policy makers. It promotes the awareness towards material criticality, the importance of a circular economy and research and innovation efforts.

In February 2023, the conference was organised in Lille (FR) and I participated with a contribution on the prioritisation of product groups in the context of Ecodesign based on the critical raw materials content in the products.

A relevant Horizon 2020 research project aiming at developing an operational methodology for product Life Cycle Sustainability Assessment (LCSA) is the ORIENTING<sup>6</sup> project. This project was run during the period 2020-2023. The main purpose is to integrate a life cycle approach considering analysis of environmental, social and economic impacts. Along with these three analysis it also consider the possibility to integrate criticality and circularity aspects. It builds on existing initiatives and contribute to a future Product Sustainability Footprint. It considers different user's needs at three levels:

1. A qualitative “entry level” tool which introduces the idea of LC sustainability thinking & materiality assessment
2. LCSA “minimum requirements” to get started with first LCSA studies

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<sup>5</sup> <https://irtc.info/>

<sup>6</sup> <https://orienting.eu/>

### 3. A comprehensive LCSA methodology

Beyond the ORIENTING project, there are other initiatives and research studies to consider criticality of raw materials as an additional dimension to LCSA. The debate about the inclusion of criticality of raw materials into the LCA has been carried on in the past years, with different attempts.

Along with ORIENTING project, there is also another Horizon 2020 project called “Sustainability Assessment of harmonised hydrogen energy systems” (SH2E)<sup>7</sup> to provide guidelines for LCSA and prospective benchmarking of hydrogen energy systems. Among the sustainability aspects treated in these two projects, both the projects provide a thorough literature review about the availability of approaches to consider the criticality of raw materials into the LCSA.

The main reference approaches were proposed by:

- (Bach et al. 2019)
- (Koyamparambath et al. 2022)
- (Mancini et al. 2015)
- (Mancini, Benini, and Sala 2018)
- (Mori et al. 2021)
- (Santillán-Saldivar, Cimprich, et al. 2021)
- (Santillán-Saldivar, Gaugler, et al. 2021)
- (Yavor, Bach, and Finkbeiner 2021)

Another relevant aspects is how criticality assessment methods can consider aspects from LCSA. Usually, the environmental pressure of activities related to raw materials are not considered into the criticality assessment. One of the exception is the study carried out by (German Environment Agency 2020). The aim of this study was to identify an indicator reflecting a country’s mining sector governance with regard to environmental aspects. The Environmental Performance Index (EPI) was recognized as best suited.

Regarding societal aspects, criticality assessments consider for example the Worldwide Governance Indicators (WGI) to measure the level of a country’s governance in covering different dimensions such as political stability, corruption control. Some of these dimensions are already covered by the existing social LCA database, e.g. PSILCA.

EPI and WGI were also included as relevant indicators within the Raw Materials Profiles dashboard of the Raw Materials Information System (please see Profile #14 in section 2.2) to reflect the level of countries’ governance in terms of environmental and social aspects.

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<sup>7</sup> Available at: <https://sh2e.eu/>

### 1.4.1. Criticality assessment

A key work where I contributed is the study on the EU's list of critical raw materials (2020) (European Commission 2020i), (European Commission 2020h), (European Commission 2020f). The final report explains how the list of critical raw materials is produced and updated. The criteria to decide whether a raw material is critical or not depends essentially on two aspects that may vary in time and context: high economic importance of the application in which a raw material is used (economic importance) and high risk of supply disruption (supply risk). The fields that are taken into account are those considered more important for EU economy and industry, namely renewable energy, e-mobility, digital space, energy-intensive industry and aerospace/defence.

The identification of materials in the list brings to research diversification of supply in order to reduce risky dependencies. Other strategies to mitigate the supply risk are sourcing primary materials from European countries and diversify the sourcing from different third countries. Also secondary raw materials may be a mitigating factor as well as material efficiency and circular economy strategies.

Alternative materials may also be identified as substitutes of the critical material under examination.

As mentioned in Bobba et al. (2020) “available studies assessing criticality of raw materials were critically reviewed by Schrijvers et al. (2020). In this study, it is highlighted that different methods have been developed to identify criticality assessment factors and indicators at different levels (global, country or region, company, technology or specific products) (Schrijvers et al. 2020). In addition, data availability is recognised as a key factor that limits the evaluation of criticality. Proxies are needed to overcome this lack of data. Furthermore, data quality, including both data uncertainty and data representativeness, is rarely addressed in the interpretation and communication of results (Schrijvers et al. 2020). Demand growth is often considered by technology-oriented methods, but not always considered by studies focusing on a national economy. This makes this exercise suitable to describe current economic situation, disregarding the future development of the economy (Schrijvers et al. 2020).”

The European Commission also carries on periodical material system analysis. The Material System Analysis (MSA) is essentially a map containing the flows of the materials through the subsequent phases of the economic system. The MSA methodology analyses the entire lifecycle of a selected material, putting in evidence hotspots, bottlenecks and weak points. Its aim is to increase the resilience of the related supply chain. It maps and quantifies the material under study according to the following phases: extraction, processing, manufacturing, use, collection, recycling, reuse, and disposal. Material stocks are identified for: tailings, landfills, products in use phase, domestic reserves, and foreign reserves. The resulting indicators are: end of life recycling input rate, end of life recycling rate, collection rate, self-sufficiency extraction, self-sufficiency processing, self-sufficiency manufacturing. A validation process by means of workshops completes the methodology.

The EC criticality methodology applied in the Criticality assessment 2020 is a revised version of the previous methodology and adopted to assess each candidate critical raw materials and to generate a final plot where the raw materials are positioned.

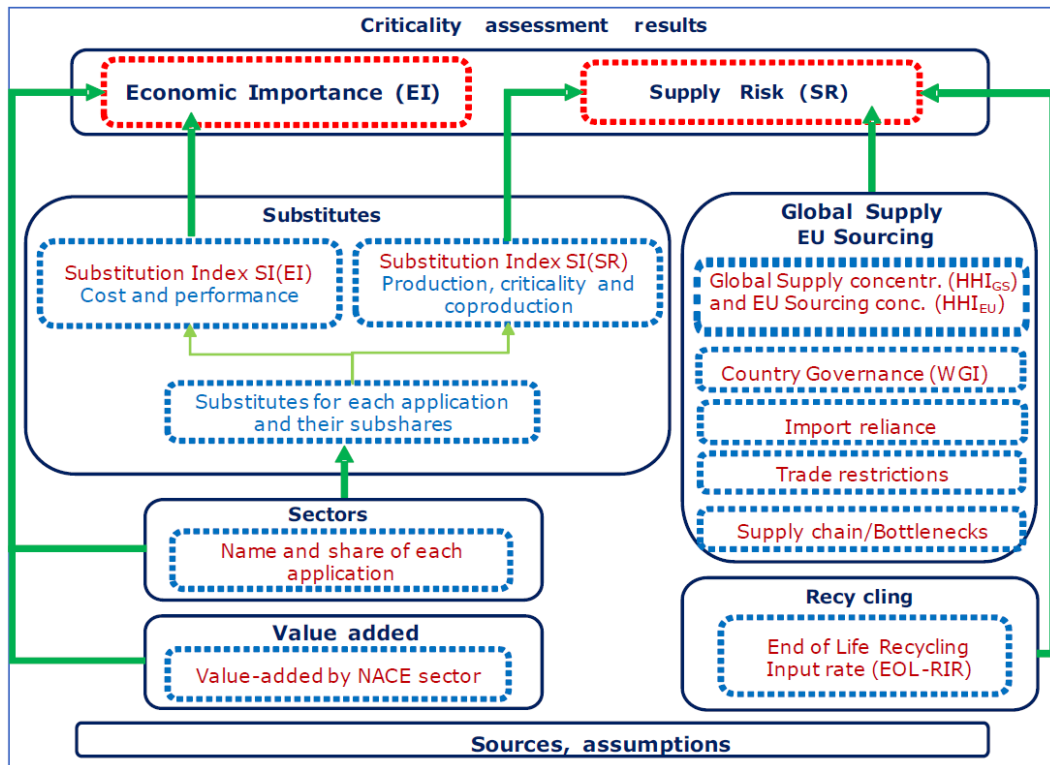
The European Commission Criticality Methodology has been defined by the EC and an Ad hoc working Group (AHWG) for the definition of critical raw materials. It was used to produce the lists in 2011 and 2014. Then a new study was carried out in 2015 to improve the methodology. This new version was applied to generate the lists for 2017, 2020 and 2023.

A few modifications were applied in the last two lists (2020 and 2023). As mentioned in (European Commission 2020i) “the 2020 assessment incorporates the following aspects:

- Analysis of a wider range of raw materials (five new candidates);
- Introduces a systematic two-stage supply chain assessment of the supply risk (mining/extracting and processing/refining stages);
- Updated factsheets for each of the materials assessed to include information on the supply chain, the criticality assessment and future trends;
- Optimise data quality and transparency, in respect to the hierarchy of data sources identified in the EC methodology, both in the assessments and factsheets; and
- Better coordination with parallel efforts to develop further Material System Analyses, as the priority data source for e.g. recycling data (EOL-RIR).”

The following figure shows the overall structure of the current methodology as proposed in the revised version (Blengini, Blagoeva, Dewulf, Torres de Matos, et al. 2017)

Figure 4: Overall structure of the criticality methodology (Blengini, Blagoeva, Dewulf, Torres de Matos, et al. 2017)



The mechanism is based on a detailed analysis of data sources and assumptions, as shown at the bottom of the figure. They represent the foundation of the work and special care is devoted to them. To obtain the economic importance (EI), the applications in which the investigated raw material is used are defined and mapped with value added of each corresponding NACE sector ( $Q_S$ )<sup>8</sup>. Each application in turn is characterized by a share. Then material substitutes are identified for every relevant application ( $A_S$ ). A substitution index is generated for economic importance ( $SI_{EI}$ ). This represents the first criterion for assessing criticality (Equation (1)).

(1)

$$EI = \sum_S (A_S * Q_S) * SI_{EI}$$

In parallel a substitution index ( $SI_{SR}$ ) is also generated related to production, criticality and co- production of the substituting material. This substitution index is further processed with a combination of two Herfindahl-Hirschman indexes country dependent to quantify Global Supply concentration ( $(HHI_{WGL,t})_{GS}$ ) and EU sourcing concentration ( $(HHI_{WGL,t})_{EI}$ ) balanced by the import reliance (IR) and with a filter considering the mitigation potential of recycling, the End of Life recycling

<sup>8</sup> Nomenclature statistique des activités économiques dans la Communauté européenne (NACE).

Input Rate (EoL-RIR). Other factors such as country governance (World Governance Index - WGI) and trade restrictions (t) are included in this calculation. This calculation leads to obtaining the Supply Risk (SR), which is the other criterion for assessing criticality, as shown in the following formula (Equation (2):

$$SR = \left[ (HHI_{WGI,t})_{GS} \cdot \frac{IR}{2} (HHI_{WGI,t})_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR} \quad (2)$$

Recycling is numerically represented by the end of life recycling input rate (EOL-RIR) which is one of the indicators used in the Circular Economy Monitoring Framework and calculated for the 83 candidate critical raw materials.

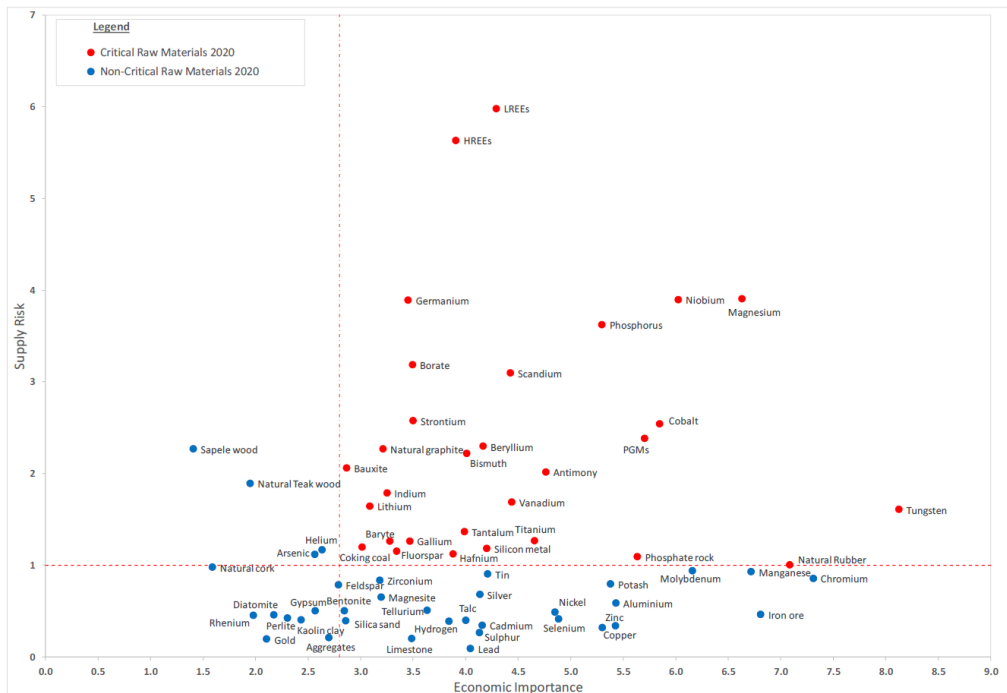
On the basis of the numerical results obtained for SR and EI a plot is generated with economic importance on the x-axis and the supply risk on the y-axis, where the candidate materials are positioned.

A material is considered critical if it overcomes the threshold both on the x and on y axis, which is if it has both high economic importance and there is a risk for its supply, see Equation (3).

$$\text{Critical Raw Materials thresholds} = \begin{cases} EI \geq 1 \\ \text{and} \\ SR \geq 2.8 \end{cases} \quad (3)$$

Figure 5 as an example reports the final plot of the criticality assessment 2020 results for individual non-grouped and grouped materials.

**Figure 5: Criticality plot. Results of the criticality assessment 2020 (individual materials and groups) (European Commission 2020g)**



As we anticipated, special care is given to input data and assumptions. One of the aspects to be considered is that the criticality assessment is an analysis based on past years. Data refer to an average of 5 years period (e.g. in the 2020 assessment the period from 2012 to 2016 was considered).

There is an attentive control of the quality of the data and of the sources they are coming from. In particular data available at EU level are considered more reliable than other sources such as public sources of data or even private and corporate data. Priority is given to open-access sources such as databases of geological surveys and Eurostat and Comtrade databases).

In order to validate data it has been found necessary to involve stakeholders in the process. Stakeholders are representatives of the industrial and of the scientific world.

It was decided to organize stakeholder consultation meetings in order to give the possibility to collect and review the data, ensure transparency of the sources and possibly add supplementary information thus also paving the way to future improvements. Stakeholder data collection and validation workshops were also organized together with the 2020 Horizon project called SCRREEN.

A summary of key stakeholder feedback was issued and helped to get wider and more accurate data.

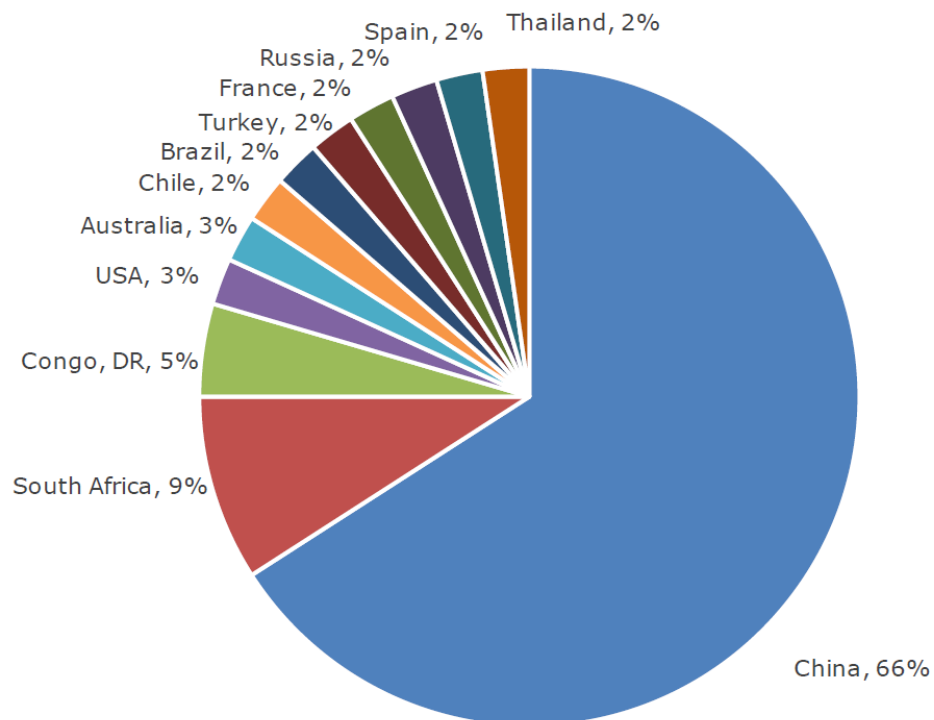
The criticality assessment was organised also in coordination with the EC Material System Analysis (European Commission 2020e)(Torres De Matos et al. 2021). This coordination represents one of the synergies useful to collect, elaborate and validate data on critical raw materials and their supply chains.

During the assessment a dynamic plot was developed to track all the changes during the assessment. The results in time of the dynamic plot showed different trends depending on the materials and availability of data and inputs from stakeholder consultation showing the strong correlation with data quality aspects.

Some improvements were made with respect to the previous implementation of the methodology. In particular to avoid problems in the decision of which is the bottleneck in case of different views about two possible candidate points it was decided to permit a double stage supply risk assessment.

It is interesting to note that according to data presented in the 2020 study China is largely the major producer of critical raw materials both for European sourcing and the entire world. Far second is South Africa and third is Congo (global data). For European sourcing far second is Congo followed by Turkey and France. This outcome clearly justifies the need of establishing reliable trade agreements and partnership with third countries as it is stated in the Critical Raw Materials Act (European Commission 2023a).

**Figure 6: Main global suppliers of CRMs (based on number of CRMs supplied), average from 2012-2016 (European Commission 2020i)**

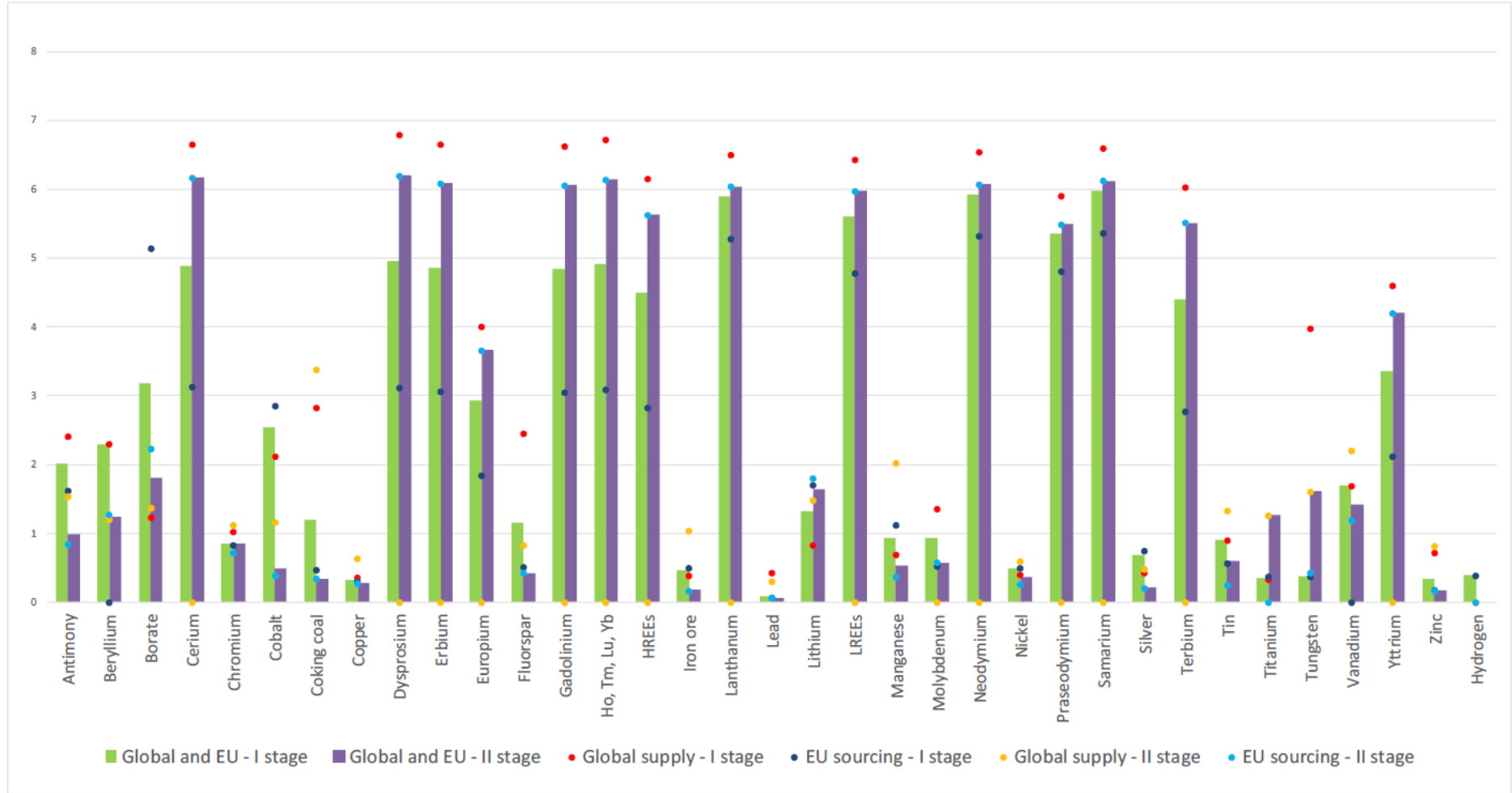


In 2020 the list of candidates for critical raw materials reached 83 individual materials while of these, 30 were considered critical.

Table 1: 2020 Critical raw materials for the EU (European Commission 2020g)

2020 Critical Raw Materials (30)			
Antimony	Fluorspar	Magnesium	Silicon Metal
Baryte	Gallium	Natural Graphite	Tantalum
Bauxite	Germanium	Natural Rubber	Titanium
Beryllium	Hafnium	Niobium	Tungsten
Bismuth	HREEs	PGMs	Vanadium
Borates	Indium	Phosphate rock	Strontium
Cobalt	Lithium	Phosphorus	
Coking Coal	LREEs	Scandium	

Figure 7: Comparison of SR results based on scope of supply data used (double stage) (European Commission 2020g)



## 1.4.2. Circular economy and Resource efficiency

*“Use it up, wear it down, make it do or do without”*

This sentence was originally written by US president Calvin Coolidge in the 1920s and reported near garbage collection centres in the United States during the Great Depression to discourage waste in a difficult period (Roberts 2010).

Circular economy represents a new approach with respect to the established consumer view of economics where a product has a life cycle that ends when it is not considered adequate to perform its role and then it becomes a waste. With this different approach the cycle becomes circular in the sense that the life of a product starts again after the application of one of the several strategies that take part in implementing circular economy: repairing, reusing, remanufacturing, reducing at source and eventually recycling. Reducing at source may be done by second-use of products or by sharing products.

In 2020, the EC adopted the Circular Economy Action Plan (European Commission 2020a) as one of the building block of the European Green Deal.

According to the Raw Materials Scoreboard (European Commission 2021a) “increasing circularity is the EU’s Green Deal objectives and strengthen the security of supply for raw materials. Data show, however, that the circular use of materials in the EU remains low. The level of circularity varies from material to material and is the highest for metals.

Recycling of waste of electrical and electronic equipment is efficient for secondary bulk metals, but not for critical raw materials since critical raw materials are often too diluted into the components/alloys and thus difficult to be recovered (European Commission 2021a). Waste of electrical and electronic equipment (WEEE) contains a wide range of materials and is a potential source of secondary critical raw materials. Data on WEEE management shows an increase in collection, but with significant differences between EU Member States. Recycling of WEEE mainly addresses bulk metals, while critical raw materials are recycled to a much lower extent. Recycling technologies to recover critical raw materials may be neither technically or economically viable (European Commission 2021a). Preparation for re-use is still limited. Overall, recycling’s contribution to meet materials demand is currently low, with several factors limiting the availability of secondary materials.

When collection and treatment is well managed, recycling can make a relevant contribution to meeting materials demand. Overall, recycling’s contribution to meeting demand stands low.”

It is necessary to monitor progress in circularity performances of critical raw materials in strategic value chains. Monitoring is useful essentially for two reasons: to assess the effectiveness of this solution and to track progress. Tracking progresses can help to identify bottlenecks that slow the process or define incentives or equivalent regulation strategies to stimulate a higher circularity.

Moraga et al. (2019) make a review of existing indicators to monitor progress of CE considering entire/ partial product lifecycle quantifying the preservation of

the materials through recycling and down cycling. They may act at different levels, namely material, component, product. These indicators do not cover reduce, reuse, manufacturing, maintenance. They are generic, not focussing on specific sectors. A sector specific approach would be more effective since the criticality of raw material is getting more and more important. Many indicators are based on Sankey diagrams and material flow analysis by quantifying stocks and flows, but they are still kept at the level of the whole economy or specific products; they are not yet available at material or component level as it would be desirable.

The Commission, as part of its monitoring of the circular economy (European Commission 2018) produces Sankey diagrams of the material flows since 2010 and available on the Eurostat's website<sup>9</sup>.

EOL-RIR is used as a mitigation factor for the supply risk of raw materials by considering it riskless. This should require specific analysis in which criticality assessments do not focus on. In addition, circularity aspects beyond recycling has not played so far a prominent role in the criticality debate even if they could potentially alter supply risks as mitigation measures (Tercero Espinoza et al. 2020). The other circular economy strategies might enhance the circularity of critical raw materials in the strategic sectors in EU providing also a further reduction of the dependency on primary materials from third countries, even though circular shorter loop activities are not currently considered as mitigation measures for supply risk (Schrijvers et al. 2020).

### **1.4.3. Environmental and social Sustainability and Life Cycle Assessment**

The first definition of sustainability was stated by the World Commission on Environment and Development (WCED) in 1987 and referred mostly to human activities and relationships. The Brundtland Report, also called “Our Common Future”, defined the sustainable development as “meeting the needs of today without compromising the ability of future generations to meet their own needs”.

Hence, sustainability is the property of a process or a state that could be kept indefinitely at a certain level. It can be applied to different fields and at different scales, going, for instance, from production processes to urban planning. The environmental, social and economic dimensions are commonly encompassed in the sustainability concept. In this definition the focus is on people well-being and it is important to understand which needs have to be considered necessary for people.

Environment, economy and society, the main fields to which this approach is mostly applied, are taking on an unbalanced interest due to their nature inside developing systems which tend to grow in a specific direction.

The ongoing European Horizon2020 project ORIENTING “Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a

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<sup>9</sup> [https://ec.europa.eu/eurostat/cache/sankey/circular\\_economy/sankey.html](https://ec.europa.eu/eurostat/cache/sankey/circular_economy/sankey.html)

Circular Economy” aims at strike a balance between environmental, economic and social benefits in the field of Life Cycle Assessment. It is developing a methodology for a comprehensive life cycle sustainability assessment of products and services in a way that considers all the variables (economic, environmental and social). Also aspects of material criticality have been included in the impact assessment.

Along with ORIENTING also other research projects in the past years have been developing methodologies to include material criticality as an impact category to be considered in the life cycle impact assessment.

### *Life Cycle Assessment*

In the sustainability assessment field different methodologies are used to evaluate impacts in production and consumption systems. One of them is the Life Cycle Assessment (LCA). It is a method defined by the international standards ISO 14040 and 14044, aiming at analysing environmental aspects and impacts of product systems.

In the introductory part of international standards ISO 14040 LCA is defined as follows: “LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.”

This definition refers to the environmental LCA. Indeed, this methodology and international standards have been developed for this field of study.

Social impacts are very important and often analysed together with the environmental impact assessment. They allow to identify and evaluate social risks in the activities related to a product or a service.

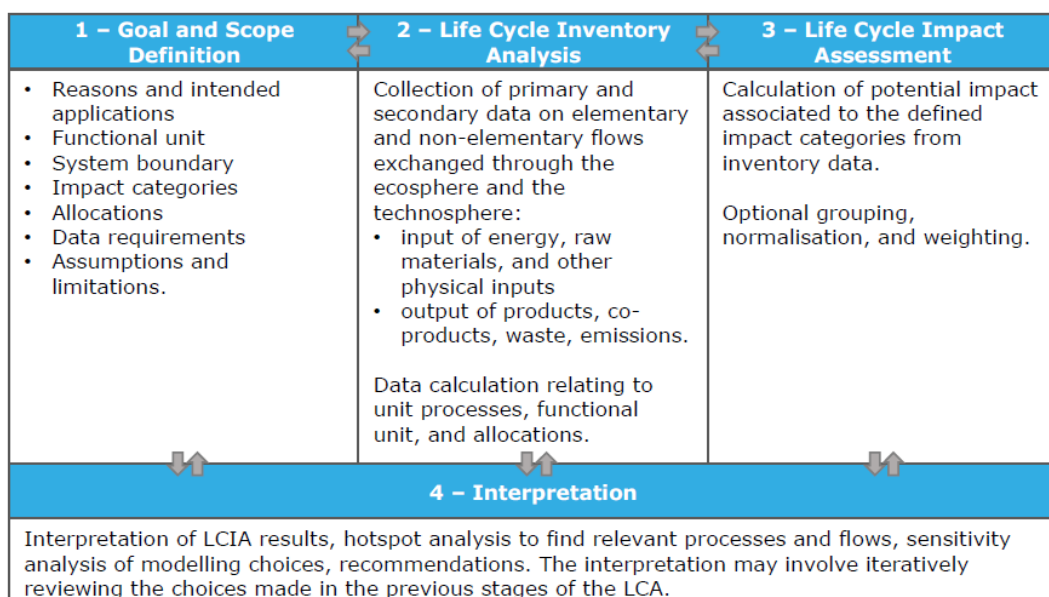
Unite Nations Environment Programme (UNEP) and The Society of Environmental Toxicology and Chemistry (SETAC) defined the social life cycle assessment methodology. The scope is to identify potential social risks. A key step is the identification of relevant social impact categories and indicators for the specific material. The four steps defined by the ISO 14040 and 14044 for the Life Cycle Assessment are defined as follows:

- Goal and Scope: where the reasons for carrying out the study and its intended use are described and where details are given on the approach taken to conduct the study. Notably, it is in this phase of the study that the functional unit is defined, and that modelling approaches are specified.
- Life Cycle Inventory (LCI): where the product system (or systems) and its constituent unit processes are described, and exchanges between the product system and the environment are compiled and evaluated. These exchanges, called elementary flows, include inputs from nature (e.g. extracted raw materials, land used) and outputs to nature (e.g. emissions to air, water and soil). The amounts of

elementary flows exchanged by the product system and the environment are in reference to one functional unit, as defined in the Goal and Scope phase.

- Life Cycle Impact Assessment (LCIA): where the magnitude and significance of environmental impacts associated with the elementary flows compiled during the previous phase are evaluated. This is done by associating the life cycle inventory results with environmental impact categories and category indicators. LCI results, other than elementary flows (e.g. land use), are identified and their relationship to corresponding category indicators is determined. LCIA has a number of mandatory elements: selection of impact categories, category indicators, and characterization models as well as assignment of the LCI results to the various impact categories (classification) and calculation of category indicator results (characterization). This can then be followed by optional elements such as normalization, grouping and weighting.
- Life Cycle Interpretation: where the findings of the previous two phases are combined with the defined goal and scope in order to reach conclusions or recommendations.

Figure 8: Standardised steps of LCA according to ISO 14040-44. Two-way arrows suggest the iterative nature of an LCA. (Damiani, Ferrara, and Ardente 2022)



### *Environmental Footprint methodology*

With the Communication COM/2003/302 (European Commission 2003), the European Commission started the process of including a life cycle thinking approach in European product policies. In 2010, the International Reference Life

Cycle Data System (ILCD) guidance<sup>10</sup> laying the foundations of a harmonised approach for life cycle data and impact assessment methods.

In 2013, the Commission adopted a Recommendation “on the use of common methods to measure and communicate the life cycle environmental performance” (European Commission 2013) which started the methodological developments of the Environmental Footprint (EF) method and its pilot phase (2013-2018). With the European Green Deal, the life cycle approach has become a major lever for guiding European policies and investments towards its environmental sustainability goals. We are currently in the transition phase that corresponds with the implementation of EF.

The Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF) are life cycle assessment (LCA) based methods to measure and communicate the potential life cycle environmental impact of products (goods or services) and organisations, respectively. Together they form the basis for the EU Environmental Footprint.

The EF builds on existing approaches and international standards (such as ISO 14040 series and the European ILCD guidelines).

In 2021 the European Commission indicated in the Recommendation C(2021 9332) (European Commission 2021b) the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.

An EF study shall follow the principles of relevance, completeness, consistency, accuracy, and transparency. For specific products and services, the EF method foresees the adaptation of the methodology by considering peculiar features that need to increase five principles abovementioned and to allow comparability. For this reason Product (or Organisation-) Environmental Footprint Category Rules (PEFCR or OEFCR) are developed.

A fundamental pillar of the Environmental Footprint method is the reliance on harmonised life cycle data.

In 2014 the Commission launched the Life Cycle Data Network (LCDN)<sup>11</sup> aiming at providing a globally usable infrastructure for the publication of quality assured LCA datasets (i.e. LCI datasets and LCIA method datasets) from different organizations. The LCDN is a registry composed by nodes (datasets repositories).

The datasets shall follow specific requirements to be registered in the LCDN. These requirements are set by the ILCD entry level guidance<sup>12</sup> and the EF Data guide (Fazio et al. 2020).

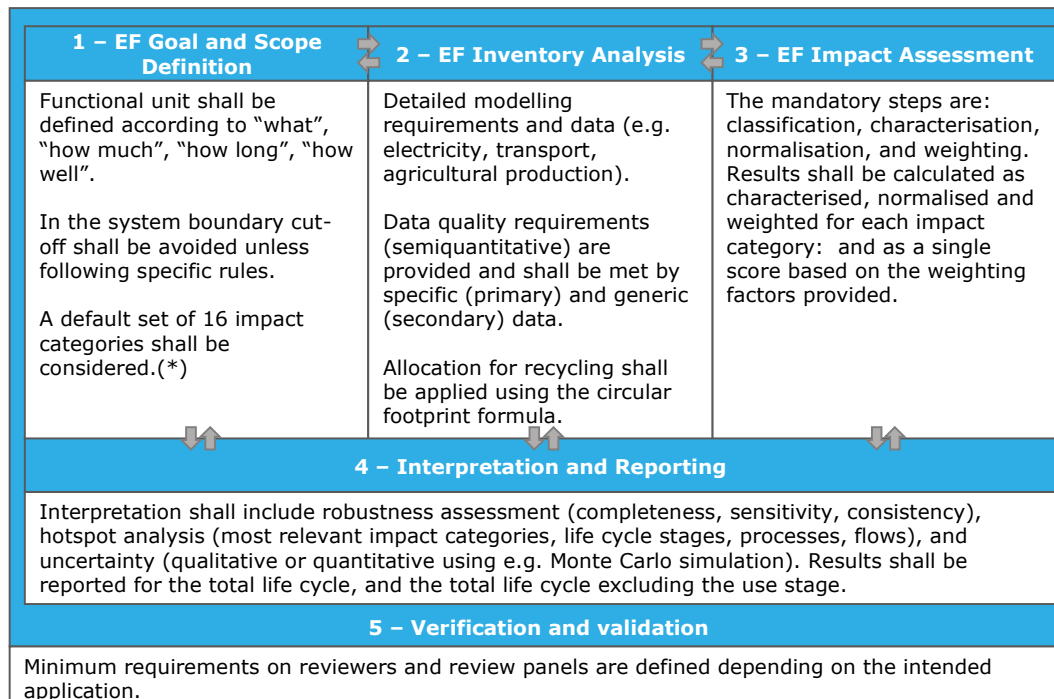
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<sup>10</sup> <https://eplca.jrc.ec.europa.eu/ilcd.html>

<sup>11</sup> <https://eplca.jrc.ec.europa.eu/LCDN/index.xhtml>

<sup>12</sup> <https://eplca.jrc.ec.europa.eu/LCDN/developerILCDDataFormat.xhtml>

Figure 9: Steps of the EF method. The main additions to ISO 14040-44 are shown in the white boxes and will be detailed further in this document (Damiani, Ferrara, and Ardenete 2022)



(\*) Climate change, particular matter, ionising radiation, photochemical ozone formation, acidification, ozone depletion, eutrophication (terrestrial, marine, freshwater), ecotoxicity (freshwater), human toxicity (cancer, non-cancer), land use, water use, resource use (minerals and metals, fossils).

### Social LCA

A social and socio-economic Life Cycle Assessment (SLCA) is a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle, encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal. SLCA complements E-LCA with social and socio-economic aspects. It can either be applied on its own or in combination with E-LCA.

Regarding this specific methodology, recognised internationally standards do not exist yet as for E-LCA, but guidelines have been produced in the document “Guidelines for social life cycle assessment of products” realised by UNEP/SETAC Life Cycle Initiative in 2009 (UNEP Setac Life Cycle Initiative 2009). This document has been written by several experts in diverse fields such as sustainability, LCA methodology, social science etc., according to its multidisciplinary nature.

Another milestone provided by UNEP/SETAC Life Cycle Initiative is The Methodological Sheets for Subcategories in Social Life Cycle Assessment" (SLCA)" (UNEP/SETAC 2013) which have been created ad hoc in order to give a structure and basis on which to develop research and studies about social indicators. In 2020 UNEP published the updated “Guidelines for Social Life Cycle Assessment of Products and Organizations 2020” (United Nations Environment Programme 2020). This document critically reviewed the previous guideline by updating and better defining some of the peculiar phases of the social

LCA methodology, such as the definition of stakeholder categories and indicators and the impact assessment. Social and Environmental LCA are both grounded in Life Cycle Thinking (LCT). This approach seeks to capture the environmental/social impacts of a good or service "from the cradle to the grave", thus considering all the steps in life cycle and avoiding shifting of burdens among geographic areas or supply chain step.

There are also a number of important dissimilarities between both approaches. One of them being that social concerns are diverse and their importance is subjective to the context (S Sala et al. 2015).

The main differences can be summarised as follows:

- Reference guidelines: UNEP 2020
- Positive/Negative impacts
- Different stakeholders perspectives
- Activity variable: worker hours/value added
- Guidelines define stakeholders and impact subcategories:
  - Workers/employees
  - Local community
  - Society
  - Consumers
  - Value chain actors
  - Children

Four phases regarding Social LCA are described in UNEP/SETAC Guidelines and summarised in the following paragraphs.

- Goal and scope: The first thing needed when initiating a SLCA is a clear statement of purpose, the goal. This statement describes the intended use and the goal pursued. The study will then be defined to meet that purpose, within any constraints. Depending on the goal, a critical review may be planned. The second step is to define the scope. As part of defining the scope, the function and the functional unit of the product is defined. Based on that information the product system will later be modelled using process or input-output data. In the scope phase, the depth of the study is defined and decisions about which unit processes requires generic or specific data collection are made. In order to define the depth of the study, activity variables (such as worker hours or value added) may be used.
- Social-Life Cycle Inventory analysis: The inventory is the phase of a SLCA where data are collected, the systems are modelled, and the LCI results are obtained. With a definition of the goal and scope of the study, an initial plan for conducting the inventory phase of the SLCA is available. Based on the definition of the functional unit, the product system is modelled and system boundaries are set and described.

- Social-Life Cycle Impact Assessment: The sLCIA phase consists of the three mandatory steps identified in ISO 14044 (2006) for LCIA, which allow to trace the Inventory data through the relevant social and socio-economic mechanisms to define a social and socio-economic impact. Those three steps are: selection of impact categories and characterization methods and models; linkage of inventory data to particular sLCIA subcategories and impact categories (classification); determination and/or calculation of subcategory indicator results (characterization).
- Social-Life Cycle Interpretation: Life Cycle interpretation is the process of assessing results in order to draw conclusions. In accordance with the goal and scope of the study, this phase has several objectives: to analyse the results, reach conclusions, explain the limitations of the study, provide recommendations and report adequately.

Materiality assessment to identify sustainability issues that are of interest for stakeholders for actual or potential influence. A set of indicators is then chosen. The indicators may involve risks related to the respect of human and social rights, and economic impact such as new jobs and development.

The databases that may be used the trade inventory and the life cycle inventory. As social aspects are more dynamic than environmental ones, it is important to keep the underlying database up-to-date.

Currently there are two databases for social LCA: Product Social Impact Life Cycle Assessment (PSILCA) database<sup>13</sup> and Social Hotspot database (SHDB)<sup>14</sup>.

Impact assessment methods. A key point is the identification of the boundaries of the system and the selection of social indicators. For example PSILCA reference scales rely on international statistical agencies such as World Bank, International Labour Organization, World Health Organization and United Nations and private and governmental data bases.

The problems are often the scarcity of disaggregated data and the uncertainty of evaluation in social aspects such as child and forced labour. It is also necessary to combine views and data from different stakeholders, which is not a straightforward operation.

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<sup>13</sup> <https://psilca.net/>

<sup>14</sup> <http://www.socialhotspot.org/>

# Chapter 2: Life cycle-based methodologies, software tools and indicators

This chapter presents the methodologies, software tools and indicators considered during the research and their interoperability. These methodologies, software tools and indicators have in common a life cycle-based approach. The selection of these methodologies, software tools and indicators and the development of some of them aim at integrating them into a tailored toolbox as presented in Chapter 3.

Section 2.1 presents how criticality, circularity and environmental and social sustainability of raw materials introduced in section 1.4 have been considered in the research analysis. Three subsections, dedicated for each of the topic identify which methodologies, software tools and indicators were deployed in all the research works performed during the doctoral period.

All the papers and works developed during the doctoral period and relevant for the development of this dissertation are summarised in research activities profiles (section 2.2). The research activity profiles are presented following a layout to easily convey the main message of each work and its relevant aspects to the reader. A graphical abstract has been drawn for all the profiles.

A transversal analysis of the main outputs is then provided at the end of the chapter in section 0.

This chapter mainly builds on previously published by the author in:

- (Bobba et al. 2020),
- (Bobba et al. 2023)
- (European Commission 2020g),
- (European Commission 2020h)
- (European Commission 2020f),
- (European Commission 2021c),
- (Gama Caldas et al. 2023),
- (Torres De Matos et al. 2021),
- (Georgitzikis, D'elia, and Eynard 2022),
- (Georgitzikis, Eynard, Bobba, Perpetuo Coelho, Ingoglia, D'elia, et al. 2023),
- (Georgitzikis, Eynard, Bobba, Perpetuo Coelho, Ingoglia, and Garbossa 2023),

- (Di Noi et al. 2020),
- (Hamor et al. 2021),
- (European Commission 2021a),
- (European Commission 2021c).

## **2.1. Multi-criteria analysis - interoperability and integration**

The necessity of applying different criteria to perform the analysis towards the requested results for each kind of problem on raw materials brings the attention to gather the various methodologies, software tools and indicators that implement such criteria. Gathering such tools suggest the idea of referring to their set as a toolbox. This idea is already present in the literature (Dewulf 2015). The fact that multi-criteria analysis must be applied to solve complex problems, implies the need for tools interoperability and integration.

As described in the graphical abstract the basic objective of the multi-criteria analysis discussed in this dissertation is the green transition to achieve a cleaner, healthier, more ethical society in an improved environment fighting global warming and climate change. But of course ensuring the supply of critical raw materials to the EU to progress on this path represents is a key step in the whole process.

Identifying which raw materials are critical, which are the hotspots and bottlenecks in the value chains and suggesting measures that overcome or at least can mitigate the foreseen criticality requires the development, adoption and application of adequate tools. Such tools are of different types such as methodologies, software tools, indicators, calculation sheets, priority techniques, risk analysis.

Many theoretical approaches and practical calculation tools have been defined in literature. In this thesis I gather and analyse the works that I participated to develop or apply in three years period (2019-2022). Sometimes they are applied to answer specific questions, elsewhere they are utilized to perform more complete analysis in more general contexts.

In general all the analysis are used to investigate problems related to raw materials supply, check the environmental compatibility, verify social impact and ensure sustainability also through circular economy strategies.

Of course it is important that the whole picture is taken into account, respecting all the dimensions of the green transition at the same time.

All these elements can be grouped them together in rather homogeneous techniques. It helps to choose which is more adequate to use situation per situation. Or it can also suggests improvements for further work.

A common problem that we can see in several scenarios is the lack of data or the insufficient quality of many data, as raised in:

- Profile #1,
- Profile #3,
- Profile #4,
- Profile #5,
- Profile #8,
- Profile #13,
- Profile #14,
- Profile #15.

A comparative view of several methodologies, software tools and indicators could help also in this respect for example suggesting common measure units and formats.

This could help data gathering and loading and cascading tools related to subsequent steps. Also the effort to convince stakeholders to provide data could be smoothed if some kind of standard way of data provision could be defined. The analysis and discussion about the toolbox is provided in Chapter 3.

Figure 10 shows how the tools are used in the papers that I co-authored during the three years (2019-2022).

As it can be seen in some cases tools are used to answer specific questions, in other cases several tools are applied in cascade to face more complex problems such as identifying the circularity strategies of critical raw materials or their social and environmental impact along the supply chain. Yet, in other situations they are applied in order to check their own value, validating the tool potential itself.

Figure 10 helps to understand how the tools are distributed among the different analysis. In some situation they are consistently used (like in Profile #4 and Profile #16), in other situations the tools are applied to specific issues (like Profile #6). It is important to analysis these relationships to understand the possible interoperability and further integration.

It shows the tools as grouped per field of intervention and a brief description is taken from the papers that report their application.

Figure 10: List of methodologies, software tools and indicators as used in the works and paper carried out during the PhD carrier.

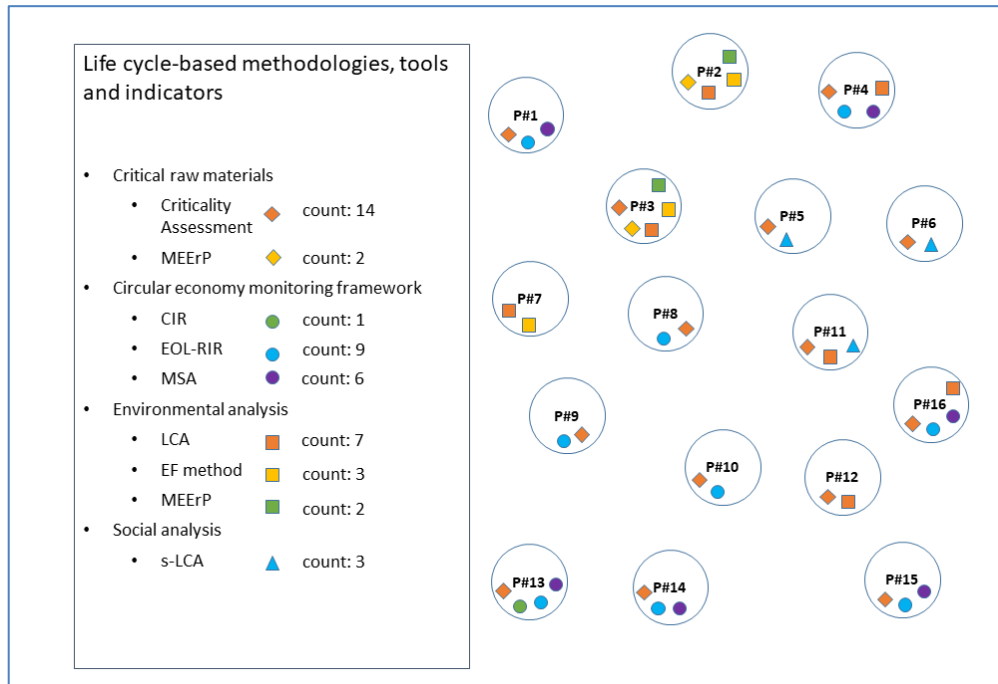
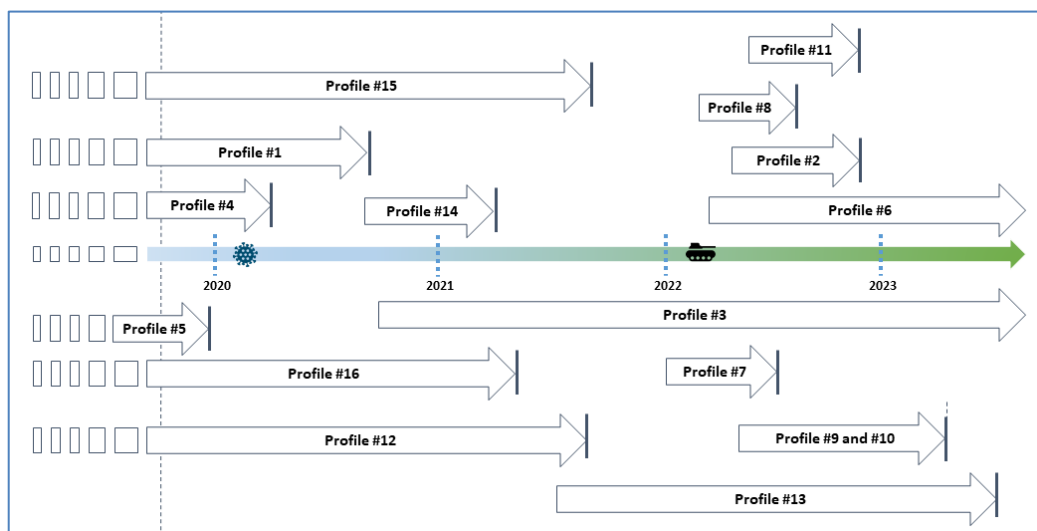


Figure 11: Timeline of the research activities profiles shows how the various tools developed in time in correspondence to when the work was written during this three year period.

Figure 11: Timeline of the research activities profiles



The time variable is interesting because studies are rapidly developing nowadays, so that gathering a parallel view is biased by the moment of observation.

It is clear that technical and economic requirements, environmental laws, social impacts should be addressed by decision makers at the same time and when a material is scarce circular economic strategies should be applied as much as possible.

The value chains present similarities that can be conceptualised in a common life-cycle structure with defined steps such as extraction, refining, manufacturing, distribution, use and end of life treatments. . Nonetheless, some exceptions occur, like in the case of Rare Earth Elements, mainly due to the sophisticated metallurgical processing and lack of production capacity outside China.

It is important to identify what are the different database, data quality, availability, type and sources, their stability, competencies and skills, technological industrial processes, different types of regulations, risks.

Input data gathering, storage and management is the basis for every activity with respect to raw materials. Important activities comprise inventory creation for input data and information management.

Several papers complain about the lack of data. For example, Profile #3 puts the emphasis on the lack of comprehensive, quantitative and qualitative information for energy related products and suggests incentivizing the disclosure of information on CRMs. Profile #15 encourages the availability of comprehensive datasets on the raw materials it analyses in order to support the development and monitoring of EU policies. Profile #5 states that due to lack of social data only a limited view on the sectoral performance for raw materials is possible. Among the objectives of Profile #1 the production of full datasets, list of data sources for transparency sake and the improvement of quality and availability of data are explicitly stated.

Other general aspects are related with policy regulations, approval procedures, and recommendation indications. Profile #2 proposes a methodology for the accounting of the carbon footprint of PV modules in order to influence the regulatory context through the EU ecodesign directive. Profile #6 suggests future use of S-LCA methodology for specific policy intervention such as due diligence requirements related to responsible sourcing of raw materials. The studies on Profile #11 on water electrolysis and hydrogen aim at defining the EU position and influence the policy context, encouraging industrial commitment and leadership in Europe.

Finally suggesting policies, monitoring schemes and validation workshops that ensure control and double checking in the perspective of rigor not only on the scientific level but also on the procedural level to ensure that good intentions are not overwrought by lack of continuous or periodic control. They are common to most papers but especially in Profile #12 and Profile #1.

The skills required range from information technology with particular to database management (data input and system management) to operational research. It is also necessary to have communication skills to make sure that also people without a sound technical background can be brought to understand the importance of the themes treated and convinced by the results obtained and by the consequent suggested actions.

In this section, we are focussing not on the content but on mechanisms and skills. Value is also given to practical applications. Everything in this respect plays a role in my technical and professional growth even when applied to different specific context.

Telling the experience may also be useful for didactic purposes. Among the research activities, it was very important the tutorship in which I was involved during my PhD for the didactic activities promoted by Politecnico di Torino, called “Challenge@Polito”<sup>15</sup> with the industrial partners Sacal<sup>16</sup> and Enel Green power<sup>17</sup>.

### 2.1.1. Criticality assessment

Throughout this work it is explained how the results of the criticality assessment can be considered as:

- a ready-to-use repository of data and information in further research applications.
- a basis of better understanding the complexity of value chains and where main hotspots occur (social and environmental impacts);
- definitions of targets regarding the material efficiency (to refer to Battery regulation proposal and CRMs Act with recycled content targets for some critical raw materials);
- prioritisation of circular economy strategies to support the EU open strategic autonomy, among others.

Profile #3 reports the list of relevant concepts and principles for the assessment of CRMs in products in the context of Ecodesign.

Considerations are made upon availability and feasibility. The possibility to define parameters and/or indexes is discussed with reference to recycled content, recyclability, substitutability.

The objective is to maximize the benefits to society per unit of CRM utilized. The lack is noted of comprehensive, quantitative and qualitative information; it is therefore reasonable to incentivize the disclosure of information on CRMs.

A targeted reporting is proposed, shortlisting product groups, based on probability to contain relevant amounts of CRMs. Then an analysis is performed of priority product groups, based upon numerical results of the latest EC criticality assessment.

Another category refers to risk assessment methodology and elements for disruption identification. This is present in Profile #9, Profile #10 regarding the risks connected with war for the supply of important raw materials such as platinum, palladium and titanium. Risk analysis is performed in a more general way in Profile #1 in the study on the list of critical raw materials for Europe in the 2020 edition.

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<sup>15</sup> <https://www.polito.it/innovazione/formazione-all-imprenditorialita/challengepolito>

<sup>16</sup> [https://clik.polito.it/challenge/a-new-life-for-alumina-based-wastes-newlaw\\_by-sacal/](https://clik.polito.it/challenge/a-new-life-for-alumina-based-wastes-newlaw_by-sacal/)

<sup>17</sup> <https://clik.polito.it/challenge/circular-and-sustainable-inputs-for-renewable-energy-by-enel-green-power/>

A key category is related to value chain analysis which is key for several studies but in particular is fundamental to identify hotspots, bottlenecks with specific techniques. Profile #8 studies the impact assessment for supply security for titanium, while Profile #9 and Profile #10 make the same for Platinum and Palladium. They study the impact of a specific disruption, in this case obviously the war in Ukraine, and they try to identify the present situation and the situation to be suggesting short term and medium term mitigation measures. Value chain analysis is also performed in Profile #11 applied to water electrolysis and hydrogen in the European Union. Profile #15 applies the Materials system analysis methodology for the analysis to 9 raw materials: barytes, bismuth, hafnium, helium, natural rubber, phosphorus, scandium, tantalum, and vanadium. The resulting indicators are: end of life recycling input rate, end of life recycling rate, collection rate, self-sufficiency extraction, self-sufficiency processing, self-sufficiency manufacturing. The results of the analysis help highlighting the weak points concerning material flows in the economic system and at each stage of the supply chain. It helps to identify where strategic interventions may have a relevant impact.

Since we are treating the availability of raw materials we thought it useful to have a category dealing with various stages of the mining cycle, as described for example in Profile #12: mineral exploration, planning and design, mine construction, operation, final closure and post-closure of mines. Operation is further detailed in the following phases. Extraction, treatment, stockpiling, waste, by product generation, reuse, recycling, transportation and handling, temporary suspension. Extraction types taken into account are: underground extraction, open pit extraction, extraction underwater, and brine extraction through deep drillings, in situ leaching of metals. Deep sea extraction and minerals by production are not taken into account in this work.

Sometimes it is necessary to devote effort for technology maturity assessment. Profile #6 shows how to analyse technology maturity status about water electrolysis techniques in support of hydrogen sustainability assessments.

### **2.1.2. Circular economy and resource efficiency**

The category about circular economy comprises the definition of mitigation measures; recycling, reuse, disposal, identification of material stocks (tailings, landfills, products in use phase). Profile #13 proposes new indicators to monitor circularity progress in a specific sector. The new indicator proposed is called Circular Input Rate (CIR) (Bobba et al. 2023). The field of application are rare earth elements during the remanufacturing process of e-vehicles motors. The factors influencing circularity in this field are identified as technology developments, consumer behaviour, company behaviour, and volume of products. The place where these specific materials are present and should be recycled is the

permanent magnet inside the motor of the electric-vehicle. It is necessary to analyse the vehicle value chain (and this reports to the techniques of another category), starting from stocks and flows to the contribution from recycling.

It is important to understand the potential role of recycling and to give thresholds a minimum percentage of recycled content.

The parameters of circular economy are the end-of-life recycling input rate (EOL-RIR) of each material and the end-of-life recycling rate (EOL-RR).

EOL-RIR is the percentage of the total material input into the production system that comes from functional recycling of post-consumer scrap. It measures the share of SRMs compared to the total demand of materials.

The end-of-life recycling rate EOL-RR represents the current recycling of products at end of life.

For some materials recycling could be not feasible from the technical point of view or it could prove to be too expensive. Or of course the recycling process could be incompatible with environmental or social impacts. In such cases of techno economic barriers, the advice is to not push too high the requirement for increasing recycling.

Hence, a new index is proposed in Profile #13. The CIR (circular input rate) index. It is an indicator that should be adopted to measure circularity of materials at sector level. It is meant to measure the contributions of all strategies together. Therefore it makes two steps forward at the same time. It reduces the scale of the application (material level) but it extends the field to all strategies.

It takes into account all the circularity strategies except second use of products.

The circular input rate index is defined as the ratio between the flows of materials from reused, remanufactured and recycled products/components compared to the demand of materials of a specific sector.

It is interesting to see how the different strategies vary their effect in time. The CIR helps to evaluate this if it is calculated for a period of several years, taking into account changes and evolution of the sector under analysis. It may also be used to help make decisions suggesting different scenarios and calculating the corresponding results.

In this way the CIR index may be used to simulate the effects of different strategies for future years.

Dynamic material flow analysis is performed in Profile #13 to represent the flows of components/materials along the whole value-chain of vehicles in the EU. The main steps are identified in order to evaluate the CIR with all the circular economy strategies including the remanufacturing practices that may be used in the automotive sector.

As it was stated in the introduction, it is important to monitor circularity for several reasons. Eurostat identified four thematic areas and adopted 10 indicators

for this aim. The areas are: production and consumption, waste management, secondary raw materials and competitiveness and innovation.

Mandatory targets in waste management policies and product policies introduce a minimum recyclability rate that must be respected to be allowed to enter the market. For example recycling efficiency targets at product level, batteries packaging material specific level through the setting of minimum recovery rates and/or minimum recycled content.

Circular economy action plan for EC 2020 requires minimum recycled content of cobalt and lithium, single use plastics and plastic in vehicles.

### **2.1.3. Environmental and social Sustainability and Life Cycle Assessment**

#### *Environmental analysis*

This category is related to understanding environmental performance and the tools here included are methods for environmental assessment, carbon footprint assessment, impact assessment elements and rules for the quantification of emissions.

Profile #2 is about the accounting of the carbon footprint of photovoltaic modules through the EU ecodesign directive. The methodology adopted in this thesis to assess carbon footprint of a product is based on a cradle to gate approach, taking into account every step and especially manufacturing and shipping. This methodology here proposed is meant to influence the regulatory context. From the PV production of energy towards the decarbonisation process rules are deducted for the quantification of emissions. Alternative regulatory approaches are proposed. The pillars for such proposals are quantitative requirements, maximum threshold for CF, information requirements on carbon footprint, CF info on energy label and quantitative requirements on specific CF relevant parameters. Profile #7 makes use of the environmental footprint (EF) impact assessment method of the European commission to decide between alternative strategies. Although the current attention is particularly focused on climate change and carbon footprint of products and services, many other categories are defined and have high importance with respect to the environment, resources and human wellbeing. As an example, the use of some materials in certain circumstances may not affect climate change, but maybe dangerous for the human beings living in proximity. The EF method takes into account 16 environmental impact categories:

1. climate change,
2. ozone depletion,
3. ionizing radiation,
4. photochemical ozone formation,
5. particular matter,
6. human toxicity non -cancer,
7. human toxicity cancer,

8. acidification,
9. eutrophication fresh water,
10. eutrophication marine,
11. eutrophication terrestrial,
12. ecotoxicity fresh water,
13. land use,
14. water use,
15. resource use fossils,
16. resource use minerals and metals.

The single score results are obtained after normalization and weighting of the absolute impacts. The results for each category are normalized to the average global per capita emissions and they are multiplied by the set of weighting factors and a final single score is obtained for each solution under evaluation. It is advisable to carry out sensitivity analyses to check how results are affected by the adoption of different assumptions.

EIA (Environment Impact Assessment) is also used in Profile #12, review of legal provisions on the environmental impact assessment of non-energy minerals extraction projects. Profile #12 also reports the schematic EIA approval procedure. The steps are:

- screening, scoping,
- EIA report,
- information and consultation,
- decision making and development consent,
- information on development consent,
- monitoring.

Profile #4 maintains that an environmental assessment single tool is not sufficient in some cases. It proposes bridging tools to better understand environmental performances and raw materials supply of traction batteries in the future EU fleet. It suggests making use of complementary information in the form of material flow analysis and criticality assessment. In this particular case the combination of environmental assessment methodology plus complementary aspects as the use of a more environmentally friendly energy mix and improved recycling can bring to a virtuous life cycle GWP of traction LIBs.

Flow analysis comprising material flow analysis and techniques for modelling flows and impacts is present in several papers but in particular Profile #4 in the research to improve the understanding of environmental performances and identifying complementary information or traction batteries.

The main instrument to assess environmental performances is the life cycle environmental assessment. Datasets are connected to the related impacts,

evaluated with the EF method based on the impact categories. The global warming potential (or carbon footprint indicator), has been defined by Intergovernmental Panel on Climate Change (IPCC). The Global warming potential is the sum of the gaseous emissions corresponding to each compound. Among the relevant recommendations ISO 14040 and 14060 defines standards and tools to quantify and verifying GHG emissions.

The Greenhouse Gas protocols define a set of standards to track Greenhouse Gas emissions. GHG protocol adds calculation tools for emissions and measure the benefits of climate change mitigation projects.

It would be desirable to progress towards a harmonization of such numerous methods. It is important to check when we are introducing new solution that are supposed to be more environmental friendly than the previous ones.

Methodologies for assessing alternatives are gathered together with methods to analyse different options such as transporting or producing locally. Profile #7 deals with the environmental life cycle assessment comparison of hydrogen delivery options within Europe. In particular it tackles the question whether it is better to transport or produce locally the hydrogen based upon the environmental impact of various solutions. Various solutions are identified according to the transformations possible for hydrogen in order to be transported in a safe and economical way. Three possibilities are proposed: compression, liquefaction, chemical bonding with other molecules. Four potential carriers have been taken into account: ammonia, liquid organic compounds, methanol and synthetic natural gas. The environmental footprint (EF) impact assessment method of the European commission is used to calculate the impact of each solution (see specific category on environmental footprint assessment methods). The obtained results show that delivery options ensure global lower warming potential than on site production but on site production has lower impacts on land use, resource use, water use, acidification, eutrophication, toxicity. The single score impact assessment method (again see the relevant category) shows that green liquefied hydrogen transported via ships and compressed hydrogen transported via pipelines are the most environmentally friendly.

### *Social analysis*

UNEP defines the social life cycle assessment methodology. The scope is to identify potential social risks. A key step is the identification of relevant social impact categories and indicators for the specific material, technologies or sectors. UNEP/SETAC produced guidelines on social life cycle assessment. A forecast of the future evolution of the market and business correlated can help to understand if the impact is positive or negative. Four subsequent steps are defined:

- analysis of value chains with forward looking approach and selected raw materials that intervene in the value chain;
- selection of relevant social impact categories and indicators, for which adequate social data should be checked to be available;

- social hotspot analysis using PSILCA database on a selected representative value chain;
- discussion and interpretation of the results.

A key point is the identification of the boundaries of the system and the selection of social indicators. PSILCA reference scales rely on international statistical agencies such as World Bank, International Labour Organization, World Health Organization and United Nations and private and governmental data bases.

Materiality assessment to identify sustainability issues that are of interest for stakeholders for actual or potential influence. A set of indicators has to be chosen. The indicators may involve risks related to the respect of human and social rights, and economic impact such as new jobs and development. The selection of the indicators may also be based on the RACER analysis (relevance, acceptance, credibility, ease, robustness). Then a relevant number of social impact categories are identified. The inventory data are implemented in the open LCA software by Green delta using the PSILCA method. Common units to measure results medium number of risk hours or medium opportunity hours

Then the SLCA of the industry under examination is performed. A contribution analysis to identify direct and indirect impacts along the related supply chains. The final step is the analysis of social performance of each sector. The final phase consists of the discussion and interpretation of the results, especially in the case that the PSILCA method is used to compare different scenarios or take decisions among several different alternatives. The lack of social data is often a limitation to the width and sensitivity of the results obtained.

The category for sustainability analysis gathers social life cycle assessment and social impact categories and indicators.

The social aspects are important especially for future occupational opportunities. Social Life Cycle assessment provides indicators coming from the context description.

Social Life Cycle assessment is applied in Profile #6 to hydrogen technologies and value chains in Europe. It is used to identify hotspots with a special focus on selected critical raw materials. A basic point is the availability of data for the development of a social hotspot analysis linked to the future deployment of FCH technologies. Data is taken from the UN Comtrade database<sup>18</sup>. After having defined the system boundaries, FCH value chains are analysed with the attention focused on raw materials and critical raw materials. The number of value chains is quite high. More than 90% of the processes involved in the value chains are located outside Europe. Relevant social impact indicators are identified and indicators are calculated. The selection is made based on a literature review involving social performance of systems within the energy and mining areas. Four indicators have been chosen, namely child labour, frequency of forced labour,

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<sup>18</sup> <https://comtradeplus.un.org/TradeFlow>

women in the sectoral labour force, contribution to economic development. Reference is made to Recommendations from UNEP/SETAC on S-LCA. PSILCA was selected as an impact assessment method. The results were obtained applying the open LCA software. They are reported as medium risk hours or medium opportunity hours. In this way the number of worker hours characterized by a degree of social risk or opportunity is put in evidence. The work is done in a forward looking perspective in terms of technology and expected size of the future market. This work paves the way towards a future use of S-LCA for specific policy intervention such as due diligence requirements related to responsible sourcing of raw materials. Further research is needed in order to incorporate a prospective vision of the inventory with geographic location of unit processes and reference scales.

Social and economic factors are also taken into account in Profile #12, in relation with the impacts of mining activities. The presence of local settlements must be analysed because they're the first animation concerning environment assets, the health and safety of the inhabitants. Local citizens are the most important stakeholder who can accept and support or fight and block a mining project. Local infrastructure can have either damage or a positive boost by the opening of a new mine. In some countries indigenous people have special rights to intervene in the decision. Safety and health in mining jobs is another important issue. An auspicated positive impact is from the new employment point of view since new jobs could be created both directly and in the related activities. In some cases even new factories could be introduced as a cascade result of the opening of a mine.

Profile #5 investigates whether and how social LCA can support responsible sourcing of raw materials in the EU policy context. The potential of social indicators available in the SLCA database is investigated. The method adopted consists of the following steps: source PSILCA database, choose six raw materials country sectors, selection of indicators based on RACER analysis, nine social impact categories, application of SLCA, direct and indirect impacts, investigation of related supply chains. As a result the most significant categories appear to be: corruption, fair salary, health and safety, freedom of association and collective bargaining. According to this work, the SLCA methodology confirms its validity to detect burden shifting and trade-offs in a complete life cycle perspective. Further methodological developments in the SLCA are suggested for fully adequate support.

## **2.2. Research activities' Profiles**

In each research activity listed in this section, I contributed to specific parts based on the skills acquired during university and subsequent work experiences. Each study sequentially over time also allowed me to delve deeper into the topics developed by fellow specialists in the individual topics in order to gain a broader vision and skills relating to the methodologies of environmental and social impacts of raw materials and strategic technologies.

Section 0 reports a summary of these profiles and their taxonomy according to the following classification and categorisation definitions:

- Methodology: the logical and technical procedure that may comprise one or more algorithms and or tools arranged in such a way adequate to get the solution of a problem. It considers either their development or direct application
- Software tools: developments of software tools or model and use of existing software to carry on the analysis
- Indicators: either definition of indicators for monitoring progress or application to different scenarios of existing indicators

*Profile #1*

<p><b>Title:</b> Study on the EU's list of CRMs:  i) final report;  ii) Critical Raw Materials factsheets  iii) Non-critical Raw Materials Factsheets</p>
<p><b>Authors:</b> i) Blengini, Latunussa, <u>Eynard</u>, Torres de Matos, Wittmer, Georgitzikis, Mancini, Unguru, Blagoeva, Pavel, Carrara, Mathieux  ii) Latunussa, Georgitzikis, Torres de Matos, Grohol, <u>Eynard</u>, Wittmer, Mancini, Unguru, Pavel, Carrara, Mathieux, Pennington, Blengini  iii) <u>Eynard</u>, Georgitzikis, Wittmer, Latunussa, Torres de Matos, Mancini, Unguru, Blagoeva, Bobba, Pavel, Carrara, Mathieux, Pennington, Blengini</p>
<p><b>Year:</b> 2020</p>
<p><b>Journal:</b> European Commission reports</p>
<p><b>Status:</b> published</p> <p>i) <a href="https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1">https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1</a></p> <p>ii) <a href="https://ec.europa.eu/docsroom/documents/42883/attachments/2/translations/en/renditions/native">https://ec.europa.eu/docsroom/documents/42883/attachments/2/translations/en/renditions/native</a></p> <p>iii) <a href="https://ec.europa.eu/docsroom/documents/42883/attachments/3/translations/en/renditions/native">https://ec.europa.eu/docsroom/documents/42883/attachments/3/translations/en/renditions/native</a></p>
<p><b>Keywords relevant for the research activity:</b> Critical raw materials, criticality assessment, applications, supply risk, economic importance, data collection and processing</p>

**Graphical abstract:**

**Data collection**



**Data processing and validation**

**Results calculation**



**Outcomes:**

- 2020 list of 30 CRMs
- 30 CRMs factsheets
- 35 Non-CRMs factsheets
- Final report

**2020 Critical Raw Materials (30)**

Antimony	Fluorspar	Magnesium	Silicon Metal
Baryte	Gallium	Natural Graphite	Tantalum
Bauxite	Germanium	Natural Rubber	Titanium
Beryllium	Hafnium	Niobium	Tungsten
Bismuth	HREEs	PGMs	Vanadium
Borates	Indium	Phosphate rock	Strontium
Cobalt	Lithium	Phosphorus	
Coking Coal	LREEs	Scandium	

**Objectives:**

- To assess the criticality of a selection of raw materials based on the EC criticality methodology.
- To analyse the production, key trends, trade flows and barriers of the raw materials with the aim to identify potential bottlenecks and supply risks throughout the value chain. To the extent possible, data and projections are based on the reference period of the last 5 years in terms of data availability.
- To produce qualitative factsheets for all the raw materials assessed.
- To produce full datasets, calculation sheets and comprehensive list of data sources in an excel-compatible format.
- To continue to improve the quality and availability of data.
- To cooperate with both EU and non-EU experts (where relevant) to improve the findings of the study.

**Abstract:**



Pressure on resources will increase - due to increasing global population, industrialisation, digitalisation, increasing demand from developing countries and the transition to climate neutrality with metals, minerals and biotic materials used in low emission technologies and products. OECD forecasts that global materials demand will more than double from 79 billion tonnes today to 167 billion tonnes in 2060. Global competition for resources will become fierce in the coming decade. Dependence of critical raw materials may soon replace today's dependence on oil. The EU Green Deal Communication adopted on 11 December 2019 recognizes access to resources as a strategic security question to fulfil its ambition towards 2050

	<p>climate neutrality and increasing our climate ambition for 2030. Secure and sustainable supply of both primary and secondary raw materials, in particular of critical raw materials, for key technologies and strategic sectors as renewable energy, e-mobility, digital, space and defence is one of the pre-requisites to achieve climate neutrality. The new Industrial Strategy for the EU addresses the security and sustainability challenge and calls for an Action Plan on Critical Raw Materials and for industry-driven raw materials alliances. This continues the work of the Commission to address the growing concern of securing valuable raw materials for the EU economy. Already in 2008, the European Commission launched the Raw Materials Initiative (RMI). This EU policy pursues a diversification strategy for securing non-energy raw materials for EU industrial value chains and societal well-being. Diversification of supply concerns reducing dependencies in all dimensions – by sourcing of primary raw materials from the EU and third countries, increasing secondary raw materials supply through resource efficiency and circularity, and finding alternatives to scarce raw materials. One of the priority actions of the RMI was to establish a list of critical raw materials at EU level. The first list was published in 2011 and it is updated every three years to regularly assess the criticality of raw materials for the EU. Critical raw materials are considered to be those that have high economic importance for the EU and a high supply risk. The present study is the fourth technical assessment of critical raw materials for the EU, based on the methodology developed by the European Commission in cooperation with the Ad hoc Working Group on Defining Critical Raw Materials (AHWG) in 2017. The first assessment (2011) identified 14 critical raw materials (CRMs) out of the 41 non energy, non-agricultural candidate raw materials. In the 2014 exercise, 20 raw materials were identified as critical out of 54 candidates. In 2017, 27 CRMs were identified among 78 candidates.</p>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• Critical Raw Materials Action Plan 2020</li> <li>• European Raw Materials Alliance</li> <li>• EU Industrial strategy</li> <li>• Green Deal Industrial Plan</li> <li>• Several policies included the issue of critical raw materials</li> </ul>
<p><b>Specific contribution</b></p>	<ul style="list-style-type: none"> <li>• Data collection, processing and calculation of the results of several raw materials</li> <li>• Update of the Study on the EU's list of CRMs final report, developing tables, figures and examples</li> <li>• Collection of all the results of the analysis and</li> </ul>

	<p>development and maintenance of the master file with all the changes from the previous version.</p> <ul style="list-style-type: none"><li>• Development of several raw materials factsheets</li><li>• Chair of the stakeholder validation workshop in Brussels</li></ul>
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<p><b>Title:</b> Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign directive</p>	
<p><b>Authors:</b> Polverini, Espinosa, <u>Eynard</u>, Leccisi, Ardente, Mathieux</p>	
<p><b>Year:</b> 2023</p>	
<p><b>Journal:</b> Solar Energy</p>	
<p><b>Status:</b> published. <a href="https://doi.org/10.1016/j.solener.2023.04.001">https://doi.org/10.1016/j.solener.2023.04.001</a></p>	
<p><b>Keywords relevant for the research activity:</b> Photovoltaics, Ecodesign requirements, Life cycle-based analysis, Carbon Footprint, Product Environmental Footprint Category Rules</p>	
<p><b>Graphical abstract:</b></p>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• Steps to set a methodology for calculating the carbon footprint of a product group under the Ecodesign Regulation proposal</li> <li>• To use the Environmental Footprint methodology as a reference methodology</li> <li>• Information requirements for consumers</li> <li>• Identification of quantitative requirements maximum threshold for the carbon footprint</li> </ul>
<p><b>Abstract:</b></p>	<p>As announced in the European Green Deal, it is critical to decarbonise the European Union energy system in order to reach climate objectives by 2030 and 2050. According to the REPowerEU plan, photovoltaics (PV) is expected to play a major role in this. Therefore, it is crucial to ensure that newly installed PV modules in the EU are affordable and competitive on</p>





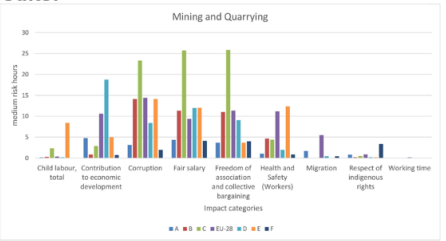
	<p>the one hand and environmentally friendly on the other. Bearing in mind that the environmental hotspots for PV modules mainly occur during the manufacturing phase, the aim of the paper is to develop a fully-fledged and adapted methodology for calculating the carbon footprint of PV modules, with particular regard to the manufacturing and shipping phases, following a cradle-to-gate approach based on the Product Environmental Footprint Category Rules (PEFCR) for PV modules. The implications of requirements for the carbon footprint of PV modules, under the existing legal framework of the Ecodesign Directive, are also discussed.</p>
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• Ecodesign regulation</li> <li>• Environmental Footprint methodology and Product Environmental Footprint Category Rules</li> </ul>
<b>Specific contribution</b>	Definition of the methodology

<p><b>Title:</b> Review of the MEErP - Methodology for Ecodesign of Energy-related Products.</p>	
<p><b>Authors:</b> Gama Caldas, Eynard, Spiliotopoulos, Blengini, Mancini, Mathieux, Ardente, Alfieri</p>	
<p><b>Year:</b> 2023</p>	
<p><b>Journal:</b> Joint Research Centre Technical Report</p>	
<p><b>Status:</b> in preparation for publication</p>	
<p><b>Keywords relevant for the research activity:</b> Ecodesign Directive, Energy-related Products, Life cycle-based analysis, Environmental Footprint methodology and datasets, Critical raw materials, tool development, End of life modelling, recycled content, recyclability, material efficiency</p>	
<p><b>Graphical abstract:</b></p> <div style="display: flex; justify-content: space-between;"> <div style="width: 30%; border: 1px solid black; padding: 5px;"> <p><b>MEErP review 2022</b></p> <p>Ecoreport tool update based on EF method:</p> <ul style="list-style-type: none"> <li>• Impact categories update;</li> <li>• End of life modelling;</li> <li>• Datasets and further improvements;</li> <li>• Review the assessment of CRMs</li> <li>• Ecoreport user manual and procedure for future updates</li> </ul> </div> <div style="width: 65%; border: 1px solid black; padding: 5px;"> <p><b>Ecoreport tool:</b> streamlined life-cycle based tool, openly available</p> <div style="display: flex; align-items: center; justify-content: space-around;">  <div> <p>Alignment with the Environmental Footprint method and database</p> </div>  </div> <p><b>NEW approach of Critical raw materials in the MEErP</b></p> <div style="display: flex; justify-content: space-between; align-items: center;"> <div style="border: 1px dashed black; padding: 5px; width: 20%;"> <p><b>Step 0:</b> numerical results of the latest EC Criticality Assessment</p> </div> <div style="border: 1px dashed black; padding: 5px; width: 20%;"> <p><b>Step 1:</b> shortlist the CRMs potentially in the product group</p> </div> <div style="border: 1px dashed black; padding: 5px; width: 20%;"> <p><b>Step 2:</b> collect quantitative data on the Bill of Material for the shortlisted CRMs</p> </div> <div style="border: 1px dashed black; padding: 5px; width: 20%;"> <p><b>Step 3:</b> look at available information from criticality assessment to define possible strategies</p> </div> </div> </div> </div>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• To update the Ecoreport tool and revise some of the methodological aspects to align them with the Environmental Footprint method</li> <li>• Critically revising the approach for Critical Raw Materials (CRMs) within the MEErP;             <ul style="list-style-type: none"> <li>○ maximize the benefits to society per unit of CRM utilized</li> <li>○ Incentivize in disclosing Information on CRMs in products</li> </ul> </li> </ul>

	<ul style="list-style-type: none"> <li>○ Shortlisting product groups based on probability to contain relevant amount CRMs</li> <li>○ Identification of strategies</li> </ul>
<b>Abstract:</b>	<p>The Methodology for Ecodesign of Energy-related Products (MEErP henceforth) consists of a techno-economic-environmental assessment of a specific product group. This assessment is the main analytical step in the potential implementation of the Ecodesign Directive for a specific product group.</p> <p>Since 2013 the current MEErP methodology has been in use and considered fit for purpose. However, since 8 years have already elapsed in this very dynamic field, the need for an update is apparent.</p> <p>The current report depicts the proposal for update put forth by the JRC at the request of DG GROW. Areas covered are:</p> <ol style="list-style-type: none"> <li>1. the updating of the EcoReport Tool;</li> <li>2. a more systematic inclusion of material efficiency aspects and of environmental footprint/ecological profile aspects in the design options and in the LLCC curve;</li> <li>3. a more systematic inclusion of societal life cycle costs;</li> <li>4. a more refined evaluation of the economic impacts in task 7 of the MEErP.</li> </ol>
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• Ecodesign regulation</li> <li>• Sustainable Product Initiative</li> <li>• Environmental Footprint methodology and Product Environmental Footprint Category Rules</li> </ul>
<b>Specific contribution</b>	<ul style="list-style-type: none"> <li>• Development of the revised EcoReport tool</li> <li>• Update of the methodology based on EF method (simplified Circular Footprint Formula, use of EF datasets)</li> <li>• Support to develop the new approach of critical raw materials (Data collection and processing and inclusion in the EcoReport tool)</li> </ul>

<p><b>Title:</b> Bridging tools to better understand environmental performances and raw materials supply of traction batteries in the future EU fleet.</p>	
<p><b>Authors:</b> Bobba, Bianco, Eynard, Carrara, Mathieux, Blengini</p>	
<p><b>Year:</b> 2020</p>	
<p><b>Journal:</b> Energies</p>	
<p><b>Status:</b> published. <a href="https://doi.org/10.3390/en13102513">https://doi.org/10.3390/en13102513</a></p>	
<p><b>Keywords relevant for the research activity:</b> Life cycle assessment, material flow analysis, criticality assessment, critical raw materials, End of Life management, Supply and demand, traction batteries</p>	
<p><b>Graphical abstract:</b></p> <p>The graphical abstract illustrates a research framework for traction batteries. At the top left, a battery icon is labeled 'Battery Raw Materials'. An arrow points to a funnel containing 'Co', 'Mn', 'Li', and 'Ni', labeled 'Criticality Assessments (supply risk)'. Below this, 'Li' and 'Ni' are shown in circles, with an arrow pointing to a gear labeled 'Current and Future Scenarios'. This gear is connected to two larger gears: 'Environmental friendly energy mix and improved recycling' (labeled 'Life Cycle Assessment') and 'Raw Materials demand, where they will be available for recycling' (labeled 'Material Flow Analysis'). A box on the right provides 'Information on recycling (end-of-Life Recycling Input Rate, EoL-RIR), future demand, stocks, ...'. An arrow labeled 'Materials to be prioritised' points from the criticality assessment to the material flow analysis. At the bottom, two boxes indicate 'Improvement of environmental performances' and 'Availability of materials depending on different End-of-Life strategies'.</p>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• Complementary Information is needed in the form of material flow analysis &amp; criticality assessment</li> <li>• To understand future life Cycle carbon footprint of traction lithium ion batteries</li> </ul>

<p><b>Abstract:</b></p>	<p>Sustainable and smart mobility and associated energy systems are key to decarbonise the EU and develop a clean, resource efficient, circular and carbon-neutral future. To achieve the 2030 and 2050 targets, technological and societal changes are needed. This transition will inevitably change the composition of the future EU fleet, with an increasing share of electric vehicles (xEVs). To assess the potential contribution of lithium-ion traction batteries (LIBs) in decreasing the environmental burdens of EU mobility, several aspects should be included. Even though environmental assessments of batteries along their life-cycle have been already conducted using life-cycle assessment, a single tool does not likely provide a complete overview of such a complex system. Complementary information is provided by material flow analysis and criticality assessment, with emphasis on supply risk. Bridging complementary aspects can better support decision-making, especially when different strategies are simultaneously tackled. The results point out that the future life-cycle GWP of traction LIBs will likely improve, mainly due to more environmental-friendly energy mix and improved recycling. Even though second-use will postpone available materials for recycling, both these end-of-life strategies allow keeping the values of materials in the circular economy, with recycling also contributing to mitigate the supply risk of Lithium and Nickel.</p>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• Battery Regulation proposal</li> </ul>
<p><b>Specific contribution</b></p>	<ul style="list-style-type: none"> <li>• Concept development and definition of the approach</li> <li>• Specific input on critical raw materials</li> </ul>



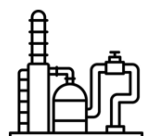
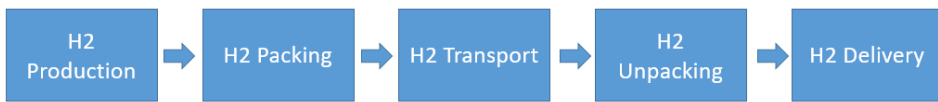
<p><b>Title:</b> Can S-LCA methodology support responsible sourcing of raw materials in EU policy context?</p>	
<p><b>Authors:</b> Di Noi, Ciroth, Mancini, Eynard, Pennington, Blengini</p>	
<p><b>Year:</b> 2020</p>	
<p><b>Journal:</b> International Journal of Life Cycle Assessment</p>	
<p><b>Status:</b> published. <a href="https://doi.org/10.1007/s11367-019-01678-8">https://doi.org/10.1007/s11367-019-01678-8</a></p>	
<p><b>Keywords relevant for the research activity:</b> Critical raw materials, social Life Cycle Assessment, social risk, value chain analysis, criticality assessment, monitoring, mining sector</p>	
<p><b>Graphical abstract:</b></p> <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p><b>Scope:</b></p> <div style="border: 1px solid black; padding: 5px; margin-bottom: 10px;">  <p><b>Geo coverage:</b> European Union + 6 extra EU countries</p> </div> <div style="border: 1px solid black; padding: 5px;">  <p><b>6 Raw Materials sectors:</b> - Mining and quarrying - Manufacture of basic metals - Manufacture of non-metallic mineral products - Forestry and logging - Manufacture of paper and paper products - Manufacture of wood and of products of wood</p> </div> </div> <div style="width: 45%;"> <p><b>Methods:</b></p> <div style="border: 1px solid black; padding: 5px; margin-bottom: 10px;"> <p><b>Data collection and elaboration:</b> PSILCA  </p> <p><b>Selection of impact categories:</b> S-LCA guidelines 2009 RACER analysis</p> <p><b>Contribution analysis:</b> direct and indirect impacts</p> </div> <p><b>Results:</b></p>  </div> </div>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>to test social-LCA methodology to support responsible sourcing of raw materials</li> <li>to test social indicators to develop new metric to monitor social risks</li> </ul>
<p><b>Abstract:</b></p>	<p>Purpose Access, affordability and sustainability of raw material supply chains are crucial to the sustainable development of the European Union (EU) for both society and economy. The study investigates whether and how the social life cycle assessment (SLCA) methodology can support responsible sourcing of raw materials in Europe. The potential of social indicators</p>

	<p>already available in an S-LCA database is tested for the development of new metrics to monitor social risks in raw material industries at EU policy level.</p> <p><b>Methods</b> The Product Social Impact Life Cycle Assessment (PSILCA) database was identified as a data and indicators source to assess social risks in raw material industries in EU-28 and extra-EU countries. Six raw material country sectors in the scope of the European policy on raw materials were identified and aggregated among those available in PSILCA. The selection of indicators for the assessment was based on the RACER (Relevance, Acceptance, Credibility, Ease, Robustness) analysis, leading to the proposal of 9 social impact categories. An S-LCA of the selected raw material industries was, thus, performed for the EU-28 region, followed by a contribution analysis to detect direct and indirect impacts and investigate related supply chains. Finally, the social performance of raw material sectors in EU-28 was compared with that of six extra-EU countries.</p> <p><b>Results and discussion</b> Considering the overall social risks in raw material industries, “Corruption”, “Fair salary”, “Health and safety” and “Freedom of association and collective bargaining” emerged as the most significant categories both in EU and extra-EU. EU-28 shows an above-average performance where the only exception is represented by the mining and quarrying sector. An investigation of the most contributing processes to social impact categories for EU-28 led to the identification of important risks originating in the supply chain and in extra-EU areas. Therefore, the S-LCA methodology confirmed the potential of a life cycle perspective to detect burdens shifting and trade-offs. However, only a limited view on the sectoral social performance could be obtained from the research due to a lack of social data.</p> <p><b>Conclusions</b> The S-LCA methodology and indicators appear appropriate to perform an initial social sustainability screening, thus enabling the identification of hotspots in raw material supply chains and the prioritization of areas of action in EU policies. Further methodological developments in the S-LCA field are necessary to make the approach proposed in the paper fully adequate to support EU policies on raw materials.</p>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• Responsible sourcing of critical raw materials</li> </ul>

<b>Specific contribution</b>	<ul style="list-style-type: none"><li>• Concept definition</li><li>• Analysis of the indicators and impact categories</li><li>• Analysis of the inventory and results in openLCA with PSILCA database</li></ul>
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<p><b>Title:</b> Social-LCA applied to hydrogen technologies in Europe: challenges for critical raw materials.</p>	
<p><b>Authors:</b> Martin-Gamboa, Eynard, Valente, Mancini, Arrigoni-Marocco, Weidner, Mathieux</p>	
<p><b>Year:</b> 2022</p>	
<p><b>Journal:</b> presented at International conference of Social Life Cycle Assessment 2022 (Aachen - DE) - Scientific paper under preparation</p>	
<p><b>Status:</b> scientific paper in preparation</p>	
<p><b>Keywords relevant for the research activity:</b> Critical raw materials, social Life Cycle Assessment, social risk, value chain analysis, criticality assessment, hydrogen, eletrolysers</p>	
<p><b>Graphical abstract:</b></p> <div style="border: 1px solid black; padding: 10px;"> <div style="display: flex; justify-content: space-between;"> <div style="width: 40%;"> <p>Analysis of different <b>value chain configurations</b>; built on <b>Comtrade database</b> and main <b>industrial players</b></p> <p>Focus on social aspects of <b>critical raw materials</b> important for hydrogen value chain;</p> <p>Selection of relevant <b>social impact categories and indicators</b> (risk and opportunities); from literature review</p> <p><b>Social hotspot analysis</b> using a s-LCA database <b>PSILCA</b></p> </div> <div style="width: 55%;"> <p><b>H<sub>2</sub> value chain</b> Time frame: 2030 Location: Southern EU - Western EU Alternatives: Northern AF, Western AS</p> <p><b>Child labour, total</b></p> <p><b>Contribution of the sector to economic development</b></p> <p>Legend: Southern Africa, Rest of regions, East Asia, East Asia, Western Europe, Northern Europe, Rest of regions</p> </div> </div> </div>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• Value chain analysis</li> <li>• Selection of social impact categories</li> <li>• Define policy recommendations for responsible sourcing of CRMs</li> </ul>
<p><b>Abstract:</b></p>	<p>Regarding the scope of the study, the S-LCA conducted incorporates for the first time a forward-looking perspective (the production and delivery of hydrogen is expected to take place in a timeframe of 2030+). To the best of our knowledge, no S-LCA studies developed so far present a prospective approach. Nevertheless, it is important to recognise that this forward-looking</p>

	<p>perspective has been applied to a part of the quantitative information of the social life-cycle inventory, in particular, the quantification of the activity variable. Further research should be required in the future with the objective of incorporating, as far as possible, a prospective vision to the completed information (qualitative and quantitative) of the inventory, i.e. geographic location of unit processes and reference scales. Furthermore, future directions of the present work should be aimed at engaging the stakeholders' vision in the choice of social indicators as well as the social evaluation of potential new scenarios in terms of delivery options and electrolysis technology. Finally, the social results presented in this study will be combined with environmental and economic ones in order to provide decision makers with a holistic interpretation based on the completed sustainability picture of hydrogen value chains.</p>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• Responsible sourcing</li> <li>• Hydrogen value chains</li> <li>• RePower EU</li> </ul>
<p><b>Specific contribution</b></p>	<ul style="list-style-type: none"> <li>• Concept development</li> <li>• Policy context</li> <li>• Selection of value chains</li> <li>• Selection of impact categories</li> </ul>

<p><b>Title:</b> Reduction of hydrogen carbon footprint in Europe via international shipping.</p>	
<p><b>Authors:</b> Arrigoni, Weidner, Dolci, Ortiz Cebolla, Eynard, Mathieux</p>	
<p><b>Year:</b> 2023</p>	
<p><b>Journal:</b> Presented at 23rd World Hydrogen Energy Conference – conference proceedings - Scientific paper under preparation</p>	
<p><b>Status:</b> scientific paper in preparation</p>	
<p><b>Keywords relevant for the research activity:</b> carbon footprint, EF impact assessment method, hydrogen, eletrolysers</p>	
<p><b>Graphical abstract:</b></p> <div style="display: flex; justify-content: space-around; align-items: flex-start;"> <div style="text-align: center;"> <p><i>Shipping Green Hydrogen</i></p>  <p>From Portugal to Netherlands</p> <ul style="list-style-type: none"> <li>• Electrolysis powered by PV systems</li> <li>• Shipped hydrogen</li> </ul> </div> <div style="text-align: center;">  </div> <div style="text-align: center;"> <p><i>Local production</i></p>  <p>Netherlands</p> <ul style="list-style-type: none"> <li>• Steam Methane Reforming</li> <li>• Electrolysis powered by the electric grid</li> </ul> </div> </div> <div style="margin-top: 10px;">  </div>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• compare shipping and local production</li> <li>• integrate life cycle assessment with life cycle green gas analysis</li> <li>• reduce carbon footprint for hydrogen</li> </ul>
<p><b>Abstract:</b></p>	<p>Green hydrogen is expected to play an important role in European decarbonisation efforts. This work investigates whether shipping green hydrogen within Europe could be a better climate solution than producing it locally. Three options for delivering hydrogen are analysed: hydrogen compression, liquefaction, and chemical bonding to other molecules (i.e., using ammonia, liquid organic compounds, methanol, or synthetic natural gas as hydrogen carriers).</p>

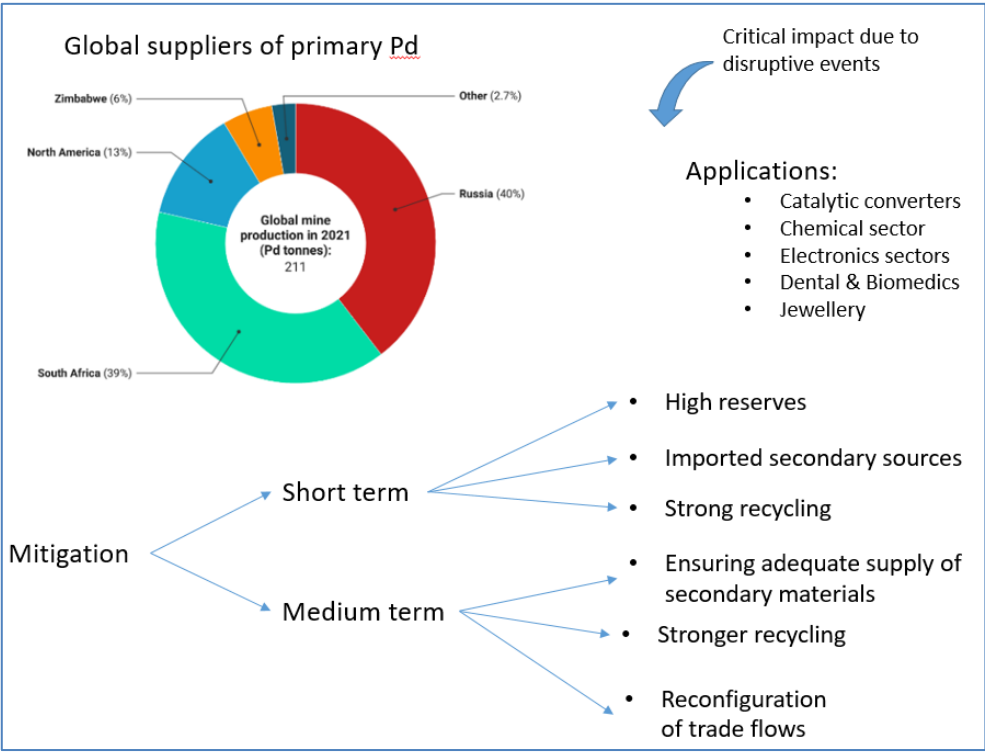
	<p>A distance compatible with the European territory was considered: i.e., production in Portugal and end-use in the Netherlands. The life cycle greenhouse gas emissions of shipped hydrogen are compared to the emissions arising from producing hydrogen locally, via either steam methane reforming or electrolysis powered by the electric grid. Preliminary results show that all the delivery options would guarantee in 2030 a supply of hydrogen with a lower global warming potential than locally produced hydrogen. Liquefaction appears to be the least greenhouse gas intense delivery solution, thanks to the lower volumes transported and the lack of an energy intensive transformation process at the delivery site. Nevertheless, much of the infrastructure for large scale hydrogen delivery does not yet exist, and therefore assumptions on technologies and emissions are subject to a high degree of uncertainty. Different delivery conditions (e.g., distances, means of transportation) can also alter the GHG emission ranking. Moreover, the present analysis was limited to the global warming impact, but an assessment of the overall environmental consequences is necessary to avoid shifting the burden from one environmental issue to another.</p>
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• geopolitical choices</li> </ul>
<b>Approach</b>	<ul style="list-style-type: none"> <li>• life cycle assessment</li> <li>• life cycle green gas analysis</li> <li>• tools integration</li> </ul>
<b>Skills</b>	<ul style="list-style-type: none"> <li>• value chain analysis</li> <li>• system boundaries expertise,</li> <li>• hydrogen packing mode techniques</li> </ul>
<b>Specific contribution</b>	<p>Multi-criteria analysis including the EF impact assessment method. Consideration on critical raw materials</p>

<b>Title:</b> Titanium: impact assessment for supply security																																																								
<b>Authors:</b> Georgitzikis, D'Elia, Eynard																																																								
<b>Year:</b> 2022																																																								
<b>Journal:</b> EC JRC Science for policy brief - Raw materials & the war in Ukraine																																																								
<b>Status:</b> published online. <a href="https://publications.jrc.ec.europa.eu/repository/handle/JRC129594">https://publications.jrc.ec.europa.eu/repository/handle/JRC129594</a>																																																								
<b>Keywords relevant for the research activity:</b> critical raw material, disruptive event management, import, export, mitigation measures																																																								
<p><b>Graphical abstract:</b></p> <p>The graphical abstract contains two main parts. The top part is a horizontal bar chart titled 'EU import value of Ti wrought products' showing the percentage of imports from various countries across four product categories: Bars, rods, profiles, wire; Plates, sheets, strip, foil; Tubes, pipes; and Articles of titanium. The bottom part is a flowchart titled 'Mitigation' that branches into 'Short term' and 'Medium term' strategies. 'Short term' includes 'High inventory levels' and 'Lower demand after pandemic'. 'Medium term' includes 'Japan, Kazakhstan' and 'US, UK'. An arrow points from the text 'Critical impact due to disruptive events' to the chart area.</p> <table border="1"> <caption>EU import value of Ti wrought products</caption> <thead> <tr> <th>Country</th> <th>Bars, rods, profiles, wire</th> <th>Plates, sheets, strip, foil</th> <th>Tubes, pipes</th> <th>Articles of titanium</th> </tr> </thead> <tbody> <tr><td>USA</td><td>48%</td><td>25%</td><td>24%</td><td>44%</td></tr> <tr><td>Germany</td><td>22%</td><td>28%</td><td>3%</td><td>6%</td></tr> <tr><td>France</td><td>15%</td><td>9%</td><td>14%</td><td>23%</td></tr> <tr><td>China</td><td>3%</td><td>28%</td><td>0%</td><td>3%</td></tr> <tr><td>Italy</td><td>10%</td><td>9%</td><td>21%</td><td>7%</td></tr> <tr><td>Canada</td><td>0%</td><td>0%</td><td>35%</td><td>3%</td></tr> <tr><td>Spain</td><td>0%</td><td>0%</td><td>0%</td><td>0%</td></tr> <tr><td>UK</td><td>1%</td><td>0%</td><td>0%</td><td>5%</td></tr> <tr><td>Japan</td><td>0%</td><td>0%</td><td>0%</td><td>0%</td></tr> <tr><td>Others</td><td>1%</td><td>0%</td><td>0%</td><td>9%</td></tr> </tbody> </table> <p><b>Applications:</b></p> <ul style="list-style-type: none"> <li>• Aerospace industry</li> <li>• Defence sector</li> <li>• Chemical industries</li> <li>• Power generation</li> </ul> <p><b>Mitigation</b></p> <ul style="list-style-type: none"> <li>Short term             <ul style="list-style-type: none"> <li>High inventory levels</li> <li>Lower demand after pandemic</li> </ul> </li> <li>Medium term             <ul style="list-style-type: none"> <li>Japan, Kazakhstan</li> <li>US, UK</li> </ul> </li> </ul>		Country	Bars, rods, profiles, wire	Plates, sheets, strip, foil	Tubes, pipes	Articles of titanium	USA	48%	25%	24%	44%	Germany	22%	28%	3%	6%	France	15%	9%	14%	23%	China	3%	28%	0%	3%	Italy	10%	9%	21%	7%	Canada	0%	0%	35%	3%	Spain	0%	0%	0%	0%	UK	1%	0%	0%	5%	Japan	0%	0%	0%	0%	Others	1%	0%	0%	9%
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<b>Objectives:</b>	<ul style="list-style-type: none"> <li>• overview of import needs for EU at short &amp; medium term</li> <li>• analyse impact of disruptive event on material supply</li> <li>• identify short &amp; medium term mitigation strategies</li> </ul>																																																							
<b>Abstract:</b>	Russia is a substantial source of titanium for the aerospace industry globally, making supply chains vulnerable to disruption. Two-thirds of titanium metal in Europe is consumed by the aerospace sector. The EU is particularly exposed to imports of wrought titanium																																																							

	<p>from Russia (16% of import value in 2020). The EU imports unwrought titanium and powders from both Russia (9% of 2020 import value) and Ukraine (8% of 2020 import value). The EU relies fully on imports of titanium sponge. Dependence on imports of wrought titanium products is significant. The most plausible sources for the EU in order to shift supply from Russia in the medium-term are its existing trade partners; Kazakhstan and Japan for unwrought titanium, and the US and the UK for wrought products.</p>
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• reconfiguration of trade flows</li> <li>• stronger impulse on circular economy</li> </ul>
<b>Approaches</b>	<ul style="list-style-type: none"> <li>• value chain assessment,</li> <li>• impact assessment,</li> <li>• CE strategy evaluation</li> </ul>
<b>Skills</b>	<ul style="list-style-type: none"> <li>• data flow analyses,</li> <li>• data base management,</li> <li>• trade flows processing</li> </ul>
<b>Specific contribution</b>	Data collection and processing

<b>Title:</b> Platinum: impact assessment for supply security	
<b>Authors:</b> Georgitzikis, Eynard, Bobba, Perpetuo Coelho, Ingoglia, Garbossa	
<b>Year:</b> 2023	
<b>Journal:</b> EC JRC Science for policy brief - Raw materials & the war in Ukraine	
<b>Status:</b> published online. <a href="https://publications.jrc.ec.europa.eu/repository/handle/JRC133245">https://publications.jrc.ec.europa.eu/repository/handle/JRC133245</a>	
<b>Keywords relevant for the research activity:</b> critical raw material, disruptive event management, import, export, mitigation measures	
<b>Graphical abstract:</b>	
<p>The graphical abstract consists of three main parts. At the top left is a donut chart titled 'Global suppliers of primary Pd' showing the distribution of global mine production in 2021 (211 Pd tonnes). The chart is divided into segments for Russia (40%), South Africa (39%), North America (13%), Zimbabwe (6%), and Other (2.7%). An arrow points from the chart to the right, where a blue curved arrow labeled 'Possible disruption on supply' points towards a list of 'Applications: Catalytic converters, Jewellery, Industrial applications, Electrolysers, Fuel cells'. Below the chart, a 'Mitigation' section branches into 'Short term' and 'Medium term' strategies. 'Short term' includes 'Recycling' and 'Alternative sources'. 'Medium term' includes 'South Africa, Zimbabwe' and 'Stabilize flows of secondary materials'.</p>	
<b>Objectives:</b>	<ul style="list-style-type: none"> <li>• overview of import needs for EU at short &amp; medium term</li> <li>• analyse impact of disruptive event on material supply</li> <li>• identify short &amp; medium term mitigation strategies</li> </ul>

<p><b>Abstract:</b></p>	<p>Russia is the second-largest producer of platinum worldwide and an important supplier to the rest of the world. In 2020, Russia accounted for 13% of global platinum mined production and 7% of world platinum exports.</p> <p>The platinum market is expected to move into an overall supply deficit until 2030. Consequently, a widespread switch globally towards non-Russian sources of supply is challenging in the aftermath of Ukraine's invasion, even though Russia doesn't have a dominant role in global supply.</p> <p>The EU depends to a large extent on imports of refined platinum. It is estimated that imports were half of total EU supply in 2011-2021. Before Russia invaded Ukraine, the EU was mildly dependent on Russia, which provided circa 10% of EU imports of refined platinum in 2021; thus, less than 5% of the total EU supply. EU imports of refined platinum from Russia stopped during July-November 2022.</p> <p>South Africa along with Zimbabwe are the prominent alternative sources for replacing primary supply from Russia in the EU. The UK is also a potential supplier of refined metal for trade diversification.</p> <p>Platinum production in the EU from secondary sources moderates supply risks. Given that platinum availability for recycling from spent autocatalysts is expected to decline in the EU in the next decade, the stable flow of secondary raw materials (domestically collected or imported) to EU-based refineries will become increasingly important for supply security</p>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• reconfiguration of trade flows</li> <li>• stronger impulse on circular economy</li> </ul>
<p><b>Approach</b></p>	<ul style="list-style-type: none"> <li>• value chain assessment,</li> <li>• impact assessment,</li> <li>• CE strategy evaluation</li> </ul>
<p><b>Skills</b></p>	<ul style="list-style-type: none"> <li>• data flow analyses,</li> <li>• data base management,</li> <li>• trade flows processing</li> </ul>
<p><b>Specific contribution</b></p>	<p>Definition of the analysis. Data collection and processing. Contribution of recycling from the automotive sector.</p>

<p><b>Title:</b> Palladium: impact assessment for supply security.</p>	
<p><b>Authors:</b> Georgitzikis, Eynard, Bobba, Perpetuo Coelho, Ingoglia, D’Elia, Garbossa</p>	
<p><b>Year:</b> 2023</p>	
<p><b>Journal:</b> EC JRC Science for policy brief - Raw materials &amp; the war in Ukraine</p>	
<p><b>Status:</b> published online.  <a href="https://publications.jrc.ec.europa.eu/repository/handle/JRC133117">https://publications.jrc.ec.europa.eu/repository/handle/JRC133117</a></p>	
<p><b>Keywords relevant for the research activity:</b> critical raw material, disruptive event management, import, export, mitigation measures</p>	
<p><b>Graphical abstract:</b></p> 	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• overview of import needs for EU at short &amp; medium term</li> <li>• analyse impact of disruptive event on material supply</li> <li>• identify short &amp; medium term mitigation strategies</li> </ul>

<p><b>Abstract:</b></p>	<p>The global supply chains of palladium, a crucial automotive metal, are heavily dependent on Russia. In 2020, Russia accounted for 41% of world's mining production, and was the leading exporter of refined palladium with a 30% share in global export value. There is limited production capacity worldwide to fill a gap in case of constrained supply from Russia in the short term. The global reliance on Russia is expected to ease gradually after 2025 due to the anticipated ample supply and weaker demand for autocatalysts. The EU relies significantly on third countries for refined palladium supply. Imports are estimated to represent about half of the EU's supply. Russia used to be a prominent supplier accounting for about one-third of the EU's imports in 2021 and 15% of the EU's sourcing in the last decade. EU imports from Russia decreased after the invasion of Ukraine compared with 2021. Diversification of EU's supply is feasible through existing producers. South Africa, Zimbabwe, and the USA are expected to contribute the most to additional primary supply in the next decade. The UK is also an important supplier of refined palladium globally. EU's industrial base to refine platinum group metals from secondary sources mitigates supply risks. The gradual decline in European demand, in combination with increased availability of secondary raw materials (imports or increased circularity) could alleviate reliance on Russia.</p>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• reconfiguration of trade flows</li> <li>• stronger impulse on circular economy</li> </ul>
<p><b>Approaches</b></p>	<ul style="list-style-type: none"> <li>• value chain assessment, impact assessment, CE strategy evaluation</li> </ul>
<p><b>Skills</b></p>	<ul style="list-style-type: none"> <li>• data flow analyses, daata base management, trade flows processing</li> </ul>
<p><b>Specific contribution</b></p>	<p>Definition of the analysis. Data collection and processing. Contribution of recycling from the automotive sector.</p>

*Profile #11*

<p><b>Title:</b> Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets.</p>	
<p><b>Authors:</b> Dolci, F., Gryc, K., Eynard, U., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., Shtjefni, D., Joanny Ordonez, G., Eulaerts, O. and Grabowsk, M</p>	
<p><b>Year:</b> 2022</p>	
<p><b>Journal:</b> EC JRC technical report</p>	
<p><b>Status:</b> published.  <a href="https://publications.jrc.ec.europa.eu/repository/handle/JRC130683">https://publications.jrc.ec.europa.eu/repository/handle/JRC130683</a></p>	
<p><b>Keywords relevant for the research activity:</b> Energy and transport; Innovation and growth; energy distribution; European Green Deal; transport research; transmission network; multimodal transport; economic analysis; sustainable development; management of resources; energy research; soft energy</p>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• feed policy making process</li> <li>• increase the effectiveness of R&amp;I policies for clean energy technologies</li> <li>• monitor research on clean energy technologies.</li> </ul>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• renewable energy directive</li> <li>• organise strategic international partnerships</li> <li>• revision of the alternative fuels infrastructure regulation</li> </ul>
<p><b>Approaches</b></p>	<ul style="list-style-type: none"> <li>• value chain analysis,</li> <li>• impact assessment,</li> <li>• Clean Energy technology assessment, circular economy strategy assessment</li> </ul>
<p><b>Skills</b></p>	<ul style="list-style-type: none"> <li>• data flow analyses,</li> <li>• technology maturity status,</li> <li>• global market positioning,</li> <li>• sustainability</li> </ul>
<p><b>Specific contribution</b></p>	<p>Social risks of hydrogen value chains. Circular economy aspects and secondary raw materials.</p>

<p><b>Title:</b> A review of EU legal provisions on the environmental impact assessment of non-energy minerals extraction projects</p>	
<p><b>Authors:</b> Hamor, Vidal-Legaz, Zampori, Eynard, Pennington</p>	
<p><b>Year:</b> 2021</p>	
<p><b>Journal:</b> EC JRC technical report</p>	
<p><b>Status:</b> published online.  <a href="https://publications.jrc.ec.europa.eu/repository/handle/JRC125111">https://publications.jrc.ec.europa.eu/repository/handle/JRC125111</a></p>	
<p><b>Keywords relevant for the research activity:</b> raw materials, mining, environmental impact directive, extractive industry</p>	
<p><b>Graphical abstract:</b></p>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• contribution to EIA directives</li> <li>• ease permitting procedures</li> <li>• reduce unnecessary administrative burden</li> <li>• create synergies</li> <li>• speed up environmental assessment process</li> </ul>
<p><b>Abstract:</b></p>	<p>Raw materials are essential to our modern lifestyle. They are used in a wide range of applications from building materials to food industries, clean energy or electronics. In 2008, the European Commission adopted the Raw Materials Initiative, which is targeted at the</p>

secure access to raw materials both within the EU and globally. It identified a range of objectives and actions, inter alia, conducting resource efficient exploration, securing the access to domestic mineral reserves and promoting streamlined permitting.

Non-energy extractive industries (NEEI) sites, if not properly designed and managed, may have significant impacts on the environment. Effects depend, inter alia, on the type of mineral, extraction methodology, substances used in mineral treatment, extractive waste characteristics, site-specific environmental conditions and the way extractive waste is managed.

The Environmental Impact Assessment (EIA) Directive provides a framework to avoid, prevent or reduce and, if possible, offset likely significant adverse effects on the environment at the earliest possible stage in technical planning and decision-making for certain public and private projects.

This study is intended to assist the sector in achieving fluent approval of EIA reports and streamlined environmental permitting. It is a concise document for developers, competent authorities, the public, and the “public concerned” encompassing all the relevant Community legislation. It provides a review of the key environmental factors and some impact assessment elements along the mining life cycle phases, in addition to a few good practice cases. It also reviews the risk assessment methodologies, environmental monitoring, mitigation measures and assessment of alternatives, as well as environmental liability and information management issues.

The list of potential key environmental aspects and impacts is not exhaustive. Environmental factors and related risks not mentioned in this document need to be addressed in the EIA of a given project. The document has limited emphasis on permitting procedural issues and it does not provide a review of the state-of-art in Member States.

This document is not binding in any way for developers or competent authorities in their application of the EIA Directive and its transposed national laws. The requirements for an environmental impact assessment are exclusively regulated in the EIA-Directive. Where this document goes beyond the requirements of the EIA or treats topics that are not covered by the EIA, the explanations and statements shall be understood as non binding opinions and recommendations. It is the exclusive mandate of the Court of Justice of the European Union to authoritatively interpret EU Community law. Nevertheless, this study may constitute

	the basis for a later EU guidance document if all stakeholders support the concept and show interest in its further development.
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• fluent approval of EIA reports</li> <li>• streamlined environmental permitting</li> </ul>
<b>Approaches</b>	<ul style="list-style-type: none"> <li>• value chain assessment,</li> <li>• environmental impact assessment,</li> <li>• Carbon footprint assessment</li> </ul>
<b>Skills</b>	<ul style="list-style-type: none"> <li>• data flow analyses,</li> <li>• information and data base management</li> <li>• mining industry</li> <li>• extraction types</li> </ul>
<b>Specific contribution</b>	Data collection and processing

<p><b>Title:</b> Circular Input Rate: novel indicator to assess circularity performances of materials in a sector - Application to rare earth elements in e-vehicles motors</p>	
<p><b>Authors:</b> Bobba, Eynard, Maury, Ardente, Blengini, Mathieux</p>	
<p><b>Year:</b> 2023</p>	
<p><b>Journal:</b> Resources, Conservation &amp; Recycling</p>	
<p><b>Status:</b> Published. <a href="https://doi.org/10.1016/j.resconrec.2023.107037">https://doi.org/10.1016/j.resconrec.2023.107037</a></p>	
<p><b>Keywords relevant for the research activity:</b> Critical raw materials, Rare earth elements, permanent magnets, electric motors, Strategic sector, Circular economy strategies and monitoring, End of Life management, Foresight analysis</p>	
<p><b>Graphical abstract:</b></p> <p>The diagram illustrates the methodology for calculating the Circular Input Rate. It starts with 'Scenario modelling' which includes 'Sectorial trends' and 'Circular Economy (CE) strategies'. These lead to 'Demand of components/embedded materials' (labeled <math>Mass_{demand,t}</math>). This demand is processed through 'Dynamic MFA' (Material Flow Analysis) within the 'Product's value-chain'. The MFA also considers 'Components/materials stocks and flows'. From the MFA, 'Secondary/Circular RM flows' are identified, which include 'Massrecycling,t', 'Massreuse,t', and 'Massremanufacturing,t'. These flows, along with the initial demand, contribute to the final 'Circular Input Rate'.</p>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• To present a new indicator (Circular Input Rate) developed to measure circularity of materials at sector-level, considering simultaneously the effects of all CE strategies</li> <li>• Literature review on remanufacturing strategy</li> <li>• To apply the indicator to a case study of Rare earth elements in electric motor</li> </ul>
<p><b>Abstract:</b></p>	<p>For a carbon neutral and more circular Europe, the development of a smarter and sustainable transport system is key, though it will require a massive supply</p>

	<p>of critical materials for both the EU and the rest of the world. Circular economy (CE) strategies can support the transition by maximizing the value of materials and through effective actions, which however require an adequate monitoring framework and ad-hoc indicators. A novel indicator assessing materials' circularity in a given sector, the Circular Input Rate (CIR), is proposed and applied to rare earths used in permanent magnets of e-motors. The CIR is used to monitor recent progresses of CE strategies in the EU fleet and estimate the effects of adopting different CE strategies in likely future scenarios. Results prove that the CIR effectively captures the contribution of all CE strategies in decreasing the primary materials demand.</p> <p>Reuse and remanufacturing of e-motors in the EU have the potential to keep in the loop up to 89 tons of Nd in 2030 (optimistic scenario). This amount can be added to 161 tons of secondary Nd obtained through functional recycling and captured by the EOL-RIR indicator.</p> <p>Further work on CIR will be needed to better understand its limitations (e.g. working on quality of data) and its potentials. In future research, the CIR could be tested to assess circularity of materials in other sectors</p>
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• Circular Economy monitoring framework</li> <li>• Material efficiency requirements in the context of Ecodesign</li> <li>• Critical Raw Materials dossiers. Measuring the mitigation of supply risk due to circular economy strategies</li> </ul>
<b>Approaches</b>	<ul style="list-style-type: none"> <li>• Material flow analysis</li> <li>• Criticality Assessment (EoL-RIR)</li> <li>• Scenario analysis</li> </ul>
<b>Skills</b>	<ul style="list-style-type: none"> <li>• Data collection</li> <li>• Data elaboration</li> <li>• Scenario modelling</li> <li>• End of Life strategies</li> </ul>
<b>Specific contribution</b>	<ul style="list-style-type: none"> <li>• Concept development</li> <li>• Definition of the indicator</li> <li>• Data collection on e-motors and rare earth elements</li> </ul>

<p><b>Title:</b> Raw Material profiles - Raw Materials Information System application</p>	
<p><b>Authors:</b> Georgitzikis, Eynard, Ciuta, Garbossa, D'Elia, Manfredi</p>	
<p><b>Year:</b> 2021</p>	
<p><b>Journal:</b> online application</p>	
<p><b>Status:</b> published online. <a href="https://rmis.jrc.ec.europa.eu/rmp/">https://rmis.jrc.ec.europa.eu/rmp/</a></p>	
<p><b>Keywords relevant for the research activity:</b> critical raw materials, criticality assessment, circular economy monitoring framework, trade, applications</p>	
<p><b>Graphical abstract:</b></p> <div style="text-align: center;"> </div>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>• To have an overview for each raw material</li> <li>• To keep the database up-to-date</li> <li>• Systematic application of indicators</li> </ul>

<b>Abstract:</b>	Collection of data and elaboration to present for each raw materials a set of indicators in an online dashboard.
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• CRMs dossiers</li> <li>• Industrial strategy</li> <li>• Ecodesign</li> </ul>
<b>Specific contribution</b>	<ul style="list-style-type: none"> <li>• Data collection and processing</li> <li>• Selection of indicators</li> </ul>

<p><b>Title:</b> Material system analysis of nine raw materials: Barytes, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum and Vanadium</p>															
<p><b>Authors:</b> Torres de Matos, Devauze, Planchon, Wittmer, Ewers, Auberger, Dittrich, Latunussa, Eynard, Mathieux</p>															
<p><b>Year:</b> 2021</p>															
<p><b>Journal:</b> EC JRC technical report</p>															
<p><b>Status:</b> published. <a href="https://op.europa.eu/en/publication-detail/-/publication/1de0016a-df96-11eb-895a-01aa75ed71a1">https://op.europa.eu/en/publication-detail/-/publication/1de0016a-df96-11eb-895a-01aa75ed71a1</a></p>															
<p><b>Keywords relevant for the research activity:</b> Material System Analysis, Critical Raw Materials, Monitoring systems, applications of new indicators</p>															
<p><b>Graphical abstract:</b></p> <p><b>Coordination with criticality assessment</b> on data collection and stakeholder consultation</p> <table border="1"> <thead> <tr> <th>Indicator</th> <th>Formula</th> </tr> </thead> <tbody> <tr> <td>End-of-life recycling input rate (EOL-RIR)</td> <td><math>(G.1.1+G.1.2)/(B.1.1+B.1.2-B.1.3+C.1.3+C.1.4+C.1.8+D.1.3+D.1.9+G.1.1+G.1.2)</math></td> </tr> <tr> <td>End-of-life recycling rate (EOL-RR)</td> <td><math>(G.1.1+G.1.2+G.1.3)/(E.1.6+F.1.2-F.1.1)</math></td> </tr> <tr> <td>Collection Rate</td> <td><math>F.1.4/(M.4.1)</math></td> </tr> <tr> <td>Self-sufficiency Extraction</td> <td><math>(B.1.1+B.1.2)/(M.1.1+M.1.2)</math></td> </tr> <tr> <td>Self-sufficiency Processing</td> <td><math>C.1.1/M.2.1</math></td> </tr> <tr> <td>Self-sufficiency Manufacturing</td> <td><math>D.1.1/M.3.1</math></td> </tr> </tbody> </table>		Indicator	Formula	End-of-life recycling input rate (EOL-RIR)	$(G.1.1+G.1.2)/(B.1.1+B.1.2-B.1.3+C.1.3+C.1.4+C.1.8+D.1.3+D.1.9+G.1.1+G.1.2)$	End-of-life recycling rate (EOL-RR)	$(G.1.1+G.1.2+G.1.3)/(E.1.6+F.1.2-F.1.1)$	Collection Rate	$F.1.4/(M.4.1)$	Self-sufficiency Extraction	$(B.1.1+B.1.2)/(M.1.1+M.1.2)$	Self-sufficiency Processing	$C.1.1/M.2.1$	Self-sufficiency Manufacturing	$D.1.1/M.3.1$
Indicator	Formula														
End-of-life recycling input rate (EOL-RIR)	$(G.1.1+G.1.2)/(B.1.1+B.1.2-B.1.3+C.1.3+C.1.4+C.1.8+D.1.3+D.1.9+G.1.1+G.1.2)$														
End-of-life recycling rate (EOL-RR)	$(G.1.1+G.1.2+G.1.3)/(E.1.6+F.1.2-F.1.1)$														
Collection Rate	$F.1.4/(M.4.1)$														
Self-sufficiency Extraction	$(B.1.1+B.1.2)/(M.1.1+M.1.2)$														
Self-sufficiency Processing	$C.1.1/M.2.1$														
Self-sufficiency Manufacturing	$D.1.1/M.3.1$														
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>to assess the flows of materials through the EU economy, including extraction, stock accumulation and end-of-life management e.g., through disposal or recovery in the EU.</li> <li>to identify weak points in the value chain</li> <li>to identify actions designed to increase the resilience of the supply chain</li> </ul>														

	<ul style="list-style-type: none"> <li>• to improve the overall circularity of the EU</li> </ul>
<p><b>Abstract:</b></p>	<p>Consistent information on raw material value chains is key for sustainable resources management, to guarantee supply of raw materials and strengthen the EU industry competitiveness. The European Commission launched the development of Material System Analysis (MSA) studies in 2015, to assess the flows of materials through the EU economy, including extraction, stock accumulation and end-of-life management e.g., through disposal or recovery in the EU. The MSA studies consider the entire life cycle of a selected material. This highlights hotspots and bottlenecks in a material value chain. Awareness of weak points in the value chain can guide actions designed to increase the resilience of the supply chain, also in the face of disrupting events. MSA, by virtue of accounting for materials in stock, can also help identifying opportunities to source materials from urban mine or waste streams, allowing to improve the overall circularity of the EU. The systemic view of the MSA also lends itself to develop and support scenarios and outlooks.</p> <p>The current report includes the MSA for the raw materials: barytes, bismuth, hafnium, helium, natural rubber, elemental phosphorus, scandium, tantalum and vanadium. These materials have been or are considered critical raw materials in the EU.</p> <p>The materials cycles analysed show a very strong dependence on imports along the value chain. The EU is highly dependent on imports of primary materials and intermediate products and has a consolidated manufacturing stage for all the materials analysed (except for helium).</p> <p>The EU is efficient in collecting end-of-life products, however most of the targeted materials are lost due to in-use dissipation, non-functional recycling, or disposal in other waste streams. This indicates that the EU is not yet able to decrease its dependency of primary material using secondary materials domestically recycled. However, for some materials (e.g. elemental phosphorus) significant efforts are undertaken to change this situation in the future to improve the EU circularity.</p> <p>The developed MSA are comprehensive datasets that may provide crucial knowledge to help the development and monitoring of EU policies including: the EU list of Critical Raw Materials, the new EU Industrial Strategy, the Green Deal transition plan, the</p>

	EU Raw Materials Initiative and the EU Circular Economy Action Plan.
<b>Possible Impact on policy:</b>	<ul style="list-style-type: none"> <li>• EU list of Critical Raw Materials</li> <li>• EU Industrial Strategy,</li> <li>• Green Deal transition plan,</li> <li>• EU Raw Materials Initiative</li> <li>• EU Circular Economy Action Plan</li> </ul>
<b>Approaches</b>	Material Flow Analysis Critical Raw Materials Alignment with Criticality assessment Value chain modelling <ul style="list-style-type: none"> <li>• End of life management</li> </ul>
<b>Skills</b>	Data collection Interaction with stakeholders Data elaboration <ul style="list-style-type: none"> <li>• Modelling</li> </ul>
<b>Specific contribution</b>	Data collection and processing of Bismuth. Preparation of the report

<p><b>Title:</b> 3rd Raw Materials Scoreboard : European innovation partnership on raw materials</p>	
<p><b>Authors:</b> Vidal Legaz, Unguru, Mancini, Latunussa, Hamor, Ardente, Mathieux, Nita, Torres de Matos, Plazzotta, Bonollo, Blengini, Pasimeni, Wittmer, Eynard, Garbossa, Pennington, Ciupagea</p>	
<p><b>Year:</b> 2021</p>	
<p><b>Journal:</b> Publications Office of the European Union, 2021</p>	
<p><b>Status:</b> published. <a href="https://op.europa.eu/en/publication-detail/-/publication/1ee65e21-9ac4-11e6-868c-01aa75ed71a1">https://op.europa.eu/en/publication-detail/-/publication/1ee65e21-9ac4-11e6-868c-01aa75ed71a1</a></p>	
<p><b>Keywords relevant for the research activity:</b> critical raw materials, indicators, circular economy monitoring framework, trade, social issues, environmental aspects, mining sector</p>	
<p><b>Graphical abstract:</b></p> <p><b>THEMATIC CLUSTERS</b></p> <ol style="list-style-type: none"> <li>Raw Materials Supply in the EU</li> <li>Raw materials in the global context</li> <li>Circular economy and recycling</li> <li>Competitiveness and innovation</li> <li>Environmental dimension</li> <li>Social dimension</li> </ol> <p>The Raw Materials Scoreboard – structure of clusters and indicators along the supply chain</p>	
<p><b>Objectives:</b></p>	<ul style="list-style-type: none"> <li>to monitor the field and the competitiveness of the specific EU industry.</li> <li>to enable the European Commission to increase the EU economy’s resilience</li> <li>to withstand shocks by basing its policies on solid evidence</li> <li>to address the need to decouple economic growth from resource use</li> <li>to identify opportunities to boost the circular economy.</li> </ul>

<p><b>Abstract:</b></p>	<p>The Raw Materials Scoreboard, a cornerstone of the European Union Raw Materials Knowledge Base (EURMKB) and an integral and permanent part of the Raw Materials Information System, is published every two years.</p> <p>The RM Scoreboard is an initiative of the European Innovation Partnership (EIP) on Raw Materials that provides relevant and reliable monitoring information to governments, industry, and other stakeholders about the main challenges to a secure and sustainable supply of raw materials to the EU.</p> <p>This edition of the RM Scoreboard consists of 27 indicators grouped into six thematic clusters: (1) raw materials supply in the EU, (2) raw materials in the global context, (3) circular economy and recycling, (4) competitiveness and innovation, (5) environmental dimension and (6) social dimension.</p>
<p><b>Possible Impact on policy:</b></p>	<ul style="list-style-type: none"> <li>• EU industrial strategy</li> <li>• Circular Economy Action Plan</li> <li>• Critical Raw Materials Act</li> <li>• European Raw Materials Alliance</li> </ul>
<p><b>Approaches</b></p>	<ul style="list-style-type: none"> <li>• Collection on different indicators</li> </ul>
<p><b>Skills</b></p>	<ul style="list-style-type: none"> <li>• Data collection and elaboration</li> <li>• Communication</li> </ul>
<p><b>Specific contribution</b></p>	<p>Support to development of some indicators 7, 25 and 26</p>

### **2.3. Summary of the section and transversal analysis**

The objective of this session is to provide a transversal analysis of all the profiles analysed in the previous section. As already mentioned in section 2.1, the link among all the studies performed cover raw materials and strategic technologies in the EU. Depending on the specific analysis the scope can have a different focus, namely at different levels either material, product or sector. This shows the importance of selecting the correct tools to use according to the scope of the study and the objectives. The three main criteria presented in section 2.1 are also reported here as a reference to understand to what extent a multi-criteria analysis approach was already applied.

**Table 2: Transversal analysis on the targeted raw materials and products**

Profiles	Targeted resources or product groups	Scope	Multi-criteria	Methodology	Software tool	Indicators
Profile #1	Critical and non-critical raw-materials for the EU (80 raw materials)	Material	Criticality assessment	X		X
Profile #2	Photovoltaic panels	Product / sector	Environmental LCA	X		
Profile #3	Energy-related products (e.g. domestic appliances, heaters, televisions, batteries, motors, etc.). Critical raw material for the EU	Products and materials	Criticality Assessment, Circular economy, Environmental LCA	X	X	X
Profile #4	Mobility, batteries, cobalt, lithium, manganese and nickel	Materials / Product / Sector	Criticality Assessment, Circular economy, Environmental LCA	X		X
Profile #5	Six raw material sectors	Sectors	Social LCA	X	X	X
Profile #6	Electrolysers, Hydrogen and Platinum Group Metals	Material / Product / Sector	Social LCA	X	X	X
Profile #7	Electrolysers, Hydrogen	Product / Sector	Environmental LCA	X	X	X
Profile #8	Titanium	Material	Supply and demand analysis, risk analysis, foresight,			X
Profile #9	Platinum	Material	Supply and demand analysis, risk analysis, foresight, Circular economy monitoring			X
Profile #10	Palladium	Material	Supply and demand analysis, risk analysis, foresight, Circular economy			X

			monitoring			
Profile #11	Electrolysers	Sector / Materials	Social LCA			X
Profile #12	Mining sector	Sector	Environmental sustainability			X
Profile #13	Mobility, electric motor, magnets, Neodymium	Materials / Product / Sector	Criticality Assessment, Circular economy monitoring	X	X	X
Profile #14	Critical and non-critical raw materials	Material	Criticality assessment		X	X
Profile #15	Barytes, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum and Vanadium	Material	Criticality assessment and Material system analysis	X		X
Profile #16	Mining sectors and raw materials	Material / Sector	Critical raw materials, Circular economy monitoring Environmental and social sustainability			X

# Chapter 3: A toolbox for the green transition

This chapter gathers comparative considerations about the integration of the tools analysed in the previous chapter. **Setting**

Collecting tools in a toolbox has several advantages such as easier choice of the most adequate tool, ensure compatibility and combinability of tools with reference to measurement units, incentive to invent and build new tools to enhance the range of problems that may be solved. In particular we focus on each tool separately based on the objectives that are represented by the results of the application of the tool. We check which tools among the analysed ones are aimed to the same type of results. Then we verify whether one or more tools are adopted in the same profile. If more tools are used in the same profile, we consider the relationship among such different tools.

Figure 12 shows exactly the benefits that could derive from this parallel view of tools. A parallel overview of tools gathered in the toolbox can generate important benefits in the quality of input elements and results especially in the view of possible integration.

Basic features which are key for high quality results are:

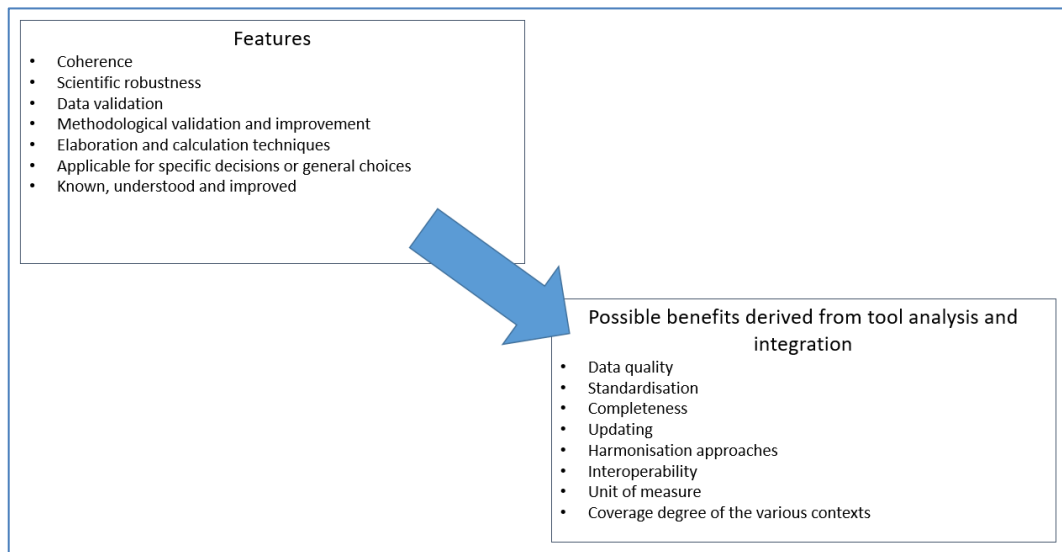
- coherence among all elements;
- scientific robustness referring to the strength of models, tests and procedures; data must be validated;
- methodologies must be validated and improved when needed; elaboration and calculation techniques should be transparent so that coherence among different tools is ensured when they apply together or sequentially
- be well documented so that they can be analysed to understand the limits of their validity in different contexts, they may be improved when necessary and the theory of error evaluation may be correctly applied.

Such specific tool and parameter quality features visibility would produce the following positive effects when tool in the toolbox are applied in combination to answer complex questions.

- Input data quality is improved since coherence is guaranteed,
- Standardization ensures easier and cheaper data gathering and further elaboration,

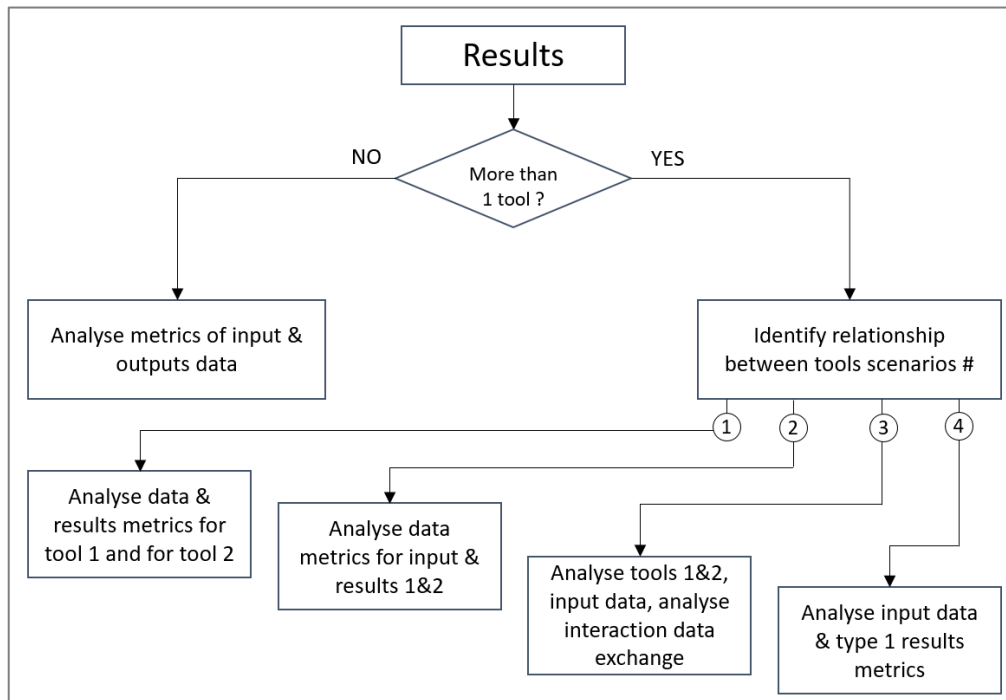
- Completeness would be easier to get because lack of some data are identified in an easier way,
- The updating process may be encouraged seeing the multiple situation that would benefit from it,
- Unit of measurement for input and output data would be standardised,
- The harmonisation would be easier because the number of users would be higher and more visible.

**Figure 12: benefits that can derive from tool analysis, interoperability and their integration**



The procedure to analyse metrics and identify relationship between tools is summarized in the flow chart in Figure 13.

Figure 13: Procedure for tools analysis – Flow chart



The procedure in Figure 13 shows how to deal with complex problems that may require the application of more than one tool. Starting from the analysis of the results that we want to obtain it needs to be decided whether one or more tools contained in the toolbox are necessary. In the case the assessed scenario is complex and more than one tool is necessary, the relationships of the multiple scenario should be identified.

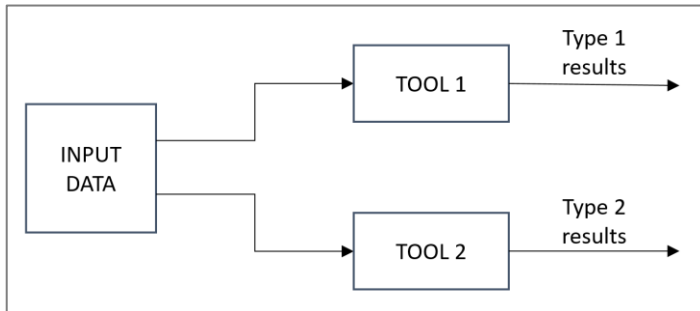
Four scenarios may be identified and explained in the next session. This approach is useful to understand how input data must be organised in the analysis of complex problems and how data quality characteristics should be managed.

### 3.2. Scenarios

By applying the approach described in Figure 13, a number of scenarios are generated. In the following flow charts (from Figure 14 to Figure 17), logical scenarios types are reported. Later in this chapter (see section 3.5) more detailed description of each scenario is done taking into account specific cases described in the previous chapters, coming from the profiles we participated in editing. The general scenarios are described in the following; reference is made to Figure 14 to Figure 17.

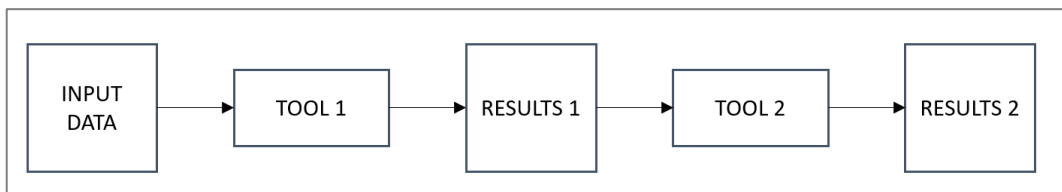
In scenario number 1 (Figure 14) two different tools are applied to the same data base of input data. They are applied in parallel to give answers to different complementary questions.

Figure 14: Parallel tools scenario



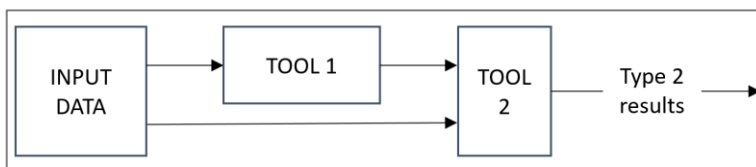
In scenario number 2 (Figure 15) two different tools are applied in cascade. Tool 1 processes its input data and the results are then used as input data for tool 2 which in turn produces the final results (Results 2)

Figure 15: Cascade tool scenario



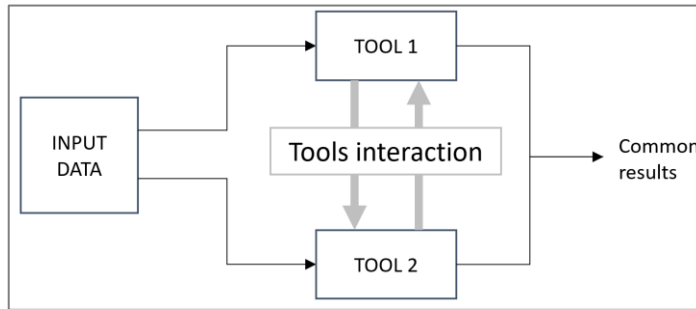
Scenario number 3 (Figure 16) combines tool scenarios where input data where tool 1 operates on primary data; while tool 2 processes at the same time primary input data and results generated by tool 1.

Figure 16: Combined tools scenario



Scenario 4 (Figure 17) is an even more complex scenario where both tools operate on primary input data but an interaction between tool 1 and tool 2 is needed to generate the results which are partly generated by tool 1 and partly to tool 2. The interaction between tools may consist of a synchronisation of parameters, an adaptation of areas of operation inside a specific tools related to for example algorithm, choice of input data sets, activation of some algorithms in one tool and another algorithm in a second tool.

Figure 17: Combined interacting tools scenario



The analysis of the scenarios is a logical considerations of possible interactions between different tools and sets of input data. Such possibilities may be further confirmed by the analysis of tool applications in some of the profiles presented in section 2.2. In section 3.5 some examples with reference to the four scenarios are reported and further analysis that go beyond the scope of this work are identified.

### 3.3. Data quality features

According to the Global Data Management Community (DAMA) data quality consists of planning, implementing and controlling activities that apply data quality management techniques, in order to ensure that they are fit for purpose and meet the needs of users (Irion 2021). Data quality verification system is fundamental to have reliable information for the business use for which it is intended, being able to activate diagnostic actions and removal of anomalies.

Data quality features shall include the aspects of accuracy, completeness, validity, consistency, uniqueness, timeliness, and fitness for purpose. These aspects are to be considered to identify data issues such as duplicate data, missing values, outliers.

The following definitions as provided by the International Business Machines Corporation (IBM)<sup>19</sup>:

- **Completeness:** This represents the amount of data that is usable or complete. If there is a high percentage of missing values, it may lead to a biased or misleading analysis if the data is not representative of a typical data sample.
- **Uniqueness:** This accounts for the amount of duplicate data in a dataset. For example, when reviewing supplier data, you should expect that each supplier has a unique supplier identity.
- **Validity:** This dimension measures how much data matches the required format for any business rules. Formatting usually includes metadata, such as valid data types, ranges, patterns, and more.

<sup>19</sup> <https://www.ibm.com/topics/data-quality>

- **Timeliness:** This dimension refers to the readiness of the data within an expected time frame.
- **Accuracy:** This dimension refers to the correctness of the data values based on the agreed upon “source of truth.” Since there can be multiple sources which report on the same metric, it’s important to designate a primary data source; other data sources can be used to confirm the accuracy of the primary one. For example, tools can check to see that each data source is trending in the same direction to bolster confidence in data accuracy.
- **Consistency:** This dimension evaluates data records from two different datasets. As mentioned earlier, multiple sources can be identified to report on a single metric. Using different sources to check for consistent data trends and behaviour allows organizations to trust the any actionable insights from their analyses. This logic can also be applied around relationships between data.
- **Fitness for purpose:** Finally, fitness of purpose helps to ensure that the data asset meets a business need. This dimension can be difficult to evaluate, particularly with new, emerging datasets

Data quality features shall include discussion on the degree of representativeness (geographically, temporally), overall robustness of the data as classically implemented in the different tools (and associated methods) assessed. Nomenclature definition and mapping to create consistency between the different approaches and scenarios. Data recovery techniques and metrics need to be harmonised with the use of systemic approaches and tools.

In particular it is noteworthy that secondary databases in Social LCA are still under development, with quality (completeness, representativeness, etc.) still more limited as compared to environmental LCA. Sometimes the scope of the analysis of the different components of a toolbox is different. For example criticality assessment are applied at country / regional levels, while the LCA is implemented at product / service level. The consistency among the tools is fundamental when integrating such tools.

A good example of the integration of different nomenclature and formatting systems in the field of LCA is the Life Cycle Data Network platform and the Global LCA Access Data (GLAD) initiative promoted by the United Nations<sup>20</sup>. The first one is a web infrastructure for the publication of quality assured LCA dataset (i.e. LCI datasets and LCIA method datasets) from different organizations such as industry, national LCA projects, research groups, and consultants.

GLAD aims to achieve better data accessibility and interoperability of LCA data of independently-operated LCA databases (nodes). One of the main functionalities of GLAD will be the conversion function to allow users to convert a dataset from its native format in the source database (node) into another format

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<sup>20</sup> Available at: <https://www.globalcadataaccess.org/>

convenient for the user. Also nomenclature mapping is a key tool to convert the information from a data provider system to another one.

### **3.4. Benefits (for stakeholders)**

As it can be seen, benefits are several and can be treated in an easier way if we analyse on a per stakeholder basis. Stakeholders in this case consist of the following sets: companies supposed to provide data about their products; entities in charge to check presence, consistency and completeness of the data required by regulations in force; research entities; design teams for the more and more frequent interactions with design tools; public sector.

On this basis main examples of benefits are to:

- Ease the data production procedure
- Ensure consistency of data and data bases
- Ease processing
- Accelerate quality checks
- Improve interpolation, extrapolation of data proxy
- Possibility to easier data integration
- Simplify transparency and communication

### **3.5. Application to specific cases and further extensions**

We focus here on the relationship between different tools inside the same study. Particularly interesting are therefore the cases that we can identify in the works we joined to write where more than one tool is applied to face complex problems.

From the analysis it appears that most profiles just contain the application of one tool such as Profile #1, Profile #5, Profile #7, Profile #15.

Examples of application of Scenario 1 are:

- Profile #8
- Profile #9
- Profile #10
- Profile #14

Examples of application of Scenario 2 are:

- Profile #2
- Profile #3

Examples of application of Scenario 3 are:

- Profile #6

Examples of application of Scenario 4 are:

- Profile #4
- Profile #13

The most interesting profile related to the combination of more than one tool is Profile #4. Here the focus is in fact on the benefits that occur when the environmental assessment is made complementing environmental assessment conducted with life cycle assessment with other tools. Material flow analysis and criticality assessment are the other tools involved. As already stated this approach creates added value as in cases the same data can serve more than one component.

“Well established tools can be adapted and combined according to the product/system’ characteristics to provide a wider understanding of the environmental performances in a life-cycle perspective. Hence, it is possible to capture different aspects of the assessed system/product and provide information according to the interests of the specific stakeholders. In addition, a flexible model and a common structure of the data collection (e.g., identification of best available sources, common data when possible) eases the update of the assessment according to the availability of data/information. Finally, consistency of input for different analyses is improved and the comparability of results is strengthened.” (Bobba et al. 2020)

Dewulf (2015) maintains the importance of having a general view of the various methodologies and techniques that can be considered as a toolbox for LCA stakeholders.

He indicates four fields as pending issues:

- The first is the availability of reliable and representative data for production and consumption chains
- The second is the possibility to get an integrative sustainability assessment, incorporating social, economic, and environmental aspects.
- The third issue is that the added value of sustainability assessment is normally difficult to measure therefore it is necessary that a financial effort is done to develop solutions of interest for the numerous stakeholders.
- The fourth point is the opportunity to quantify beneficial impacts of renewables based products or services.

In the case of different tools that are used in different works to cover the same step, differences should be evaluated to see whether a common solution can be envisaged. Alternatively a deeper reflection on the causes that pushed towards different choice should be considered.

An example of a possible integration of different tools that could be developed in the future, is the combination of Profile #9 (Platinum: impact assessment for supply security) with Profile #6 (Social-LCA applied to hydrogen technologies in Europe: challenges for critical raw materials). The integration of this two existing studies may represent an application of the approach described in section 3.2 with reference to Scenario 3. The possible mitigation of supply risk of platinum in the future can also have an impact on the social aspects considered in the supply chain of hydrogen production in Europe.

In the identification of the four scenarios made in section 3.2 we have made reference to only two tools. Of course, when facing more complex problems in the view of global approaches and policy needs, more tools may be required to be combined. However, the relationships among several tools may be lead back to the basic scenarios already described.

The work shall then need to be focused with particular care on input data. The quality characteristics and processes that have to defined and/or improved to obtain such goals will then be the key aspect to concentrate for the next steps.

# Chapter 4: Conclusions

The work is based upon the application of several methodologies to a variety of questions related to the green and digital transition. Specifically, reference is made to the identification of which raw materials are critical for the European Union based on the methodology updated by the European Commission in 2017. Particular effort was devoted to the study of the 2020 list of critical raw materials and the mechanisms and tools through which the list is identified and periodically updated and where the results of the assessment can be further used.

Material flows analysis and circular economy progress were also investigated taking into account all the mitigation strategies beyond recycling such as remanufacturing and reuse. Attention was given to present and future indicators necessary to monitor the progress of the circular economy, to suggest solutions to improve it and to guide the choice of the most appropriate strategies in dependence of the specific context or the best combination of some of them.

Sustainability has been the third pillar of this work, treating assessment techniques and methodologies for both environmental and social impact evaluation of mining activities and complex value chains using a life cycle-based approach.

This thesis then reports a number of studies selected to cover the main areas concerning the above mentioned three pillars: social life cycle assessments, indicators to monitor the circularity progress, carbon footprint assessment related to green energy production, technology development and maturity assessment of specific technologies, environmental life cycle assessments of alternative solutions or reduction of carbon footprint, Ecodesign methodology application, impact assessment of actual disruptive events on specific materials supply, material system analysis of important raw materials, review of regulations and methodologies related to environmental and social impact assessment, bridging tools identification for improving environmental performances, social life cycle assessment application to raw materials, studies on critical raw materials 2020 report.

Several tools have been analysed covering the main themes about critical raw materials investigation. A wide range of techniques and methodologies exist and are under development so the choice was made to concentrate on the tools contained in the papers written during the doctorate as it was possible to cooperate and learn from many colleagues of various expertise.

The need to face different and several challenges allowed to learn database creation, loading and access, processing methodologies, bridging tools, identification and development of indicators to monitor the evolution of materials flows in a system, techniques to evaluate choice and guidance for decision

making. The wide range of methods and applications has allowed us to have a still limited but nonetheless general view of several approaches that has pushed us to investigate the state of the art and to identify ways to analyse them in a comparative way. This brings us to interpret the various approaches, techniques and methodologies as component of a kind of toolbox.

As described in chapter 3 an attempt is made to subdivide tools in profiles and categories that would help in classifying and comparing them. The potential for integration of various tools is also investigated with a few schemes the possible combinations.

To my knowledge this is the first attempt to produce a view focussed on tools rather than to specific studies as it is the case for the papers that we contributed to produce.

The integration of these approaches and their standardisation will also lead to mutual benefits in terms of data quality, completeness of the analysis and reliability of the results.

Further benefits from such an approach could be guidance and choice among different tools and to start a path towards a standardisation of input data. A key aspect in general is the availability of adequate data with the necessary completeness and quality. A common problem that we can see in several scenarios is in fact the lack of data or the insufficient quality of many data. A comparative view of several tools could help in this respect for example suggesting common measure units and formats common to several tools. This could help data gathering and loading and cascading tools related to subsequent steps. This path towards standardisation requires further work but could hopefully prove effective to improve the quality of data in terms of completeness, format, updating rate. Also the effort to convince stakeholders to provide data could be smoothed if some kind of standard way of data provision could be defined. Other positive effects could be simplification of database management and the possibility to use the same data for tools related to different steps of the various methodologies.

Further study is required beyond the scope of this work, but according to the experience gained working with our colleagues and from the literature, the future steps that should be faced are the improvements of the availability and quality of data and the integration of more than one approach to give a more powerful way to get significant results. The most relevant work in this respect with reference to the reported set of papers is (Bobba et al. 2020) - Profile #4.

This plethora and definition of a toolbox has stimulated our interest to widen the knowledge and deepen the comparative and integrative analysis, although we have reported here just the first hints. In particular the availability and quality of data appears to be considered one of the most critical aspects that influence the reliability and significance of results. This is acknowledged by all the sources with which we have investigated. In perspective therefore this represents a field where it is worth to devote much effort both from the research and the regulation

point of view, without neglecting the contribution that the most recent developments in data management scientific discipline will soon be able to provide. Further efforts are still required to consolidate the framework considering further developments in the technical, scientific and policy domains.

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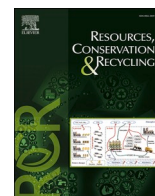
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# **Chapter 5: Selection of publications**

As already stated in Chapter 2, in each research activity, I contributed to specific parts based on the skills acquired during university and subsequent work experiences. Each study sequentially over time also allowed me to delve deeper into the topics developed by fellow specialists in the individual topics in order to gain a broader vision and skills relating to the methodologies of environmental and social impacts of raw materials and strategic technologies.





Full length article

## Circular Input Rate: novel indicator to assess circularity performances of materials in a sector – Application to rare earth elements in e-vehicles motors

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## ABSTRACT

A smarter and sustainable mobility is key for a carbon-neutral and circular Europe, although electrification will require a massive supply of critical materials. Circular strategies can support the transition by maximizing the materials' value and through effective actions, which however require an adequate monitoring framework.

To assess materials' circularity in a given sector, the novel Circular Input Rate (CIR) indicator is proposed and applied to rare-earths in e-motors' permanent magnets to monitor recent progresses of circular strategies and estimate their effects in future scenarios. Results prove that the CIR effectively captures the contribution of all circular strategies: in 2030, reuse and remanufacturing can keep in the loop about 90tons of Nd, to be added to 161tons of secondary Nd from functional recycling (captured by the EOL-RIR indicator).

In future research, the CIR could be tested to assess materials' circularity in other sectors, which also will allow to better understand its limitations and potentials.

## 1. Introduction

Since climate neutrality will require a 90% reduction in transport greenhouse gas emissions by 2050, in its European Green Deal for the European Union (EU) and its citizens (EC, 2019), the European Commission has taken the commitment to “accelerate the shift to sustainable and smart mobility”. One of the pre-requisites of the low carbon transition is to ensure the sustainable supply of (critical) raw materials ((C) RM), by diversifying supply in particular from secondary sources. The relevance of analysing supply of raw materials and circularity options for specific strategic value chains is also stressed by EC (2020a, 2020b, 2020c): these policy documents clearly highlight that sectors compete for the same materials. Therefore, developing knowledge on the use of materials in specific applications and sectors is relevant information for decision makers and the future development of inter-related CE strategies. This is particularly true for raw materials with high economic importance and high supply risk, i.e. belonging to the list of Critical Raw Materials (CRMs) to the EU (EC, 2020b).

To secure supply of raw materials and maximize the benefits to

society, various Circular Economy (CE) strategies can be implemented. In line with the Waste Framework Directive and the CE action plan, products (and hence embedded materials) should be kept in the economic system as long as possible, maximizing their value and decreasing the demand of new products (EC, 2020a; EU, 2008). In general, such strategies consist of: repairing, reusing, remanufacturing, reducing at source (e.g. by second-use of products or even by sharing products) and eventually recycling. Recycling produces Secondary Raw Materials (SRMs) that can be recirculated and can replace virgin materials (EC, 2020c). Besides all strategies focusing on the development of sustainable and smart mobility, a need of re-think the mobility system and focus on systemic sustainable solutions is highlighted by several studies to support the reduction of products/waste production (Alonso Raposo et al., 2019).

In this paper, remanufacturing is defined as an established industrial process through which used products or parts are returned to same-as-new, or better, condition and performance; during the process, changes in products/parts will not influence *the safety, original performance, purpose or type of the product*. Key definition comes from the EN

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45,553:2020 standard and from the definition provided by the remanufacturing associations (Staff, 2016).

### 1.1. Measuring the circular economy strategies

The effects of CE strategies should be properly monitored in order to track progresses made and to assess the effectiveness of policy interventions. To this aim, robust indicators measuring circularity of products/materials are needed. In 2018, a set of 10 indicators was adopted by EUROSTAT to “monitor the progress towards a circular economy” at EU level, and they cover four thematic areas: production and consumption, waste management, secondary raw materials and competitiveness and innovation.

The CE action plan (EC, 2020a) highlights the need of “*monitoring and assessing the progress towards decoupling economic growth from resource use and its impacts in the EU and beyond*”, possibly developing “*new indicators*” that “*will take account of the focus areas in this action plan and of the interlinkages between circularity, climate neutrality and the zero pollution ambition*”. One of the first steps in this perspective relates the update of the CE Monitoring Framework (EUROSTAT, 2020a).

To enhance the EU circularity, various strategies could be adopted according to the sector/product. Firstly, “*circular economy transition, in particular by applying product-as-service solutions [can] reduce virgin material consumption*” (EC, 2020a). Concerning products and embedded materials, they can be kept in the economic system for longer if the lifetime of products/components is extended, e.g. through repair, reuse, remanufacturing and second-use. When these strategies are not economically or technologically viable, recycling can recirculate SRMs within the system and potentially decrease the demand of virgin materials.

To ensure a transition to a more CE, policy makers have been focusing on the introduction of mandatory targets both in waste management policies (output side) and in product policies (input side). For the case of vehicles, higher circularity is both enhanced by the end-of-life vehicles (EU, 2000) that in particular establishes minimum re-use and recycling rates in its article 7 and by the Type Approval 2005/64/EC Directive (EU, 2005) that establishes that only vehicles that reach a minimum recyclability rate can enter into the EU market. This is particularly the case for EU legislation with the deployment of recycling efficiency targets at product level (e.g. batteries, packaging) as well as material specific level through the setting of minimum recovery rates for the most critical elements (e.g. lithium, nickel and cobalt in batteries).

More recently, some EU legislative instruments have been proposing to also include provisions related to minimum recycled content of certain materials in product policies (i.e. input side): stemming from the ambitious circular economy action plan (EC, 2020a), some novel recycled contents mandatory provisions are now under discussions for batteries (for e.g. cobalt, lithium) (EC, 2020d), for single-use plastics (EU, 2019) and also for vehicles (for plastics) (EC, 2020; Maury et al., 2023). The objective is to create a “demand pull” to ensure a solid market and therefore a good recirculation of secondary materials in the EU economy. Some other studies carried out by the European Commission have looked at the benefits of encouraging re-use of products and components in the input side (Ardente et al., 2018) but such provisions were not yet implemented in mandatory legislation. This short analysis shows that there is more and more tendency to implement policy interventions on the input side of products.

So far, several indicators have been developed to monitor progress of CE, most of which have been developed in Europe (Saidani et al., 2019; Sassanelli et al., 2019), and some of them consider entire/partial product life cycle (Saidani et al., 2019; Moraga et al., 2019). In most of the cases, those authors show that the aim is to quantify the preservation of the materials mainly through recycling, which is often downcycling, while reduce, reuse, remanufacturing, maintenance or other circularity strategies are very rarely captured by indicators. Of course, indicators can be applied at different scales (Harris et al., 2021; Moraga et al.,

2019; Saidani et al., 2019), providing information on materials, components, products, groups of products as well as services, considering different geographical scales (e.g. consumers, company, inter-corporate / eco-industrial parks, city, region, nation, groups of nations, world). According to Moraga et al. (2019), the scale is a fundamental characteristic for the indicator to provide meaningful information.

It is highlighted that most of the indicators are not focusing on specific sectors but are rather generic and usually can be used for monitoring different products belonging to different sectors (Saidani et al., 2019); however, because several industrial sectors are rapidly evolving and because significant quantities of CRMs are needed, the European Academies’ Science Advisory Council has stated that sector-level indicators “*may be desirable, in consultation with industries*” (EASAC, 2016a, 2016b).

Finally, a quite relevant share of indicators is based on the analysis of stocks and flows of materials/products through e.g. Sankey diagrams and Materials Flow Analysis (Moraga et al., 2019; Saidani et al., 2019). Material Flow Analysis (MFA) can be applied either on materials at the level of the whole economy like in the EC Monitoring Framework (Mayer et al., 2018) or at the level of specific products to assess the effects of adopting various EoL strategies (e.g. Bobba et al., 2020) for the re-purposing of batteries). However, based on the authors’ knowledge, indicators to measure circularity of materials/components based on MFA/MSA results at sector level are still missing.

Within the EC Monitoring Framework, within the cluster “*contribution of recycled materials to raw materials demand*”, the indicator End of life recycling input rate (EOL-RIR) measures the share of SRMs compared to the total demand of materials. This indicator provides useful information on the potential decrease of input materials within the EU economy. For this very reason, this indicator is also considered as a risk reducing factor for the assessment of supply risk in the EC criticality assessment (Blengini et al., 2017). However, this indicator currently only addresses the recycling strategies, while other strategies such as reuse and/or remanufacturing are completely disregarded. Moreover, EOL-RIR is an average across sectors and applications.

### 1.2. Transport/mobility as strategic sector for the EU and CE strategies

Various key EU policy documents, which support or announce political decisions taken by EU institutions, classify transport as a strategic sector that needs to accelerate its shift towards circularity (EC, 2020e, 2020c): as a matter of fact, even though some discussion is still in place, the transition towards a smart and sustainable mobility is currently mainly driven by the penetration of non-conventional vehicles, e.g. hybrid, plug-in and full battery electric vehicles (HEV, PHEV and BEV). Powertrains used in these vehicles embed CRMs in traction batteries (e.g. Co, Li, Mn) and e-motors (e.g. REE), which demand is expected to rapidly increase (EC, 2023; EC, 2020c; Vázquez et al., 2021). In this perspective, a product/sector level analysis could support the implementation of strategies to keep CRMs in the EU economy by optimizing the demand of vehicles, maximizing the lifetime of the xEVs’ components and improving collection, dismantlability and recycling.

Concerning CE strategies, in the EU, the minimum reuse and recycling target for ELV is set to 85% since 2015 (EU, 2000) and the European reuse and recycling rate was already 89.6% in 2019 (EUROSTAT, 2021). From EU statistics it is still unclear the real potential of reuse/remanufacturing practices to increase overall re-use and recycling rates, and even less for decreasing the demand for virgin CRMs. Despite the untapped potential (Parker et al., 2015), the automotive sector is one of the most important for the EU remanufacturing industry. Together with the aerospace remanufacturing industry it exceeds one third of the EU remanufacturing industry (Lange, 2017).

Expertise available in the EU and its potential contribution towards a more resource efficient manufacturing industry are drivers for further developing automotive remanufacturing; moreover, the development of new technologies (e.g. digitalization, additive manufacturing, robotics,

new materials) and the penetration of new components (e.g. e-motors and batteries) are opportunities for automotive remanufacturers (Lange, 2017; Matsumoto, 2020; Parker et al., 2015; Sundin and Bras, 2005; Weiland, 2019). However, the adoption of remanufactured products is still challenged by various barriers: the most important barriers are (1) social barriers (e.g. acceptance of using not new brand products by both consumers and OEMs), (2) economic (e.g. increasing market of low-cost components, volumes and access to cores available for remanufacturing), (3) technological (e.g. increase of complexity of components and poor design for remanufacturing) and (4) regulatory (e.g. lack of a clear definition, lack of incentives and trade restriction for remanufactured products) (Lange, 2017; Matsumoto, 2020; Sundin and Bras, 2005; Weiland, 2019).

### 1.3. Aim and structure/outline of the paper

In the scientific literature, various studies already addressed raw materials embedded in batteries (e.g. Co, Li, Mn) from both a current and future perspectives, while the scientific literature concerning CRMs for e-motors (e.g. rare earth elements (REE) used in permanent magnets) is scarcer, especially when focusing on sustainability aspects (Bailey et al., 2017). Moreover, recent studies (Alves Dias et al., 2020; Bailey et al., 2020; EC, 2023; Fishman et al., 2018; Habib et al., 2020) highlight the policy relevance of tackling REE supply risks. The launch of the European Raw Materials Alliance (ERMA)<sup>1</sup> in September 2020 also proves the EU's willingness to gain resilience and strategic autonomy for REEs and magnets value chain in the EU and such position is reinforced in the ERMA's call for action (Gauß et al., 2021).

Despite awareness of the potential environmental benefits associated to CE strategies aiming at extending the lifetime of products/components (e.g. Liu et al., 2018), adequate metrics and quantitative data on impacts of such strategies are lacking. As an example, most of the available studies in the scientific literature address remanufacturing of specific components and the reduction of materials and energy to their primary manufacturing (e.g. BORG AUTOMOTIVE (2021); Dias et al. (2013); Liu et al. (2016, 2014); McKenna et al. (2013)) without focusing on the effects of the whole EU automotive sector and on the impact of the activity in the whole EU material flows.

With the above limitations in mind, this paper presents the Circular Input rate (CIR), a new indicator developed to measure circularity of materials (i.e. nano scale) at sector-level (i.e. meso scale), considering simultaneously the effects of all CE strategies (Section 2). The CIR is then applied to a case-study sector among the strategic sectors for the EU, i.e. mobility (Section 3); more in detail, Section 3.1 introduces the use and the circular economy strategies related to REE in e-motors, the developed dynamic MFA and the adopted scenarios are summarized respectively in Sections 3.2 and 3.3; results of the assessment are presented in Section 3.4 and discussed in Section 3.5. Section 4 reports the main conclusions of the study.

## 2. Materials and methods: circular input rate (CIR) calculation

As mentioned in the introduction, available indicators taking a life-cycle thinking approach, i.e. considering the whole value-chain of products are not usually capturing CE strategies higher than recycling in the waste hierarchy (EC, 2018a; Moraga et al., 2019). In the scientific literature, the environmental effects of extending the lifetime of products as circular strategy is mainly addressed by dynamic MFAs, i.e. by quantifying the stocks and flows of materials/products and their variation in time (Ardente et al., 2017; De Meester et al., 2019; Mayer et al., 2018).

Among available indicators, the EoL-RIR of a material provides information about the flow of recycled materials and their recirculation as

secondary materials within the considered system (Blengini et al., 2017). The EoL-RIR is regularly updated, in particular in the indicator "Recycling's contribution to meeting materials demand" of the Raw Material Scoreboards (EC, 2018b, 2021) and in the Eurostat circular Economy indicators table (EUROSTAT, 2022). Based on Moraga et al. (2019), the EoL-RIR is often used to monitor the recycling effects on products (products, businesses, and companies). Besides being used in the official EC monitoring framework, the EoL-RIR indicator has been also introduced since 2017 as mitigation factor in the EU methodology for establishing the EU list of CRMs (Blengini et al., 2017) as SRMs actually contribute to decrease the demand of materials imported from third Countries. It is noted that CE strategies other than recycling are not captured in the EoL-RIR, and hence not included among the mitigation measures of materials demand and EU supply dependency. This is also confirmed by Poncelet et al. (2022), who argue that available indicators, among which the recycling rate indicator used by the EC, falls short in capturing all CE strategies and more generally sustainable management of metals and they call for novel indicators, in particular to better address lifetimes and loss rates.

Adopting a life-cycle perspective to the whole value-chain of materials in a specific sector, the EoL-RIR has been enlarged in the present research work to capture in the CIR not only the functional recycling<sup>2</sup> but also the flows of materials recirculated in the system through the extension of the lifetime of products in which they are embedded. Building on a figure originally presented in Blengini et al. (2017), Fig. 1 presents all the flows of material considered in the CIR, in particular those related to remanufacturing and reusing products are identified by the arrows "R.1.X" according to the applied CE strategy.

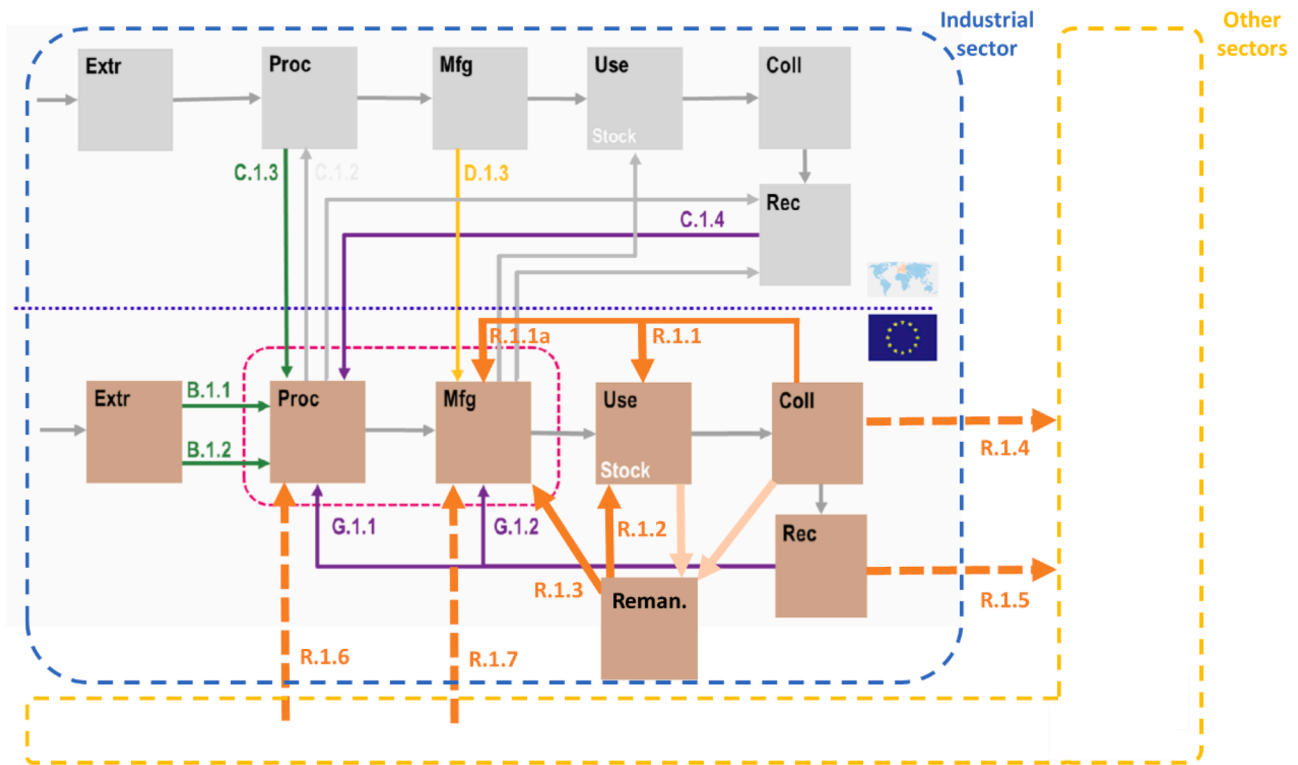
Before being addressed to recycling, some materials can be recirculated within the in-stock products through repair and reuse of spare parts (R.1.1): for instance, in the case of vehicles, rear-view mirrors or bumpers which are directly dismantled and sold for use in operating vehicles (Ballweg et al., 2021). Even though not a common practice, reused products can potentially be used in new products (R.1.1a), without compromising the quality and the safety of the final product, e.g. as stated in the Directive 2005/64/EC (EU, 2005). Some materials embedded in products/components are recirculated in the in-stock products/components through remanufacturing (R.1.2): this can be the case in vehicles for REE in e-motors or aluminum, copper, steel and iron in alternators (Russell, 2018). Moreover, according to experts of the field and considering an emerging CE strategy, a flow of materials representing the use of remanufactured products in manufacturing new products (Tiwari et al., 2021; Weiland, 2019) is added by the R.1.3 arrow.

Another strategy maximizing the values of materials is second-use of products, i.e. extending the lifetime of products through their repurposing and second-use in another application (see R.1.4). In this case, because repurposed products are used in a different sector from the one they were used previously, this flow R.1.4 cannot be considered when the CIR is applied to a single sector. Hence, this CE strategy is not captured by the CIR and the R.1.4 is in Fig. 1. This is case for instance, of traction batteries that after initially used in e-vehicles and then repurposed and used in applications with "lower requirements", such as e.g. stationary energy storage (Bobba et al., 2018; EC, 2020d). Another example is related to tires that can be repurposed and used in civil engineering applications (Lamour and Cecchin, 2021). Similarly, also secondary materials can be used in other sectors (R.1.5) or from other sector (R.1.6 and R.1.7) to manufacture new products.

Based on the above considerations, the Circular Input Rate indicator (CIR) is defined as the ratio between the flows of materials from reused, remanufactured and recycled products/components compared to the demand of materials for a specific sector (note that R.1.4, R.1.5, R.1.6

<sup>2</sup> the flow of materials from old scraps used to replace virgin materials in inputs, i.e. used in processing and manufacturing (EC, 2017)

<sup>1</sup> <https://erma.eu/>



**Fig. 1.** Schematic representation of the “material system analysis of a raw material”, including European Reuse and Remanufacturing flows, **R.1.1** = flow of materials embedded in products/components subject to direct reuse, **R.1.2** = flow of materials embedded in products/components subject to remanufacturing and recirculated in the in-stock products/components, **R.1.3** = flow of materials embedded in products/components subject to remanufacturing and recirculated in manufacturing new products/components, **R.1.4** = flow of materials embedded in products/components subject to repurposing and second-used in another sector, **R.1.5** = flow of secondary raw materials to be used in another sector, **R.1.6** = flow of secondary raw materials from another sector compared to the product processing, **R.1.7** = flow of secondary raw materials from another sector compared to the product manufacturing, Adapted from [Blengini et al. \(2017\)](#). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and R.1.7 are out of scope since materials are used of are deriving in/ from different sectors) (Formula (1)). In case the CIR is applied to a material for which R.1.X flows are null, the CIR corresponds to the EOL-RIR.

R.1.3 materials embedded in products/components subject to remanufacturing and recirculated in manufacturing new products/components;

In order to track the effects of different CE strategies in time, the CIR

$$CIR_{object\ of\ the\ analysis, scale, t} = \frac{R.1.1 + R.1.1a + R.1.2 + R.1.3 + G.1.1 + G.1.2}{B.1.1 + B.1.2 + C.1.3 + D.1.3 + C.1.4 + G.1.1 + G.1.2 + R.1.1 + R.1.1a + R.1.2 + R.1.3} \tag{1}$$

Where:

- B.1.1 production of primary material as main product in the EU sent for processing in the EU;
- B.1.2 production of primary material as by-product in the EU sent for manufacturing in the EU;
- C.1.3 imports to the EU of primary material;
- D.1.3 imports to the EU of processed material;
- C.1.4 imports to the EU of secondary materials;
- G.1.1 production of secondary material from post-consumer functional recycling in the EU sent for processing in the EU;
- G.1.2 production of secondary material from post-consumer functional recycling in the EU sent for manufacturing in the EU;
- R.1.1 materials embedded in products/components subject to direct reuse;
- R.1.2 materials embedded in products/components subject to remanufacturing and recirculated in the in-stock products/component;

indicator should be calculated in different years to simulate its trend in time and according to the evolution of both the sector and the CE strategies. To provide meaningful information to decision-makers (incentives, regulatory support, etc.) in a very uncertain technological future, different scenarios can be set-up modeling both the demand of materials (affected by e.g. technological evolution and behavioural patterns) and the evolution of CE strategies (e.g. enhanced remanufacturing, improved recycling efficiency).

Based on the scenarios and the materials content in products, the demand of components/materials, the stocks and flows of materials in time and along the whole value-chain of the product are quantified to then calculate the CIR.

### 3. Case study: application of CIR to rare earth elements (REE) in e-vehicles motors

The CIR indicator is used now to simulate the effects of possible future CE strategies to be deployed in the EU on passenger vehicles that

are important components of the mobility. The identified case-study relates to Rare Earth Elements (REE) embedded in infotainments and in permanent magnets used in electric motors (e-motors): they are today widely used in key components for the transition towards a more smart and sustainable mobility. REEs are particularly relevant materials since they have been classified as CRMs to the EU since the first list in 2011 because of very high supply risks. This is why the EU is now initially focusing on resilience in the REE and magnets value chain through its recent European Raw Materials Alliance (EC, 2020b). Although very different from each other, scenarios forecasting the future EU fleet are already available in the literature and they reflect various trends for the EU mobility evolution (environmental targets, social and economic variables, technological development, etc.) (e.g. Harrison and Thiel, 2017; Kishita, 2020). However, data on new components and embedded materials is rather scarce due to confidentiality issues and the novelty of the topic (Løvik et al., 2021): for the presented case-study, available literature was therefore complemented by consultation of experts in the field to model future trends of both EU mobility and evolution of possible CE strategies.

Most relevant information of e-motors embedding REE and future perspectives on their remanufacturing are reported in Section 3.1. The dynamic MFA and adopted scenarios for the assessment are illustrated respectively in Sections 3.2 and 3.3. Section 3.4 reports the results obtained for Neodymium and Section 3.5 their discussion.

### 3.1. REE in e-motors and circular economy strategies

REE are key elements of infotainment electric and electronic systems, which have a central role in cars (e.g. fuel injection control, anti-lock braking systems, safety and driver assistance features) (Alonso Raposo et al., 2019; Løvik et al., 2021). Even though already embedded in conventional vehicles (between 0.08 kg and 0.44 kg (Alonso et al., 2012; Field et al., 2017; Guyonnet et al., 2015; Witkamp, 2018; Yang et al., 2017), REE content in xEVs is much higher as they are essential materials of permanent magnets in e-motors (EC, 2020c; Harvey, 2018; Løvik et al., 2021; Månberger and Stenqvist, 2018).

Among the permanent magnets used in xEVs, the Nd(Dy)FeB magnets are the most used due to their performances (Gauß et al., 2021; Widmer et al., 2015). China represented 92% of annual magnet production in 2020 (Smith et al., 2022) followed by Japan (7%), Vietnam (1%) and European countries with relatively limited capacity. Nd, Dy and Pr use in magnets represent around 85% of the total REE value and about 20% of the volume (EC, 2020f). While the Nd production is about 15% of the total Rare Earth Oxides produced worldwide, the share of Dy is around 1%. The forecasted growth of permanent magnets and the importance of Dy to improve magnet performances at higher temperature will implicate a demand of Dy that will exceed the global annual production by 2030 (Castilloux, 2019). In 2015–2018 China exported 65% of the Nd(Dy)FeB output in the form of magnet or finished products. For the time being, Chinese magnet prices are the cheapest and influence the entire market. Currently, recycling of PM is quite limited (EC, 2020f); nonetheless, the development of recycling processes to recover REE from PM as well as other CE strategies is considered as extremely important (ERMA; EC, 2020). E-motors are quite similar to starters and generators from a technological perspective, making remanufacturing of e-motors in principle feasible from a technological perspective (Rematec, 2020; Toptas and Fekete, 2019; Weiland, 2019). Also, permanent magnets do not face a significant degradation over time (Van Hout, 2018; Yang et al., 2017), which means that they can last much more than the lifetime of vehicles. Hence, this makes such components very interesting from a reuse/remanufacturing perspective to be recirculated in the EU fleet but also promising to be used for manufacturing new vehicles. In addition, remanufacturing permanent magnets will postpone the flow of REE available for recycling, which is still an immature technology in the EU (EC, 2020g). Recycling of magnets is challenging due to difficulty to disassembly and lack design of

‘design-for-recycling’ implementation (Akil et al., 2017; Yang et al., 2017), low price of virgin materials which slowed down in 2012 (EC, 2020f) and lack of recycling technologies (Yang et al., 2017).

In conclusion, shifting the REE flow collected at end-of-life and making it available for re-use and remanufacturing instead of only recycling could represent an opportunity to enhance the EU circular capability, as well as create new business models able to develop market channels for the secondary REE (ERMA). This is why the CIR is applied to REEs contained in electric vehicles and in particular in e-motors and in infotainment devices.

### 3.2. The dynamic MFA

A life-cycle approach and information gathered from both experts and literature are used to identify the main steps along the whole value-chain of vehicles in EU. Compared to parametrized MFA model presented in Bobba et al. (2020), a box (and related flows) representing remanufacturing practices in the automotive sector was added. Thus, the model schematized in Fig. 2 includes all possible CE strategies. The novel remanufacturing processes are modelled as follows.

The majority of cores (i.e. used parts intended to become remanufactured products) are from garage (“Components to remanufacturing”), while the remaining from ELVs (“ELVs pre-treatment (dismantling)” box) (Weiland, 2019). Note that some components entering in the remanufacturing process are imported from extra-EU Countries (“New components materials for remanufacturing”). Even though a small share, some cores are directly reused without being remanufactured (“Direct reused components”).

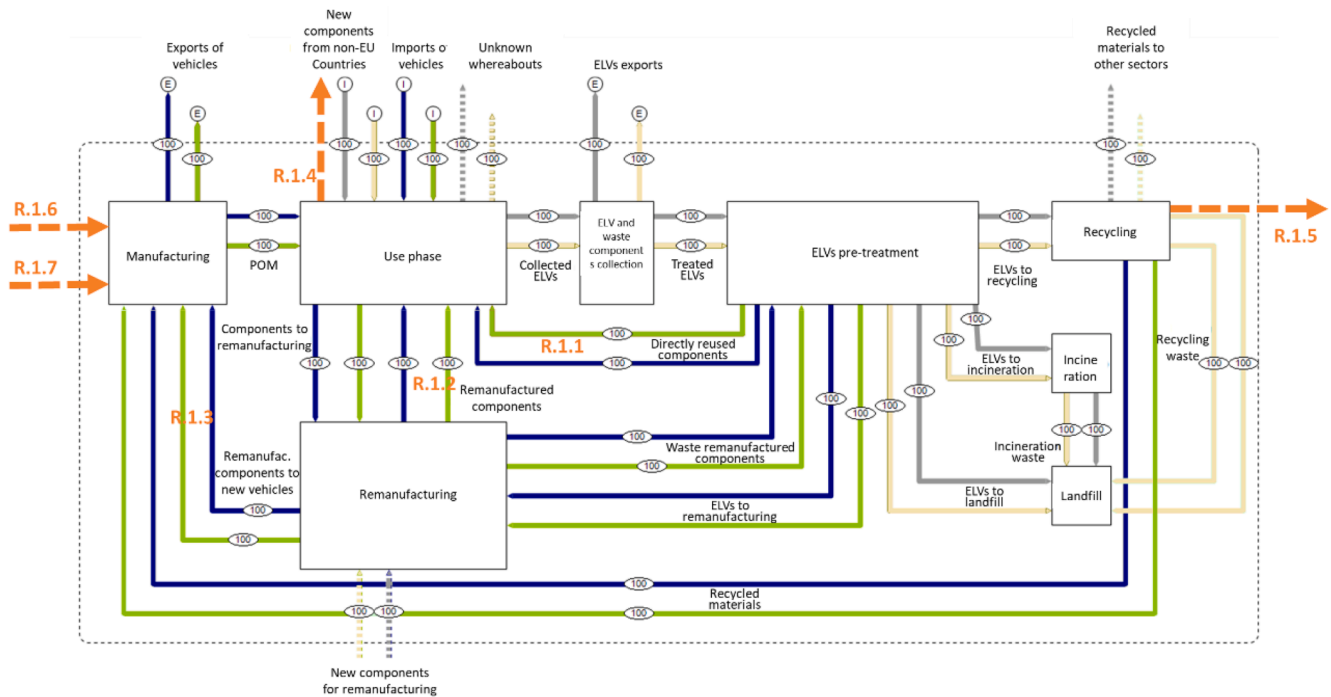
During remanufacturing, cores are inspected after disassembly, and defective components are repaired and/or replaced and the units are then reassembled to be addressed to the final quality test (Colledani et al., 2014; Gaudillat et al., 2017; Weiland, 2019). The tests and certification of remanufactured products’ quality allow to place in the market a new product with a “warranty that is equivalent or better than that of the newly manufactured product” (BSI, 2009). The quality of remanufactured product is essential in increasing reliability of remanufactured products (Matsumoto, 2020) and it can support the potential development of a new flow of products related to the adoption of remanufactured components in manufacturing new vehicles (Weiland, 2019).

“Remanufactured components”, which is the main output flow of the “Remanufacturing” process, are mainly used for the maintenance of in-stock vehicles (i.e. in the “Use phase” process in Fig. 2). However, currently about 56% of the aftermarket demand is provided by the Asian market (“New components from the Asian market”), mainly due to the increasing flows of new low-cost components. In addition, remanufactured components can in principle be used in manufacturing new vehicles (“Remanufactured components to new vehicles”) (Weiland, 2019): this potential flow is included in the model as high quality remanufactured components can be potentially suitable for the use in new vehicles in the future.

### 3.3. Developed scenarios

To capture the expected changes in the automotive sectors, from both technological and users’ sides, different scenarios were considered.

Coupled with low-carbon technologies, new business models and user patterns are already changing the EU mobility (Alonso Raposo et al., 2019). In particular shared mobility potentially contributes to decrease vehicles sales and hence the EU fleet; on the other hand, to satisfy users’ needs, vehicles are expected to be used more intensively (Alonso Raposo et al., 2019). Ownership of shared cars remains with car-sharing companies, and it is therefore possible to assume an improved EoL management compared to private vehicles (Kjaer et al., 2019). In line with the goal of the study, CE strategies are expected to enhance in time driven by an increased acceptance for



$\nu_{ICEV/EV, y}$	Share of "unknown whereabouts" on waste generated	$\lambda_{recovery}$	Share of ELVs to landfill on Treated ELVs
$\phi_{ICEV/EV, y}$	Share of collected ELVs on waste generated	$\theta_{recy, ICEV/EV, y}$	Recycling efficiency
$\varepsilon_{ICEV/EV, y}$	Share of ELVs exports on waste collected	$\theta_{reco, ICEV/EV, y}$	Recovery efficiency
$\gamma_{ICEV/EV, y}$	Share of ELVs to recycling on Treated ELVs	$\sigma_{rem, ICEV/EV, y}$	Share of remanufactured components to new vehicles on the total amount of remanufactured components
$\iota_{recovery, ICEV/EV, y}$	Share of ELVs to recovery on Treated ELVs	$\beta_{rem, ICEV/EV, y}$	Share of ELVs to remanufacturing on treated ELVs
$\beta_{direct\ reuse, ICEV/EV, y}$	Share of ELVs to direct reuse on Treated ELVs	$\phi_{rem, ICEV/EV, y}$	Share of waste addressed to remanufacturing from ELV pre-treatment

Fig. 2. Dynamic Material Flow Analysis (MFA) model representing the flows of components/materials along the whole value-chain of vehicles in the EU.

reused/remanufactured products from both consumers and companies, the development of regulatory tools supporting the creation of a business case and the technological development (e.g. improved recycling processes, digitalization, additive manufacturing, robotics, new materials). Overall, although shared mobility that corresponds to the “reduce” CE strategy is not formally addressed in the CIR calculation, it is indirectly captured since stocks (i.e. Use box of Fig. 1) and demand (i.e. Ext., Proc., and Mfg boxes and B.1.1 and B.1.2 flows of Fig. 1) for vehicles would in principle be reduced, the CIR would increase. It is likely as well that R.1.1 and R.1.1a would be larger in shared mobility scenarios and hence the CIR higher.

Considering these 2 main aspects, various scenarios can be developed (Fig. 3). For this analysis, the Business as Usual Scenario (BaU-sc)

represents current CE strategies (i.e. mainly recycling) applied to the current EU fleet, with an increased penetration of xEVs in time. On the opposite side, the Circular Mobility Scenario (CM-sc) assumes a faster penetration of xEVs in the EU and a simultaneous development of all the CE strategies (i.e. re-use, remanufacture and recycling) on top of an enhanced shared mobility (i.e. decreased EU fleet and lifespan of vehicles).

Based on the current trends, it is assumed that the majority of PMs in xEVs motors are Nd(Dy)FeB magnets and that this trend will not change in time. Moreover, it is assumed the adoption of 1.1 motors for both BEVs and PHEVs along their whole lifetime.

Main assumptions are summarized in Supplementary Materials (Table S1).

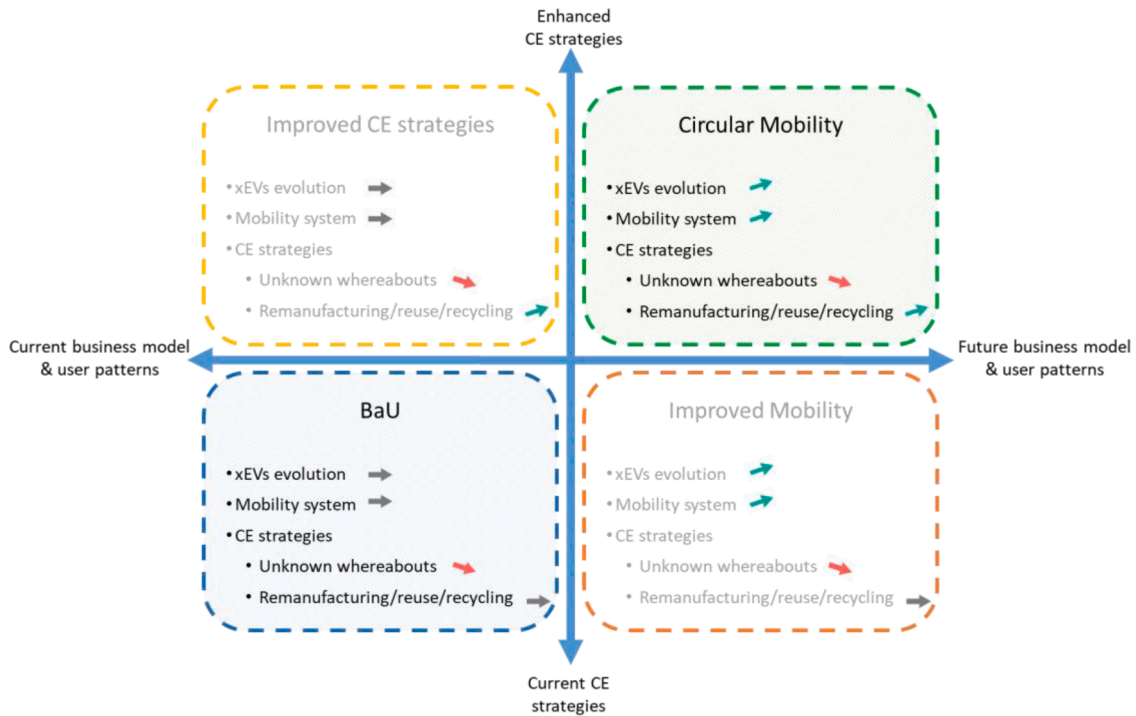


Fig. 3. Scenarios for the analysis.

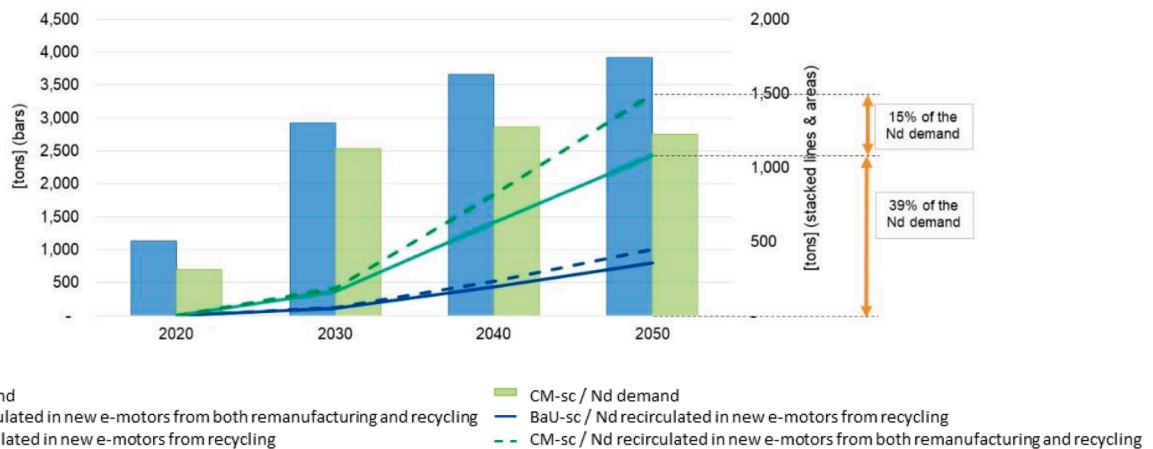


Fig. 4. Flows of Nd placed on the EU market (bars), secondary Nd from e-motors recycling (plain lines), additional Nd embedded in e-motors from remanufacturing (dot lines), for both the for the Business as usual (BaU) and Circular Mobility (CM) scenarios (blue and green, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 3.4. Results of the assessment

The dynamic MFA model presented in Section 3.3 is applied to the EU fleet between 2000 and 2050 under both the BaU-sc and the CM-sc scenarios, in order to estimate the flows and stocks of e-motors and hence of REE embedded. The MFA allows to consider all possible CE strategies and their potential evolution in time through the adoption of parameters set in the modeling. According to the goal of the study, this section reports the most relevant information to calculate the CIR<sub>mobility</sub>, REEs, 2010–2050 related to REEs embedded in e-motors.

Note that the assessment focused on the materials content in permanent magnets; hence, the Nd embedded in other vehicles' components is not included in the presented results Fig. 4.

The main outcomes of the assessment are schematized below:

- MFA results are confirming the available literature (Busch et al., 2017; EC, 2020a; Yang et al., 2017), on the increasing trend of Nd demand due to the fast penetration of xEVs in the EU fleet. The contribution of Nd from conventional cars and components other than e-motors is quite limited, especially in a long-term view where xEVs will dominate the EU fleet. Demand of Nd in 2040 ranges between 3 and 4 times the demand of Nd in 2020, corresponding to 2.8–3.6 thousand tons of material.
- The improved waste management related to a more effective collection of ELVs, is key in increasing the availability of e-motors to be properly addressed to remanufacturing, reuse and/or recycling. In 2050, compared to the BaU-sc, where almost 1000 tons of Nd are lost due to a disappointing 70% of collection rate, in the CM-sc only 130 tons of Nd are not properly addressed to EoL patterns (i.e. thanks to 95% collection rate). Differences are less relevant in 2030 due to

different collection rates but bigger flow of xEV in the CM-sc than in the BaU-sc (Figure S1).

- Focusing on CE strategies, results show that in a long-term perspective, the Nd available for recycling compared the Nd demand will be lower for the CM-sc than for the BaU-sc. This is related to both a lower fleet of vehicles and the enhancement of CE strategies oriented to extend the lifetime of e-motors (i.e. remanufacturing and reuse). On the other side, demand of virgin materials decreases due to the recirculation of secondary Nd but also due to the recirculation of remanufactured e-motors adopted in manufacturing new vehicles. In 2020, almost the total demand of Nd for e-motors is satisfied by primary Nd, while in 2030 the demand of primary Nd decreases respectively by 2% and 7% for the BaU-sc and the CM-sc. This share respectively increases up to 6% and 29% in 2040 and 11% and 54% in 2050 considering a strong development of remanufacturing of e-motors and the penetration of more efficient recycling technologies.
- In particular, the improved recycling efficiency allows to recover more than 160 tons of Nd in 2030 and 4 times more in 2040. Moreover, almost 25 tons of Nd are assumed to be recirculated through the use of remanufactured e-motors in the manufacturing phase in 2030 (and 8 times more already in 2040).
- Demand of primary Nd can be also lowered thanks to the flow of Nd in e-motors directly reused and remanufactured and recirculated in the in-stock vehicles. The flow of Nd in reused e-motors increase in time especially due to the improved collection of waste e-motors, but it remains quite low compared to the Nd demand, remaining less than 2% for the BaU-sc and never exceeding 6% up to 2050 for the CM-sc. It is also highlighted the flow of Nd in remanufactured e-motors never exceed 10% of the Nd demand in both scenarios; this is related to the scenario assumptions for which the creation of a business case for remanufacturing e-motors is mainly related to recirculate remanufactured e-motors in new vehicles.

Based on these flows, the CIR was calculated and compared to the EoL-RIR calculated for Nd in the xEVs sector (Fig. 5).

- 1 EoL-RIR already captures the current and potential future role of recycling to keep materials in the same sector. Note that in the scenarios, it is assumed that all secondary materials are recirculated in the same sector and hence the quality of recovered materials is suitable to be used in the automotive sector; in case secondary REE are used in other sectors than mobility, they are not accounted in the CIR as in Formula (1).

- 2 However, the CIR provides additional information of the contribution of CE strategies other than recycling. In fact, considering also flows of materials kept in the EU through remanufacturing and reuse, in 2030 the CIR for BaU-sc and CM-sc is respectively equal to 3.8% and 9.9%, increasing potentially to 15% and 60% in 2050. This shows that the CIR is able to capture contributions of various coupled CE strategies while the EoL-RIR only addressed recycling.

### 3.5. Discussions of the results

The life-cycle approach and the modeling of the whole products' value-chain provided a holistic perspective on the transition of the EU mobility towards a more circular, as concluded by [Hartley et al. \(2020\)](#). Compared to the MFA presented in [Bobba et al. \(2019\)](#), the addition of the remanufacturing process and related flows permitted to capture the effects of various and more virtuous CE strategies ([EC, 2020b, 2020a](#)); scenarios of future mobility and can be set according to practitioners' interests and the research questions.

Stocks and flows of Nd in e-motors were quantified along the whole EU automotive value-chain considering different trends focusing on (i) fleet evolution and (ii) circular economy strategies such as the increase of reusing and remanufacturing e-motors and the technological development of recycling.

Results show that, unlike the EoL-RIR, the CIR effectively captures that the contribution of CE strategies other than recycling can drastically decrease (or at least slow down) the demand of virgin Nd, hence potentially contributing to significantly reduce for the EU supply risks of CRMs for low-carbon technologies. Moreover, in the current absence of recycling technologies for REEs in e-motors that are still under development, postponing recycling through remanufacturing can also be seen as an added value

The model would need to be run again and the CIR and EoL-RIR would need to be tested again, not only for future mobility scenarios or deployment of various CE strategies, but also for assumption of future technologies. For example, expected decrease of REE content per e-motor could be tested as it is assumed to improve resource efficiency in time ([Alves Dias et al., 2020](#); [EC, 2020a](#); [Harvey, 2018](#)). Moreover new scenarios could be analysed taking into account also the substitution of Nd(Dy)FeB magnets (e.g. with SmCo, ferrite, AlNiCo magnets) and motors not using permanent magnets at all (as induction motors) ([Widmer et al., 2015](#)), although these substitutes can currently not compete with Nd(Dy)FeB in terms of costs and performances ([EC, 2020c](#)).

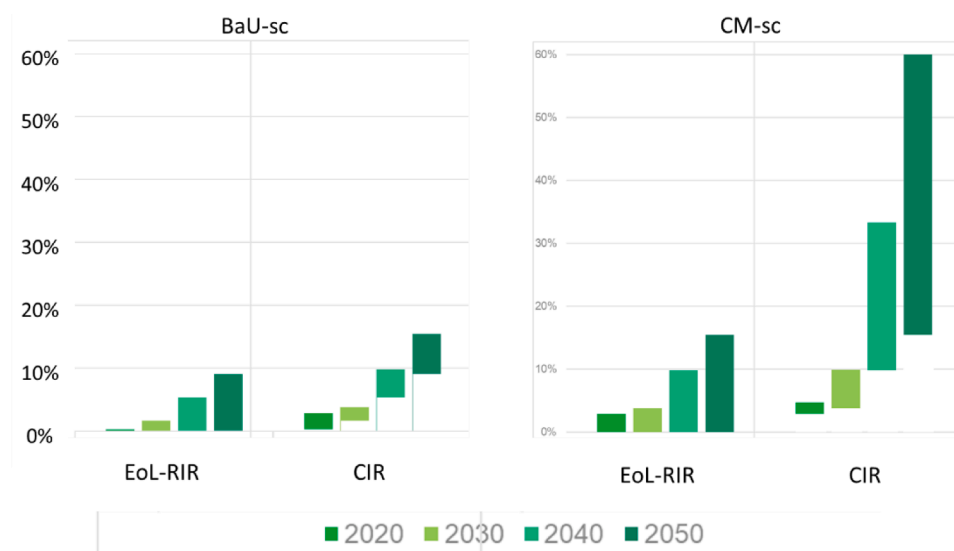


Fig. 5. Evolution of End-of-Life Recycling Input Rate (EoL-RIR) and Circular Input Rate (CIR) of Nd between 2020 and 2050.

Traceability of e-motors and quality of both remanufactured and recycled materials have been recognised as key factors to enhance CE strategies and to promote the creation of related business cases. In addition, other key aspects potentially contributing to the development of CE strategies are: certified/labelled quality of remanufactured e-motors and of SRMs; improved designed for disassembly / design for re-usability; economic incentives based on re-usability or reparability index scores as well as mandatory provisions in the frame of legislative act (EC, 2022). Such mandatory provisions could take the form of specific targets for reuse that could be implemented separately from recycling. This has been debated during the Open Public Consultation of the ELV Directive revision (see Q.5 of the summary report). Similar initiatives paving the way for a mandatory dismantling and subsequent reuse/recycling of selected parts can be found in the Swiss legislative act 814.120 (Conseil Fédéral Suisse, 2021) which stipulates in its art.10 d that precious metals such as Neodymium should be recovered from electronic equipment when appropriate processes and facilities would be available. Adopting such targets would hence require systematic disassembly of some targeted parts or ELV electronic equipment including permanent magnets in e-motors.

This underlying the extreme importance of a “design for circularity” to facilitate stakeholders to disassemble e-motors (and components in general), pushing recycling as the last option of the value-chain of products.

So far, the CIR has been used only to assess re-use and remanufacture of components in the same sector, in the case of e-motors in other vehicles. The CIR can potentially be adapted to be applied also to monitor circularity of materials contained in specific components that can be used in other industrial sectors. Indeed, it might be sensible to also include the effects of extending the lifetime of products through their second-use in other applications from which they were initially conceived. This is for instance the case of second-use of batteries which is currently listed among the promising CE strategies in the proposal for an EU Battery Regulation (EC, 2020d). Therefore, the second-use flow (R.1.4 arrow in Fig. 1) as well as SRM to other sectors and from other sectors (R.1.5, R.1.6, R.1.7 arrows in Fig. 1) could be included in the CIR as in Formula (2).

$$CIR_{\text{object of the analysis, scale,t}} = \frac{R.1.1 + R.1.1a + R.1.2 + R.1.3 + R.1.4 + R.1.5 + R.1.6 + R.1.7 + G.1.1 + G.1.2}{B.1.1 + B.1.2 + C.1.3 + D.1.3 + C.1.4 + G.1.1 + G.1.2 + R.1.1 + R.1.1a + R.1.2 + R.1.3 + R.1.4 + R.1.5 + R.1.6 + R.1.7} \quad (2)$$

Where:

- R.1.4 materials embedded in products/components subject to second-use and recirculated in products/components used in a different sector than the original one.
- R.1.5 flow of secondary raw materials to be used in another sector
- R.1.6 flow of secondary raw materials from another sector compared to the product processing
- R.1.7 flow of secondary raw materials from another sector compared to the product manufacturing

As highlighted in the scientific literature (Bobba et al., 2020), the combination of assessment tools and indicators focusing on different criteria across the same strategy gives a better overview and allows more informed decisions. This includes a better picture of the possible effects of prioritizing and/or promoting specific strategies, including unintended effects for other materials or energy use. Hence, the developed analysis demonstrated that the CIR can provide relevant information to identify the best circular strategies among a set of available CE strategies; however, such information should be complemented/integrated by

relevant social-economic-environmental information derived from other assessment tools (e.g. Life Cycle Assessment, Criticality Assessment, social and economic analyses).

Finally, and especially in case of foresight analyses focusing on emerging technologies, it is important to underline that the use of rates alone, without absolute figure, can sometimes be misleading. For that reason, it is highly recommended to present the CIR results in combination with an adequate set of absolute values for the related materials flows.

#### 4. Conclusions

Measuring circularity of materials is essential to assess the performances of a sector and to monitor its recent and futures trends. The paper shows that such an approach appears particularly useful for strategic sectors such as e-vehicles, which are expected to substantially contribute to the low carbon transition, but contain significant quantities of CRMs. Various CE strategies can mitigate the risk of supply disruptions keeping materials longer in the EU economy and recirculating SRMs in manufacturing new products. To capture the effects of all possible CE strategies and provide information of the actual mitigation of primary RMs demand, a novel Circular Input Rate (CIR) indicator is proposed.

According to the sectors and applications in which materials are used, CE strategies can evolve differently due to various factors, including available CE technologies, volumes of products, consumer behavior, and regulatory framework. This underlines the needs of providing meaningful information to decision-makers, to support the development of adapted incentives for CE strategies. As a consequence, it is proposed in the paper to apply the CIR indicator on flows and stocks of materials embedded in specific product groups.

The proposed CIR has been applied to REE (Nd) embedded in permanent magnets of e-motors. The case-study appears particularly relevant as demand of CRMs is rapidly increasing due to increasing penetration of electric vehicles, as recycling is currently little developed, and remanufacturing is offering relevant possibilities.

Results of the test of the CIR confirmed that the CIR allows to appropriately capture contributions of various CE strategies beyond

recycling, including reuse and remanufacturing. In fact, from the analysis, it emerged that reuse and remanufacturing of e-motors in the EU have the potential to keep in the loop up to 89 tons of Nd in 2030 (optimistic scenario). This amount can be added to 161 tons of secondary Nd obtained through functional recycling and captured by the EOL-RIR. Subsequently, it emerged that CIR can adequately assess circularity benefits related to various CE strategies, helping understand which strategies should be prioritized.

Further work on CIR will be needed to better understand its limitations (e.g. working on quality of data) and its potentials: the CIR will then need to be applied to other materials/(groups of) products/services at different scales, including inter-related sectors to better understand the best conditions for its application; the CIR will need to be applied not only to simulate possible future but also to monitor past and recent evolutions, in particular for materials and components in sectors with high potential of reuse and remanufacturing practices; the CIR will also have to be tested for cases where components can be significantly repurposed into other applications (e.g. batteries from electric vehicles repurposed into stationary applications, or e-motors to be used in other applications). Also, possible changes related to new and innovative

mobility solutions (e.g. shift to cycling in urban areas or enhanced Mobility as a Service, or other strategies proposing systemic sustainable solutions) should be further explored in building robust and relevant scenarios; the adoption of rates, in combination with absolute values is particularly relevant in both monitoring current practices and supporting the future design of policies and targets related to the transition towards a more circular EU.

In fact, CIR could consider also other shorter loop activities beyond recycling which can reduce the reliance on primary raw materials from third countries. A long-term perspective and improved robustness of input data are needed to understand the effects of EoL strategies on the whole economic system.

Experts and stakeholders should be constantly and pro-actively involved in these analyses to face issues related to data (e.g. confidentiality, representativeness) and modeling (e.g. potential creation of new flows and market sectors).

## Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

## CRediT authorship contribution statement

**Silvia Bobba:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Umberto Eynard:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Thibaut Maury:** Conceptualization, Methodology, Writing – review & editing. **Fulvio Ardenente:** Conceptualization, Supervision, Writing – review & editing. **Gian Andrea Blengini:** Conceptualization, Methodology, Writing – review & editing. **Fabrice Mathieux:** Methodology, Project administration, Supervision, Validation, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

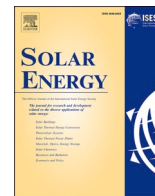
## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2023.107037](https://doi.org/10.1016/j.resconrec.2023.107037).

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# Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive

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## ABSTRACT

As announced in the European Green Deal, it is critical to decarbonise the European Union energy system in order to reach climate objectives by 2030 and 2050. According to the REPowerEU plan, photovoltaics (PV) is expected to play a major role in this. Therefore, it is crucial to ensure that newly installed PV modules in the EU are affordable and competitive on the one hand and environmentally friendly on the other. Bearing in mind that the environmental hotspots for PV modules mainly occur during the manufacturing phase, the aim of the paper is to develop a fully-fledged and adapted methodology for calculating the carbon footprint of PV modules, with particular regard to the manufacturing and shipping phases, following a cradle-to-gate approach based on the Product Environmental Footprint Category Rules for PV modules. The implications of requirements for the carbon footprint of PV modules, under the existing legal framework of the Ecodesign Directive, are also discussed.

## 1. Introduction

The European Union (EU) is promoting grid decarbonisation by requiring 1 TW of installed solar photovoltaics (PV), up from ~ 130 GW in 2021 (European Commission, 2022a).

The rapid deployment of renewable energy and PV is at the core of the REPowerEU plan – the EU initiative to put an end to its dependency on Russian fossil fuels. By the end of 2020, the EU reached approximately 136 GW of solar PV installed generation capacity, having added more than 18 GW in 2020. This delivered around 5 % of total EU electricity generation. The REPowerEU strategy aims to bring online over 320 GW of solar PV by 2025 (more than double compared to 2020) and almost 600 GW by 2030. To address the challenge of climate change, societies and economies will need to transform, phasing out unsustainable practices in production and consumption. Despite PV being considered a green or low-carbon technology, the manufacture is an energy-intensive process and it has obvious impacts on land due to the large space required. PV cannot be designed without taking

environmental criteria into account, just because it produces green energy. In order to maximise emissions reductions, not only must PV modules and inverters have a high conversion efficiency, but materials should have been sourced – and products manufactured, used and disposed of – in an environmentally sensitive manner.

If solar energy is going to play a significant role among the energy sources of the future, this is the right moment to reflect and to steer this production towards truly sustainable technology. To reduce the carbon footprint of the PV sector, it is therefore of paramount importance to identify, quantify and assess the material and energy flows of PV (waste).

Globally, many countries have declared national decarbonisation goals. For example, the United States aspires to decarbonise its electricity grid by 2035 (The White House, 2021). France and South Korea have already worked out solutions to start cutting emissions from PV, by including greenhouse gas (GHG) emissions targets in their national tenders (Commission de régulation de l'énergie, 2021; Korean Ministry of Economy and Finance, 2021).

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To improve the sustainability of PV, not only voluntary goals, but compulsory regulations are needed that could set limits or targets for the next generations of PV modules to come on the market. It will then be necessary to set rules for clear quantification of the emissions.

Quantification of the carbon footprint of a product (CFP) is one of the first steps to complete in order to maximise reduction in GHG emissions. A number of companies in the PV sector are currently aiming to significantly reduce GHG emissions along their value chain and are closely aligning with the United Nations Sustainable Development Goals (SDGs) (Energy Global, 2022).

The units of CFP are ‘gCO<sub>2</sub>eq/kWh’, i.e. grams of carbon dioxide equivalent per kilowatt-hour of electricity generated. Carbon dioxide is the most significant GHG and is produced, for example, when fossil fuels are burned. GHGs other than carbon dioxide, such as methane, are quantified as equivalent amounts of carbon dioxide. This is done by calculating their global warming potential relative to carbon dioxide over a specified timescale, usually 100 years.

In many cases, emissions from ‘low-carbon’ generation technologies do not arise directly from the operation of the generators. Their carbon footprints are therefore dominated by indirect emissions, such as those produced during construction and the production of fuels (where applicable). For solar energy, the location-specific energy resource also has an important influence on the footprint. This is because higher electricity outputs cause lower footprints, as total emissions are spread over a greater amount of electricity.

Ecodesign (European Union, 2009) and Energy Labelling (European Union, 2017) are EU market regulations that make it easier and less costly for businesses, citizens and governments to contribute to the clean energy transition and deliver on the EU energy efficiency and wider European Green Deal objectives (European Commission, 2019), including the Circular Economy agenda. They create business opportunities and increase resilience by setting harmonised rules for energy-related products on aspects such as energy consumption, water consumption, emission levels and material efficiency. These measures also promote supply and demand for more sustainable products, while significantly reducing energy user expenditure: estimates indicate that savings in 2021 exceeded EUR 120 billion and could reach double this in 2022. Furthermore, these policies will help to achieve the EU target of reducing GHG emissions by at least 55 % by 2030 (European Commission, 2020), compared to 1990 levels.

Within this policy framework, the European Commission established a third Ecodesign Working Plan (European Commission, 2016), which identified PV modules and inverters as one of the non-regulated product groups with the largest potential for environmental savings and indicated the need for more detailed investigation into possible environmental improvements. Following the inclusion of PV products in this Ecodesign Working Plan, the Joint Research Centre of the European Commission conducted a study of the environmental impact of PV products (Dodd et al., 2020).

The policy relevance at EU level of the potential carbon footprint requirements for PV modules has been also announced in the recently published EU Solar Energy Strategy (European Commission, 2022a): ‘the Commission is also assessing options covering [...] the carbon footprint of PV modules’ and ‘these measures are also expected to foster innovation and provide a common reference for potential buyers to compare different products’.

This paper elaborates on the findings of the study (Dodd et al., 2020), focusing in particular on analysing potential requirements for the carbon footprint of PV modules.

The aim of this paper is to contribute to the knowledge base by developing a methodology for quantifying the carbon footprint of PV modules, which can be applied in regulatory contexts.

This paper is organised into five sections. Starting with an analysis of existing studies and legislation affecting the carbon footprint of products (Section 2), it develops a ready-to-use methodology to be applied in the specific case of PV modules (Section 3). Section 4 presents the results

and Section 5 outlines potential policy approaches to regulate the carbon footprint of PV modules, in particular through requirements within the legal framework of the EU Ecodesign Directive. Finally, Section 6 presents the conclusions of this paper.

## 2. BACKGROUND: Literature review of existing studies and legislation

### 2.1. Preparatory work on PV modules

The Commission recently carried out a preparatory study (Dodd et al., 2020) to analyse technical, environmental and economic aspects of PV modules, inverters and systems.

One of the main indications provided by the preparatory study is that the carbon footprint of the manufacturing phase of PV modules is one of the most salient aspects of this product group. This is also intuitive: given that PV modules are energy-generating products, the use phase – an important contributor to the environmental impacts of products such as refrigerators (European Union, 2016) or washing machines – here contributes negligibly to the (negative) environmental impacts, while also offset by the electrical energy produced by the module. A similar indication can be found in the Product Environmental Footprint Category Rules (PEFCRs) used for PV power systems (PEFCR PV Technical Secretariat, 2019) developed under the Product Environmental Footprint (PEF) pilot phase. This established the methodology for calculating environmental impacts for the main PV technologies and for a representative (virtual) product. The climate change impact category is expressed in kgCO<sub>2</sub>eq/kWh. When considering the weighting of the environmental footprint for the raw material acquisition and pre-processing phase (including manufacture of the PV modules), this study also discusses how the ‘climate change’ impact (i.e. the one measured with the carbon footprint) is one of the most significant categories for the manufacturing phase. The composition of carbon footprints and their sensitivity to underlying assumptions varies among technologies. However, it is clear that for all PV modules, the carbon footprint is largely determined at the design stage (Mueller et al., 2021). Firstly, the manufacturer’s choice of materials and components – in terms of their volume, origin and quality – largely decides the overall carbon intensity of the module. Secondly, the inverse ratio between the output of the module (also largely dependent on its design) and the carbon intensity of these material inputs then determines the carbon footprint. In addition to these design factors, the carbon intensity of the energy mix used during the manufacturing process also influences the carbon footprint (Leccisi et al., 2016). The preparatory study (Dodd et al., 2020) therefore showed that there is significant potential for improvement through such design choices.

A widely used tool for industries to report carbon emissions and environmental impact is the International EPD (Environmental Product Declaration) System. As an example, the Norwegian EPD Foundation and EPD Italy have Product Category Rules to conduct a life cycle assessment (LCA) for PV modules, which is coded EN15804:2012+A2:2019. These are valid for 6 years. The allocation is made in accordance with the provisions of ISO 14025, which means for example that incoming energy and water, and waste production in-house, is allocated equally among all products through mass allocation. Following this standard, a number of companies have recently issued Environmental Product Declarations. The Global Electronics Council has also developed EPEAT (Electronic Product Environmental Assessment Tool), which is a ranking system that helps purchasers in the public and private sectors to evaluate, compare and select products within the IT sector based on their environmental attributes. EPEAT evaluates products according to seven environmental performance criteria: materials selection, supply chain GHG emissions reduction, design for circularity and product longevity, energy conservation, end-of-life management and corporate responsibility. In following these performance objectives, organisations can meet one of three

performance levels (bronze, silver or gold) depending on the percentage of criteria conformity. A new criterion, ‘ultra low-carbon solar’, is under development.

## 2.2. Carbon footprint product (CFP) requirements in the European Union and worldwide

In specific cases, CFP requirements are set by national authorities. There are currently two countries that have such criteria in their public tenders: France and South Korea.

France has had specific carbon-footprint criteria in place for public tendering for PV modules since January 2019. Revised specifications and a new scope for public tenders have been issued by the CRE (*Commission de régulation de l'énergie*, 2021). These criteria aim to select the most sustainable modules on the market by setting a maximum threshold for the carbon footprint. Up to November 2020, the threshold was 1 150 kgCO<sub>2</sub>eq/kW, but for the period 2021–2026 this value has been revised to 550 kgCO<sub>2</sub>eq/kW for PV in the ground and in buildings, and 500 kgCO<sub>2</sub>eq/kW for innovative PV technologies. The methodological approach is to quantify and verify the total amount of GHG per unit output (1 kW) emitted by the entire process of manufacturing solar modules (polysilicon, ingot, wafer, cell, module and frame), for products from domestic and foreign PV module manufacturers.

The South Korean Ministry of Trade, Industry and Energy has developed a CFP system with the objective of contributing to global reduction in GHG emissions but also further strengthening the competitiveness of the domestic solar energy industry. This system will be applied to the Renewable Portfolio Standard (RPS)<sup>1</sup> and public projects.

The calculation of the CPF in South Korea will be used to classify solar modules into three grades, depending on their carbon emissions (*Ultra Low-Carbon Solar Alliance*, 2021). The score will be directly linked to incentives in the RPS selection bidding market, and government projects (to be implemented in the near future). The rating I corresponds to a CFP below or equal to 670 kgCO<sub>2</sub>eq/kW, being therefore slightly less stringent than the French rating.

These regulations, largely inspired by the French public tender rules, require module manufacturers to submit an application to the government for verification and approval of the calculated carbon footprint. This calculation can be done by two methods: Method by Standard Emission Factor or Methods by Life Cycle Assessment (LCA). Evaluation of the Standard Emission Factor of PV modules.

The South Korean CFP default calculation is based on official default values per component and country (as per French tenders) without breakages and losses (as per French methodology CRE3), as shown in Fig. 1.

## 3. Methodology

In the carbon accounting field, there is a plethora of methods, guidance documents and standards that can be applied to calculate the carbon footprint. These are listed in Table 2.

The carbon footprint indicator refers to the quantification of GHG emissions caused during the processes involved in manufacturing or producing goods or services. The carbon footprint of an individual, organisation or nation can be measured by undertaking a GHG emissions assessment, a life cycle assessment (LCA) or other calculations referred to as carbon accounting.

The carbon footprint indicator known as global warming potential (GWP) has been developed by the Intergovernmental Panel on Climate

<sup>1</sup> The RPS programme requires the 13 largest power companies (with installed power capacity higher than 500 MW) to steadily increase their renewable energy mix in total power generation over the period 2012–2024. Source: IEA/IRENA Renewable Policies Database.

Change (IPCC, 2021). It refers to time horizons of 100 years for a number of known greenhouse gases, such as CO<sub>2</sub>, CH<sub>4</sub>, chlorofluorocarbons (CFCs), N<sub>2</sub>O, hydrofluorocarbons (HFCs) and other halogenated hydrocarbons. The GWP formula can be expressed as:

$$GWP [kgCO_2eq] = \sum GWP_{ix} m_i$$

where  $m_i$  corresponds to gaseous emissions of each compound  $i$  expressed as kg per functional unit. Table 1 shows the existing standards, documents and guidelines that can be used for calculating the carbon footprint.

In particular, the International Organization for Standardization has set a standard, ISO 14040:2006, that provides a framework for conducting an LCA study (*International Organization for Standardization*, 2006). The ISO 14060 family of standards provides further tools for quantifying, monitoring, reporting and validating or verifying GHG emissions. In particular, ISO 14067:2018 lists the requirements and guidelines for quantifying the carbon footprint of products (*International Organization for Standardization*, 2018).

Another method, established by the Greenhouse Gas Protocol, consists of a set of standards for tracking GHG emissions across scope 1, 2 and 3 emissions within the value chain.<sup>2</sup> GHG Protocol have also developed a suite of calculation tools to assist companies in calculating their GHG emissions and measuring the benefits of climate change mitigation projects (*World Resources Institute and World Business Council for Sustainable Development*, 2011).

Among the methods and standards discussed above, there is a need to harmonise carbon footprint calculation specifically for PV products, at EU level. To address this need, the PEFGR for PV modules represents a useful tool for guiding the development of environmental footprint studies, on the basis of international agreements. It identifies foreground unit processes which require product-specific data, versus background processes which are based on pre-specified data (*Wade et al.*, 2017).

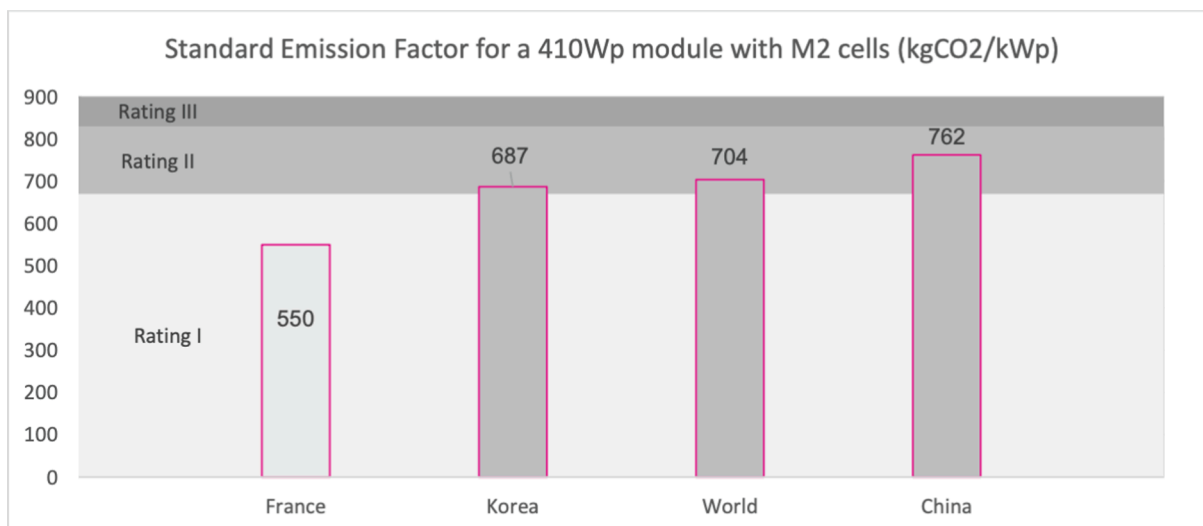
The methodology presented in those category rules is therefore useful for defining harmonised calculation rules for carbon footprints in a regulatory context. It is focused on products that are within the scope of the Ecodesign Directive (*European Union*, 2009), i.e. energy-related products. This method is applied to the specific case of PV modules, with the objective of being conceptually applicable to different technologies and product groups.

As shown in Fig. 2, the first step (step 1) is a hotspot analysis devoted to identifying the areas where environmental impacts are most significant. In the current example we focus on the carbon footprint, but the same approach may be followed for other impact categories of environmental footprint, such as water use, resource (fossil and mineral) use, etc. Considering the most significant impact categories throughout the life cycle of the product, and the processes that contribute most, helps to identify the hotspots.

Identification of the hotspots (step 2) focuses attention on the areas where policymakers may concentrate regulatory efforts. For instance, in the case of the EU Ecodesign policy, preparatory studies are carried out, with a techno-economic and environmental assessment at product-specific level, to provide policymakers with the evidence basis to assess whether to implement policy instruments.

It is important to define the technologies that are most relevant for

<sup>2</sup> The GHG Protocol Corporate Standard classifies a company's GHG emissions into three 'scopes'. **Scope 1** emissions are direct emissions from sources that are controlled or owned by an organisation (e.g. emissions associated with fuel combustion in boilers, furnaces or vehicles). **Scope 2** emissions are indirect emissions associated with the purchase of electricity, steam, heat or cooling. **Scope 3** emissions are all indirect emissions (not included in scope 2) that are a consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples of scope 3 activities are extraction and production of purchased materials, transportation of purchased fuels, and use of products and services.



**Fig. 1.** Rating of modules in the South Korean standard according to the standard emissions model. Source: [Ultra Low-Carbon Solar Alliance, 2021](#). There is also a list of default values for calculating the Standard Emission Factor of PV modules, depending on the origin of the raw material (see [Table S1, Annex](#)). In light of the existing scientific indications, policy regulations and industry certifications analysed above, it seems relevant to further investigate the carbon footprint of the PV manufacturing phase because it is among the most salient aspects of this product group. The following section discusses the methodological aspects that can be applied to calculate the carbon footprint.

the market being assessed and that are covered by the analysis. The hotspot analysis aims to identify the processes and stages that contribute most to the overall impacts in the life cycle.

As discussed in Section 2, the PEFCRs are needed to provide guidance on carrying out a life cycle assessment based on the Environmental Footprint method ([European Commission, 2021](#)). PEFCRs reflect international agreements and technical/scientific progress in the area of life cycle assessment. Specifically, the PEFCRs can cover 16 environmental impact categories, including their normalisation and weighting, with the aim of identifying the most significant ones.

These rules help to direct focus to those aspects and parameters that matter most, and hence contribute to increased relevance, reproducibility and consistency of the results. Finally, PEFCRs are a useful tool for providing consistent comparisons between different PV manufacturing technologies and various products.

As per step 3 of [Fig. 2](#), the harmonised calculation rules build on the latest version of the PEF method and PEFCR. The list and coverage of existing PEFCRs is being expanded to cover different product groups<sup>3</sup>.

The next step (step 3a) of the analysis is to check whether a PEFCR is already available for the product group in scope and whether it can be adapted for the purpose of setting ecodesign requirements.

If a PEFCR is not available, it must be developed for the product in scope (step 3b), since PEFCR is used as a basis for defining harmonised calculation rules. The process of developing category and sector rules is articulated and involves several steps which are described in detailed guidance ([European Commission, 2017](#)).

If a PEFCR is available (step 3a), the harmonised calculation rules are developed following the same standardised structure as the PEFCR. Since the PEFCR could have a larger scope, including a larger system, it should be adapted to suit the scope of the analysis (step 4).

Each section of the PEFCR needs to be checked and modified according to the chosen policy in developing ecodesign requirements. The main aspects (not exhaustive) to be considered in adapting the PEFCR for inclusion in the harmonised calculation rules are shown in [Table 2](#).

At step 5, the harmonised calculation rules are defined and can be used to calculate the results. A sensitivity analysis (step 6) needs to be

performed to evaluate the results under various scenarios. Interpretation of the results (step 7) is fundamental for identifying the quantitative values that may result in a threshold for acceptance of a product. Throughout the process, stakeholders must be involved to ensure a more comprehensive view (step 8). Finally (step 9), the proposed methodology could be applied to set market entry requirements.

The methodology described above has been applied to a set of representative PV modules for potential ecodesign requirements. It represents a quantitative example of the concept defined in the flow chart in [Fig. 2](#). Each step in the flow chart was applied as follows.

As mentioned in the introduction, PV modules have been identified by the Ecodesign Working Plan 2016–2019 ([European Commission, 2016](#)) as one of the non-regulated product groups with the largest potential for environmental savings. This indicates the importance of more detailed investigation into potential environmental improvements ([Fig. 2](#), step 1). As discussed in the previous sections, the Commission carried out a preparatory study ([Dodd et al., 2020](#)) which identified a number of areas for potential regulatory intervention; the manufacturing phase was found to be highly significant for the life cycle of this product group, especially in terms of climate change impact (step 2).

Thus, individual PV modules placed on the EU market and intended for use in PV systems for grid-connected electricity generation have been identified as a good product group for application of the method.

As described in step 3 of [Fig. 2](#), it is therefore relevant to identify how rules for calculating the carbon footprint of PV modules, as derived from the PV PEFCRs, could be modified or adapted to potentially serve the purposes of the Ecodesign Directive.

As discussed, in 2019 PEFCRs were developed for PV modules under the Environmental Footprint pilot phase ([PEFCR PV Technical Secretariat, 2019](#)). This document sets detailed requirements on how to conduct a Product Environmental Footprint (PEF) study and assesses several life cycle impact categories for PV modules (including climate change).

PEFCRs for PV modules have been adapted and streamlined for use in ecodesign secondary legislation (i.e. implementing measures) for PV modules, in particular for calculating the *carbon footprint of the manufacturing phase* of PV modules (step 4). The structure of the PV PEFCR is kept as a blueprint and changes and adaptations are highlighted.

<sup>3</sup> List of existing PEFCRs is available at: [ec.europa.eu/environment/eussd/smgp/PEFCR\\_OEFSR\\_en.htm](https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm).

**Table 1**

Non-exhaustive list of standards, documents and guidelines that can be used for calculating the carbon footprint.

Standards and other guidelines/ reference documents	Description	Method
<i>ISO 14067:2018</i> Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification	Requirements and guidelines for quantification of CFP	ISO 14067:2018.
<i>GHG Protocol Product Standard</i>	Product Life Cycle Accounting and Reporting Standard to evaluate the full life cycle GHG emissions of a product	GHG Protocol Product Standard
<i>EU Member States Product Category Rules (Italy, France, Norway, Finland, Netherlands)</i>	Databases and Product Category Rules for construction products/ services where PV modules and inverters are part of new and renovated buildings	EN 15804
<i>European PEFCR Guide for PV modules</i>	Guidance for calculating and reporting life cycle environmental impacts of products	PEF method
<i>Italy's LCA legislation Promotion of the Green Economy</i>	Legislation fully based on the Environmental Footprint methods. Voluntary 'Made Green in Italy' label	PEF method
<i>NSF/ANSI 457 Sustainability Leadership Standard for PV Modules and PV Inverters</i>	Standard to establish product sustainability performance criteria and corporate performance metrics exemplifying sustainability leadership in the market. Basis of conformity assessment, such as third-party certification.	NSF/ANSI 457–2019
<i>France's public tenders for utility scale PV plants</i>	Public tenders include carbon footprint requirements to prioritise projects with low-carbon manufacturing processes	French Agency for Ecological Transition (ADEME) guidelines
<i>South Korean regulations on carbon footprint assessment for PV modules</i>	Carbon footprint assessment method and requirements to prioritise projects with low-carbon manufacturing processes	French methodology CRE3 LCA according to ISO 14040

The specific adaptations mentioned in [Table 2](#) are detailed in [Table S2](#) in the [supplementary information](#). The main aspects (not exhaustive) are summarised below:

- The scope was adapted according to the technologies covered.
- The adapted functional unit is 1 kWh of the total direct current electrical energy generated over the service life of a PV module. The functional unit refers to the electricity yield, calculated according to the methods included in the Ecodesign Regulation under preparation.
- The system boundary is edited to be cradle-to-EU market.
- Life cycle inventory includes only PV modules and their distribution in the EU.
- Use of the Circular Footprint Formula (CFF) is limited to the material part and applied to recycled materials in input. The full formula is reported in the [supplementary information](#).

At this point (step 5), the harmonised calculation rules are developed. They now provide all the recommendations and basis for carrying

**Table 2**

Main aspects to be considered when adapting PEFCRs for use in ecodesign requirements.

PEFCR sections	Aspects to be considered
Scope	technologies covered definition of system boundaries (explain and justify what stages are excluded) functional unit (aligned as far as possible with the PEFCR for comparability of results) reference flow (as above) methods and models to calculate the results of the impact category – based on Environmental Footprint (EF) method application of end-of-life modelling (Circular Footprint Formula)
Life Cycle Inventory	elements beyond the scope of the harmonised calculation rules to be left out most up-to-date EF datasets to be used possible limited use of company-specific data relevant to the adapted scope definition of list of processes and components for which company-specific data is to be used, including the most relevant raw materials and production processes in terms of impacts if the applicant has access to company-specific data for other processes along the supply chain (e.g. electricity mix), the applicant may use such data following the rules of the Data Needs Matrix which can be adapted according to the scope allocation rules: if multiple products are produced in the processes under scope, rules from PEFCR and EF method need to be followed

out the LCA analysis. For PV modules, some aspects deserved deeper analysis to check to what extent their variance in the modelling and selection of datasets can change the results. Therefore, a sensitivity analysis (step 6) was performed on three different parameters of the PV modules: i) silicon content, ii) module yield, iii) electricity grid mix used in the manufacturing phase.

#### 4. Results

[Table 3](#) summarises some values for carbon footprint given in Environmental Product Declarations (EPDs) from Sunpower, Trina Solar, First Solar and REC Solar. The calculated ones are based on assumptions stated in Notes below [Table 3](#).

As discussed, the category rules for PV modules (Product Environmental Footprint Category Rules, 2019) establish the methodology to calculate environmental impacts for the main PV technologies, the values of which are shown in [Table 4](#).

The LCA results, in absolute values according to the Ecoreport tool, for 1 kWh produced by a multi-Si back surface field (BSF) PV module are shown in [Fig. 3](#) (reference year 2014, balance of system excluded). [Fig. 3](#) demonstrates the significance of the environmental impacts of the manufacturing phase (accounting for more than 70 % in all impact categories).

The section below reports on a sensitivity analysis carried out in line with the methodology established in the previous section, and on the basis of the three parameters set out in the table below (silicon content, yield over time and energy mix of the manufacturing phase). Among all physical properties, performance parameters and characteristics of the manufacturing process for PV modules, these parameters are the most significant ones for the carbon footprint value of PV modules, as discussed in the background section. Both yield values are deemed to be representative of the current market; they obviously correspond to different market segments – the top half of the market for the high yield value ([LG Business Solutions, 2022](#)), and the lower part of the market for the low yield ([Canadian Solar Inc, 2022](#)). In terms of quantity of silicon, the 'low' content should be the one typical of modules currently in production (the 'high' content being more representative of PV modules produced in the 2010 s). Again, the thresholds are targeted to current module production.

[Fig. 4](#) shows, for monocrystalline and polycrystalline silicon PV

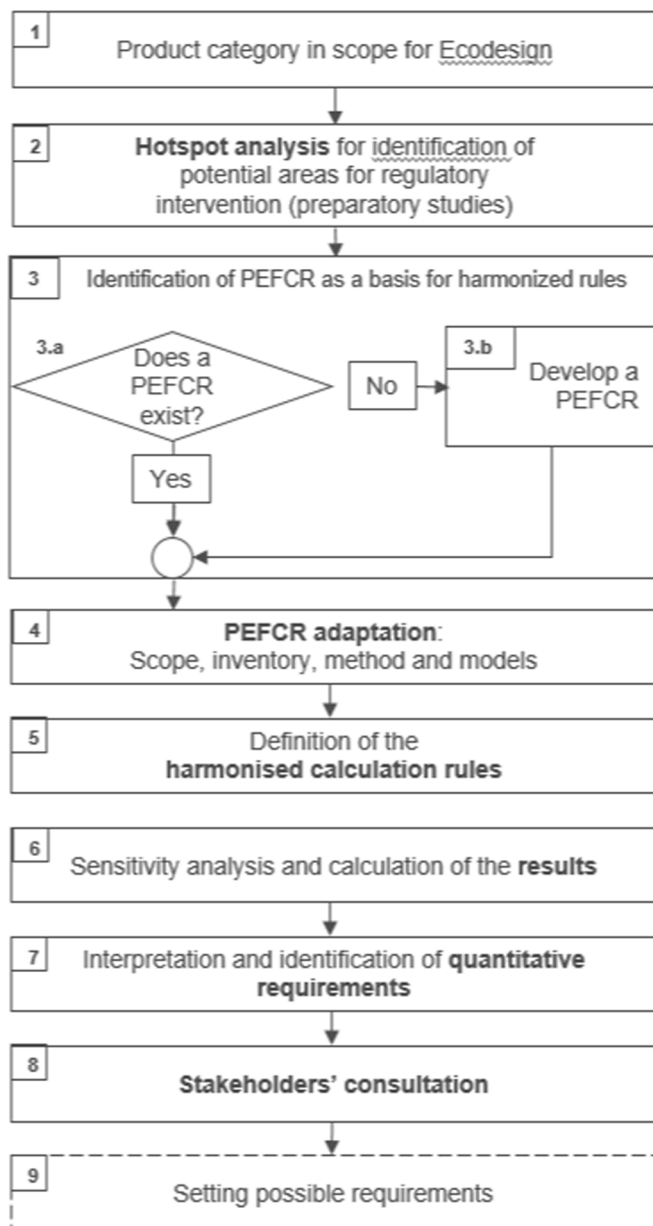


Fig. 2. Method summary for the ecological profile requirement under the Ecodesign Directive.

modules, the distribution of values of the carbon footprint (expressed in kgCO<sub>2</sub>eq/kWh) based on the sensitivity analysis described in Table 5. When interpreting the results (step 7), it is worth noting that carbon footprint values range between best and worst scenario by a factor of 3.2 for monocrystalline silicon and a factor of 2.3 for multicrystalline silicon. A change of around 5 % in the electricity production efficiency of a PV module has less effect on the carbon footprint than the sources/mix of electricity during the production stage. The analysis also showed that reducing the aluminium frame weight by 50 % is not significant compared to the other scenarios.

Based on the results of the harmonised calculation and feedback from stakeholders (step 8), the proposed methodology suggests setting requirements, for instance based on thresholds (step 9). The policy considerations are addressed in the next section.

### 5. Policy discussion

The methodology set out in the previous section could provide an

Table 3

Summary table for carbon footprint values reported in EPDs for some PV products.

	kgCO <sub>2</sub> eq/ W or kg	kgCO <sub>2</sub> eq/ kWh	Comments
Sunpower EPD	3.42E-01	2.28E-01	400Wp monocrystalline PV module
Trina Solar EPD	1.91E-02	1.27E-02	PV plant 30 MW
First Solar EPD	2.67E-01	1.78E-01	1 Wp of Series 6 CdTe PV module
REC Multi-Silicon block	1.12E + 01	7.47E + 00	Per kg of silicon block
REC Solar grade silicon EPD	1.60E + 01	1.07E + 01	1 kg of manufactured Solar grade silicon (SoG-Si)
Norsun monocrystalline silicon wafer EPD	3.54E + 01	2.36E + 01	Per kg of m <sup>2</sup> of manufactured monocrystalline silicon wafer

Notes: 1 500 kWh/kWp

Table 4

CFP values corresponding to the climate change impact category, calculated as per the PEFCR (European Commission, 2019).

PV technologies	Life cycle excl. use stage (kgCO <sub>2</sub> eq/kWh)	Use stage (kgCO <sub>2</sub> eq/kWh)
Representative (virtual) product	5.93E-02	1.05E-05
CdTe	1.99E-02	1.07E-05
CIGS	3.59E-02	1.39E-05
Micromorphous silicon	4.30E-02	1.50E-05
Multicrystalline silicon	4.88E-02	1.02E-05
Monocrystalline silicon	8.04E-02	9.93E-06

approach to calculating the carbon footprint of PV modules for application in regulatory contexts, in particular within the framework of the Ecodesign Directive. Carbon footprint requirements for PV modules would be the first of their kind within ecodesign (or energy labelling) measures.

Based on the analysis in the previous sections, the following alternative regulatory approaches to the carbon footprint of PV modules could be proposed.

1. Quantitative requirements establishing a maximum admitted threshold for the carbon footprint of PV modules.
2. Quantitative requirements for specific relevant parameters influencing the carbon footprint, such as the silicon content or the module yield.
3. Information requirements on the carbon footprint of PV modules.
4. Carbon footprint information to be reported on the energy label of PV modules, and/or in the related product information sheet.

The first typology of requirements (quantitative requirements establishing a maximum threshold) would represent a straightforward policy approach to reduce the carbon footprint of PV modules and achieve the EU's environmental objectives. Maximum thresholds would be set to ensure that only those products that meet a minimum level of ambition in emissions reduction are available on the market. The proposed thresholds could follow a multi-staged approach, e.g. with a first maximum footprint after a period of 2–3 years after the Ecodesign Regulation comes into force, and a second – and more ambitious – maximum footprint after a period of 5–6 years. This would result in progressively phasing out the worst performing products (in terms of CFP) from the EU market.

The second typology of requirements (quantitative requirements for specific relevant parameters) would be close to the previous one in terms of intended effects on the market. In conceptual terms, it would be implemented by targeting specific design parameters, instead of the first

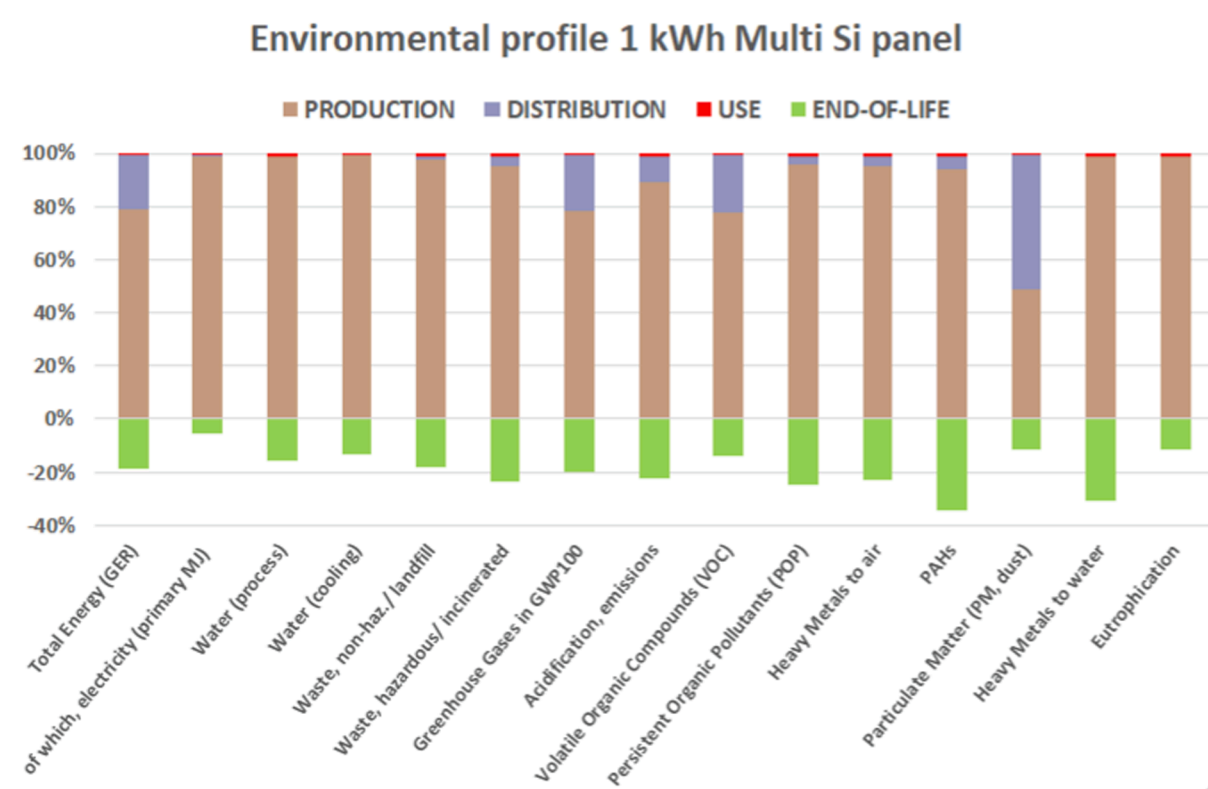


Fig. 3. Environmental profile of a multicrystalline silicon PV module, for 2014 reference year, in absolute values. . Source: Dodd et al. (2020)

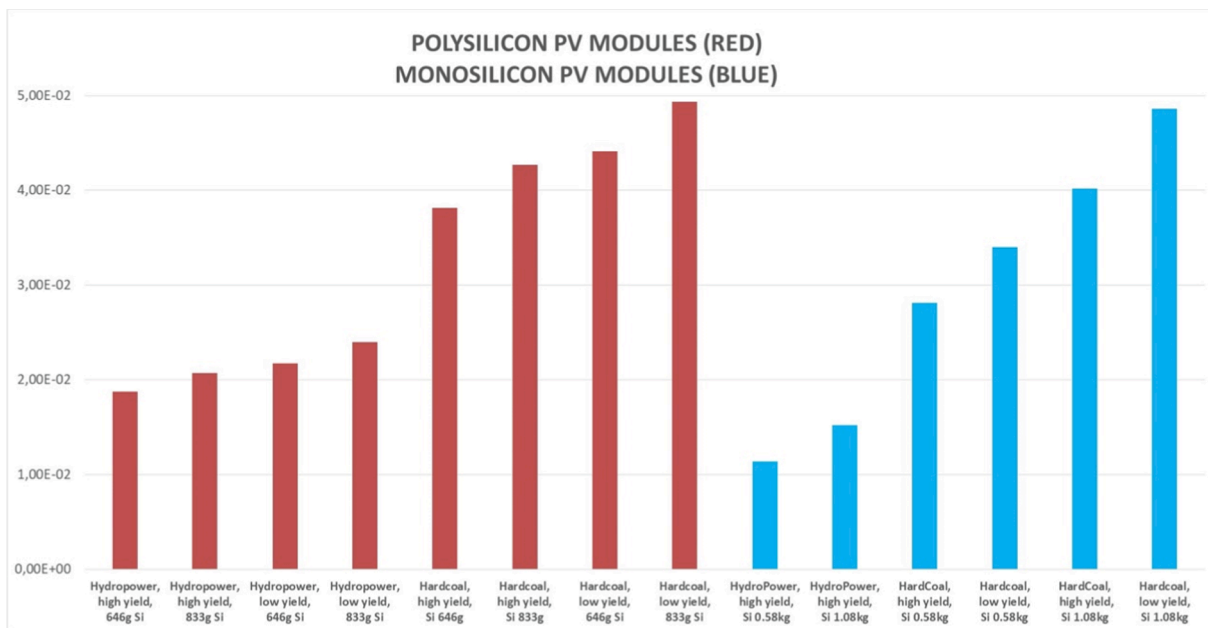


Fig. 4. Carbon footprint values of monocrystalline and polycrystalline silicon PV modules (manufacturing and distribution phase). Source: European Commission, 2022b, 2022c, 2022d).

approach which is more ‘holistic’ (and thus leaves the designer or manufacturer with more room for manoeuvre in terms of choosing which parameter to optimise).

The third typology of requirements (information) would consist of a mandatory carbon footprint declaration. This would create transparency on the market and allow consumers and public authorities to compare

the carbon footprint of different modules placed on the market. As such, PV modules with adverse environmental and climate change impacts could still be available on the EU market. However, the transparency with regard to the carbon footprint content could act as an incentive for manufacturers to improve the environmental performance of their production phase, thus contributing to the ‘ecodesign’ of their products.

**Table 5**

Main values considered for PV modules based on monocrystalline silicon and multicrystalline silicon.

Parameter	High value	Low value
Silicon content (g per functional unit)		
Monocrystalline silicon	1 080	588
Multicrystalline silicon	833	646
Yield over 30 years <sup>4</sup> (kWh/m <sup>2</sup> )		
Monocrystalline silicon	6 730	5 540
Multicrystalline silicon	5 920	5 120
Energy mix of the manufacturing phase	'hard coal' (worst) scenario	'hydropower' (best) scenario

<sup>4</sup>Total energy yield in direct current over service life (30 years), calculated according to Annex III, point 4.3, to the Ecodesign working document (European Commission, 2022).

This standardised information could also serve as a tool for green public procurement schemes, such as those referred to in Table 1.

The fourth typology of requirements (carbon footprint information on an energy label for PV modules) is conceptually close to the previous one, in the sense that it would represent a way to display the information within a tool (the energy label) that helps users to make an informed choice when buying the product. Obviously, it should be carefully designed in order to provide concise but at the same time relevant and effective information. Experiences with other product groups, typically white goods, already regulated with energy labelling show that the energy label can be a very powerful driver for fostering continuous product innovation towards higher energy efficiency (Michel et al., 2017).

Independent of the chosen policy approach, the following considerations are relevant when evaluating the feasibility of regulating the carbon footprint of (PV) products:

- To ensure comparability, the declared carbon footprint should be based on harmonised calculation rules. This is why a specific methodology is presented in this paper.
- The carbon footprint could be calculated using a single, ideally freely accessible calculation tool based on harmonised rules. This would greatly contribute to reducing the administrative burden on manufacturers.
- The carbon footprint calculation should focus on those life-cycle stages where the bulk of emissions occur. In this case, these are the raw material acquisition and pre-processing, the manufacturing, and potentially the distribution phases. The choice of these life-cycle stages is also beneficial from the legal perspective. Ecodesign rules apply to products sold on the EU market, at the moment they are 'placed on the market'. This means that it is not feasible to enforce or verify compliance with eco-design requirements after placing on the market, only during life-cycle stages prior to that point.
- To ensure that the declared carbon footprint of PV modules is reliable, credible and correct, manufacturers should apply for verification of their declared footprint by an independent conformity assessment body. Third-party verification further ensures comparability of claims and enables more effective management of the environmental and non-compliance risks involved. In particular, verification should ensure the reliability of the company-specific data used by manufacturers. Such data, for example relating to the energy used in the production process, cannot be verified on the product itself, as is also the case for the energy yield. The verified carbon footprint should be valid for a fixed period (e.g. 3 years) and should be updated, including during its validity period, in the event of significant changes.

## 6. Conclusions

This paper proposes a harmonised methodology for calculating the carbon footprint of PV modules, for use in regulatory contexts, in

particular within eco-design regulations that would affect the EU market. The gross energy consumption associated with PV modules will evolve in line with the expected increase in deployed PV in the EU market. In light of the recent commitments laid down in the EU Solar Energy Strategy (European Commission, 2022a) to boost the installation of PV modules on EU buildings, this increase can be expected to occur at an even faster pace. Due to this expected growth, setting eco-design requirements for the carbon footprint of PV modules could result in significant energy savings, in particular within the energy-intensive manufacturing stage for these products.

The approach presented in this paper is novel in that it provides a methodology for calculating the carbon footprint of PV modules with the specific aim of applying it in regulatory contexts. The methodology presented in this paper could very well be used to tackle other categories of environmental impact through policy intervention. For instance, in the case of PV modules, other relevant impacts of interest beyond the emission of greenhouse gases may include resource use (fossil fuels), resource use (minerals and metals), acidification and particulate matter/respiratory inorganics. The method could also be adapted to consider the full life cycle of PV modules, including end-of-life phase. This would also extend the applicability of the methodology to policy fields related to secondary and critical raw materials. The methodology could obviously be applied and modified for other product groups, in particular those already covered by PEFCRs. It could thus be seen as a basis for setting market entry requirements based on the 'ecological profile' of products, as referred to in the Ecodesign Directive (European Union, 2009).

## 7. Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.solener.2023.04.001>.

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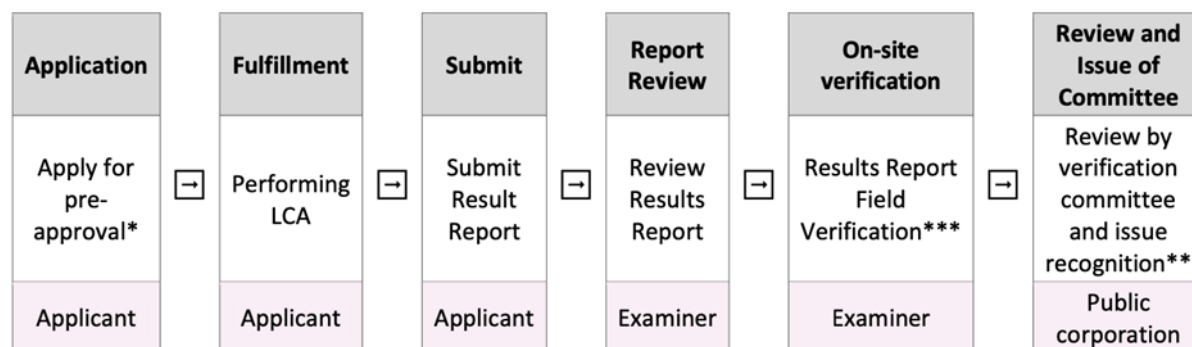
## Supplementary information

Table S1. List of default values for South Korean Standard Emission Factor of PV modules

Category	Korea	China	USA	France	Germany	Japan	Taiwan	Malaysia	Canada	India	Norway	Thailand	World
Polysilicon (kg)	89.871	122.568	93.605	30.674	105.109	85.575	105.357	146.812	63.785	142.726	25.241	97.841	97.294
Ingot (kg)	52.820	70.631	54.854	20.574	61.121	50.480	61.256	83.837	38.610	81.611	17.614	57.161	56.864
Wafer (pcs, 156*156mm <sup>2</sup> )	0.821	0.862	0.826	0.748	0.840	0.816	0.841	0.892	0.789	0.887	0.741	0.831	0.831
Cell (pcs, 156*156mm <sup>2</sup> )	0.396	0.483	0.406	0.238	0.437	0.385	0.437	0.548	0.326	0.537	0.224	0.417	0.416
Module (m <sup>2</sup> )	10.485	11.885	10.645	7.951	11.138	10.301	11.148	12.923	9.368	12.748	7.718	10.827	10.803
Glass (kg)	1.008	1.041	1.012	0.949	1.024	1.004	1.024	1.066	0.982	1.062	0.943	1.016	1.016
Tempered glass(kg)	0.167	0.204	0.171	0.100	0.184	0.162	0.185	0.232	0.138	0.227	0.094	0.176	0.176
EVA (kg)	2.304	2.403	2.316	2.125	2.350	2.291	2.351	2.477	2.225	2.464	2.109	2.328	2.327
PET (kg)	3.088	3.145	3.094	2.983	3.114	3.080	3.115	3.188	3.041	3.181	2.974	3.102	3.101
PVF (kg)	19.312	20.147	19.407	17.800	19.701	19.202	19.707	20.766	18.645	20.662	17.661	19.515	19.501
Aluminum frame (kg)	7.243	7.715	7.297	6.387	7.463	7.181	7.467	8.066	6.866	8.007	6.309	7.358	7.350

Source: Ultra Low-Carbon Solar Alliance (2021)

Figure 5. Verification process for emissions in South Korean tenders



\* LCA can be carried out after the approval of the Corporation for LCA pre-approval.

\*\* Issue of recognition if the results of the review by the verification review committee are appropriate.

\*\*\* Regarding the present sanitary situation, the onsite audit has been exempted.

Source: Ultra Low-Carbon Solar Alliance (2021)

Table S2: Changes and adaptations in harmonised calculation rule compared to PEFCR for PV panels

PEFCR Index		Included in the harmonised calculation rules	Changes to original PEFCR contents	Motivation
1	Introduction	No	-	Not relevant
2	General information about the PEFCR	No	-	Not relevant
3	PEFCR scope	Yes	Technologies covered  Allowed the use of data records shorter than 12 months for the calculation of the carbon footprint.	<ul style="list-style-type: none"> <li>- Monocrystalline silicon (mono-Si) PV modules</li> <li>- Micromorphous silicon (micro-Si) PV modules</li> <li>- Multicrystalline silicon (multi-Si) PV modules</li> <li>- Cadmium-Telluride (CdTe) PV modules</li> <li>- Copper-Indium-Gallium-Selenide (CIS/CIGS) PV modules</li> </ul> <p>Allow applicants still in early stage of product development and deployment to apply the harmonised calculation rules</p>
3.1	Product classification	No	-	Not relevant
3.2	Representative product	No	-	Not relevant
3.3	Functional unit and reference flow	Yes	Functional unit is 1 kWh of the total direct current electrical energy generated over the service life of a PV module. The functional unit refers to the electricity yield calculated according to the methods included in the Ecodesign Regulation.  Reference flow: amount of product needed to fulfil the defined function, measured in m <sup>2</sup> of PV module per kWh of the total energy required by the application over its service life.	Alignment with energy yield calculation methods included in the Ecodesign Regulation.
3.4	System boundaries	Yes	Edited to include only cradle-to-gate + distribution. Terminology of life cycle stages amended to align it with cradle-to-EU market assessment.	Aligned with the scope (cradle-to-EU market).
3.5	EF impact assessment	Yes	Edited to include only GWP impact category.	Other impact categories, normalisation and weighting not relevant.
3.6	Limitations	No	-	Not relevant
4	Summary of most relevant impact categories, life cycle stages and processes	No	-	Not relevant
5	Life cycle inventory	Partially (see below)	Elements beyond the scope have been left out.	Aligned with the scope.

PEFCR Index		Included in the harmonised calculation rules	Changes to original PEFCR contents	Motivation
5.1	List of mandatory company-specific data	Partially	Only mandatory company-specific data relevant to the scope	Aligned with the scope.
5.2	List of processes expected to be run by the company	Yes	Same as 5.1	Same as 5.1
5.3	Data gaps	No	-	Not relevant.
5.4	Data quality requirements	No	-	Data quality assessment out of scope.
5.5	Data needs matrix (DNM)	Yes	Edited, deleting some options not applicable and deleting Data Quality Requirements (DQR)	Data quality assessment out of scope
5.6	Which datasets to use?	Yes	Only those relevant for the selected stages	According to the scope of the harmonised calculation rules.
5.7	How to calculate the DQR for the study	No	-	Data quality assessment out of scope
5.8	Allocation rules	Yes	Minor text editing (e.g. external references)	-
5.9	Electricity modelling	Yes	Minor text editing (e.g. external references)	-
5.10	Climate change modelling	No	-	Not relevant, only total GWP needs to be reported
5.11	Modelling wastes and recycled content	Partially	<p>Application of the Circular Footprint Formula (CFF) is limited to the material part and applied to recycled materials in input. The formula is reported below:</p> $(1 - R_1) \cdot E_v + R_1 \cdot \left( A E_{\text{recycled}} + (1 - A) \cdot E_v \cdot \frac{Q_{\text{Sin}}}{Q_p} \right) + (1 - A) \cdot R_2 \cdot \left( E_{\text{recyclingEoL}} - E_v^* \cdot \frac{Q_{\text{Sout}}}{Q_p} \right)$ <p>Where:  A = allocation factor of burdens and credits between supplier and user of recycled materials.  R<sub>1</sub> = proportion of material in the input to production that has been recycled from a previous system.  R<sub>2</sub> = proportion of material in the product that will be recycled (or reused) in a subsequent system. R<sub>2</sub> shall therefore take into account inefficiencies in collection and recycling (or reuse) processes. R<sub>2</sub> shall be measured at output from the recycling plant.  E<sub>v</sub> = specific emissions and resources consumed (per functional unit) arising from acquisition and pre-processing of virgin material.  E<sub>recycled</sub> = specific emissions and resources consumed (per functional unit) arising from recycling processes for the recycled (reused) material, including collection, sorting and transportation.  E<sub>recyclingEoL</sub> = specific emissions and resources consumed (per functional unit) arising from recycling processes at end-of-life, including collection, sorting and transportation.</p>	Since the system boundaries are limited to cradle-to-gate + distribution, the elements of the CFF pertaining to end-of-life stage have been excluded.

PEFCR Index		Included in the harmonised calculation rules	Changes to original PEFCR contents	Motivation
			<p><math>E^*_v</math> = specific emissions and resources consumed (per functional unit) arising from acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.</p> <p><math>Q_{sin}</math> = quality of ingoing secondary material, i.e. quality of recycled material at point of substitution.</p> <p><math>Q_{Sout}</math> = quality of outgoing secondary material, i.e. quality of recyclable material at point of substitution.</p> <p><math>Q_p</math> = quality of primary material, i.e. quality of virgin material.</p> <p>The <math>R_1</math> values applied shall be supply-chain specific or default ones. Material-specific values based on supply market statistics are not accepted as a proxy. The applied <math>R_1</math> values shall be subject to verification.</p> <p>When using supply-chain specific <math>R_1</math> values other than 0, traceability throughout the supply chain is necessary. The following general guidelines shall be followed when using supply-chain specific <math>R_1</math> values:</p> <ul style="list-style-type: none"> <li>• Supplier information (through e.g. statement of conformity or delivery note) shall be maintained during all stages of production and delivery by the converter.</li> <li>• Once the material is delivered to the converter for production of the end products, the converter shall handle information through their regular administrative procedures.</li> <li>• The converter for production of the end products claiming recycled content shall demonstrate through their management system the percentage of recycled material input into the respective end product(s).</li> <li>• Demonstration of the latter shall be transferred upon request to the user of the end product.</li> <li>• Company-owned traceability systems can be applied as long as they cover the general guidelines outlined above.</li> </ul> <p>The default parameter values for applying the CFF and the default values for <math>R_1</math> and <math>R_2</math> are listed in the spreadsheet 'CF_Annex_PV_modules-Life_cycle_inventory9', sheet CFF-parameters. For all materials not listed in the sheet CFF-parameters, it is assumed that <math>R_2=0</math>.</p>	
6	Life cycle stages	Partially (see below)	<p>Elements out of the scope have been removed.</p> <p>Text edited to leave out descriptive content not relevant for a normative act.</p>	Aligned with the scope
6.1	Raw material acquisition and pre-processing	Yes	-	-
6.2	Distribution and storage	Yes	<p>Only distribution.</p> <p>Transportation scenario for distribution has been edited and divided into two steps:</p> <ul style="list-style-type: none"> <li>• Transport from manufacturing gate to EU border (only for manufacturers outside Europe, with distance as mandatory company-specific data)</li> </ul>	<p>Aligned with the scope.</p> <p>The changes made to modelling of the distribution phase are intended to level the playing field for EU manufacturers, while</p>

PEFCR Index		Included in the harmonised calculation rules	Changes to original PEFCR contents	Motivation
			<ul style="list-style-type: none"> <li>Transport from EU border to EU regional storage (default distance for all)</li> </ul>	including the impacts from transport of PV modules coming from non-EU countries.
6.3	Production of the main product	No	-	Out of scope
6.4	Use stage	No	-	Out of scope
6.5	End-of-life	No	-	Out of scope
7	PEF Results	No	-	Not relevant
8	Verification	No	-	Verification requirements addressed in other parts of the Ecodesign Regulation. See Chapter 4 of this technical report.
9	References	No	-	Not relevant
Annex 1	List of normalisation and weighting factors	No	-	Not relevant
Annex 1	Check-list for the PEF study	No	-	Not relevant
Annex 1	Review report	No	-	Not relevant

Article

# Bridging Tools to Better Understand Environmental Performances and Raw Materials Supply of Traction Batteries in the Future EU Fleet

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**Abstract:** Sustainable and smart mobility and associated energy systems are key to decarbonise the EU and develop a clean, resource efficient, circular and carbon-neutral future. To achieve the 2030 and 2050 targets, technological and societal changes are needed. This transition will inevitably change the composition of the future EU fleet, with an increasing share of electric vehicles (xEVs). To assess the potential contribution of lithium-ion traction batteries (LIBs) in decreasing the environmental burdens of EU mobility, several aspects should be included. Even though environmental assessments of batteries along their life-cycle have been already conducted using life-cycle assessment, a single tool does not likely provide a complete overview of such a complex system. Complementary information is provided by material flow analysis and criticality assessment, with emphasis on supply risk. Bridging complementary aspects can better support decision-making, especially when different strategies are simultaneously tackled. The results point out that the future life-cycle GWP of traction LIBs will likely improve, mainly due to more environmental-friendly energy mix and improved recycling. Even though second-use will postpone available materials for recycling, both these end-of-life strategies allow keeping the values of materials in the circular economy, with recycling also contributing to mitigate the supply risk of Lithium and Nickel.

**Keywords:** Life Cycle Assessment (LCA); Material Flow Analysis (MFA); Criticality; traction batteries; forecast; supply

## 1. Introduction

Sustainable and smart mobility, when articulated with appropriate energy systems, is a key asset to decarbonise the EU and develop a clean, resource efficient and carbon-neutral future. This is confirmed by several policy initiatives, among others: the European Green Deal [1] and the EC COM(2019) 22 [2]. In addition, the transition towards a low-carbon mobility contributes to the United Nations Sustainable Development Goals (UN SGDs), for instance Goal 7—ensure access to affordable, reliable, sustainable and modern energy for all [1].

To achieve the 2030 and 2050 targets, technological and societal changes concerning mobility are needed. To improve circular economy and resource efficiency in the automotive sector, the technological

aspects should cover the whole value chain of vehicles, from their design to their End-of-Life (EoL), e.g., new vehicles, light-weighting materials, easier reusability and recyclability of materials, recycled content in vehicles and transport infrastructure [2,3]. In addition, the behaviour of consumers should change toward choices oriented to more environmental-friendly practices, e.g., increase of the occupancy rate of vehicles and the adoption of public transport, sharing of vehicles, teleworking options [3,4]. Automation of vehicles is already proceeding but further efforts are required in the research field to reduce emission and avoid rebound effects (e.g., higher demand for mobility) [4].

This transition will inevitably change the composition of the EU fleet in the future: the increasing share of electric vehicles (xEVs) is already occurring and this trend is expected to accelerate in the next decade [3,5,6]. Meanwhile, new technologies can have an important role in the next future, even though nowadays they are at a very early stage, e.g., fuel cells electric vehicles [7]. Several scenarios are already available in the literature, considering new technologies appearing in the EU market and their evolution according to various parameters (environmental targets, consumers' lifestyles and behaviour, electric driving ranges, economic factors, etc.) (e.g., [6,8]). Such forecasts are quite complex to compare due to the adoption of different assumptions behind the models. Although there is no consensus in the scientific literature on a specific model to adopt in forecasting the uptake of xEVs, the trend is quite clear: xEVs will rapidly increase and will have a very important share on the EU fleet up to 2050, with a consequent increase of traction batteries required for such vehicles.

Among the traction batteries, the most common and most promising chemistry currently used in the EU market are the Li-ion batteries (LIB). The characteristics of LIBs are suitable for their use in different type of xEVs, especially battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs) [5]. Note that According to the scope of the analysis, since HEVs need relatively small batteries and will have a lower impact on the LIBs market, HEVs are not included in the following analysis.

When traction LIBs reach about 70–80% of their capacity, they are usually extracted from xEV and they have to be properly collected and recycled according to the in-force Directives (2000/53/EC and 2006/66/EC) [9]. However, pilots and research projects are demonstrating that the residual capacity of extracted batteries could be even used in less energy-demanding applications, e.g., residential buildings [9–11]. Even though the second-use of LIB is an industrial practice, there is potential for the creation of a business case beyond 2030 [5]. The second-use of batteries, before their recycling, is an example of circular economy practice where the value of batteries (and therefore embedded materials) is retained within the economy and the resource efficiency is maximised. On the other hand, the flow of batteries available for recycling is delayed in time, which means that also the availability of Secondary Raw Materials (SRMs) from waste batteries is postponed in time due to their higher lifetime [12]. Therefore, an in-depth knowledge of the processes along the value chain of complex products as LIBs is fundamental to assess the effects and the trade-offs of different strategies, e.g., the EoL options.

The New Circular Economy Action Plan [13] and the New Industrial Strategy for Europe (EC, 2020), two of the main building blocks of the European Green Deal [1], stress the role of Critical Raw Materials (CRMs) to achieve a climate-neutral, circular and competitive economy. Future sustainability requirements for batteries could in the future consider, for instance, the carbon footprint of battery manufacturing, ethical sourcing of raw materials and facilitating reuse, repurposing and recycling. Secure and sustainable supply of both primary and secondary raw materials for key technologies such as e-mobility is hence a prerequisite to achieve climate neutrality. With the transition of Europe's industry to climate-neutrality, the reliance on available fossil fuels could be replaced with reliance on non-energy raw materials, many of which are sourced from abroad and for which global competition is becoming more intense [14]. According to OECD forecasts, global demand for raw materials will more than double by 2060, making diversified sourcing essential to increase Europe's security of supply. CRMs are also crucial for markets such as e-mobility, batteries, renewable energies, pharmaceuticals, aerospace, defence and digital applications [15].

The performance of LIBs is related to various aspects, in particular to which materials are used in their cathodes and anodes [5]. The combination of the increasing demand for xEVs and the dynamics related to battery chemistries translate into a growing and diversified demand for raw materials; among the key materials for the manufacturing of high-performant LIBs, some have been classified as CRMs in the EU and/or worldwide [16], e.g., cobalt, natural graphite and lithium. The EU heavily relies on imports for many materials used in batteries. According to the EC Raw Materials Information System (RMIS—<https://rmis.jrc.ec.europa.eu/>), as the future demand of materials for strategic sectors is concerned, the EU will continue to be almost entirely dependent on third countries, in particular for traction batteries. In fact, the EU produces only 1% of all battery raw materials overall. Materials needed for the batteries manufacturing are mainly extracted in China (32%), Africa and Latin America (both 21%), but also the manufacturing process is mainly occurring in Asian countries. In this framework, some EU initiatives are focusing on improving the EU capacity in manufacturing batteries and improving the EU value chains (e.g., European Battery Alliance and Strategic Action Plan on Batteries).

Due to high cost of specific cathodes, e.g., Li-Co-based such as NMC (nickel-manganese-cobalt) or NCA (nickel-cobalt-aluminium), chemistries with lower cobalt content are already available [17,18]. For instance, the NMC111 is already replaced by cathodes with lower Co content, e.g., NMC811 or NMC9.5.5, which means a strong reduction of the cobalt and manganese content and an increase of nickel. Increased collection of end-of-life vehicles (ELVs) and boosting recycling could increase the amount of recovered materials that can be potentially recirculated in the economic system, i.e., their value is retained within the EU and the EU dependency can reduce [2,14]. The recovery of such materials is particularly relevant for the EU since they are materials with a high supply risk and high economic importance [19]. Note that nickel needed for the batteries manufacturing should belong to CLASS I nickel, i.e., 99% pure nickel [20,21], which should be considered when assessing the recirculation of recovered nickel from recycling processes.

Recycling of the battery at its EoL can be advantageous from both resource conservation and environmental perspectives [22]. Recycling can provide SRMs that according to their quality can be used by the battery sector (e.g., cobalt) or by other industries [23], avoid the extraction of virgin raw materials and generally have lower environmental impacts.

Directive 2006/66/EC14 defines the minimum recycling rates of batteries: 45% of LIBs at their EoL have to be collected and at least 50% of the average weight of LIBs should be recycled, excluding energy recovery. Nevertheless, as underlined by Ellingsen et al. (2018) [22], this Directive often incentivises batteries industries to recover base metals, which are massively used and relatively abundant in nature and available in commodity markets (such as iron and copper). On the other hand, it is known that the market value of metals contained in batteries is an important economic driver for battery recycling. In particular, the higher prices of cobalt and nickel relatively can explain why recycling processes are currently focusing on these metals [22].

To assess the potential contribution of batteries in decreasing the environmental burdens of the EU mobility in the future, several aspects should be included in the assessment. Focusing on the environmental impacts of batteries along their life-cycle, in the literature Life-Cycle Assessment (LCA) studies are already available (e.g., [24–26]). However, “*guidelines or harmonized approaches do not yet exist*” [27] and some issues emerging from the available literature still need to be addressed [28], which make it even more challenging to capture the environmental performances of different type of traction batteries in xEVs, especially in relation to the adoption of energy mix and taking into account different EoL options. Again, a single assessment tool does not likely provide a complete overview of such a complex system; in fact, some aspects are not captured through LCA, e.g., resource efficiency of some EoL options, hence LCA should be integrated with other assessment tools [29]. To obtain a more complete understanding of products’ status [30], different assessment tools should be combined [29,31,32]. There are already some studies demonstrating the added value of combining LCA and (dynamic) Material Flow Analysis (MFA), which identify and quantify the stocks and flows

of products/materials along their whole value chain. Bridging tools and the complementary use of their results support a more prospective decision-making, especially when different strategies are assessed, e.g., waste strategies [31]. Finally, the relevance of specific materials in terms of availability and vulnerability of a system, can be captured by the criticality assessments, providing relevant information of supply disruption and mitigation measures, taking into account flows of both primary and secondary materials [16].

Well established tools can be adapted and combined according to the product/system' characteristics to provide a wider understanding of the environmental performances in a life-cycle perspective. Hence, it is possible to capture different aspects of the assessed system/product and provide information according to the interests of the specific stakeholders. In addition, a flexible model and a common structure of the data collection (e.g., identification of best available sources, common data when possible) eases the update of the assessment according to the availability of data/information. Finally, consistency of input for different analyses is improved and the comparability of results is strengthened.

For a sustainable management of traction batteries, in an exponentially growing market and with a life-cycle perspective, some key questions need to be answered:

1. To what extent will the environmental performance of future mobility systems improve due to the uptake of EVs and therefore batteries? Is this improvement in line with expectations (e.g., the EU Green Deal and the SGDs)? How relevant is the relative contribution of traction LIBs life-cycle impacts in terms of environmental performance?
2. To cover the forecasted demand of traction LIBs for the EU fleet in the future, will the CRMs used for their manufacturing be available in adequate quantity and quality?
3. What can the role of recycling in terms of improving the environmental performances of LIBs be? To what extent can it contribute until the production of traction batteries peak and stabilise? At what stage of the LIB value chain are the CRMs to be recycled in the future (i.e., SRMs)?
4. In which way are CRMs key to the change of mobility patterns? In which way will the change in mobility patterns affect criticality, e.g., in terms of growing demand for S(C)RMs)?
5. How much can circular economy strategies help speed up the change and improve the overall environmental performance of mobility systems? How can trade-offs between different EoL strategies be quantitatively considered?

#### *Aim and Structure of the Paper*

This paper builds on a toolbox of existing assessment methodologies and bridges them to assess the environmental performances of complex systems. The adoption of different methodologies providing different type of information of the potential effects of the rapid evolution of a key sector for the EU is the core of the paper. For this reason, well established assessment tools are integrated: (1) to consider specific characteristics of the assessed LIBs; (2) to provide a more holistic and comprehensive understanding of traction LIBs; and (3) to build structured and comprehensive responses to relevant questions made by different stakeholders of the whole value chain of traction LIBs (e.g., manufacturers, recyclers, consumers and policy makers).

The authors believe that bridging tools and a more structured use of their results, as well as a mutual informing among the tools, is an added value in improving the knowledge of complex system and can support decision-making. The main focus of the performed assessment is the environmental performances of traction batteries (mainly LIBs) in decreasing the environmental burdens of the EU fleet up to 2050. In particular, LCA, MFA and criticality assessments, with emphasis on supply risk, are the three tools to bridge and use in a complementary manner. As mentioned in the Introduction, for this paper, the criticality of materials is used as filter to prioritise materials. The criticality of materials is used as filter to prioritise materials. In particular, among the key materials for the future development of batteries in the EU, as defined by the SWD (2018) 45, criticality of materials is used

to identify those to be firstly studied. LCA is used to understand the environmental performance of traction batteries in the current and future EU fleet. MFA is used to trace flows in anthropogenic flow cycles, to understand the current and future demand of (C)RMs, including where they are stocked, when they will be available for recycling, etc. In a mutual fashion, criticality is used to prioritise the materials that undergo LCA and MFA, while LCA and MFA provide information to assess potential effects of variation of primary/secondary materials in terms of supply risk in the future (e.g., potential decrease of supply risk due to higher recycling).

The study also aimed at identifying synergies in gathering data and information to be used in the three methodologies and applied them to a specific case study.

A concise literature review about the main aspects affecting the environmental performances of traction batteries (in particular LIBs) is provided in Section 2. A short description of the methodologies is reported in Section 3 and the application to traction LIBs in the current and future EU fleet is described in Section 4. Section 5 summarises the main outcomes of the analysis, highlighting also the main limitations of the study. The main conclusions and further research needs are illustrated in Section 6.

## 2. Literature Review: Main Aspects Affecting the Environmental Assessment of LIBs in the Future EU Fleet

The research on xEV batteries is currently significantly active and rapidly evolving, as proved by the annual number of publications focusing on EV increased since the 1990s [33,34] and the increasing number of patents worldwide focusing on EV [35]. This section reports the main outcomes of the performed literature review, mostly referred to scientific publications between 2016 and 2019, with some exceptions for particularly relevant data published during 2010–2015. The critical review was carried according to the main research questions presented in the Introduction.

Traction batteries are recognised as key components for the future uptake of xEV and for the decrease of the environmental impacts of the future EU mobility system [13,17,36]. Forecasts and market trends of LIBs are available in the literature from both policy and research studies and manufacturers declarations. Most of the consulted studies are characterised by an exponential increase of both BEVs and PHEVs in EU, although other studies suggest that the uptake of new technologies can be described through an S-curve [6,37]. The modelling of such a curve entails the definition of the saturation level, which depends on technological/economic/social aspects, e.g., increase of occupancy rate of cars, price of new vehicles, concept of mobility and social acceptance of new technologies (see Alonso Raposo et al. [3]). Due to the different scopes, but also modelling, boundaries and assumptions of the explored studies, the comparability of the future EU fleet is quite complex.

Many recent studies have focused on the life-cycle impacts of LIBs, recognising in LIBs the main element differentiating xEVs from ICEVs [38,39]. Even though LCA is a standardised (ISO 14040–44) [40] and mature methodology, more methodological efforts to quantify the life-cycle impact of LIBs are needed [9]. In 2018, the Product Environmental Footprint Category Rules (PEFCR) provided a “detailed and comprehensive technical guidance on how to conduct a PEF study” [41]; among the application fields covered by the document, traction LIBs are included. Despite the guidance, available results from different LCA studies on LIBs end up being very heterogeneous and it is still difficult to clearly define the environmental battery performances [42,43]. These discrepancies are due to different factors: lack, in many cases, of primary data; necessary simplifications and assumptions of the LCA model; and different chemistries of LIBs and therefore different performances [42]. In this context, Peters and Weil [44] started a deep work of review, selection of data and unification of the Life Cycle Inventories (LCIs) of LCA studies that were, until that moment, published on the manufacturing stage of batteries. Peters and Weil [44] analysed 79 studies developed between 2010 and 2016, but just five of these studies used exclusively own primary inventories and clearly disclosed the data [24–26,38]. Other LCA studies provide detailed LCI of LMO-NCM battery based on primary data [45], of NCA cell from its dismantling [46], of Li-Sulphur batteries integrating lab experimentations and theoretical

modelling [47], and of lithium manganese batteries (LMO) and lithium iron phosphate batteries (LFP) collecting data from a manufacturer [48]. Among the above-mentioned LIBs, NMC could become the most used Li-ion battery chemistry in 2030, followed by LFP and NCA with a 40% combined market share [5].

Because of the growth of LIBs, the demand of raw materials for manufacturing will increase according to their content in different LIBs chemistries. An increasing number of studies aimed at quantifying the future demand of materials for LIBs, especially if such materials are critical (e.g., cobalt). MFA is often used to quantify the stocks and flows of materials in and between processes along the value chain of LIBs. Among the consulted studies, the majority adopt a global approach, while few focus on the EU value chain; in addition, the analyses often focus on the demand of primary raw materials without including the contribution deriving from SRMs. In addition, more circular options than recycling are arising in the EU. This is the case of extending the lifetime of LIBs, e.g., through their second-use in less energy-demanding applications [9,49]. Thus, a proper management of EoL can have benefits in terms of environmental impacts and supply of SRMs, as well as effects and trade-offs between different EoL options should be further explored to provide information to be used in properly manage waste batteries.

Focusing on the environmental impacts of reuse and second-use of batteries, relevant aspects to be considered in assessing the impacts of LIBs were identified. As the reuse is concerned, key aspects to be considered are electricity mix [50–52], efficiency losses of batteries [50,52] and the characteristics of both the battery and the second-use application [9,45,53–55]. Due to the novelty of the topic and the scarce availability of data, input data are often based on warranties of LIBs and assumptions [9].

As far as concern recycling, guidelines for the impact calculation of LIBs recycling are provided in the PEF CR on batteries [41]. Bobba et al. [12], using information from industries [56], assessed the impacts of different EoL options, mainly focusing of the materials assessment, i.e., through a dynamic MFA. R&D projects and industrial companies are currently investing some efforts to improve the recovery of materials embedded in batteries to increase the sustainability of LIBs and tackle with economic barriers, which in some cases are important obstacles to the development of recycling at industrial scale, e.g., in the case of lithium recycling. For that reason, the amount of SRMs available in the future is expected to increase and contribute to partially cover the demand of raw materials for LIBs.

Available studies assessing criticality of raw materials were critically reviewed by Schrijvers et al. [16]. In this study, it is highlighted that different methods have been developed to identify criticality assessment factors and indicators at different levels (global, country or region, company, technology or specific products) [16]. In addition, data availability is recognised as a key factor that limits the evaluation of criticality. Proxies are needed to overcome this lack of data. Furthermore, data quality, including both data uncertainty and data representativeness, is rarely addressed in the interpretation and communication of results [16]. Focusing on the EU, the list of CRMs and the criticality methodology are a key instrument in the context of the EU raw materials policy, a precise commitment of the Raw Material Initiative [57]. Since the publication of the first list in 2011 and subsequent updates in 2014 and 2017, the EC criticality methodology responded to the needs of governments and industry to better monitor raw materials and inform decision makers on how security of supply can be achieved through diversification of supply, resource efficiency, recycling and substitution. To prioritise needs and actions at the EU level, the list of CRMs supports in negotiating trade agreements, challenging trade distortions and in programming the research and innovation funding. The EC methodology [58] defines CRMs as the combination of high economic importance (EI) for the EU and high risk of supply disruption (SR, supply risk). The assessment is essentially based on past data, e.g., the 2017 list was based on the five-year average (i.e., 2010–2014). Demand growth is often considered by technology-oriented methods, but not always considered by studies focusing on a national economy. This makes this exercise suitable to describe current economic situation, disregarding the future development of the economy [16].

The performed literature review highlights the complexity of the topic and the fact that several aspects should be taken into account to provide valuable and complete information on the environmental performances of traction LIBs in the EU in the future. In this framework, the integration of LCA and MFA to better understanding complex systems and environmental impacts is an added value [29,30,32]. Studies combining LCA and MFA of products are already available in the literature [31,59] and synergies between LCA and criticality were already proposed by Mancini et al. [60]. Specific consideration of future availability and demand of primary/secondary (critical) raw materials for traction LIBs in the EU were explored by Golroudbary et al. [61] and Pillot [62]. Song et al. [63] developed a detailed study on dynamic MFA of the CRMs for the Chinese LIB industry combining both the MFA and a CRMs evaluation model based on Blengini et al. [58] considering future scenarios up to 2025. Studies on the criticality of raw materials embedded in LIBs were investigated by Olivetti et al. [18] and Helbig et al. [64]. The results of criticality assessment and LCA were combined by Gemechu et al. [65]. However, the results do not provide specific information related to the potential variation of the supply risk due to the potential improvement of specific circular strategies and related environmental impacts. Finally, synergies among LCA, MFA and potential supply risk should be further improved at inventory level since some input data can serve all (e.g., processes efficiency and materials content).

The literature review confirms that, to the authors' knowledge, there are no studies specifically addressing traction batteries in the EU along their whole value chain integrating information provided by all LCA, MFA and supply risk considerations together. In addition, a future-oriented approach requires more scientific efforts in terms of methodology, to develop models taking into account key aspects of foreseeable future, e.g., physical scarcity or the future development of the economy [16].

### 3. Methodology: Modelling Flows and Impacts of LIBs in the EU Fleet

The integration of assessment tools able to analyse different but complementary aspects is a key feature to improve an in-depth and comprehensive knowledge of the EU fleet. In the following paragraphs, the main features of performed assessment of the environmental impact of traction LIBs in the EU fleet are illustrated.

A Life-Cycle Thinking (LCT) approach is adopted to include in the assessment all the relevant aspects along the whole value chain of products, taking also into account external aspects affecting environmental performances of products, e.g., socioeconomic aspects.

#### 3.1. LCA of Traction LIBs

The developed LCA follows the (ISO 14040-44) and the PEFCR for batteries [41]. The LCA tool provides the necessary background information on environmental impacts of products/services under analysis along their whole value chain. Considering the potential development of technology and the complexity of some products, the development of modular LCAs and the adoption of parameters make the LCA model flexible: (1) to update according to available input data; (2) to speed-up the LCAs of different products; and (3) to enlarge the analysis (e.g., new materials and/or components).

According to PEFCR for batteries, the functional unit (F.U.) for rechargeable batteries can be defined as *1 kWh of the total energy provided over the service life by the battery system*. Nevertheless, this functional unit requires referring to the expectancy life of the battery, which is often hard to estimate because it is affected by many different parameters [10,42]. Moreover, since the majority of available LCA studies on batteries show impact results for 1 kg of battery or for 1 Wh of storage capacity, the developed LCA tool provides results for both 1 kWh of energy provided and 1 kg of battery pack. The LCA tool provides information on the specific LCI datasets used for the analysis, with reference to Environmental Footprint (EF) and Ecoinvent databases (see Supplementary Materials for details). Datasets are connected to the related impacts, evaluated with the EF method; this enables the user to easily assess the batteries for all the impact categories available within this method. In this manuscript, attention is however focused on the Global Warming Potential (GWP), as one of the most

robust categories and of high societal and policy interest [66]. Results for the other EF impact categories are reported in the Supplementary Materials.

The unified database of Peters and Weil [44] is used to assess the environmental impacts of different LIBs chemistries according to available inventories in the literature. In addition, this analysis updates and extends the unified database with recent data on the manufacturing of LIBs data [45,46] and on other stages of batteries life-cycle (use and EoL stages). Table 1 lists the main characteristics of the analysed batteries and the selected source of the LCI data.

**Table 1.** Main characteristics of the analysed batteries and the selected source of the LCI data.

Battery Chemistry	Type of Vehicle	Weight [kg]	Capacity [kWh]	LCI Data Source for Manufacturing Stage	LCI Data Source for Use Stage	LCI Data Source for EoL Stage
NMC 111	EV	253	26.6	[24,44]	[41]	[41,45,67]
NMC 424	EV	n.a.	n.a.	[26,44]	[41]	[41,45,67]
NCA	EV	142	18.9	[44,68]	[41]	[41,45,67]
NCA	EV	154	20	[46]	[41]	[41,45,67]
LMO/NMC	PHEV	175	11.4	[45]	[41]	[41,45,67]

The use stage is defined by the energy losses due to the battery and charger efficiency [41]. The model was built in a way that the total energy used by a xEV before replacing the traction LIB is obtained by multiplying the distance covered by vehicles and the average fuel economy (energy necessary to cover the distance of 1 km). The change of the energy mix along time is considering through an increasing share of renewables in the energy mix, based on EC projections [69,70].

The EoL stage includes dismantling of components, the conversion into recycled material, other operations and credits connected to the re-availability of material after the recycling process [41]. The LCI of the EoL stage was unified with reference to data provided by the PEFCR on batteries, with exception of input/output data of lithium, nickel, manganese, cobalt, graphite, copper and aluminium. For these latter, quantities of recycled material (and consequent credits) were calculated considering the amount of materials available in each battery and the recovery of the same material after the recycling process.

To make the LCA replicable and updatable, the LCI of each LIB chemistry is provided in a spreadsheet (included in the Supplementary Materials), where each input/output flow of material, energy, waste and emission is related to 1 kg of battery pack. Each flow is connected to the related impacts, enabling the automatic calculation of the impact of the battery life-cycle. The changing of input/output quantities or parameter values allows the evaluation of different scenarios, as shown in Section 5. Moreover, the modularity of the model allows quick and consistent comparisons between environmental performances of different batteries. Additionally, due to the fast development of the technology, the modularity of the LCA model allows enlarging it, adding e.g., new materials and/or components.

### 3.2. MFA of traction LIBs in the EU

MFA is used to better understand the value chain of products through the representation of the main processes along the value chain but also to quantify the stocks and flow of products/materials over time [71].

According to Bobba et al. [12], the adoption of parameters in the MFA model makes it customisable and flexible to assess different scenarios and identifying e.g., circular economy aspects and/or effects of EoL options along the whole value chain of LIBs. In addition, the modularity of the model allows easily adding/updating modules within the MFA model in case of new/more data would be available. In case some modules are not of interest of the assessment (e.g., second-use of specific LIBs' chemistries or in addressing some future EoL scenarios), parameters allow simply not considering these modules

for the quantification of stocks and flows. In addition, different aspects of LIBs can be assessed, i.e., stocks and flows of both batteries, materials embedded in LIBs and storage energy capacity.

Figure 1 shows the MFA model created to estimate the stocks and flow of the EU fleet in the future. Differently from Bobba et al. [12], the model was enlarged to also include the recirculation of SRMs in the system and incineration/landfilling of LIBs. Due to the difficulty in collecting all the needed data, some flows were estimated through the adoption of a parameter which was made varying in-time. In line with the goal of the study, the model is used to quantify the stocks and flows of traction LIBs, lithium, nickel and the energy storage capacity for various LIBs chemistries and applications (i.e., PHEV and BEVs).

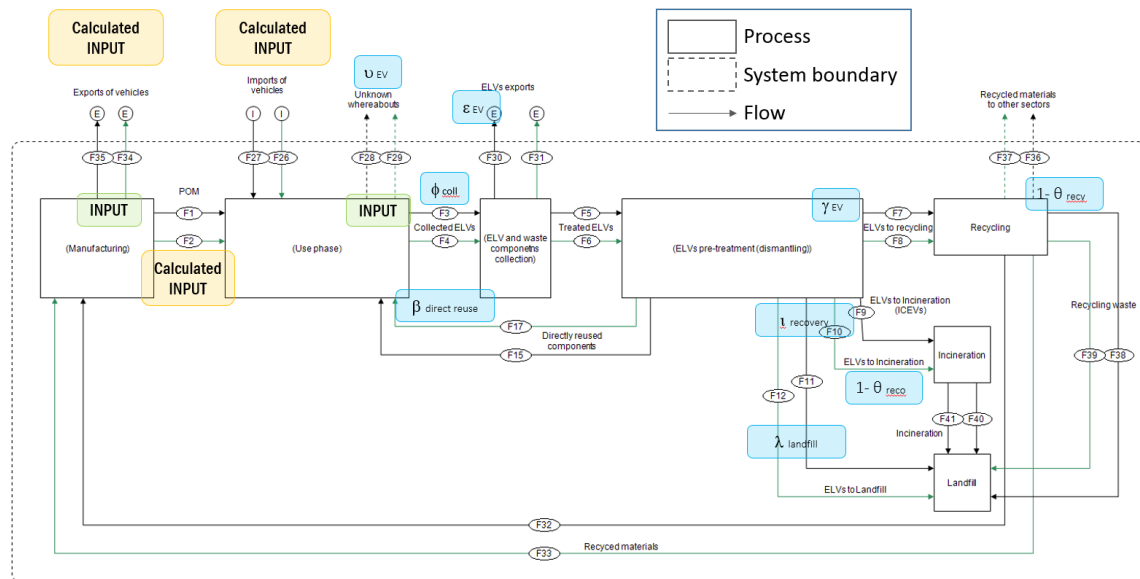


Figure 1. Modelling of stocks and flows of LIBs in the EU (adapted from Bobba et al. [12]).

Where:

- $\upsilon$  ICEV/EV,  $y$  = Unknown whereabouts
- $\Phi$  coll,  $y$  = Collected ELVs
- $\epsilon$  EV,  $y$  = ELVs exports
- $\gamma$  EV = ELVs to recycling
- $\iota$  recovery = ELVs to recovery
- $\beta$  direct reuse = ELVs to direct reuse
- $\lambda$  recovery = ELVs to landfill
- $\theta$  recy = Recycling efficiency
- $\theta$  reco = Recovery efficiency

### 3.3. Criticality and Supply Risk of LIBs Raw Materials

According to Schrijvers et al. [16], “the raw material criticality is the field of study that evaluates the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame”. In line with the system boundary of the study, the analysis on materials supply risk is applied at EU level, focusing on battery’s raw materials. As mentioned in Section 2, the EC methodology [58] defines CRMs as the combination of high economic importance (EI) for the EU and high risk of supply disruption (SR, supply risk).

In this paper, we focus on the contribution of recycling as a supply risk mitigation factor, according to the EC methodology [58]. Recycling of end-of-life products is in fact considered a more secure source of raw materials, in comparison to primary production [58].

The battery materials initially prioritised in this study include cobalt, lithium, natural graphite and nickel; manganese is considered too, although less often identified as CRMs [16,72] due to the lower

supply concentration and subsequent lower supply risk. Among the batteries' materials, technologies for recycling Li are currently available in the EU, even though not yet at industrial scale [73,74]. Concerning nickel, it is to be considered that nickel used for manufacturing traction LIBs needs to be of high quality; in fact, Nickel Class I has a Ni content higher than 99% [20]. Despite some examples of high-quality nickel recovered from batteries (e.g., [75]), most of the nickel recycled nowadays is not suitable for the manufacturing of new LIBs [76]. In the EU, stainless steel is the biggest user of primary and scrap nickel, which already uses nickel scrap recycling for stainless steel production and will increase by 2025.

Despite limitations, data provided by MFA, in particular amount of materials recovered from traction LIBs recycling, are used to estimate the potential reduction of the SR for both Li and Ni in relation to the expected evolution of the EU fleet.

### 3.4. Common Inventory and Data Gaps

Availability of data is a key point for all the above illustrated assessment methodologies. In some cases, the same data can serve two or three components, which is an added value for an already difficult data collection. Moreover, the adoption of the same data and/or information improve the consistency of the obtained results and ease the replicability of the assessment in case new data will be available in the future. Finally, a common inventory facilitates the clear definition of the needed assumptions for the three components.

Table 2 provides an overview of the data and assumptions included in the study that are common to at least two out of the three components. However, it is highlighted that the adoption of the same data for multiple components requires more efforts in terms of data quality and geographical/temporal representativeness.

**Table 2.** Overview of possible synergies between LCA, MFA and Criticality (supply risk) in terms of inventory data.

	LCA	MFA	Criticality (Supply Risk)	Unit	Notes
Weight of the battery	X	X		[kg]	
Lifetime	X	X		[year] or [provided kWh]	
Materials content	X	X	X	[kg/kg battery] of [kg/kWh]	
Process efficiency (i.e., losses)	X	X		[kg/kg battery]	
Import/export	for transport	for flows and stocks	X	[tonne]	- impacts of transport - outbound/inbound flows - import reliance
Collection rate	X	X		[-]	- indirectly availability of SRMs
Battery reuse	X	X	X	[%]	- lower impact of the battery life-cycle (longer lifetime) - stocks increase, creation of new stocks - indirectly availability of SRMs
Battery dismantling efficiency	X	X		[%]	
Recycling efficiency	X	X	X	[%]	- impacts of recycling process / avoided materials - available SRMs to be recirculated in the system
Quality of recycled materials	X	X	X	[-]	- closed/open loop - available SRMs for specific sectors

Table 2. Cont.

	LCA	MFA	Criticality (Supply Risk)	Unit	Notes
Materials substitutability	X	X	X	[-]	- increase/decrease of materials content - LCA of different chemistries
Future technological change	X	X	X	[-]	- different chemistries, materials, components - potential improve of recycling technologies
Geographical considerations	X	X	X (import reliance and production)	[-]	- evaluate transports and import/export flows - EU dependency on third Countries - import reliance
WGI	Social (not assessed in this study)		X	[-]	
New energy sources	X		X	[-]	
Trade agreements and restrictions		X	X	[-]	

#### 4. Case-Study: Traction Batteries in the Future EU Fleet

The selected methodologies were applied to traction LIBs in the EU fleet between 2015 and 2030 to assess the environmental contribution of traction LIBs to the potential decrease of the impacts of the EU fleet in the next decades, but also the role of the key materials embedded in batteries. In this section, a brief description of the case-study is provided; to assess the potential added value of the coordinated approach, different scenarios were considered.

##### 4.1. Description of the Case-study and the Assessed Scenarios

The environmental assessment focuses on traction batteries used in both PHEVs and BEVs, especially on LIBs embedding Ni and Li. Note that, even though some LIBs are already used for HEVs, this technology was excluded from the analysis since the main power source is a combustion engine. A Base-Case Scenario was created to capture most of the aspects mentioned in the research questions (Section 1); in addition, the effects of some key aspects (i.e., EoL management and change of energy mix) are considered through the creation of ad-hoc scenarios hereinafter described (see Table 3).

##### 4.1.1. “Base-Case Scenario”

The evolution of BEVs and PHEVs in EU between 2015 and 2030 is based on the EU Long-Term Strategy (LTS 1.5°C Technical), which assumes a reduction of the EU greenhouse gas emissions for 2030 of about 50% and zero emissions in 2050 [4].

The case-study is mainly focused on traction NMC and NCA chemistries, which are expected to dominate the traction LIBs EU market in the future (Section 2); LMO/NMC chemistry is also included in the analyses of current scenarios, while it is excluded in the calculations of future scenarios because of the scarce availability of data on possible trends for these chemistries. For the use stage of LIBs, the default amount for energy density is 9.6 kWh/kg (aligned with the PEFCE for batteries) and fixed for all the LIBs. Default values for the battery use are: 100,000 km for the driven distance (in line with the warranty generally given for batteries by BEV producers) and a fuel economy of 0.2 kWh/km (according to Fuel Economy data provided by EPA). For the EoL, no remanufacturing and second-use are assumed to develop at industrial scale in the EU. The recuperation of materials is calculated as the product of the collection rate, the dismantling rate and recycling rate. A collection rate of 95% is assumed, according to the PEFCE [41], and the recycling rate is based on Lebedeva et al. [74] and Cusenza et al. [45]. These rates are parameters which can be easily modified for assessing future scenarios.

The specific energy mix considered in the study is based on literature data [69,70]. The estimation of the stocks and flows of LIBs/energy storage capacity/embedded materials is adapted from [12], with additional modules and flows; the value chain of batteries in the EU (Figure 2) is assumed to mainly maintain the current characteristics. This means that the manufacturing of batteries is assumed in the EU, according to Peters and Weil [44].

Concerning the assessment of Li and Ni, as representative of key materials in the battery sector for the EU, their content in LIBs is assumed to vary in time according to available roadmaps (e.g., [5,72,74,77]). Currently, the recirculation of Li and Ni in a closed loop (i.e., to manufacture new LIBs) is almost null. The recovery of Li is not yet developed at industrial scale in the EU, mainly due to economic reasons [73,74]; therefore, it is assumed a current recycling efficiency equal to 1% in 2018 [41], linearly increasing in the future thanks to the ongoing research activities (up to 3% in 2030). On the other hand, the recycling rate of Ni is already quite high, i.e., 96% [41]; however, to be used for manufacturing new cathodes, the purity of Ni has to be very high, and, according to the authors' knowledge, there are few examples of companies that are using secondary Ni to manufacture new cathode (e.g., [78]).

#### 4.1.2. Scenario A: Extension of the LIBs Lifetime Through Their Second-use

Second-use of batteries in less energy demanding applications is an EoL option that can reduce the environmental impacts and boost resource efficiency [79]. Despite not yet occurring at large scale in the EU, the ongoing pilots and research activities have demonstrated that this option is valid and can increase in the next decades, if also supported by an adequate regulatory framework. Therefore, based on the Base-Case Scenario, Scenario A was created to assess the environmental effects of extending the lifetime of batteries. In particular, the life-cycle impacts include both the first- and second-use, the energy storage capacity of LIBs is further exploited before their recycling and the embedded materials are locked in the in-use stock for longer compared to the Base-Case Scenario.

The total amount of energy that is provided by the battery during its first and eventually second life is quite complex, since it depends on different connected variables, e.g., depth of discharge (DoD), charging-rate and operation temperature [10,42], and the environmental benefits depends on both the LIB's and the system's characteristics [9]. For this study, Scenario A considers a default value of 20,000 kWh provided by the xEV battery first life and a second life providing 5143 kWh, according to Bobba et al. [9,12]. A linear increase of second-use of batteries from 0% (current situation) to 10% in 2030 and 30% in 2050 is assumed.

#### 4.1.3. Scenario B: Improved EoL Extension of the LIBs Lifetime Through Their Second-use and Improvement of Recycling

Recovery of key materials is essential to decrease the dependency of the EU from third countries (Section 3.3). Then, the effects of an improvement in the management of EoL practices in terms of both second-use of LIBs and improved recycling efficiency is assessed in Scenario B. The trend of LIBs in second-use applications is the same as in Scenario A. In addition, it is assumed that the recycling technology allows higher recycling efficiency of Li (15% in 2030 and 2050) and higher level of purity for covered Ni, which can be used again to manufacture LIBs (linear increase of the closed loop of Ni, from 0% to 25% between 2018 and 2030).

#### 4.1.4. Scenario C: Renewable Energy for the Manufacturing Stage

The amount and the source of energy used in the life cycle of LIBs can highly influence its environmental performance [24,80–82]. Currently, there are examples of producers of LIBs' cells that are using high share of renewables in the production process, e.g., Tesla and Northvolt Ett. In particular, Tesla claims to design its Gigafactory 1 in Nevada to be completely powered by solar array installed on its roof and wind turbine installed nearby, while Northvolt Ett declares that its plant in Sweden will rely on clean electricity from wind and hydroelectric power [83].

Hence, to observe the effects of a more environmental-friendly energy mix in the life-cycle of LIBs, Scenario C assumes that electricity for battery manufacturing is equally provided by photovoltaic panels, wind turbines and hydroelectric plants. All other input/output flows and related variables follow the Base-Case Scenario.

**Table 3.** Summary of the main differences between assessed scenarios.

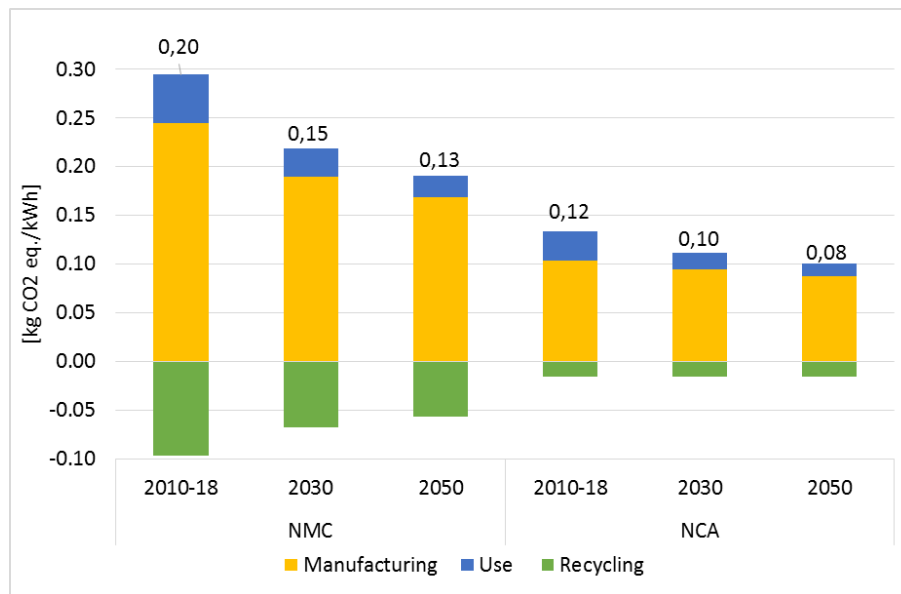
Variables	Scenarios			
	Base-Case Scenario	Scenario A	Scenario B	Scenario C
Change in European energy mix (current/2030/2050)	X	X	X	X
Change in battery material contents (current/2030/2050)	X	X	X	X
Batteries are reused in a second life (10% in 2030; 30% in 2050)		X	X	
The recycling rate of lithium and nickel is enhanced (2030/2050)			X	
Energy for manufacturing is completely provided by renewable sources (current/2030/2050)				X

## 5. Results and Discussion

Section 5 reports the main outcomes of the assessment. In particular, for the LCA analysis, results are reported on GWP impacts provided by the LCA tool for 1 kWh of the total energy provided by the battery during its entire life-cycle. Note that, as previously discussed, this latter F.U. is influenced by the battery lifetime, which is by default set to 20,000 kWh for all the analysed batteries. In addition, results reported in Section 5 mainly refer to the NMC and NCA chemistries as most of the consulted sources provide information of future trends of these two chemistries and almost no data about the uptake of LMO/NMC batteries are available.

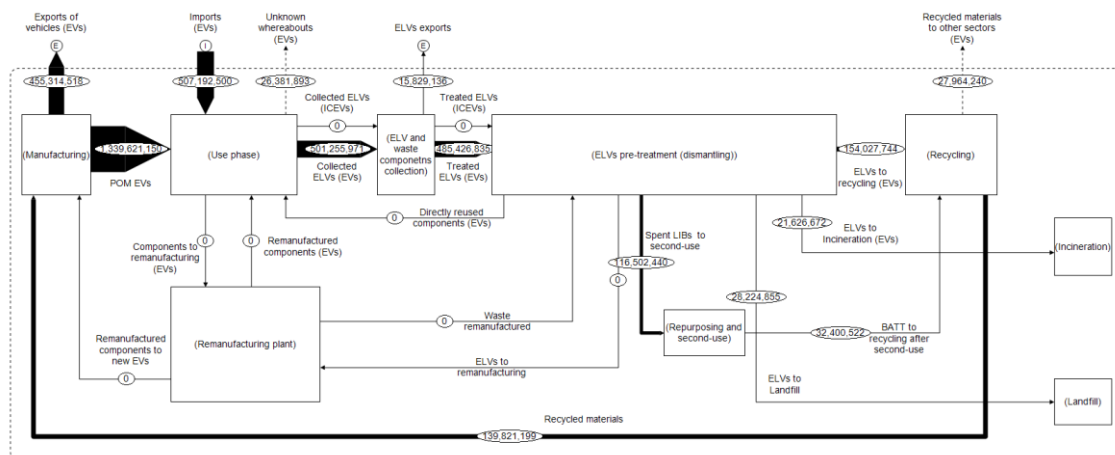
### 5.1. Results

The Life-Cycle Impact Assessment (LCIA) of the assessed LIBs shows that the current life-cycle GWP is on average 0.16 kg CO<sub>2</sub> eq/kWh. The impact of NMC batteries results slightly higher than the NCA one. This difference could be partly due to the different material composition and partly to the higher mass of NCM batteries. The contribution analysis confirmed that the manufacturing stage highly contributes to the life-cycle GWP. In addition, the EoL recycling can reduce the impact of the battery by 22% on average. Among the LIBs' chemistries, the NMC 111 battery manufacturing has the highest impacts per kWh of provided energy. At the same time, NMC shows the highest benefit from its recycling, mainly related to the credits due to the availability of secondary raw materials after the battery recycling, mainly copper, nickel sulphate and cobalt sulphate. In the Base-Case Scenario, it is highlighted that the change of materials in different LIBs (e.g., from NMC111 to NMC811) and the increase of renewable energy share lead to a decrease of GWP in time (Figure 2). The manufacturing impacts of NMC batteries will decrease by 22% and 31% in 2030 and 2050 compared to the NMC nowadays in the market (2010-2018), while the reduction is lower (9% and 15%) for NCA batteries manufacturing. High reductions are observed for the use stage: about 42% in 2030 and 56% in 2050 for both chemistries.



**Figure 2.** Life-cycle Global Warming Potential (GWP) of NMC and NCA chemistries in the Base-Case Scenario for different years. Labels at the top of each column indicate the respective values of the life-cycle GWP.

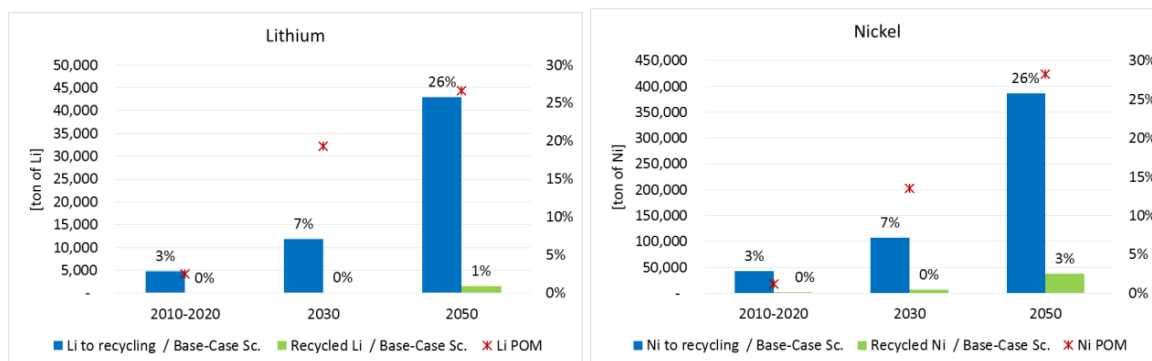
Focusing on the MFA, the results of the Base-Case Scenario show that the increasing demand of LIBs in the EU will not significantly affect the energy capacity storage and materials flows in the EU until 2030; then, waste flows start to be relevant in terms of quantities, especially recycling flows. Figure 3 shows an example of stocks and flows of energy capacity and materials in the studied system (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article). Combining the above-illustrated GWP and energy storage capacity of LIBs placed on the EU market, it is estimated that the GWP of traction LIBs entering in EU fleet in 2015 is about 12 kt of CO<sub>2</sub> eq., and it will increase up to 35 kt in 2030 and 95 kt in 2050.



**Figure 3.** Flows of energy capacity storage in the EU in 2050.

Focusing on materials embedded in batteries, is observed that the amount of Li required for traction LIBs demand in 2030 and 2050 is, respectively, five and seven times higher than the 2020 demand (Figure 4). For Ni, these values increase to 7 and 14 times. Once extracted from EVs, the amount of Li/Ni entering in the recycling process can potentially provide 7% of the Li/Ni demand in 2030 and 26% in 2050. However, the recovered Li in 2030 is lower than 40 tonnes in 2030 and about 400 tonnes in 2050, mainly due to the lack of recycling processes at industrial scale; similarly, the recovered Ni in

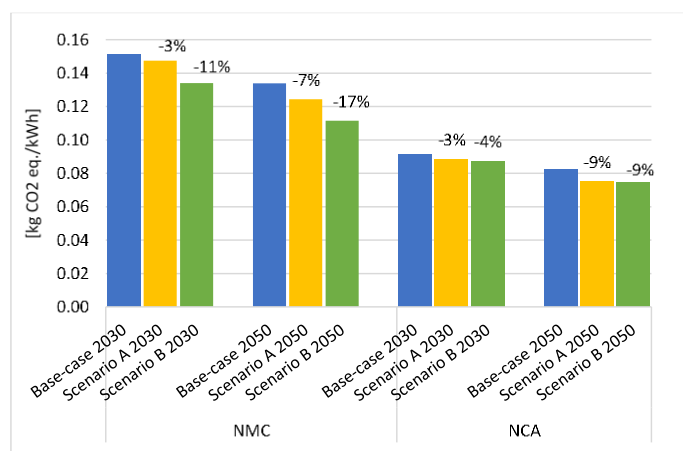
2030 is about 900 tonnes and 11,000 tonnes in 2050. Note that almost all the recovered Ni is recycled in an open-loop, hence not used for manufacturing new LIBs. Secondary Li is lower than 0.5% of the Li demand in 2030, while secondary Ni is 0.4% of Ni demand for LIBs; these values slightly increase up to 1% for Li and to 2.5% for Ni in 2050.



**Figure 4.** Li and Ni embedded in traction LIBs placed on the EU market (POM), available for recycling and recovered in different years.

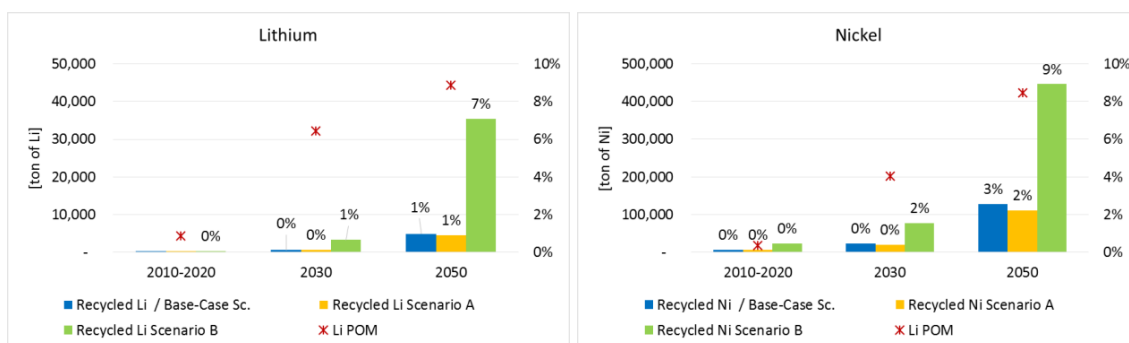
If second-use will develop in the EU (Scenario A), LIBs and embedded materials will last longer within the system, decreasing the life-cycle impacts and postponing the amount of materials available for recycling. Assuming a second-life providing additional 5143 kWh, the GWP impact per kWh of provided energy necessarily decreases. With the assumption that the percentage of reused batteries is of 10% in 2030 and 30% in 2050, the LCIA results show an average GWP reduction, respectively, of 3% and 8% (Figure 5). If, in addition to the reuse of batteries, the recycling efficiency of LIBs will increase in time (Scenario B), reductions of 11% and 17% are observed for NMC in 2030 and 2050, respectively. The reduction is lower for the NCA chemistry: 4% and 9% in 2030 and 2050, respectively (Figure 5).

The adoption of a completely renewable energy mix for the NMC and NCA manufacturing (Scenario C) decreases the GWP of the manufacturing stage for both the current and future scenarios (see also Supplementary Materials). Benefits of manufacturing plants powered by renewables become progressively less evident over time, because of the enhanced sustainability of the European energy mix in 2030 and 2050. Compared to the Base-Case Scenario, Scenario C shows a GWP reduction of 23% in the current situation, 15% in 2030 and 12% in 2050.



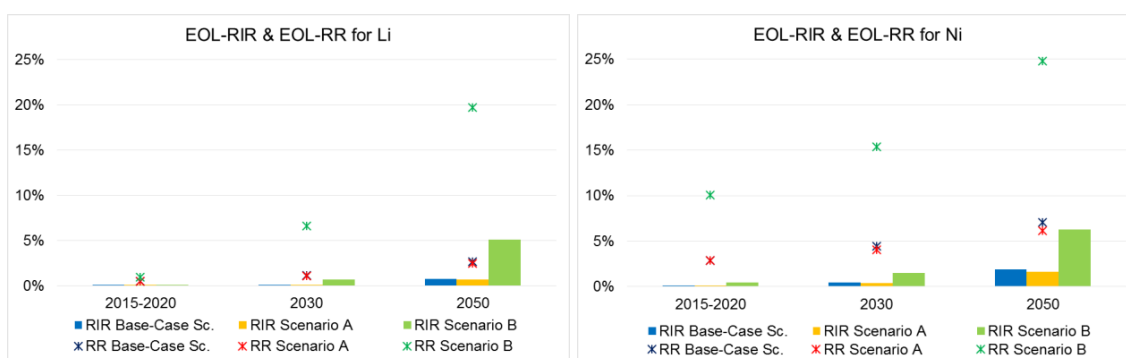
**Figure 5.** Life-cycle Global Warming Potential (GWP) of NMC and NCA batteries for Base-Case Scenario, Scenario A and Scenario B in different years. Percentages indicates the reduction of GWP impacts with reference to the Base-Case Scenario for the same year.

The development of second-use of LIBs (Scenario A) confirmed a delay in availability of Li and Ni for recycling and the consequent decrease of secondary Li and Ni in the EU: in 2050 about 400 tonne of secondary Li and 9,500 tonne of Ni will be available (about 0.9% and 2% of the Li and Ni demand in 2050) (yellow bars in Figure 6). Difference of secondary Li and Ni compared to the Base-Case Scenario are almost null since the stock of LIBs in second-use application will become more relevant around 2040. Finally, from the analysis of stocks and flows of materials, it emerged that the increase of recycling efficiency will result in a significant flow of SRMs (green bars in Figure 6). In this case, the secondary Li and Ni in 2050 will be respectively 7% and 9% of the Li and Ni demand in 2050, i.e., 3000 and 38,000 tonnes.



**Figure 6.** Li and Ni embedded in traction LIBs placed on the EU market (POM) and recovered from recycling processes for the Base-Case Scenario, Scenario A and Scenario B in different years.

Finally, Figure 7 reports the EOL-RIR and the EOL-RR [58] calculated for all the assessed scenarios. The increasing recovery of Li as SRMs (Scenario B, green bars) significantly increases both indices; a similar result is observed if the technological development of recycling Ni will allow reaching a high level of purity, i.e., >99%, in order to use Ni as SRMs for manufacturing new LIBs' cathodes. Note that the amount of materials stocked in second-use application is not importantly affecting the indices since second-use is still a limited EoL option (Scenario A, yellow bars).



**Figure 7.** EOL-RIR and EOL-RR of Li and Ni according to the Base-Case Scenario, Scenario A and Scenario B in different years.

The EOL-RIR of Li and Ni is used to better understand the role of recycling in mitigating the SR in 2050 according to the expected evolution of the EU fleet. The current and future EoL-RIR is estimated by the MFA tool (average 2015–2020) and in the future (2050), based on the assessed scenarios.

The supply risk reduction of Ni is < 1% in the Base-Case Scenario (2015–2020) and 6.3% in Scenario B (2050). Ni used to manufacture LIBs requires a higher grade (Class I) than Ni used in, e.g., steel applications, which is its main use according to the Ni Institute [21] and the overall EoL-RIR is estimated to be about 34% [84]. Even though the recycling rate (RR) of Ni from LIBs is quite high

and its trend is rising, the required grade is higher to feed the input for batteries with SRM. Thus, the EoL-RIR can slightly reduce the supply risk.

The figures are quite similar for Li, with a supply risk reduction <1% in the Base-Case Scenario (2015–2020) and 5% in Scenario B (2050).

Moreover, it is well known that the supply risk for Ni is much lower than that of Li according to several criticality assessments run internationally [16], thus it appears that recycling as a risk mitigation factor seems even more important for Li than for Ni. Unfortunately, at present and in the future, recycling, alone, does not seem a relevant mitigation factor for the supply risk of neither Li nor Ni (all other factors being equal, and taking into account the limits of the model).

## 5.2. Discussion

The complexity of batteries and the assessment of their (environmental) performances is certainly a major challenge in this and in other studies. A single assessment tool cannot provide a complete overview of the impacts of LIBs and can unlikely capture all the effects of different EoL options [29,85]. This is particularly relevant for those new options that have shown potential to develop in the next future (e.g., second-use of batteries), as well as in case of raw materials with high supply risk (e.g., Li).

LCA and MFA are applied to traction LIBs in the current and future EU fleet, to assess the life-cycle GWP of specific LIBs chemistries currently available in the market and LIBs entering in the EU fleet up to 2050 (Section 3.1); in addition, stocks and flows of LIBs/storage capacity/embedded materials were quantified along the EU value chain of LIBs for different scenarios (Section 3.2). The criticality of materials in this study was used to filter the raw materials to firstly focus on and to assess the supply risk of such materials using data provided by the MFA results. Among the key materials for the future development of batteries [72], those selected for the study are Li and Ni embedded (Section 3.3). Due to the uncertainty of input data related to the fast evolution of the technology, the complexity of the LIBs' components, the globalised market and different assumptions behind available LCA and MFA studies, assessment models are built using modules and parameters. This makes the model flexible and updatable according to available data (e.g., in case of new components/processes/stocks) and addresses uncertainty through the creation of different scenarios (e.g., change in energy mix and increase/decrease of processes efficiency). Obtained results confirm the added value of the adoption of different assessment tools to improve the knowledge of complex systems, as traction LIBs [29,30,32].

Since the vehicle electrification certainly plays an important role in the decarbonisation of mobility, the investigation on the environmental performance of traction batteries is of crucial importance, being the main element that differentiates ICEVs and EVs. The lack of reliable data highlighted by several authors (e.g., Peters et al. [42] and Zackrisson et al. [25]), and therefore the difficulty in consistent comparison between LCIA results is addressed in the study through the adoption of the unified database proposed by Peters and Weil [44], used to assess the GWP of NMC, NCA and LMO/NMC chemistries. To bypass the barriers for information sharing and reuse often caused by the only partial interoperability between the main LCA software and database currently available [86], to ease the replicability of results and to further enlarge the proposed analysis, the LCA tool is provided in the Supplementary Materials as a spreadsheet file. LCIA results obtained for 1 kg of battery pack (provided in the Supplementary Material) are aligned with the available literature [24,26,44]. The results expressed for the F.U. of 1 kWh provided by the battery are not easily comparable with previous literature since most authors did not provide results with this F.U. In addition, it is necessary to underline that LCIA results for 1 kWh of provided energy directly depend on the lifetime of the battery. This latter is fixed in this paper to 20,000 total kWh provided, but can vary among different batteries. This parameter can however be easily modified in the LCA tool provided in the Supplementary Material and according to available data, its variation is recommended to understand its relevance in line to the goal of the analysis. The change of the energy mix plays a key role in decreasing both the manufacturing impacts and the life-cycle impacts of LIBs in 2030 and 2050. In fact, manufacturing LIBs with renewable energy sources (Scenario C) reduces the impacts of LIBs placed on market in 2020 of almost 4000 tonnes of

CO<sub>2</sub> compared to the impacts of LIBs placed on market the same year and manufactured with the current EU energy mix. In addition, the increased share of renewables (Base-Case Scenario) is the most important factor in reducing the life-cycle GWP of NMC and NCA chemistries: respectively, by 24% and 22% in 2030 and by 32% and 30% in 2050. To better understand the contribution of LIBs in decreasing the impacts of the EU mobility system in the future, a wider analysis should be performed to include the life-cycle impacts of different types of vehicles, even though this means a further level of uncertainty related to needed assumptions and simplifications, e.g., losing the detail on different chemistries and performances due to the high amount of information to be processed. In addition, electricity mix importantly affects the life-cycle impacts of EV vehicles, thus is a key aspect requiring more in-depth analysis, especially in the case of future energy mix [28]. The developed spreadsheet file can be used to model the contribution of LIBs taking into account key parameters and without losing details about performances of batteries (see Supplementary Information).

In 2030, 32 kt of Li and 202 kt of Ni will be required according to the targets established by the EU Long-Term Strategy [4]. These values increase up to 44 kt and 423 kt in 2050. The assessment of different trend of xEVs uptake, as discussed in Section 2, is recommended. In fact, input data concerning materials content in LIBs are currently poor and should be updated with new available data, and it is expected that new technologies will appear in the market, like fuel cell EVs [3,7].

The results of the analysis confirm that the growth of LIBs in the future EU fleet corresponds to an increasing flow of energy storage capacity, which is better exploited through second-use of LIBs [12]. As a consequence of the extension of LIBs' lifetime, Li and Ni are locked in the second-use stock, and therefore they cannot be available for recycling and potentially be recovered as SRMs.

Even though LIBs are not second-used, current recycling of Li is quite poor [73,74] and the secondary Ni is not pure enough to be used again for LIBs manufacturing [20,21]. In fact, without any improvements in recycling processes (Base-Case Scenario), the contribution of secondary Li and Ni to the EU materials demand is and will remain quite limited (1% of the Li demand and 2.5% of the Ni demand in 2050). Even though the availability of Li and Ni is delayed in time according to the extended lifetime of LIBs in second-use applications (Scenario A), the potential increase of recycling (Scenario B) of Li and Ni entails environmental benefits in terms of GWP (17% and 9% of the life-cycle GWP for, respectively, NMC and NCA chemistries in 2050, compared to the GWP of currently LIBs in the market). Moreover, this improvement also means an increasing amount of SRMs, hence a slight mitigation of the supply risk in the future (2050). In fact, although supply risk of Ni is relatively low at present and the recycling could lead to a more sustainable production, the overall risk would not be affected significantly. The supply risk of Li is very high due to the high concentration of EU sourcing in Chile and completely reliant on import from third countries. Despite a rising trend of Li in the future, EoL RIR will not be able to mitigate this important supply risk. It can be concluded that, with the aim of pursuing strategies of mitigation, fostering European domestic production and diversifying the EU suppliers seems the best option to reduce the supply risk, rather than the way of recycling.

Batteries require specific grade of materials for their chemistry and a sectorial level assessment would draw a more precise picture for their risk of supply disruption [63]. In addition, the EU consumption of raw materials used in batteries is extremely low compared to other sectors, e.g., Li is mostly consumed by the glass and ceramics industries, and only 1% feeds the battery industry. Ni is mainly used to produce different stainless and alloy steels, which is the biggest user of primary and scrap Ni [21]. The Ni consumption in the EU battery industry is negligible compared to the other sectors. Within this context, the competition among sectors which use the same raw materials for different purpose could play an important role to define the supply risk and/or economic vulnerability of battery raw materials. According to Nassar et al. [87], the industry's relative vulnerability can be quantified by calculating "the ratio of an industry's expenditures for a given commodity relative to that industry's profitability". This approach seems to fit well to a sectorial level such as battery manufacturing, although it requires a well-structured breakdown of economic sectors and data availability.

It is worth noting that assumptions about, e.g., the share of materials recovered in a closed/open-loop, evolution of recycling efficiency, extended lifetime of LIBs, materials content, variation of LIBs capacity, supply data, etc., are based on available literature and often refer to past and current situation. Modularity and parameters in the developed models are used: (1) to make the application of selected tools flexible and updatable according to available data; and (2) to address uncertainty through the creation of different scenarios. Relevant parameters identified in the performed analysis are energy mix, recycling efficiency and supply risk. More efforts are needed to further explore the effects of, e.g., improved lifetime, one of the key parameters identified in the literature [10,42] and future supply risk.

Finally, the proposed approach could in the future be used to enlarge the performed analysis covering more aspects, e.g., different deployment scenarios, improved EoL practices and new materials. An interesting example on new materials expected to be used in manufacturing future traction LIBs is Niobium [88]. Niobium, which belongs to the CRMs list [19], is mainly produced in Brazil and Canada, even though exploration activities are taking place in several countries [89]. Currently, niobium is not massively used for manufacturing batteries, but its application has some potential, e.g., for anodes [88,90,91], which means a potential increase of demand. Very few studies on niobium in batteries are available and environmental impacts are almost unknown [92]. According to the authors' knowledge, the GWP of ferro-niobium were provided by Dolganova [93], who used primary data provided by CBMM (Companhia Brasileira de Metalurgia e Mineração). Such gap of data requires more efforts in assessing the environmental impacts of niobium for batteries, but also in investigating various aspects affecting both MFA and its supply, e.g., niobium content in anodes, which materials it will substitute (see Table 2).

Overall, the combination of information provided by different tools and experts in different fields, as well as the assessment of different scenarios, is recommended to identify key aspects that can contribute to decrease the environmental impacts of a strategic sector for the EU, such as mobility.

## 6. Conclusions

LCA, MFA and criticality (supply risk) considerations are contrasted and discussed in a mutually interactive manner, with focus on the environmental impacts of traction LIBs and some of their constituting materials in the current and future EU fleet from different perspectives. Modules and parameters used in both the LCA and MFA models allow identifying relevant aspects in terms of impacts and assessing different scenarios, including different possible EoL options. Criticality mainly contributes to prioritise materials to be studied and improve knowledge on the potential contribution of SRMs in the supply risk for specific materials.

The Supplementary Materials support the replicability of the assessment, as well as future studies. Users can easily access to relevant information on both the LCI and LCIA results, being able to: (1) directly compare input/output flows of the life-cycle of different LIBs; (2) further enlarge the assessment; and (3) modify and/or add input/output flows. The dynamic MFA tool describes the value chain of traction LIBs in the EU including all EoL options, and it allows quantifying the stocks and flows of LIBs/energy storage capacity/embedded materials in the EU for different scenarios and under different assumptions. Criticality assessments run worldwide suggested to initially focus on Li and Ni as key raw materials embedded in LIBs. The paper provided information of the role of recycling as mitigation factor of the supply risk of both Li and Ni used in LIBs.

Results point out that the life-cycle GWP of traction LIBs will likely improve in the future, mainly due to more environmental-friendly energy mix and improved LIBs' recycling. Even though second-use will postpone the availability of materials for recycling, recycling improvement can importantly increase the flows of SRMs, boosting resource efficiency and keeping the values of materials in the EU. In addition, recycling can further contribute to reducing the supply risk of both Li and Ni in 2050. Such enhancements are related to both the development of recycling technologies at large scale (in case of Li) and the higher grade of recovered materials (in case of Ni).

Lack of knowledge about the LIBs value chain, lack of robust data as input for the assessments and adoption of data based on past and current trends are importantly reflected in the obtained results, thus suggesting to intensify research efforts. Obviously, further methodological work, concerning, e.g., scenario setting, uptake and impacts of future technologies, adoption of consequential LCA, substitution of materials, effects of stocks and flows, etc. would also be advisable to appropriately support more prospective decision-making.

Both the literature review and the performed analysis confirmed the added-value of performing a multi-criteria analysis, especially when addressing complex systems. Involvement of different expertise and running scenarios varying relevant parameters are keys in updating both the modelling and the input data in order to provide reliable information to identify circular economy aspects that support decision making to properly manage the whole value chain of a strategic sector for the EU, such as batteries for e-mobility.

**Supplementary Materials:** The following tables in excel file that provides the main assumptions of the assessment reported in this paper are available online at <http://www.mdpi.com/1996-1073/13/10/2513/s1>. Moreover, to make the LCA replicable and updatable, the LCI of each LIB chemistry is provided in the spreadsheets of this excel file, where each input/output flow of material, energy, waste and emission is related to 1 kg of battery pack. Each flow is connected to the related impacts, enabling the automatic calculation of the impact of the battery life-cycle. The LCIA for all the impact categories included in the assessment are reported in the last spreadsheet (“Impact\_calculation”).

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