Neda Bahremandi Tolou
Jordan Lindsay
Robert Pell
Gareth Hatch

Image: Lynas Rare Earths, Ltd.

Product Category Rules (PCR)

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Rare-Earth Concentrates, Oxides, Metals, and Magnets

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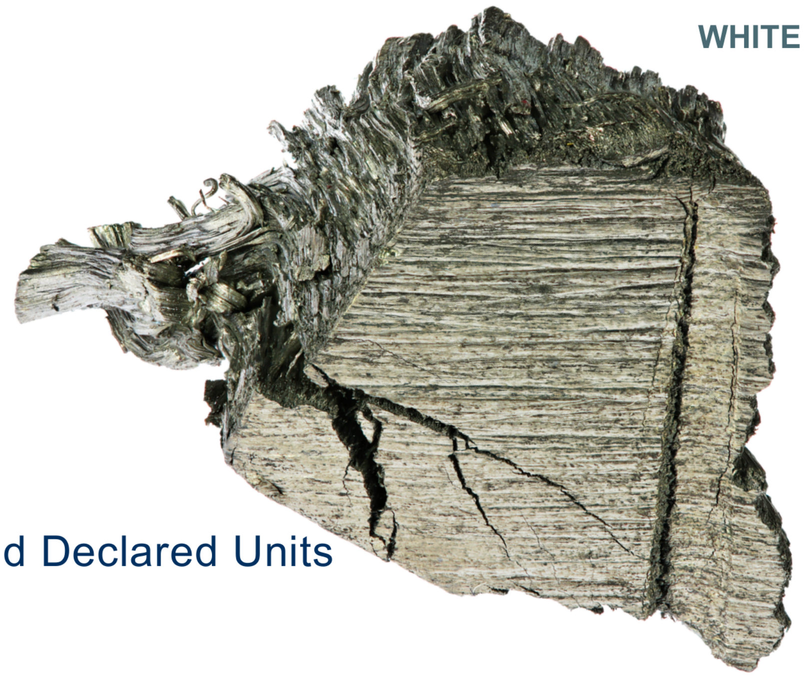

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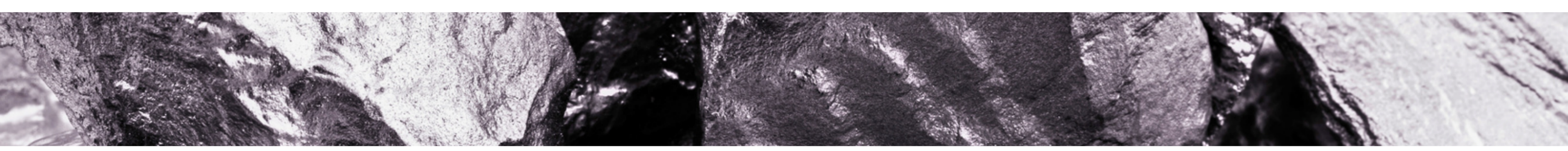


About the authors

Neda Bahremandi Tolou

Neda is a Research Fellow with the Belgium-based Rare Earth Industry Association (REIA). She holds a PhD in materials engineering from the Isfahan University of Technology. Neda has experience in research, sustainability projects, and industry collaboration, with a focus on rare-earth elements.

Robert Pell

Robert is the CEO of UK-based Minviro, which he founded after completing his PhD at the Camborne School of Mines and Tsinghua University. He has specialist knowledge on life-cycle assessment and rare-earth elements.

Jordan Lindsay

Jordan is R&D Manager at UK-based Minviro. He holds a PhD from the Camborne School of Mines, which was focused on platinum-group-metal geology. Jordan has experience in geology and metal chemistry.

Gareth Hatch

Gareth is the founder of UK-based Strategic Materials Advisory and is an advisor to the Belgium-based Rare Earth Industry Association (REIA). He holds a PhD in metallurgy & materials from the University of Birmingham, where he is also the Royal Academy of Engineering Visiting Professor of Critical Minerals and Materials.

Introduction

Growing concerns for environmental sustainability have led industries worldwide to seek ways to operate more sustainably and to reduce their environmental impacts. One important tool in this effort is the Life-Cycle Assessment (**LCA**), which provides a comprehensive, quantitative evaluation of the environmental impact of a product or service across its entire life cycle, from raw-material extraction to disposal. To conduct an LCA, industrial professionals need clear and consistent guidelines for assessing the environmental impact of their products. This is where Product Category Rules (**PCR**) are useful.

PCRs are a set of guidelines and rules for producing Environmental Product Declarations (**EPDs**) for one or more product categories, and they provide detailed instructions on what should be included in the LCA, how to calculate environmental impacts, and how to report the results. However, PCR do not yet exist for all products in all sectors, which makes it difficult for many companies to compare and to communicate the environmental performance of their products. In particular, there were no PCR available for assessing the environmental impacts of rare-earth-element (**REE**) processing across the entire supply chain. To address this issue, a committee of scientific and industrial experts collaborated to develop the PCR presented in the current work, providing a framework for assessing the environmental performance of the entire REE supply chain.

The goal of developing PCRs is to ensure consistency and comparability of LCA results for products within the same category, which allows for meaningful comparison between products based on their environmental performance. They are a key part of the ISO 14025 standard as they enable transparency and comparability between EPDs [1].

The purpose of the present work is to provide a comprehensive overview of the PCR for rare-earth concentrates, rare-earth oxides (**REOs**), REEs in metallic form, and REE permanent magnets, and the declaration of this performance by an EPD. It will also explain how industrial organisations across all nodes of the entire supply chain, from mine to oxide production, oxide to metal conversion, and metal to magnet manufacturing, can utilize the associated PCR document to assess and improve their environmental impact. The present work will highlight the key features of the PCR document for conducting an LCA for every product category of the entire REE supply chain. For more detailed information, please refer to the main PCR document, which can be accessed on the EPD website [2].

Key Terminology, Process Overview and Declared Units

In order to fully understand this PCR, it is important to clarify some of the technical terminology used throughout the document. To ensure comprehensive coverage of all REE products across the entire supply chain, we have defined each REE product and precursor. The definitions are listed here:

- **REE-bearing ore**: The extracted ore after mining;
- **REE mineral concentrate:** physically separated material produced following mineral processing of REE-bearing ores, using processes such as gravity separation, magnetic separation, and froth flotation;
- **Mixed REE concentrate**: material produced following either a) the cracking / dissolution of a REE mineral concentrate, or less commonly b) direct dissolution of REE-bearing ores, followed in either case by basic purification processes;
- **Mixed REE oxide**: materials produced following the partial separation and purification of mixed REE concentrates, followed by precipitation and calcining, e.g. a single oxide material containing Ce, La, Nd and Pr; and
- **REE oxide (specified)**: the oxide form of an individual / single REE, e.g., Y_2O_3

To utilize the PCR for REOs, REE metals, and REE permanent magnets, there are several key steps that must be taken. First, the user must identify their specific product from the technical specification table (Table 1). Once the product has been identified, the user must then define the declared unit for the LCA. It should be mentioned that the EPDs based on this PCR document shall use a declared unit instead of a functional unit. This is because it is not possible to capture all relevant functional aspects in one or a few predefined functional units.

The declared units in the present PCRs, with some specific example products, are:

- 1 kg of **REE-bearing ore** (after extraction);
- 1 kg of **REE mineral concentrate** (after mineral processing);
- 1 kg of **mixed REE concentrate** (after cracking / dissolution);
- 1 kg of **mixed REO** (specified) (after separation);
- 1 kg of **REO** (specified) (e.g., 1 kg of yttrium oxide) (after separation);
- 1 kg of **REE metal** (specified) (e.g., 1 kg of neodymium metal) (after separation);
- 1 kg of **REE metal alloy** (specified) (e.g., 1 kg of neodymium-praseodymium);
- 1 kg of **REE magnet powder** (specified) (e.g., 1 kg of isotropic Sm-Fe-N magnet powder); and
- 1 kg REE permanent-magnet product (specified) (e.g., 1 kg of sintered Sm-Co magnet).

All relevant functional aspects shall, however, be taken into consideration when comparing EPDs based on this PCR.

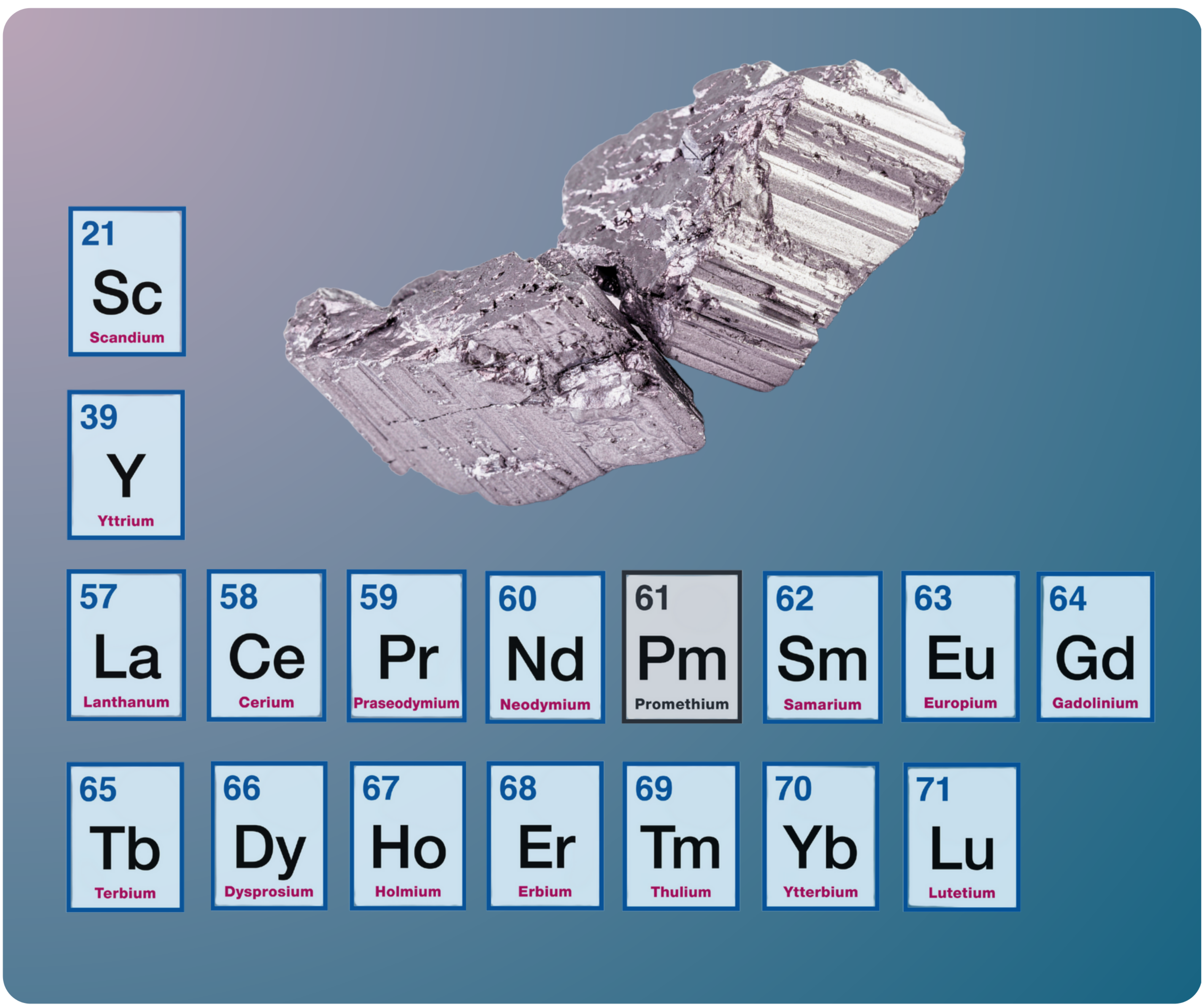


Table 1: Technical specifications of each category of REE product category covered by this PCR.

Rare-Earth Chain stage	Rare-Earth Product	Specifications of Product	Example of Product	Example of Market Use of Product
Mine to oxide	REE-bearing ore	Type of ore and percent composition of the mineral in ore shall be reported	Ore sand, hardrock ores, ion-adsorption clay deposits	Purchased for mineral processing to produce REE mineral concentrate (intermediate)
	REE mineral concentrate	Type of REE-bearing mineral and percent composition of the mineral in concentrate shall be reported	REE mineral concentrate	Purchased for cracking / dissolution to produce mixed REE concentrate (intermediate)
	Mixed REE concentrate	Designated proportion of REEs shall be reported	Mixed REE concentrate	Purchased for separation to produce mixed and individual REE compounds (intermediate)
	Mixed REO	Designated proportion of REEs shall be reported	Mixed REO	Catalysts, glass-related industries, polishing, permanent magnets, metallurgy industry, ceramics, battery alloy components, solid-oxide fuel cells
	Specified REO	Single REE in oxide form shall be reported	Individual REO	Catalysts, glass-related industries, polishing, permanent magnets, metallurgy industry, ceramics, battery alloy components, solid-oxide fuel cells
Oxide to metal / alloy	Specified REE metal	Single REE metal shall be reported	Metal ingots	Magnets, metal alloys, electronics, new materials and some other high-technology fields
	REE metal alloy	Designated proportion of metals shall be reported	Metal ingots	Magnets, metal alloys, electronics, new materials and some other high-technology fields
REE permanent magnets	Anisotropic Sm-Fe-N magnet powder - Process (1)	Properties of magnet powder (e.g., particle size, coercivity, etc.) shall be reported.	Magnet powder	Purchased for further processing to manufacture magnets

Table 1: (Continued)

REE permanent magnets	Anisotropic Sm-Fe-N magnet powder - Process (2)	Properties of magnet powder (e.g., particle size, coercivity, etc.) shall be reported.	Magnet powder	Purchased for further processing to manufacture magnets
	Anisotropic Sm-Fe-N magnet powder - Process (3)	Properties of magnet powder (e.g., particle size, coercivity, etc.) shall be reported.	Magnet powder	Purchased for further processing to manufacture magnets
	Isotropic Sm-Fe-N magnet powder	Properties of Magnet powder (e.g. particle size, coercivity, etc.) shall be reported.	Magnet powder	Purchased for further processing to manufacture magnets
	Sintered Nd-Fe-B magnet	Magnet specifications shall be reported, including metal mix and function	Permanent magnets	Wind turbines, DC motors, medical devices, computer hard drives, printers and speakers, etc.
	Bonded Nd-Fe-B magnet	Magnet specifications shall be reported, including metal mix and function	Permanent magnets	Wind turbines, DC motors, medical devices, computer hard drives, printers and speakers, etc.
	Sintered Sm-Co magnet	Magnet specifications shall be reported, including metal mix and function	Permanent magnets	Aerospace, defence systems, high-performance motors, actuators, generators, turbo machinery, etc.
	Compression-moulded bonded Sm-Fe-N magnets	Magnet specifications shall be reported, including metal mix and function	Permanent magnets	Hard disk drives, electrical motors, smart phones, audio devices, etc.
	Injection-moulded bonded Sm-Fe-N magnets	Magnet specifications shall be reported, including metal mix and function	Permanent magnets	Hard disk drives, electrical motors, smart phones, audio devices, and etc.
	Extruded / sheet magnets Sm-Fe-N magnets	Magnet specifications shall be reported, including metal mix and function	Permanent magnets	Smart phones, audio devices, and other small electric motors

System Boundary

Once the declared unit has been defined, the user must define the system boundary for their LCA. The system boundaries specify the portion of the product system that will be evaluated in the LCA. Annexes 1, 2, and 3 of the PCR document provide flowsheets for determining system boundaries, depending on the specific stage of the REE supply chain being evaluated (i.e. mine to oxide, oxide to metal, or metal to magnet). Figure 1 shows the system boundary for the entire REE supply chain [2].

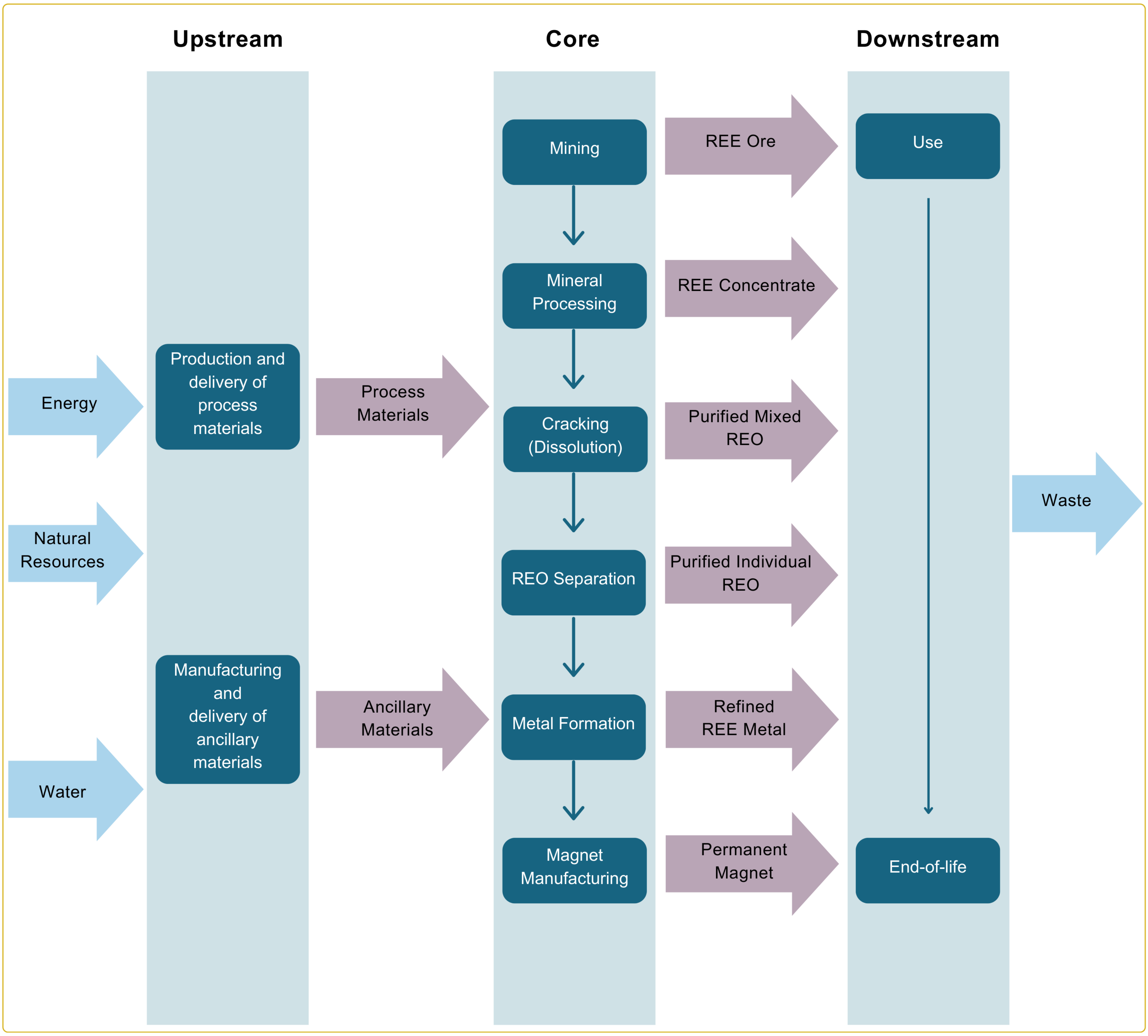


Figure 1: System diagram illustrating the processes that shall be included in the product system, divided into upstream, core and downstream processes. The illustration of processes to include may not be exhaustive.

For the purpose of different data-quality rules and for the presentation of results, the life cycle of the product is divided into three life-cycle stages:

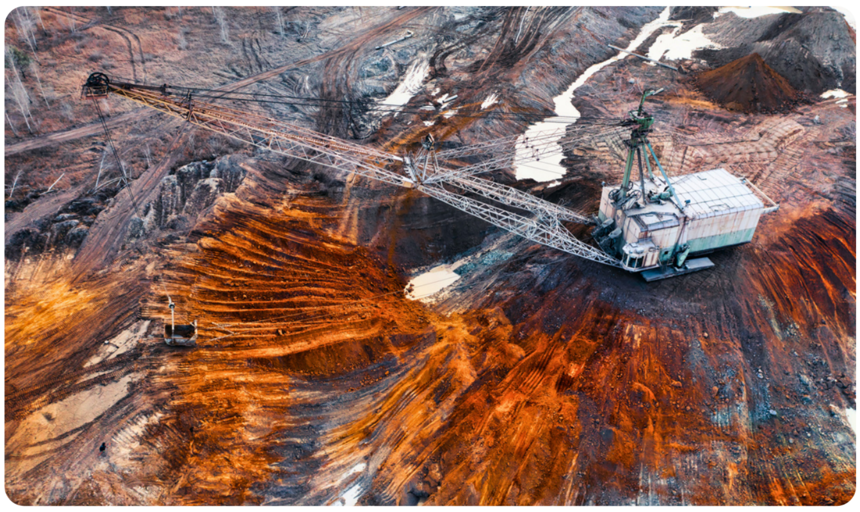
- Upstream processes (from cradle-to-gate);
- Core processes (from gate-to-gate); and
- Downstream processes (from gate-to-grave) (optional, see Section 4.3 of the PCR document [2]).

In the EPD, the environmental performance associated with each of the three life-cycle stages above shall be reported separately and in aggregated form. The descriptions of the life-cycle stages and the processes included in the scope of the PCR document are listed below.

Upstream Processes

The following unit processes are part of the product system and shall be classified as upstream processes:

- Extraction and processing of raw materials required for the core processes;
- Recycling processes of secondary materials from other product life cycles;
- Production of input components;
- Transport of raw materials and components along the upstream supply chain;
- Production of distribution and consumer packaging; and
- Generation of electricity and production of fuels, steam and other energy carriers used in upstream processes.



Upstream processes not listed may also be included. All elementary flows at resource extraction shall be included, except for the flows that fall under the general cut-off rule in Section 4.5 of the PCR document [2].

Core Processes

The following unit processes are part of the product system and shall be classified as core processes:

- Mining and processing of REE-bearing ore, except for the permanent-magnets product category (for which these processes shall be included among the upstream processes);
- Transportation of materials and components to the manufacturing of the product under study;
- Manufacturing of the product under study;
- End-of-life (**EOL**) treatment of manufacturing waste, even if carried out by third parties, including transportation; and
- Generation of electricity and production of fuels, steam and other energy carriers used in core processes.

Core processes not listed may also be included. Manufacturing of a minimum of 99% of the total weight of the declared product including packaging shall be included.

The following processes **shall not** be included:

- Business travel of personnel;
- Travel to and from work by personnel; and
- Research and development activities.

For modelling of infrastructure and capital goods, see Section 4.3.2 [2].

Downstream Processes

The following unit processes are optionally part of the product system and shall be classified as downstream processes:

- Transportation of the product to retailer / consumer;
- Product use, e.g. use of electricity or water, use activities causing direct emissions, and maintenance activities;
- EOL treatment of the used product and its packaging, including transportation; and
- Generation of electricity and production of fuels, steam and other energy carriers used in downstream processes.

In addition, there exist other system boundaries including: the boundary towards nature, other technical systems, temporal boundary, and geographical boundary. Specific considerations should be made for the flow of materials and energy resources leaving nature and entering the product system, as well as the flow of materials and components to/from other product systems. The temporal boundary defines the time period for which the life-cycle inventory data is recorded, and the geographical boundary defines the geographical coverage of the LCA. For further guidance, see Section 4.3.3.1 to 4.3.3.4. of the PCR document [2].

Allocation Rules

Allocation can be divided into allocation of co-products, i.e. allocation of unit processes that generate several products; and allocation of waste, i.e. allocation of unit processes that generate materials that are, for example, landfilled, recovered, recycled or reused, and which require further processing to cease being waste to become products (see criteria for end-of-waste state in Section 4.6.2 of the PCR document [2]).

The principles for allocation of co-products and allocation of waste are described separately in the following subsections.

Co-Product Allocation

The following hierarchy of allocation methods shall be followed for co-product allocation:

1. Allocation shall be avoided, if possible, by dividing the process to be allocated into sub-processes and collecting the inventory data for each sub-process.
2. If allocation cannot be avoided, the inventory data should be partitioned between the different co-products in a way that reflects the underlying physical relationships between them, i.e. allocation should reflect the way in which the inventory data changes if the quantities of delivered co-products change.
3. If a physical relationship between the inventory data and the delivery of co-products cannot be established, the inventory data should be allocated between the co-products in a way that reflects other relationships between them. For example, inventory data might be allocated between co-products in proportion to their economic values. If economic allocation is used, a sensitivity analysis exploring the influence of the choice of the economic value shall be included in the LCA report.

The following instructions should be applied to REE products if allocation cannot be avoided:

In the case of REE-bearing ores or minerals, mass allocation shall be applied provided that the ratio of product prices per kg is equal to or less than five (5), otherwise economic allocation shall be applied [3]. In the case of multiple co-products, this allocation criteria should be applied to each individual co-product. For other REE products, the preferred method is economic allocation based on prices per kilogram of each product. This is because some REE products are significant to certain technologies, which in turn drive the market for REEs. Therefore, using price per kg is a more representative characteristic for their allocation. Refer to Table 2 for the main products and co-products in the REEs value chain and the suggested allocation method for each. Prices to use in the economic allocation should be calculated from process-specific engineering studies or from the process or product data. EPDs should document the reference year and the price range used for each co-product. If the most recent and process-specific prices are not available, a 5-to-10-year average price, to account for fluctuations, or prices from a reference document shall be used. Prices are available on the Rare Earth Industry Association (REIA) website.

In case of comparing EPDs based on this PCR, the prices and the reference year should be equivalent.

The allocation method used shall be clearly documented in the EPD.

The following method shall be applied for economic allocation, for example, for REOs. Let Pi represent the market prices of the ith REO, and Cij represent the concentration of the ith REO in the derived REO mixture from ore type j. The allocation coefficient for the ith REO from ore type j can be calculated as:

$$x_{ij} = (P_i * C_{ij}) / \sum_i (P_i * C_{ij}) = (P_i * C_{ij})/V_j$$

Where Vj is the market value of REO mixture derived from ore type j.

Specific allocation guidance for example REE-product systems is displayed in Table 2, with a visual example in Figure 2.

Table 2: Main products and co-products within the REE value chain and the suggested allocation methods

PROCESS	MAIN PRODUCT AND CO-PRODUCTS	ALLOCATION METHOD
Mining	REE ore, iron ore, industrial minerals	Different ores (e.g. Fe and REE) will use mass-based allocation unless the price ratio for each is >5.
Mineral Processing	REE-bearing and non-REE-bearing minerals	Economic allocation
Cracking	Mixed REE concentrates	Economic allocation
REE Separation	Individual REOs	Economic allocation
	Mixed REOs	Unlikely to have secondary product
Metal Formation	Individual REE metals	Unlikely to have secondary product
Magnet Manufacturing	Magnet products	Unlikely to have secondary product

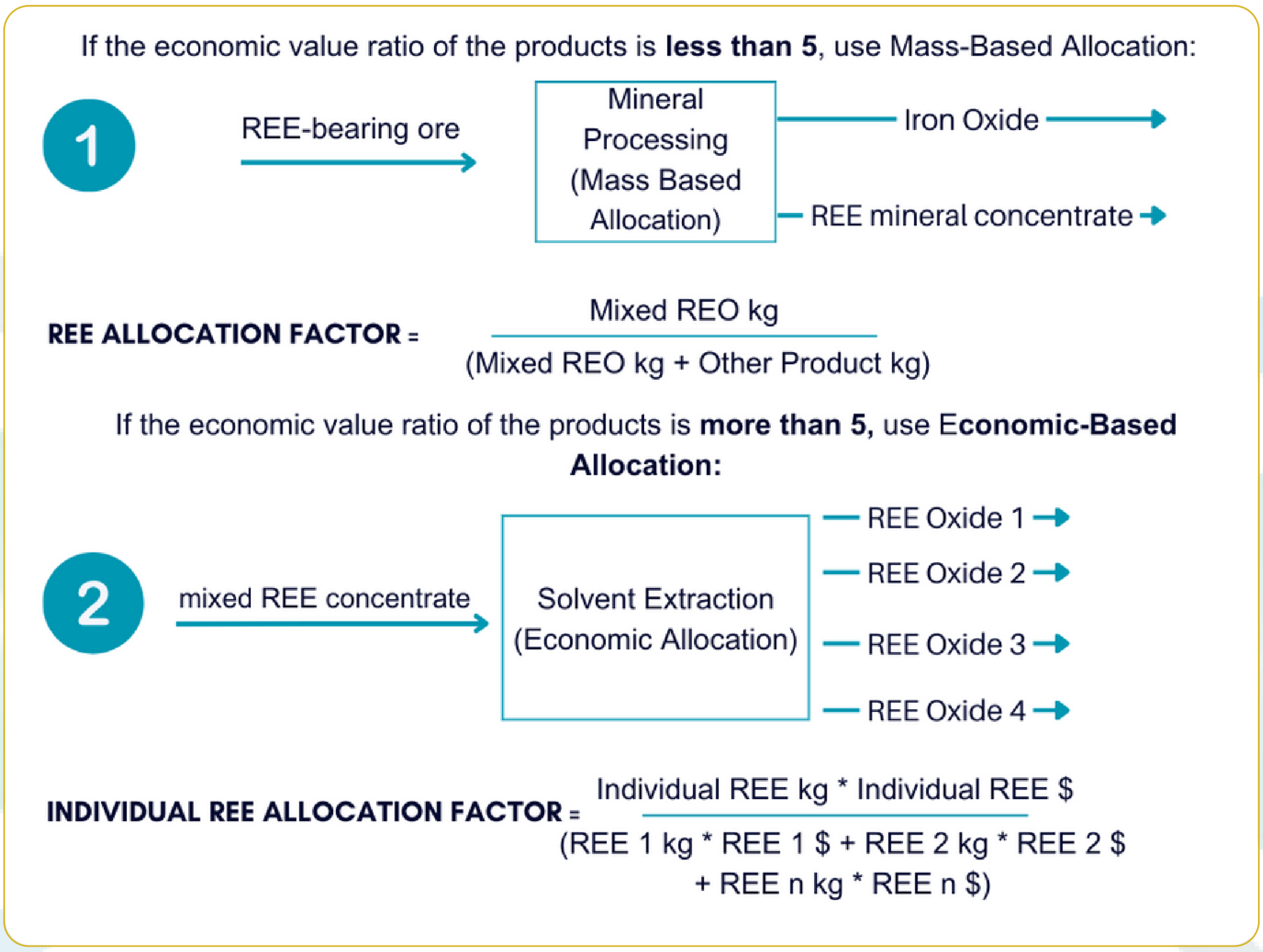


Figure 2: Allocation method examples for both methods using specific REE examples for key processes in the product system. Note that the metals used for the economic value calculation are for example only, and prices/masses shall reflect the exact mix of products in a given product system.

Allocation of Waste-Treatment Processes

Allocation of waste shall follow the 'polluter pays' principle and its interpretation in the EN 15804 standard: "processes of waste processing shall be assigned to the product system that generates the waste until the end-of-waste state is reached" [5]. The end-of-waste state is reached when all the following criteria for the end-of-waste state are fulfilled:

- The recovered material, component or product is commonly used for specific purposes;
- A market or demand, identified e.g. by a positive economic value, exists for such a recovered material, component or product;
- The recovered material, component or product fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- The use of the recovered material, product or construction element will not lead to overall adverse environmental or human health impacts.

The above outlined principle means that the generator of the waste shall carry the full environmental impact, until the point in the product life cycle in which the end-of-waste criteria are fulfilled. Waste may have a negative economic market value, and then the end-of-waste stage is typically reached after (part of) the waste processing and further refinement, at the point at which the waste no longer has a negative market value. This allocation method is (in most cases) in line with a waste generator's legal and financial responsibilities. See the General Programme Instructions for further information and examples [6].

The treatment, disposal and/or storage of radioactive waste must be described and accounted for within the PCR.

Data Quality Requirements and Selection of Data

Life-cycle inventory data is classified into two categories: specific data (also referred to as "primary data" or "site-specific data") and generic data. Specific data comes from the manufacturing plant and actual data from other parts of the life cycle. Generic data is divided into selected generic data and proxy data. Selected generic data include commercial databases and free databases that fulfil prescribed data-quality requirements for precision, completeness, and representativeness. Proxy data include commercial databases and free databases that do not fulfil all of the data-quality requirements of "selected generic data".

Specific data should be used for core processes and upstream and downstream processes, and generic data may be used when specific data is not available. Any data used should represent average values for a specific reference year, and variations should be declared. Data sourced from proxy/generic values shall be declared within the limitations of the EPD, with recommendations to update the EPD once specific data is available. There are some rules for using general data which can be found in sections 4.7.1 (Rules for Using General Data) and 4.7.2 (Examples of Databases for Generic Data) of the PCR document [2].

There are further data-quality requirements per life-cycle stage. To learn more about the specific requirements for each life-cycle stage (upstream process, core process, and downstream process), it is highly recommended to refer to section 4.7.3 of the PCR document [2].

Content and format of EPD

EPDs based on this PCR shall contain the information described in section 5 in the PCR document [2]. In this section one can find guidance to writing EPD report. It covers aspects such as EPD content and format, languages, units and quantities, use of images, reporting format, references, executive summary, program, and product information. It also addresses content declarations which shall declare the weight of one unit of product, as purchased, and contain information about the content of the product in the form of a list of materials and chemical substances including information on their environmental and hazardous properties. Tables 3 and 4 show examples of content declaration lists for 1 kg of REE ore concentrate and for sintered Nd-Fe-B permanent magnets respectively.

Table 3: Example of 1 kg REE concentrate from hard-rock content list

REE	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y
Ratio in concentrate	0.23	0.5	0.06	0.19	0.01	0	0.01	0	0	0.01

Table 4: Example of 1 kg sintered Neodymium-Iron-Boron (NdFeB) permanent magnets content list

Element	Nd	Pr	Dy	Fe	Other
Ratio in NdFeB magnet	0.21	0.06	0.02	0.66	0.05

This section also outlines environmental performance including environmental impacts, use of resources and waste production and output flows with the specific indicators provided on www.environdec.com/indicators.

Conclusions

In a world increasingly concerned with environmental sustainability, industries are under growing pressure to reduce their environmental footprints. LCA has developed as an important tool for evaluating the environmental impact of products and services throughout their life cycles. To ensure the accuracy and comparability of LCA results, PCRs play a vital role by providing clear guidelines and instructions for conducting LCAs.

The present work has highlighted the significance of PCRs in the context of REE products, offering a standardised framework from REE-ore extraction to magnet manufacturing. The selection of product categories, definition of declared units, and establishment of system boundaries are explained, along with the requirements for data quality and the selection of data, as well as the explanation of allocation methods. This guidance enables the conduct of an LCA that can be compared with others based on the same PCRs. Further guidance is provided on the writing the EPD report, along with rules and guidance for consideration in various sections.

In conclusion, the development of PCRs for REEs is a significant step towards a more sustainable and environmentally responsible future for the REE industry. It promotes transparency, consistency, and accountability in assessing and improving environmental performance throughout the entire REE supply chain.

Abbreviations

LCA	Life-cycle assessment
PCRs	Product Category Rules
EPDs	Environmental Product Declarations
REE	Rare-earth element
REO	Rare-earth oxide
REIA	Rare Earth Industry Association

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Graphic Design, Layout and Visuals: Alexandra-Cristina Donea (REIA)

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Get in touch

info@global-reia.org

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Connecting matters

Co-funded by the European Union

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