



cnrs

COLLECTIVE SCIENTIFIC ASSESSMENT

Towards a responsible use of rare earth elements throughout their life cycle

What are the prospects
in terms of sufficiency, recycling
and production methods?

Synthesis of the report

To cite this document:

CNRS. *Towards a responsible use of rare earth elements throughout their life cycle : what are the prospects in terms of sufficiency, recycling and production methods?* Synthesis of collective scientific assessment. 2025.

Cover photo : ©Photo credit Cyril FRESILLON / Mecaware / CNRS Images

Illustration : ©Julie BORGESE

Layout : Morwenna Moal based on a design by Sarah LANDEL

Editor-in-Chief

Antoine PETIT, President and Director General of the CNRS.

Coordinated by the CNRS

The expert authors who contributed to this document

Scientific leads

Pascale RICARD is a lawyer specialising in international, maritime and environmental law, and a research fellow at the CNRS at the laboratory Droits international, comparé et européen — DICE (Aix-Marseille Université — CNRS).

Clément LEVARD is a physical chemist and specialist in environmental geoscience, and a research director at the CNRS at the Centre de Recherche et d'Enseignement des Géosciences de l'Environnement — CEREGE (Aix-Marseille Université — CNRS — INRAE — IRD).

Romain GARCIER is a geographer, a specialist in geographical approaches to critical materials and rare earths, and a senior lecturer at the ENS de Lyon, affiliated with the laboratory Environnement Ville Société — EVS (CNRS — ENTPE — ENS de Lyon — ENSA Lyon — Université Jean Monnet — Université Lumière Lyon 2 — Université Lyon 3 Jean Moulin).

Principal experts

Kevin BERNOT is a chemist, professor at the Institut National des Sciences Appliquées (INSA) in Rennes at the Institut des sciences chimiques de Rennes — ISCR (CNRS — ENSC Rennes — Université de Rennes).

Bénédicte CENKI is a geologist and professor at the Université de Montpellier at the laboratory Géosciences Montpellier (CNRS — Université de Montpellier).

Marie FORGET is a geographer and senior lecturer at the Université Savoie Mont Blanc at the laboratory Environnement, Dynamique et Territoires de la Montagne — Edytem (CNRS — Université de Savoie Mont Blanc).

Olga FUENTES is a specialist in life cycle analysis with a background in electronic engineering, a junior researcher at the Université de Bordeaux at the Institut des Sciences Moléculaires — ISM (Bordeaux INP — CNRS — Université de Bordeaux), working in partnership with Guido Sonnemann.

Laure GIAMBERINI is an ecotoxicologist, professor of exceptional rank at the Université de Lorraine and director of the Laboratoire interdisciplinaire des environnements continentaux — LIEC (CNRS — Université de Lorraine).

Émilie JANOTS is a geologist and senior lecturer at the Université Grenoble-Alpes at the Institut des Sciences de la Terre — ISTerre (CNRS — IRD — Université Grenoble Alpes — Université Savoie Montblanc).

Brice LAURENT is a sociologist and researcher at Mines Paris-PSL at the Institut interdisciplinaire de l'innovation-I3 (CNRS — École Polytechnique — Mines Paris-PSL — Télécom Paris). He is also director of the Direction Sciences Sociales, Économie et Société de l'Anses.

Gilles LHUILIER is a lawyer, professor of private law at the ENS de Rennes, and a senior member of the Institut Universitaire de France.

Frédéric MAZALEYRAT is a physicist and professor at the ENS Paris-Saclay in the laboratory — Systèmes et applications des technologies de l'information et de l'énergie — Satie (CNAM — CNRS — CY Cergy Paris Université — ENS Paris-Saclay — Université Paris-Saclay).

Stéphane PELLET-ROSTAING is a chemist and CNRS research director at the Institut de chimie séparative de Marcoule-ICSM (CEA — CNRS — ENSC Montpellier — Université de Montpellier).

Guido SONNEMANN is a chemist and specialist in life cycle analysis, and a professor at the Université de Bordeaux at the Institut des Sciences Moléculaires — ISM (Bordeaux INP — CNRS — Université de Bordeaux).

Eric VAN HULLEBUSCH is a biogeochemist and professor at the Institut de physique du globe de Paris — IPGP/IPGP-UMR (CNRS — IPGP-Université Paris Cité).

Fanny VERRAX is a philosopher and associate professor of ecological transition and social entrepreneurship at EmLyon Business School.

Alexandre VIOLLE is a sociologist and junior researcher at Mines Paris-PSL at the Institut interdisciplinaire de l'innovation — I3 (CNRS — Ecole Polytechnique — Mines Paris-PSL — Télécom Paris), working in partnership with Brice Laurent.

Contributing experts¹

Yacine AMARA is a physicist and a lecturer at the Université de Le Havre Normandy within the Groupe de Recherche en Électrotechnique et Automatique du Havre — GREAH (Université Le Havre Normandie).

Valentin BAUDOUIN is a lawyer and researcher at the Centre européen de recherche sur le risque, le droit des accidents collectifs et des catastrophes — CERDACC (Université de Haute-Alsace).

Laurent CALVEZ is a chemist and professor at the Université de Rennes within the Institut des Sciences Chimiques de Rennes — ISCR (CNRS — ENSC Rennes — Université de Rennes — INSA Rennes).

Laurent CASSAYRE is a chemist and research director at the Laboratoire de Génie Chimique — LGC (CNRS — Toulouse INP — Université de Toulouse).

Florian JAROSCHIK is a chemist and researcher at the Institut Charles Gerhardt Montpellier — ICGM (CNRS — ENSC Montpellier — Université de Montpellier).

Elsa LAFAYE DE MICHEAUX is an economist, a professor at INALCO, and a researcher at the Centre Asie.

Alexandra LANGLAIS is a lawyer and researcher at the Institut de l'Ouest : Droit et Europe — IODE (CNRS — Université Rennes).

Florian LEBLANC is an economist and research engineer at the International Centre international de recherche sur l'environnement et le développement — CIRED (AgroParisTech, Université Paris-Saclay, CIRAD, CNRS, EHESS, ENPC, Institut Polytechnique de Paris).

Louis-Marie MALBEC is an engineer and economist, and a researcher at IFP Energies nouvelles — IFPEN.

Alexander STINGL is a sociologist and researcher at the *School of Political Science & Sociology* (University of Galway).

Luca TENREIRA is a lawyer and a researcher at the European University Institute.

Raphaël TRIPIER is a chemist and professor at the Université de Bretagne Occidentale in the laboratory Chimie, Électrochimie Moléculaires et Chimie Analytique — CEMCA (CNRS — Université Bretagne Occidentale EPE, Brest).

Francesco RICCI is an economist and professor at the Université de Montpellier in the Centre d'Economie de l'Environnement de Montpellier — CEE-M (CNRS — INRAE — Institut Agro de Montpellier — Université de Montpellier).

¹ These experts contributed by reviewing scientific publications and/or drafting notes incorporated into the deliverables and/or proofreading the report or summary and/or being interviewed on substantive aspects of the subject matter.

Other authors

Simon BEYNE, project lead for the collective scientific assessment project at the CNRS Mission Pour l'Expertise Scientifique

Valérie LALLEMAND-BREITENBACH, Director of the CNRS Mission Pour l'Expertise Scientifique.

Acknowledgements

Jean-Claude BÜNZLI, for his presentation given at a plenary meeting of the expert group.

Camille DE SALABERT and Viviane HAGUENAUER, Institut de l'Information Scientifique et Technique (INIST), CNRS, for their support in compiling the bibliographic corpus.

The members of the Scientific Expertise Monitoring Committee.

The members of the Steering Committee for the CNRS Scientific Expertise.

Mission Pour l'Expertise Scientifique of CNRS

Director : Valérie LALLEMAND-BREITENBACH

Head of Expertise Coordination : Aude VÉDRINES

Head of the Collective Scientific Assessment Project : Marie DÉCHELLE then Simon BEYNE

This document has been translated into English in May 2026 by the expert group and the MPES.



COLLECTIVE SCIENTIFIC ASSESSMENT

Towards a responsible use of rare earth elements throughout their life cycle

What are the prospects
in terms of sufficiency, recycling
and production methods?

Synthesis of the report

Introduction

The *Rare Earths* Collective Scientific Assessment (CSA) aims to answer the following question: *how can the scientific literature inform public debate and decision-making on the responsible use of rare earths in France and in Europe, against a backdrop of strengthening national sovereignty regarding the supply of strategic resources?*

The uses of rare earths are primarily **industrial**: the magnetic, chemical, catalytic, mechanical and optical properties of the seventeen elements in the periodic table — grouped under the term *rare earth elements* (REEs) — justify their use in numerous fields such as energy, digital technology, the medical and military sectors as well as the environmental transition. REEs are found almost everywhere: electric cars, smartphones, offshore wind turbines, lasers, aircraft, missiles, etc., and are difficult to substitute.

Meeting these needs depends heavily on **mining**. France does not have any exploitable geological resources in the short term. In 2017, REE resources were distributed across around ten countries: China (35%)², Brazil (11%), Australia (10%), Russia (10%), Greenland (9%), Canada (7%), Sweden (6%), Vietnam (3%), the United States (3%) and others (6%), but global ore extraction and REE refining is dominated by China (70% and 90% respectively). The industrial use of REEs requires complex processing

beforehand, necessitating expertise which China has mastered to become the world's leading operator. Most of the REEs mined today must be sent to China for refining. The European Union and the United States, for example, have therefore classified REEs as *critical metals*. A *critical* material is subject to supply risks that threaten the sovereignty or autonomy of importing countries. These supply risks may arise from a lack of geological availability of materials, but far more often depend on the origin of the raw materials used.

This is why the uses of REEs also have a **political** dimension. Even if it were technically possible to restart metal extraction in our territories long neglected by mining activity, the reserves of REEs available in Europe would not be sufficient to meet the current or short-term needs of our industries in the context of environmental and energy transition. **This calls for thinking the sufficiency (or *sobriety*) in use of REE resources.** How could we rethink our consumption, for example by prioritising essential uses over less essential ones, by developing research into substitute materials, by promoting new forms of end-use, and so on? Developing the circularity of our economies appears to be a key lever for the sustainability of their supply. And even though extraction remains necessary, it must be carried out under conditions that are socially,

politically and environmentally acceptable for Europe, without externalising the negative impacts of mining to countries of the Global South.

In this context, the CNRS wished to conduct a **collective scientific assessment, with the aim of providing scientific insight to inform public decision-making and debate**. The purpose of this CSA is to provide a critical review of the scientific knowledge regarding the possibility of responsible use of REEs throughout their entire life cycle, and the challenges and opportunities associated with such use. It was conducted in accordance with the principles of competence, independence, impartiality and transparency. A multidisciplinary group of 17 scientific experts in the physical, geological and environmental sciences, chemistry, as well as humanities and social sciences, including legal science, analysed over 4,100 publications, with occasional assistance from 13 other scientists, to produce a reference report (in french) and enable the drafting of this synthesis (see methodological appendix). The CSA identifies existing knowledge, gaps and controversies. Three key areas are explored for an interdisciplinary and systemic examination of the responsible use of REEs: **reducing** their consumption, **recycling** them and **extracting** them **using alternative methods**.

² These figures are taken from the report by the USGS, the *United States Geological Survey*

Contents

Introduction	4
I. Uses, resources and geopolitical issues	8
I.1 Definition	9
What REEs are not	9
What are REEs?	9
I.2 Applications	11
Links between the properties of constituents, materials and devices	11
Trends in use	13
From dispersed to concentrated uses	16
I.3 Resources, reserves, production	16
Geological resources and reserves that are well distributed geographically	16
Centralisation of the majority of extraction and refining in China	18
The environmental and health impacts of mining	18
The ' <i>balance problem</i> '	19
The REE market	20
I.4 REEs as political objects	20
The structure of the global REE market from the 1950s to the 1980s	20
The structuring of the REE market from the 1980s to the 2010s	21
Responses from non-Chinese states and companies to the rare earth crisis	22
I.5 Objectives and plan	25
II - Reducing	28
II.1 Overview of uses and possibilities for reducing or substituting REEs	29
Materials with high REE content	30
Materials with low REE content	32
II.2 The legal framework applicable to REEs: from security of supply to the circular economy	34
The European framework for the production and supply of REEs through the prism of security	34
The relationship between regulations on REEs and the principles of the circular economy	35
II.3 Designing, consuming and owning differently	
Designing and manufacturing differently	38
Ownership differently	38
Consuming differently	39
II.4 Putting things into perspective	39

III - Recycling	44
III.1 Institutionalisation of recycling	44
Recycling: a systemic activity	44
The need for a cross-cutting vision of the barriers to REE recycling	47
The existence of a general legal framework applicable to the recycling of products containing REEs in France and Europe	48
III.2 Practical organisation and stages of recycling	51
Process front-end: dismantling and pre-treatment	53
Core process	54
III.3 Putting things into perspective	56
IV – Extracting differently	61
IV.1 The development of primary and secondary resources in France and Europe: resources mapping	63
Primary deposits that formed under deep geological conditions	63
Deposits that formed under shallow geological conditions	64
‘Avenues for the future’	64
Secondary sources	66
IV.2 The existence of innovative, more environmentally friendly processes	68
New exploration technology pathways	68
Extraction of REEs from primary sources	69
Extraction of REEs from secondary sources	71
IV.3 Integrating human and environmental considerations into extraction	72
The emergence of ‘corporate social responsibility’ and ‘sustainability’ requirements: limited slogans for mining differently.	72
The ‘tightening’ and adaptation of the legal framework in response to the shortcomings of CSR	73
The renewal of the ambition for corporate (social) responsibility and sustainability through the energy transition, a source of new asymmetries	74
How can we do better to extract differently?	75
IV.4 Putting things into perspective	76
General conclusion	80
Glossary (<i>Terms described in the glossary are marked with an asterisk* on their first occurrence</i>)	82
Appendix: Summary of the methodology	84
Formation of the expert group	84
Establishment of the scientific resource base	84
Writing and working methods	85
References	86

I. Uses, resources and geopolitical issues

COLLECTIVE SCIENTIFIC ASSESSMENT

**Towards a responsible use
of rare earth elements
throughout their life cycle**

What are the prospects
in terms of sufficiency, recycling
and production methods?

I. Uses, resources and geopolitical issues

I.1 Definition

Rare earth elements (REEs) refer to a family of **17 chemical elements**³ (Figure 1). Most of them are found in the same row of the periodic table: these are the 15 lanthanides (from lanthanum to lutetium). To these are added yttrium (Y) and scandium (Sc), although the latter is excluded from the scope of this report⁴. REEs are often classified into two groups: light REEs (from lanthanum (La) to gadolinium (Gd)) and heavy REEs (from terbium (Tb) to lutetium (Lu), including yttrium). The distinction between light and heavy elements is purely conventional and does not correspond to a classification based on their properties⁵.

Beyond this purely chemical definition, this report addresses the issue of REEs from geological, economic, social, geographical, legal, political and environmental perspectives, focusing in particular on their uses and dynamics, their availability, the power dynamics and controversies they give rise to on a global scale, as well as their implications for public policies on transition and the assertion of sovereignty. These various dimensions are explored in the CSA report (Chapter I) and summarised in the following sections

What REEs are not

REEs are sometimes incorrectly referred to by other terms, and these designations may be imprecise or misleading depending on the context.

Rare metals : REEs are relatively abundant in the Earth's crust, far more so than metals such as gold, rhenium or iridium. Light REEs (from lanthanum to gadolinium) are more abundant than heavy REEs (from terbium to lutetium and yttrium).

Precious metals : precious metal is a rare and generally expensive metal such as gold, silver or platinum. Its value is linked to its beauty and rarity, but also to its exceptional chemical and physical properties, as well as its historical use in coins and valuables. Precious metals are often highly resistant to oxidation, corrosion and wear. This is not the case for REEs, which are not stable in the metallic state and are therefore stable in the ionic state.

Heavy metals : criticised by the scientific community (Dufus, 2002), this term nevertheless remains widely used in the public sphere to refer to highly toxic and ecotoxic elements such as lead, zinc or mercury. From this perspective, heavy REEs, despite their high atomic mass, do not fall into this category.

What are REEs?

Strategic metals* : metals associated with certain strategic sectors such as defence or those involved in transition policies (energy, mobility, etc.). Some REEs belong to this group, which also includes other metals (lithium, cobalt, etc.).

Critical metals* : metals that play an important economic role, are difficult to substitute and present supply risks. REEs belong to this group, which also includes other metals.

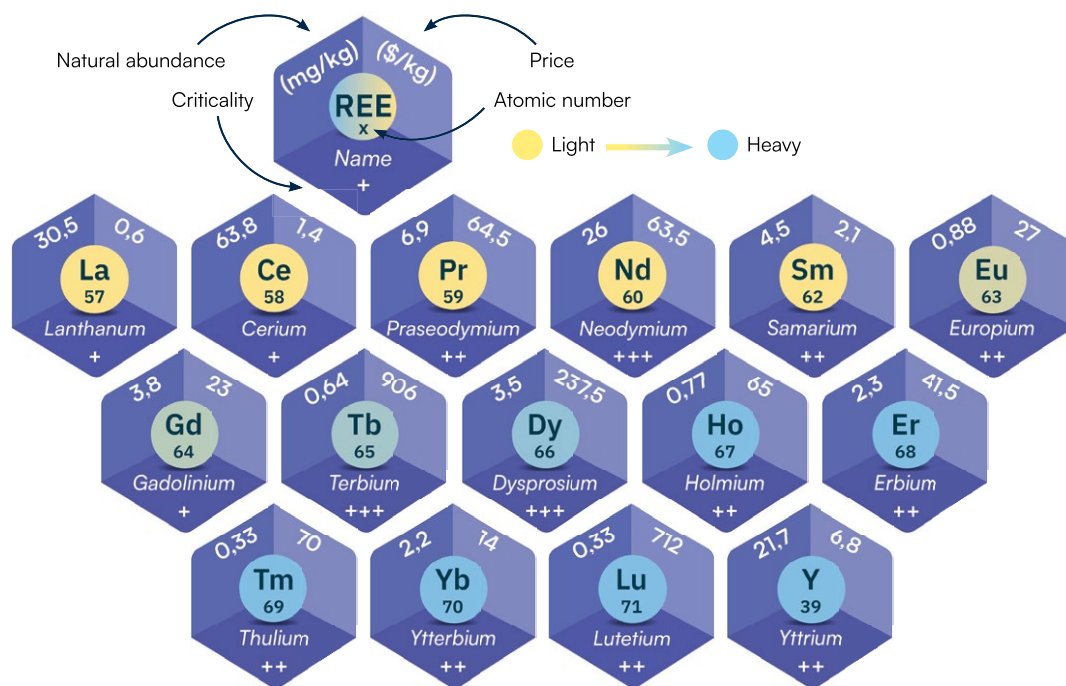
It is therefore useful to clearly distinguish the REEs from other groups of metals, and it is always preferable to use precise terms such as 'Rare Earth Elements' (REEs) or to specify the elements concerned (e.g. neodymium, dysprosium, europium, etc.).

3 - According to the International Union of Pure and Applied Chemistry (IUPAC).

4 - Scandium is distinguished by its ionic radius and geochemical affinities. It is not found alongside the other REEs in geological environments. It therefore represents distinct resources and markets.

5 - Nevertheless, their ionic radius, for example, decreases progressively from lanthanum to lutetium, and this may influence their geological and physico-chemical behaviour.

WHAT ARE REEs



REEs: DEBUNKING COMMON MISCONCEPTIONS

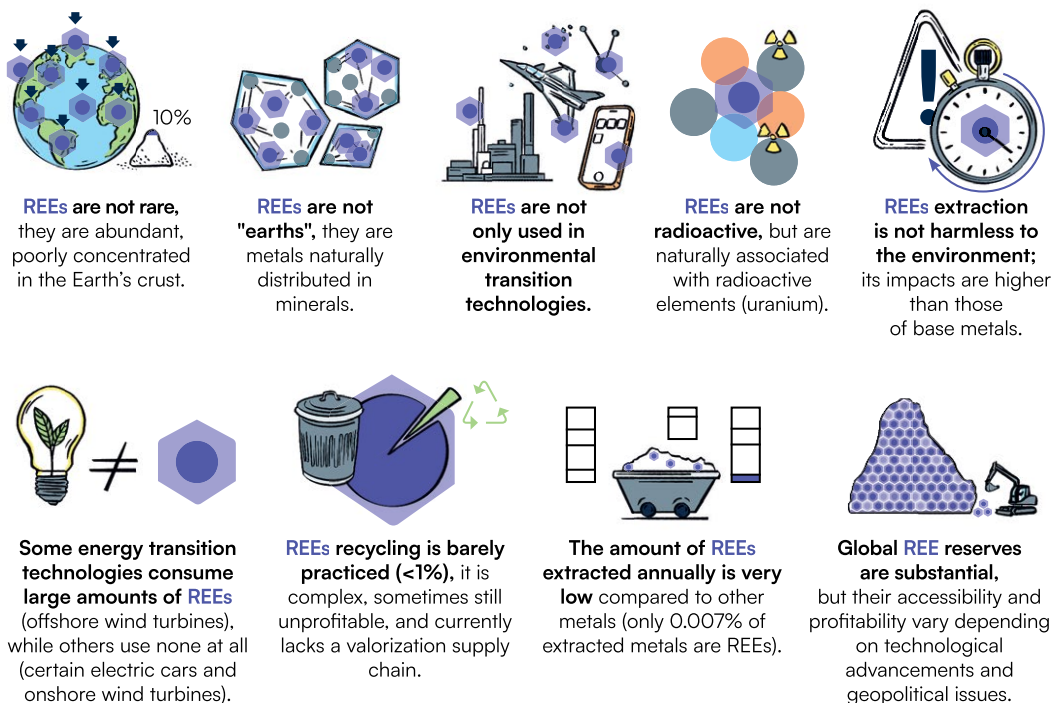


Figure 1 : What REEs are as chemical elements (top) and clarifications regarding certain misconceptions (bottom). The concentration shown is the average concentration in the Earth's crust (UCC average); the price indicated corresponds to the price of REE oxides of a purity greater than 99% in March 2025⁶. The level of criticality of REEs is represented on a scale of three '+' (a single '+' being the lowest criticality). Promethium and scandium are not included here: the former does not exist in a stable state in nature, whilst the latter is distinguished by its properties (notably its ionic radius) and by uses that differ from those of the other sixteen REEs.

6 - Price list for rare earth products as at 3 March 2025. Source: Epoch Material.

To identify the stages involved in creating an object and enabling its use, the continuum ‘constituent, material, device’ is generally used.

By constituent, we mean here the molecule, compound, phase, mineral, metal or alloy in which REEs are involved. The literature focusing on the study of REE-based constituents is therefore essentially fundamental and characterises their specific physico-chemical properties (luminescence, magnetism, chemistry, etc.). A material is a constituent (or a set of constituents) that has been shaped to maximise and make usable one or more of its properties (e.g. the magnetic flux of a magnet). The associated literature is therefore based on fundamental studies of the constituents and examines their conversion into a material. The device (or product) is the stage that enables use by fulfilling a given function (e.g. the rotation of a magnetic flux to drive a motor). It may combine different materials and is only meaningful if it is subjected to conditions of use that allow the material’s performance* to be exploited. The associated literature is often applied to, or even derived from, technological studies, patents, etc.

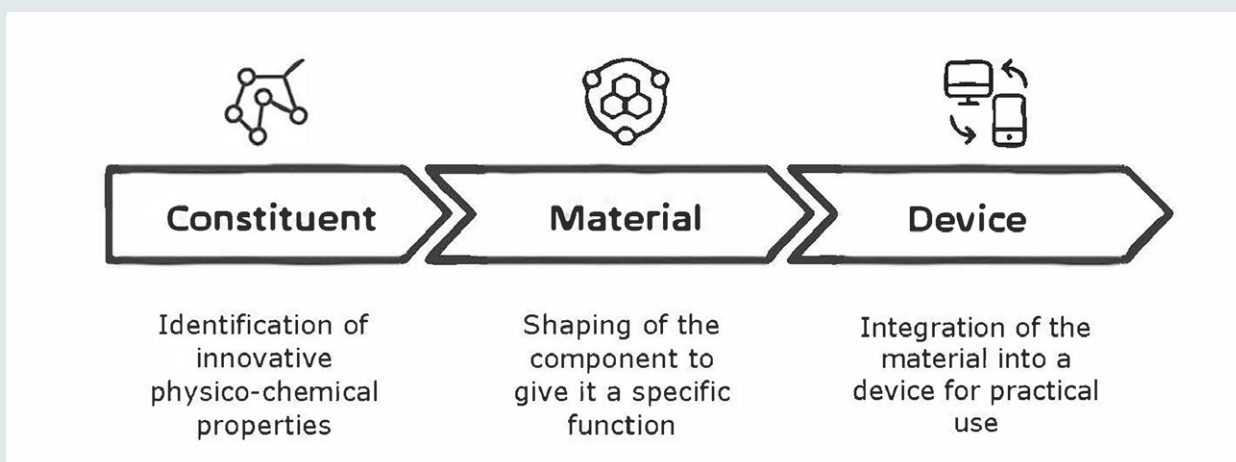


Figure 2 : From constituent to use: the ‘constituent, material, device’ continuum.

1.2 Applications

Links between the properties of constituents, materials and devices

REEs possess unique properties that make them essential in many technological fields (Bünzli, 2022; Piguët, 2019) (Figure 3): neodymium, dysprosium, praseodymium, terbium and samarium (constituents), for example, possess unique **magnetic properties** used in the manufacture of permanent magnets* (materials) which are used in a wide range of technologies such as the motors of hybrid cars and certain electric cars and offshore wind turbines, as well as in numerous electronic devices (devices or products). Magnets now account for nearly a third of REE usage and are particularly strategic for the decarbonisation of energy. Cerium, lanthanum, neodymium and praseodymium possess **chemical properties** that have been used for over 60 years to **catalyse** numerous chemical reactions on an industrial scale (notably petroleum cracking for fuel production) and in the automotive sector (catalytic converters to reduce harmful exhaust emissions), which accounts for nearly 21% of their uses. **The chemical and (thermo-)mechanical properties** of

certain REEs (lanthanum, cerium, praseodymium, neodymium, gadolinium) are used to improve the high-temperature oxidation resistance of several metals and alloys (particularly in the aerospace industry), as well as certain types of glass. Polishing powders manufactured mainly from CeO_2 are used to polish all types of glass, and primarily those requiring very fine polishing, such as computer screens, optical lenses, or semiconductors. These applications account for approximately 20% of REE uses. **The unique optical properties** of certain REEs (cerium, praseodymium, neodymium, europium, gadolinium, terbium, dysprosium, holmium, erbium, ytterbium) also make them key components in numerous photonic devices: solid-state lasers, optical amplifiers for telecommunications, phosphor screens and lamps, luminescent biomarkers for medical imaging, light-to-energy converters in solar panels (Figueiredo et al., 2024) or luminescent anti-counterfeiting markers (Bünzli, 2019). Finally, their **electrochemical properties** (cerium, lanthanum, neodymium, praseodymium) are used in the manufacture of anodes for nickel-metal hydride (NiMH) batteries.

In summary, REEs are used in numerous materials for their unique properties, which vary greatly from one REE to another; the REEs used in materials vary depending on

RARE EARTHS: PROPERTIES, MATERIALS AND APPLICATIONS

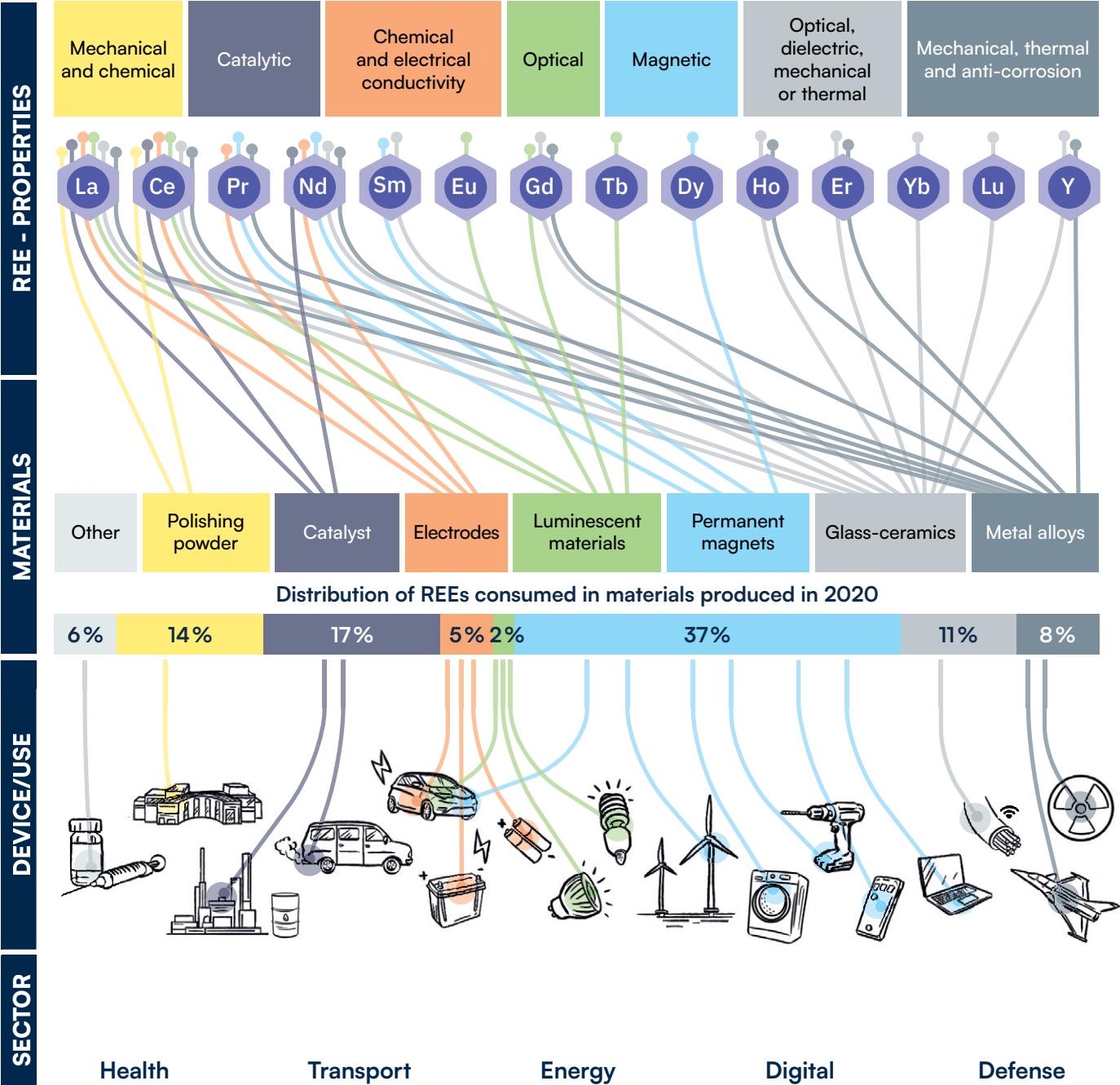


Figure 3 : The use of REEs in materials according to their properties, the distribution of REE consumption in materials produced in 2020 (only contributions of REEs representing at least 2% of the REEs used in a given material are shown here) and the use of these materials in numerous devices. These devices are involved in various ways across several sectors. This figure was produced using data from Vaughan et al. 2023 and Alonso et al. 2023.

the desired property (e.g. neodymium, praseodymium and dysprosium, used for their magnetic properties in permanent magnets). These materials are in turn used in various devices spanning a wide range of application areas such as energy, the environment, digital technology, medicine and even defence, giving them a character often described as ‘strategic’. Furthermore, a single device may contain different materials containing REE. For example, hybrid cars may contain REE in the permanent magnets (neodymium, praseodymium, dysprosium, terbium) in the main motor and small auxiliary motors, in the NiMH battery (neodymium, praseodymium, dysprosium), in the exhaust catalyst (cerium) and in the phosphors of LED headlights (europium, yttrium, etc.).

Trends in use

Another distinctive feature of REE is that, unlike other metals, their field of application has evolved considerably over time and diversified, to the point where REE have become indispensable in many technologies.

The market for technologies using REE is growing very strongly overall, but certain sectors are experiencing different trends (Figure 4). For example, certain applications, such as permanent magnets, are growing significantly. The amount of REE used worldwide for **permanent magnets** rose from 37 to 60 kilotonnes (kt) between 2012 and 2020 (Vaughan et al., 2023). Similarly, the production of **polishing agents** more than doubled over the same period (11 to 23 kt). Other uses stabilised between 2012 and 2020. This is the case, for example, with catalysts and batteries (29 and 8 kt on average). Finally, **the only application to have seen a sharp decline is that of phosphors** (9 to 4 kt), which can be explained by the replacement of phosphor lamps with LEDs, most of which still use REEs but in much smaller quantities. Most REEs are used in several fields of application where demand for REEs is changing rapidly.

Based on three scenarios for limiting greenhouse gas emissions, the International Energy Agency (IEA) projects **a doubling of demand for REEs for permanent magnets by 2050**, notably due to strong demand for electric vehicles (which account for 7% of demand for permanent magnets in 2023 and are projected to account for 30% of this demand in 2050). These scenarios assume strong growth in certain markets without systematically incorporating sobriety (or sufficiency)* options. Conversely, ADEME indicates that for the same decarbonisation target by 2050, REE requirements can vary by a factor of 1 to 3 depending on societal choices regarding energy efficiency, ranging from the ‘Frugal Generation’ scenario—which envisages lighter vehicles and increased car-sharing—to, at the other end of the spectrum, the ‘Repair-focused’ scenario, which extends current trends. ADEME emphasises that vehicles represent the main driver of metal consumption in the energy transition. Mobility policies could therefore play a significant role in shaping future demand for REE.

Since the 2010s, several research teams have analysed trends in future demand for REE, generally looking ahead to 2050. The vast majority of these quantitative studies conclude that to ensure the supply of REE, action is needed on both the supply side (increasing production) and the demand side (sufficiency practices). These assessments agree on a number of points:

- 1 • Demand is driven by new technologies (**wind power and electric vehicles**). Alonso et al. (2012), as early as 2012, proposed an assessment of demand for neodymium and dysprosium based on five usage scenarios (evolutionary scenarios and revolutionary scenarios involving a technological breakthrough). By varying four factors (the increase in installed wind power capacity and electric mobility, the persistence of current technologies, the need to keep atmospheric CO₂ levels in the atmosphere below 450 ppm, and the absence of recycling), the article showed that, over 25 years, new technologies could increase demand for neodymium by up to 700% and for dysprosium by 2,600% compared to 2010.
- 2 • **Global demand for REEs will exceed supply**, leading to shortages or even scarcity in the short to medium term for metals such as dysprosium or neodymium. Some publications emphasise that the situation will not be so critical, as recognised reserves are sufficient to meet demand (de Koning et al., 2018). The specific figures vary depending on the scenarios and assumptions used — for example, the proportion of recycling. In their scenario with 100% recycling of magnets, Liang et al. (2023) estimate that primary demand for neodymium will fall from 60 to around 25 kt/year (Table 1; for approximately 400 GW installed per year and 150 million vehicles sold per year). **Measures to reduce demand (sufficiency) or boost secondary supply (recycling) are essential**. Granvik et al. (2025) thus show that for dysprosium, supply-demand balance is achievable only in a low-demand scenario: with relatively stringent sufficiency policies, balance is reached in 2060 provided that recycling is implemented. The same authors show that for neodymium, a significant increase in recycling from 2035 onwards is a prerequisite for achieving balance under a medium-demand scenario.

For wind turbines, Kleijn and van der Voet (2010) estimate the neodymium requirement for 24 TWe of electricity generated by wind turbines by 2050 at 3.6 million tonnes, which is 180 times the annual production at the time of writing. Demand for neodymium, praseodymium and dysprosium for wind turbines could rise from 9.5 kt (2011–2015) to 105.9–230.9 kt (2046–2050), according to Li et al. (2020). The authors estimate the cumulative increase (over 5 years) in demand for neodymium, praseodymium and dysprosium to be 22%, 22% and 97%, respectively, assuming neutral technological progress and no further improvements in material

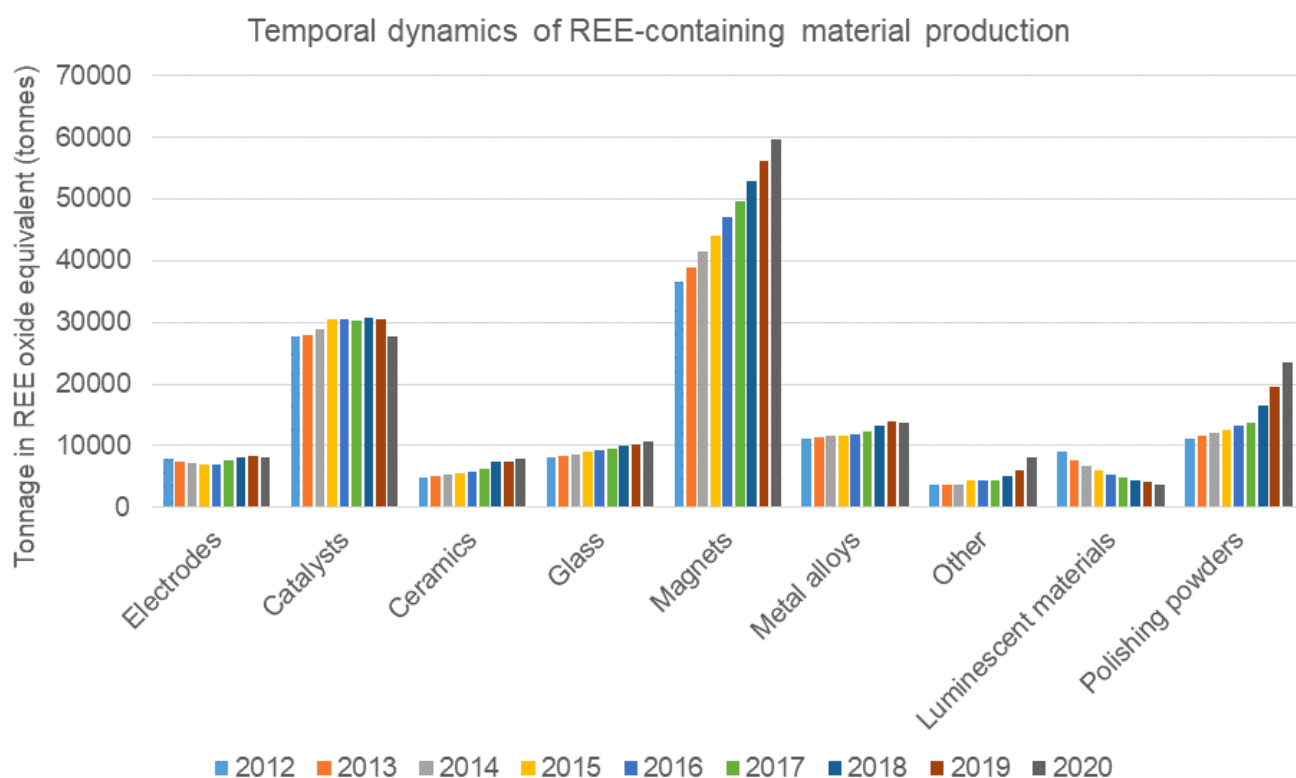


Figure 4 : Temporal trends in the main uses of REEs, according to Vaughan et al. 2023.

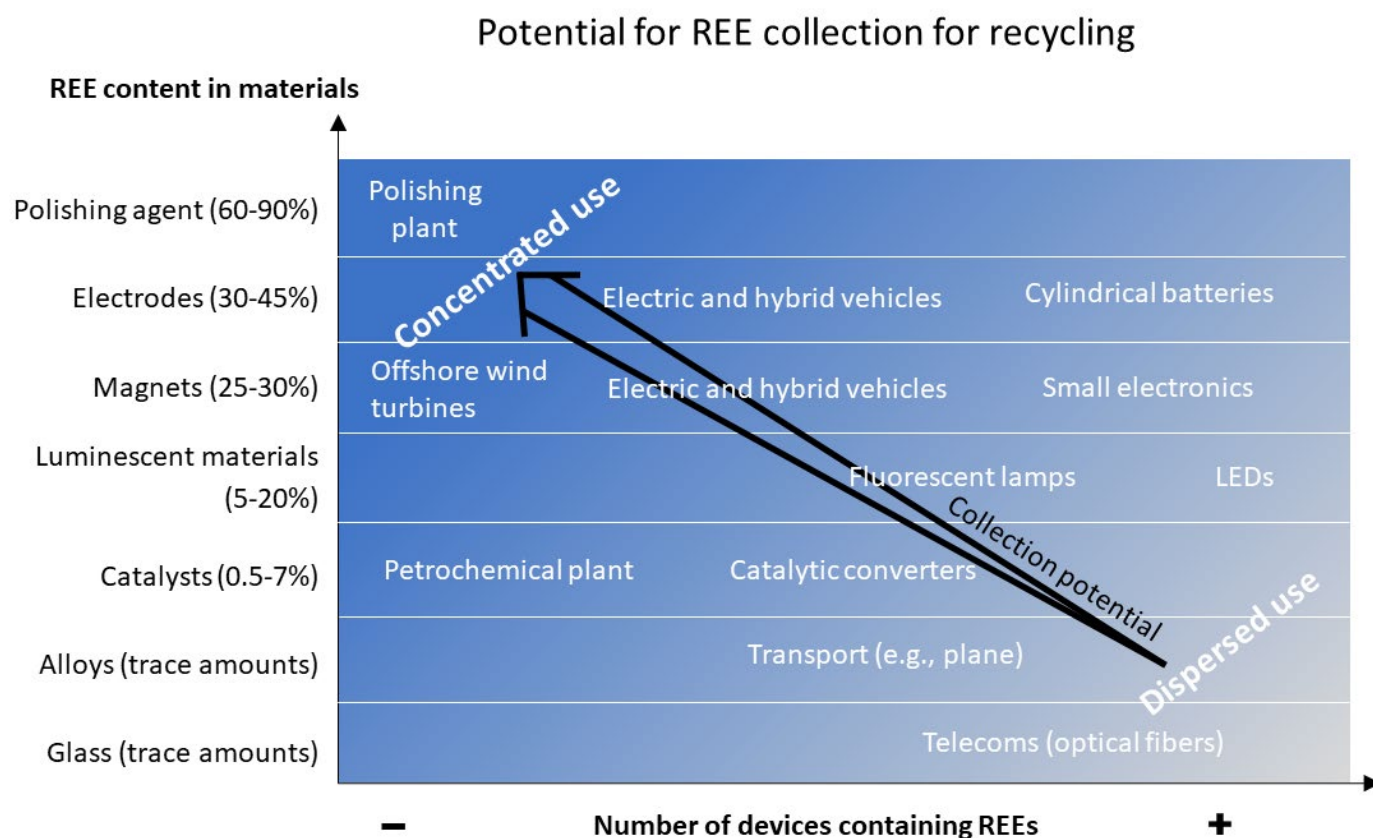


Figure 5 : Impact of the dispersion of REEs across technologies on the potential for collection for recycling.

	Installed wind power capacity	Number of electric vehicles sold	Annual demand for neodymium in 2050
Kleijn et van der Voet (2010)	400 GW	2 G in total	60 kt ⁷
Schulze et Buchert (2016)			Between 27 and 70 kt depending on the scenario
Li et al. (2020)	700-1500 GW		105-230 kt
Deng et Ge (2020)			70 kt
Liang et al. (2023)	400 GW	150 M/year	60 kt

Table 1 : Comparison of estimates from several studies of annual neodymium demand in 2050.

⁷-Kleijn and van der Voet (2010) also estimate that 2 to 4 Mt of neodymium will be in circulation by 2050.

efficiency by 2050. Projecting wind turbine demand, Deng and Ge (2020) show that as wind turbine demand increases, the relative share of installed capacity using 'direct-drive' turbines (technology containing REEs) grows.

For electric vehicles, Kleijn and van der Voet (2010) estimate that there will be 2 billion cars by 2050, which would correspond to 2 to 4 million tonnes of neodymium (200 times the current annual production in 2010). According to Habib et al. (2020), future demand for neodymium and dysprosium stems mainly from permanent magnets in electric vehicle motors and to a lesser extent from NiMH batteries in hybrid vehicles.

In both cases, **the demand for REE stems mainly from magnets.** According to Liang et al. (2023), demand for REEs contained in NdFeB magnets over the period 2040–2050 will be two orders of magnitude greater than in the previous decade (2011–2020) (18, 60 and 18 kt, respectively in 2050 for dysprosium, neodymium and praseodymium).

Generally speaking, the orders of magnitude cited in the various publications are consistent (Table 1).

The approach proposed here does not treat future growth in demand for REEs as a given, but as a prevailing assumption in the literature. An inventory of essential needs, across all uses, and of the various means of meeting them would go far beyond the scope of our expertise and would require establishing a hierarchy among these uses; however, it would constitute an essential preliminary step for any prospective study on possible trends in REE demand.

From dispersed to concentrated uses

However, REE consumption is not considered solely in terms of tonnage, but also in terms of *concentration of uses*, which refers to the quantity of REE used in a single material or device. This concept can be applied at two levels: 1) at the material level, where one can arbitrarily distinguish **materials with high REE content** (> 10% by mass), such as permanent magnets, polishing powders or phosphors, and **materials with low REE content** (< 10% by mass and sometimes in the order of 1 mg/kg, i.e. 0.0001%) such as glass. These materials themselves may be dispersed or concentrated within devices. It is therefore important to consider both the quantity of REE per device and the number of devices. From a recycling perspective, the dispersion of REE-containing materials across technologies is indeed an important factor to consider, particularly during the collection and dismantling stages. Two main types of use can thus be distinguished (Figure 5). **Concentrated uses** (e.g. wind turbine motors) are characterised by a limited number of devices containing a significant mass of materials (permanent magnets in the motor), which are themselves concentrated in REE (30% REE in permanent magnets, amounting to around one tonne for an offshore wind turbine). Conversely, **dispersed applications** (e.g. optical fibres) are characterised by a very large number of devices in circulation containing materials with a low concentration of REE (0.01% REE by mass), thus using a small quantity of REE per device (in the order of milligrams to grams).

The growing demand for REEs, driven in particular by the requirements of the energy transition, raises a key question: that of supply. These elements, which have become strategic for many sectors, are naturally distributed across the globe, but their extraction* and refining* remain largely concentrated in the hands of a few *de facto* dominant players. Understanding resource availability, the geological nature of deposits, and the dynamics of global production is essential for assessing the sustainability of this growing demand.

I.3 Resources, reserves, production

Geological resources and reserves that are well distributed geographically

The resources of a deposit depend on the volume (tonnage) and concentration of the raw material (grade). If exploitation conditions meet the criteria for economically viable mining*, the resources* are reclassified as **reserves***. Consequently, a country's reserves fluctuate depending on geological discoveries and exploitation conditions that would allow non-exploitable resources to be converted into reserves.

In 2017, global REE **resources** were estimated at 478.14 millions tonnes (Mt) of 'REE oxide equivalents' (Zhou et al., 2017). This does not refer to oxides actually produced, but rather to a standardised method of comparing the total quantity of REE contained in a deposit or produced. The uneven distribution of REE resources across a dozen or so countries (see introduction and Figure 6) is explained by the geology of the subsoil. The **deposits** result from REE enrichment processes under very contrasting environmental conditions (Charles et al., 2022). In the deep Earth's crust, REE deposits form from magmas or through interaction with hydrothermal fluids. REE enrichment can also occur on the Earth's surface, either through sediment accumulation or rock weathering. According to the United States Geological Survey (USGS), global REE **reserves** are estimated at approximately 100 Mt of REE oxides by 2025. Two-thirds of these reserves are concentrated in two countries: China (44%) and Brazil (21%). Other countries also have reserves exceeding one million tonnes, including India (6.9%), Australia (5.7%), Russia (3.8%), the Vietnam (3.5%), the United States (1.9%) and Denmark (Greenland, 1.5%). Added to these are countries such as South Africa, Myanmar, Canada, Madagascar, Malaysia, Nigeria, Sri Lanka, Tanzania and Thailand, which together account for around 3%. In Europe, the main REE deposits are found on the Scandinavian Shield, with reserves estimated at around 1% of global reserves. However, European reserves are not included in the USGS data.

GLOBAL REE RESERVES, RESOURCES AND EXTRACTION

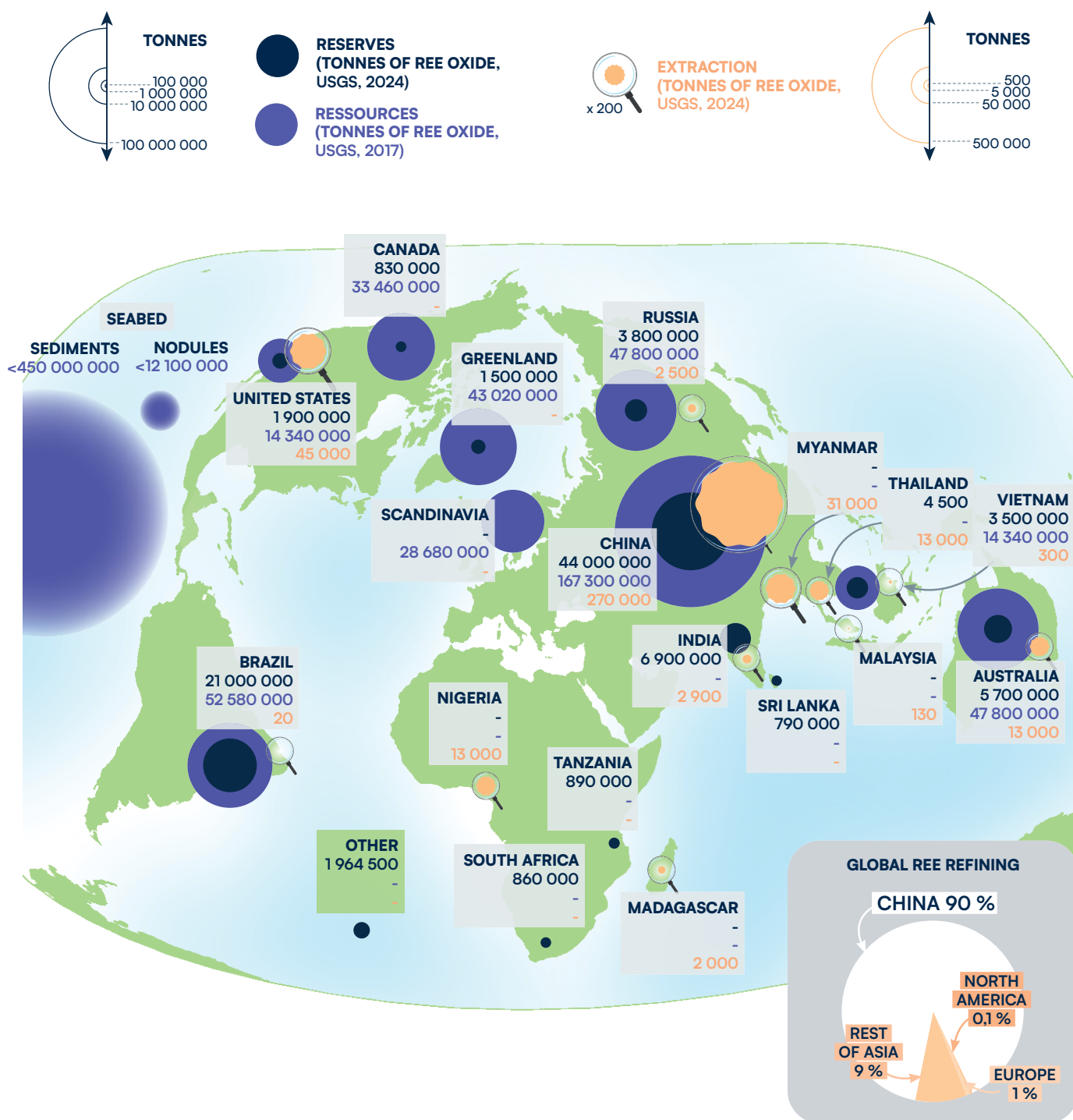


Figure 6 : Map of global REE reserves, resources and extraction (based on USGS data), as well as the distribution of refined REE production (based on IEA data).

Beyond primary REE resources, **secondary sources* of REE are emerging as potential alternatives, particularly for countries without primary deposits.** These secondary sources include mining waste (e.g. bauxite tailings*, phosphogypsum*), industrial waste (e.g. coal ash, scrap from permanent magnet manufacturing) and end-of-life products containing REE, also known as the ‘urban mine’* (e.g. smartphones, electric cars, wind turbines, contrast agent solutions, etc.). The potential of these sources is examined in Chapters III and IV of this synthesis.

Centralisation of the majority of extraction and refining in China

Global production of REE has been growing at a near-exponential rate since the opening of the Mountain Pass mine in the United States in 1952. Until 1965, global production barely exceeded 10,000 tonnes of REE oxides per year. By 2024, it is approaching 390,000 tonnes per year, with an average growth rate of 13% since 2015. Annual production remains relatively low compared to identified reserves (a factor of 230 between reserves and annual production in 2024).

Whilst resources are unevenly distributed globally, global REE extraction and production has been predominantly controlled by China since the 1990s (Figure 7). In 1992, during a visit to Inner Mongolia, Deng Xiaoping, then leader of China, declared: “The Middle East has oil, China has rare earths”. With foresight, China then invested heavily in the exploitation of REE across all stages of the value chain, from extraction from deposits to their separation*, processing* and refining, and finally to their transformation into intermediate (materials) or finished (incorporated into end-use products) goods. This strategy has borne fruit. By the mid-1990s, Chinese production had surpassed the production historically provided by the United States. In the 2000s, Chinese production achieved a virtual monopoly (97% of production). Following the 2010 crisis, triggered by the export embargo on Japan and a tenfold increase in prices (see below ‘The politicisation of REE’), new sources of supply were sought. From 2011 onwards, the development of new deposits and the reopening of historic mines diversified the origin of the mined ores. New exploration projects were launched (Barakos et al., 2016). By 2024, other producers (excluding China) account for one-third of global extraction and are mainly represented by the United States, Australia, Myanmar, Nigeria and Thailand. Despite this diversification of mining activity, the majority of extracted REEs are subsequently sent to China for refining (around 90% in 2024 according to the IEA).

The environmental and health impacts of mining

The environmental impacts of mining must be considered beyond the intrinsic toxicity of the elements. The impacts of the REE extraction process are significantly higher than those associated with base metals (aluminium, copper, steel,

nickel and zinc) but lower than those associated with the extraction of precious metals (gold, palladium, platinum, rhodium and silver) (Ikhlaiel, 2017). Studies show that **the use of numerous chemicals** during the various stages of REE extraction and processing is responsible for the main impacts (Marx et al., 2018). For example, in the case of the Bayan Obo mine in Inner Mongolia, a single enrichment stage for one tonne (t) of REE requires 4.41 t of sulphuric acid, 12.32 t of sodium chloride, 1.64 t of sodium hydroxide, 1.17 t of hydrochloric acid, 1.90 t of water and the grinding of nearly 50 t of ore (Yin et al., 2021). However, these impacts vary significantly depending on the type of deposit, mineralogy, ore grade, processing techniques and by-products (Peiro and Mendez, 2013). Among the identified impacts, the **generation of radioactive waste** is a major issue specific to the extraction of rare earth elements (Yin et al., 2021). Indeed, naturally occurring radioactive elements such as uranium (U) and thorium (Th) are geochemically associated with REEs, particularly in monazite and bastnäsite. Thus, depending on the nature of the deposit, rare earth element extraction processes can produce up to approximately 1.4 tonnes of radioactive waste per tonne of rare earth oxide.

A significant environmental risk is evident mainly around heavily contaminated areas such as mines or industrial processing facilities, particularly due to the high concentration and **intrinsic toxicity of REEs**. Consequently, REE extraction disrupts soils, vegetation and ecosystems. This is particularly the case in China, where concentrations of toxic metals in the soil of mining regions exceed the geochemical background levels. Mining also generates significant air and surface water pollution, with REE levels sometimes 200 times higher than normal (Yin et al., 2021). These impacts are exacerbated by the presence of mining waste which, when exposed to the elements, is itself likely to pollute the air, soil, surface water and groundwater, thereby worsening environmental degradation and risks to human health. REEs accumulate mainly at the lowest levels of food chains and particularly in plants, increasing human exposure through the food chain (Sager and Wiche, 2024). Light REEs are generally more mobile and more readily absorbed than heavy ones. The toxicity of REEs varies depending on the element and conditions, with observed effects such as oxidative stress, neurotoxicity or malformations. The effects on aquatic organisms are still poorly understood, particularly in marine environments. Tests show significant variations in toxicity depending on the species tested and the protocols used. Beyond extraction sites, REEs from anthropogenic sources (arising from various uses) can be of particular concern for the environment when they are released in a mobile form and are more readily available to organisms, including humans (Balaram, 2019).

With regard to **health impacts**, the toxicity of REEs is often underestimated despite their potentially serious effects on human health, particularly among workers exposed in the mining, refining and recycling sectors. REEs can accumulate in the body and cause cellular damage, oxidative stress and various lung and kidney disorders. However, direct epidemiological data remain limited, with the exception of certain medical uses (Balaram 2019).

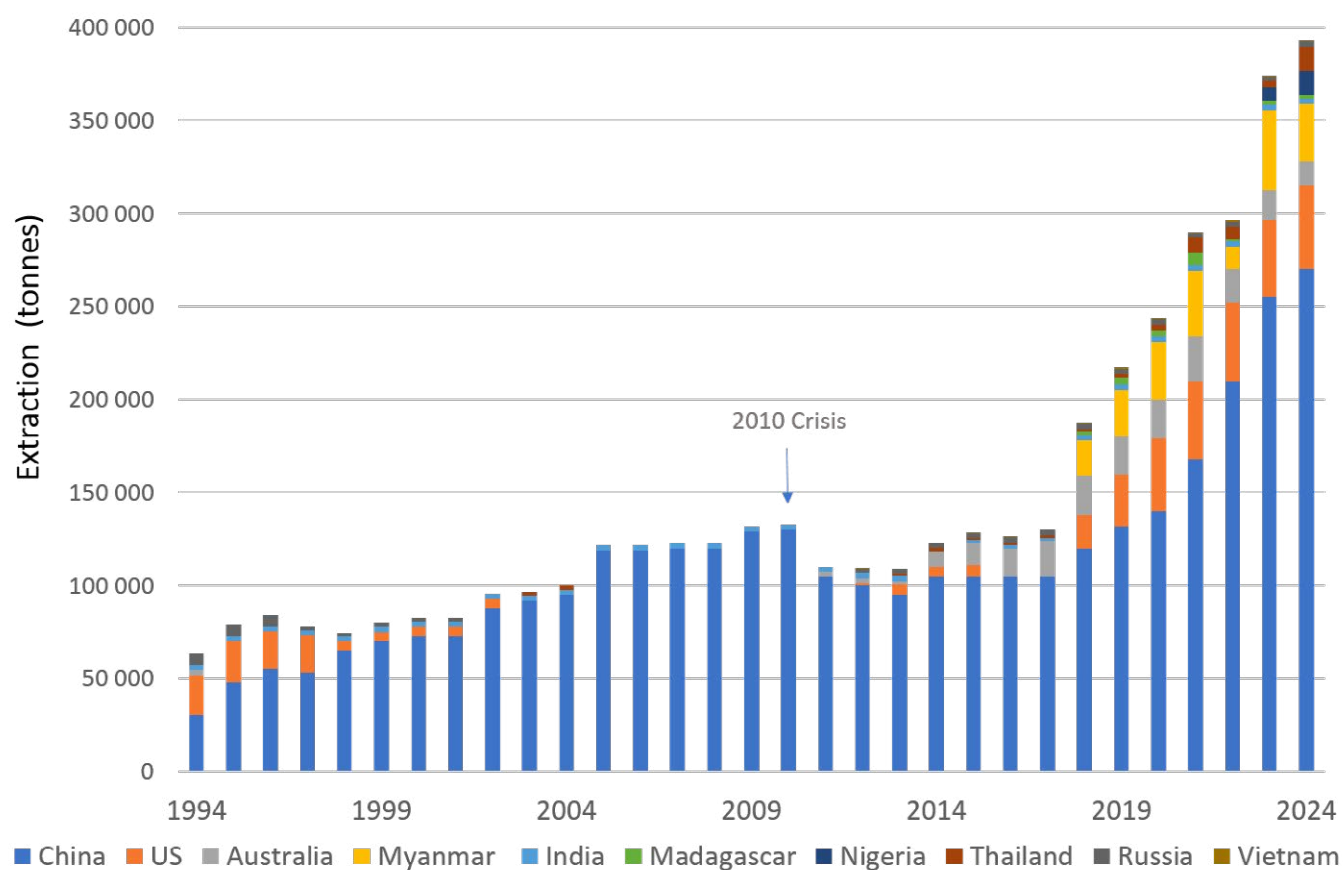


Figure 7 : Evolution of global REE production between 1994 and 2024 (in tonnes, according to the USGS).

The ‘balance problem’

Unlike other elements, the REEs are a family of elements that are necessarily extracted together. Nevertheless, they are not all used for the same applications. Consequently, an imbalance may arise between their production and consumption. Indeed, technological requirements are highly specific: each technology often uses only one to five REEs, whereas in nature—and particularly in ore deposits—the 17 REEs are always found together in relative abundances that can vary depending on the geological origin of the substrate. **There is therefore a significant imbalance between production and demand, known as the ‘balance problem’.** This imbalance leads to overproduction of certain REEs (e.g. cerium and lanthanum, which are also the most abundant naturally) and tensions surrounding the REEs that are most widely consumed and/or least naturally concentrated (e.g. dysprosium and terbium), with significant consequences for the market. It is therefore important to consider the supply and demand for REE on an individual basis, particularly in the context of growing demand for permanent magnets, which exacerbates this phenomenon for neodymium, praseodymium, dysprosium and terbium.

The REE market

The REE market is modest (around \$7 billion per year), much smaller than that for base metals, due to significantly lower production volumes (390,000 tonnes per year in 2024 compared to over 2.5 billion tonnes per year for iron).

Light REEs (lanthanum, cerium, neodymium) are the most abundant and account for around 90% of production. Conversely, heavy REEs such as lutetium are rarer and more expensive. **The price of REE varies according to their natural abundance in deposits and their uses.** For example, lanthanum and cerium cost around \$1,000/t in March 2025, whilst lutetium cost \$700,000/t. Neodymium, prized for its use in magnets and found in deposits at concentrations similar to those of lanthanum and cerium, commands prices 60 times higher (around \$63,000/t).

Between 2015 and 2024, the market appears fairly stable for the majority of REE (according to the USGS). A special case concerns europium. Its value has fallen very significantly, from \$344 to \$27/kg. This is due to the decline in the production of phosphor lamps, the main application for this REE, which have been replaced by LED technology. For the others, price fluctuations are more moderate. Lanthanum and cerium have seen their prices fall from \$3 to \$1/kg over this period. Conversely, the prices of neodymium, dysprosium and terbium (used in the manufacture of permanent magnets) are rising steadily but modestly, peaking in 2021/2022, when they were two to three times higher than in 2015.

Whilst REEs have become key resources for supporting the energy and digital transition, their extraction, processing and refining simultaneously raise serious environmental and health concerns.

I.4 REEs as political objects

Given the economic importance of REEs for a wide range of strategic uses, the supply risks and the scale of the environmental and social impacts associated with their extraction, the question of their governance has become central. These issues are not solely a matter of technical or ecological considerations, but are also embedded within a complex web of power relations, economic strategies and political choices. Consequently, **REEs are no longer merely industrial resources: they are becoming geopolitical and geo-economic objects, at the heart of intervention mechanisms driven by a variety of actors.**

Historically, the REE market has been structured primarily around significant state intervention by China and the United States. The literature on the geopolitics and commodification of REEs provides a clearer understanding of the famous ‘2010 rare earth crisis’ and the successive state responses at both national and international levels. The ‘2010 rare earth crisis’ refers to an episode of geopolitical tension that has been extensively analysed in the literature. That year, China threatened to restrict its exports of REE to Japan in order to secure the release of a Chinese trawler captain. This triggered panic on global markets. Between September 2010 and August 2011, REE prices rose approximately tenfold; the price of dysprosium oxide increased by 1,100% and that of neodymium by over 1,000% (Boudia, 2019). This crisis was widely interpreted in media and policy debates as revealing a Chinese strategy to demonstrate its hegemony in REE production, a hegemony long in the making to secure market power (Gholz and Hughes, 2021).

Nevertheless, the literature qualifies this interpretation by noting that **the structure of the global REE market is linked to a multitude of intertwined state and private interventions over the long term.** All REE-producing states have sought to influence the restructuring of global markets by strengthening the value chains over which they have total or partial control (Hatakeyama, 2015).

The structure of the global REE market from the 1950s to the 1980s

China has not always dominated global rare earth production. **From the 1950s to the 1980s, a variety of producers coexisted.** In the 1950s, the world’s leading producer of rare earth elements was the United States (Medeiros and Trebat, 2017). Mining and production were concentrated at Mountain Pass in California’s Mojave Desert. During this period, this mine not only supplied the government’s strategic reserves but was also the world’s leading supplier of REEs for export until the 1980s. In 1982, the Mountain Pass mine accounted for 70% of annual global production of REE oxides (Goldman, 2014). In addition to the Mountain Pass mine, the United States controlled the entire REE value chain, from separation and refining to the production of manufactured goods using REE. The United States produced various higher value-added products containing

REEs, such as neodymium-iron-boron (NdFeB) magnets, developed and patented in 1983 by General Motors and manufactured for two decades by a subsidiary company called Magnequench.

Furthermore, whilst China was historically one of the first countries in the world to establish a national REE economy from the 1950s onwards, this was not initially to seek dominance of the global REE market, but rather for **reasons of national policy and internal security** (Kraus, 2010). The focus of Chinese geological research and REE extraction is in the Bayan Obo region, near the city of Baotou in northern China, on the border with Mongolia. This geographical distribution of the Chinese value chain is neither coincidental nor due solely to favourable geological conditions. The geopolitical literature highlights in particular the fact that, as early as 1949, the People's Republic of China developed rare earth element mining in this area in order to further integrate this territory near Mongolia into its national project, on the one hand by creating economic opportunities for its inhabitants in a disadvantaged region, but also to localise the pollution associated with rare earth element mining on the periphery of its own national territory (Klinger, 2018a).

The structuring of the REE market from the 1980s to the 2010s

From the 1980s onwards, political transformations in the United States and China generated a dynamic that reshaped the global division of production and export of rare earth elements. These political transformations are linked both to the liberalisation of Anglo-American economies during the era of Ronald Reagan and Margaret Thatcher, and to the new economic policies driven by the Chinese government at the turn of the 2000s to restructure its value chain (Kiggins, 2015). In this context, **the enrichment and value-added processing of REEs began to shift from the United States to China**, culminating in the concentration of global REE production in Baotou and Bayan Obo at the turn of the millennium (Butler, 2014).

In the United States: a policy of production relocation in the 1980s

In the United States, two factors drove the relocation of the REE value chain. At the end of the Cold War, there was first the gradual emergence of a government consensus around the idea that an international market was likely to supply the metals and REEs that the United States might need without requiring the support of a dedicated public policy sector. This analysis was notably reinforced by the **significant fall in commodity prices** at the end of the Cold War, following in particular the sale of American and Soviet wartime stockpiles, which caused their prices to collapse (Humphreys, 1995). Furthermore, the outsourcing of certain stages of the REE enrichment process to China was driven by a political desire

on the part of private and public actors to shift the environmental consequences of REE refining away from the places of consumption (Dobrinsky, 2015).

Indeed, from the 1980s onwards, the Mountain Pass mine was responsible for numerous instances of pollution that were documented and penalised by the US Environmental Protection Agency (EPA). In particular, Mountain Pass experienced numerous leaks of wastewater into the environment. An EPA investigation revealed sixty spills between 1984 and 1998, several of which were unreported. Between 1994 and 1997, seven spills are said to have released 1.3 million litres of wastewater along a section of pipework near Mojave National Park (Klinger, 2018a). Federal authorities estimated that approximately 2.3 million litres of radioactive wastewater had been discharged into the desert. In 1998, the mine suspended its processing operations following an order from the San Bernardino District Attorney, who issued a clean-up injunction.

In the early 1980s, Edward Nixon, a geoscientist and brother of US President Richard Nixon, suggested to Mountain Pass executives that **they outsource certain enrichment operations to China to reduce their environmental impact in California and achieve cost savings** (Klinger, 2020). Faced with repeated fines for environmental violations and price pressure from cheap Chinese products, the Mountain Pass mine closed in 2000 (Goldman, 2014). This consolidated 97% of REE production in China.

In parallel with the relocation of part of the Mountain Pass operation and its subsequent closure, key US companies specialising in **the manufacture of REE-based permanent magnets also relocated their operations to China** (Barteková and Kemp, 2016). This was the case with Magnequench, whose management relocated the company in 1998 following a takeover by its two main clients at the time, San Huan New Materials and China National Non-Ferrous Metals Import and Export Corporation, two major players in the Chinese REE trade. At the time of this decision, representatives from both parties in Congress demanded that the Committee on Foreign Investment in the United States (CFIUS) examine what they considered to be a Chinese takeover of permanent magnet production. The US Committee ultimately did not oppose this relocation (Barteková & Kemp, 2016).

In China: the decision to strategically retain high-tech industries from the 2000s onwards

The relocation of major US companies in the early 1980s was followed by a shift in China's economic policy regarding REEs. From the 2000s to the 2010s, China shifted from maximising REE production—primarily for economic development—to the **strategic conservation of these resources, coupled with the export of manufactured goods with higher added value**.

To explain this reversal, the literature cites two main factors: on the one hand, managing the economic consequences of industrial overcapacity; on the other, restricting REE production to address the environmental and epidemiological consequences of its extraction in the Bayan Obo region (Klinger, 2020).

In 2003, the central government published an updated version of its mineral resources policy. Unlike previous laws (1986 and 1993), this new text emphasised the need to promote more technologically advanced mining exploration and exploitation, as well as to improve environmental monitoring in the Bayan Obo region. To implement this policy, the Chinese government enacted the abolition of refunds on a range of export taxes on REE. The aim was to discourage exports and increase imports of raw materials, whilst developing domestic processing and component manufacturing capabilities. With this in mind, on 1 November 2006, the Ministry of Commerce announced that a **10% export tax on REE** would come into force on 1 June 2007 (Klinger, 2018b).

Furthermore, the Chinese government's new policy at the turn of the 2000s aims to acquire strategic resources abroad, including REE, or to encourage Chinese companies to do so, in order to limit the impact of their production on national territory. Chinese companies succeeded in acquiring a stake in the Australian REE producer Arafura and also attempted to take control of Lynas, Australia's largest REE producer, but this project failed due to a veto by the Australian government (Barteková and Kemp, 2016). Furthermore, China has offered grants and loans to certain countries in exchange for access to their raw materials (not only for REE), particularly in Africa (Hanauer and Morris, 2014).

Responses from non-Chinese states and companies to the rare earth crisis

A complaint to the WTO following the 2010 crisis

In 2011, the Chinese government published a high-level action plan for comprehensive regulation of the industry, emphasising sustainable development, and announced **the imposition of export quotas and stricter regulations for the REE sector**. At the same time, the Chinese government had adopted a white paper noting the harmful effects of REE production on the environment and public health, particularly through the generation of toxic waste, whether at the Bayan Obo and Sichuan mining sites, or — and above all — small mines operating illegally and developing beyond any government control (Gavin, 2015). The country has thus set out the objective of restructuring and protecting its industry, notably by imposing export quotas on importing countries in general. These measures, officially justified by the need to conserve natural resources and ensure the sustainable development of the mining sector, would at the same time enable China to strengthen its industrial and geopolitical position, notably by reserving these strategic resources for high value-added Chinese industries.

These indiscriminate export restrictions were interpreted as a veritable declaration of war. On 13 March 2012, **the European Union, followed by the United States and Japan** on 22 March and **Canada** on 26 March, requested the opening of consultations with China and subsequently the establishment of a panel on 27 June — which amounts to a complaint — before the Dispute Settlement Body of the World Trade Organisation (WTO), due to the restrictions imposed. According to the complainants, the restrictions put in place by China have caused **massive distortions and disruptions in the global supply chain** for REEs⁸. They **thus allegedly violate international trade law**, which prohibits quantitative restrictions on trade, whether direct or indirect, and export duties in the form of taxes, and argued that the restrictions were intended to grant Chinese industries protected access to the materials in question.

The Panel issued its report on 26 March 2014 and found that the general exceptions invoked by China (protection of the environment and public health) could not be used to justify a breach of the obligation to eliminate export duties on the listed products upon its accession to the General Agreement on Tariffs and Trade (GATT, 1947). It concluded that the export quotas imposed were intended to achieve industrial policy objectives other than the conservation of natural resources — as 'conservation' does not authorise Members to adopt measures aimed at controlling the international market for a natural resource (Verrax, 2014; Wang, 2018). China lodged a direct appeal against this ruling. The Appellate Body issued its report on 7 August 2014, rejecting its claims. Following this case, China made significant changes to its legislative framework: **in addition to lifting export restrictions, compliance with WTO law required it to regulate the environmental impacts of its activities more rigorously, whilst regaining control over its industry** to combat illegal mining (Wang, 2018; Gavin, 2015).

On 4 April 2025, in response to the imposition of tariffs by the United States on a range of Chinese products, China decided to restrict REE exports once again. **The resurgence of this 'rare earth war' in the news** clearly illustrates the scale of the consequences resulting from policy changes across the entire value and supply chain, against a backdrop of a Chinese quasi-monopoly. Furthermore, this resurgence highlights the need for states to anticipate these issues, notably by implementing a critical metals policy. In this context, several countries are indeed attempting to develop a strategy aimed at gradually securing a comprehensive REE supply chain and **thereby limiting their dependence on China** (the United States, Australia, Brazil, South Africa, Saudi Arabia, Japan and Vietnam). This is also what **the European Union** has done **with the adoption of the Critical Raw Materials Act (CRMA)** in 2024 (Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework to ensure a secure and sustainable supply of critical raw materials, known as the 'Critical Raw Materials Regulation', analysed *below*).

8-WTO, cases DS431, DS432, DS433: China — Measures relating to the export of rare earths, tungsten and molybdenum.

The resurgence of US state interventionism

The United States is a key player in the organisation of REE production (when it organises the offshoring or reshoring of production). Although a proponent of economic liberalism, the US has, paradoxically, been highly interventionist since 2010 in **an attempt to bring a value chain back** onto its national territory. This involves not only research and development policies and subsidies, but also defence measures related to the stockpiling of REE (aimed, therefore, at breaking free from market logic in the name of strategic interests).

More than thirty bills concerning REEs were considered by the US Congress between 2010 and 2014 (Klinger, 2018a). Although the legislative framework varied across the proposals, they all called for state intervention in the global REE market in order to repatriate production to the United States. The proposals ranged from the removal of mining regulations in the United States to encourage the return of investors, to the creation of federal funds to support the revival of an industry considered strategically vital. Debates in Congress were heated regarding the environmental and financial consequences of the various proposals.

Following these debates, the federal government developed the **'Critical Materials Strategy'** (US Department of Energy (2011) Critical Materials Strategy).

This strategy is based on three main pillars:

- 1 • **diversifying** global supply chains for REE to reduce risks,
- 2 • the development of **alternative** materials and technologies (notably improving the performance of REE-free technologies for batteries, as well as alternative designs for electric motors and wind turbine generators),
- 3 • **promoting recycling and the more efficient use** of critical materials.

The importance of research and development has been reinforced, as evidenced by the creation of new laboratories dedicated to research into critical materials, the establishment of university programmes on the next generation of permanent magnets (notably at the University of Delaware) and the funding of early-stage technological innovation (the ARPA REACT programme) (US Department of Energy (2011) Critical Materials Strategy). The US Department of Defence has also authorised the **Defence Logistics Agency to build up stocks of heavy REEs** (Barteková and Kemp, 2016). A subcommittee on critical and strategic metal supply chains, established by the White House Office of Science and Technology Policy, has also been set up to coordinate efforts between federal agencies.

Furthermore, the rise in REE prices following the 2010 crisis prompted some private operators to resume production of these minerals in the United States (Machacek and Fold,

2018). This led to the reopening of the Mountain Pass mine in 2012. However, the mine went bankrupt in 2015 due to competition from China and the fall in global prices.

In June 2017, an American consortium called MP Materials — comprising MP Mine Operations LLC, majority-owned by JHL Capital (65%), alongside QVT Financial (25%) and the Chinese company Shenghe Resources (10%, non-voting) — purchased the mine at auction. In 2020, the US Department of Defence provided strategic support to MP Materials as part of the revival of the Mountain Pass mine, in order to secure the national supply of REE. That same year, in April, initial funding was granted to plan the **construction of a heavy REE separation facility**. Then, in November, a \$9.6 million contract was awarded to enable the resumption of on-site refining of light REE, which had previously been exported to China. This support was reinforced in February 2022 by an additional \$35 million grant for the construction of another industrial heavy REE separation unit. These investments form part of a broader strategy aimed at **restoring a complete value chain on US soil**, reducing dependence on China and supporting critical needs for permanent magnets in defence, renewable energy and advanced technologies.

European interventions are tied to 'criticality' policies

In other countries around the world, and particularly in Europe, responses to the 2010 rare earth elements crisis have largely been linked to 'criticality policies'. These are based on criticality studies, which do not exclusively concern rare earth elements. These studies draw on **geological and economic knowledge** to anticipate the metal or mineral resource requirements of a given economy, with a view to **securing supplies through public or private initiatives**. Criticality studies have been the subject of theorising and research throughout the 20th century across all developed countries, and particularly in the United States during periods of war (De Young et al., 2017).

Criticality studies were carried out by geologists on behalf of the European Commission in 2011, 2014, 2017 and 2023, funded by a European research network (Lovik et al., 2018). The most recent European criticality study was carried out under the Critical Raw Materials Act. The Commission justifies its policy by referring to a criticality matrix published in 2023 (Figure 8). This **matrix is based on commodity market prices** to deduce their economic importance, taking into account, in particular, the OECD's forecasts of rising metal consumption⁹ up to 2060 (the higher the price of a substance, the more likely it is to be in demand in the future and the more likely it is to be critical). The matrix enabled the Commission's experts to identify **34 critical substances based on thresholds established by experts**. In France, criticality studies have also been carried out regularly by the Bureau de Recherche Géologique et Minière (BRGM) since the rare earths crisis. From now on, these studies are being carried out by the French Observatory of Mineral Resources for Industrial Sectors (OFREMI), established in late 2022 within the BRGM and comprising five other partner institutions (CEA, ADEME, IFRI, IFPEN, CNAM).

9 - The Organisation for Economic Co-operation and Development (OECD) is an economic research organisation with 38 member countries, primarily acting as a consultative body.

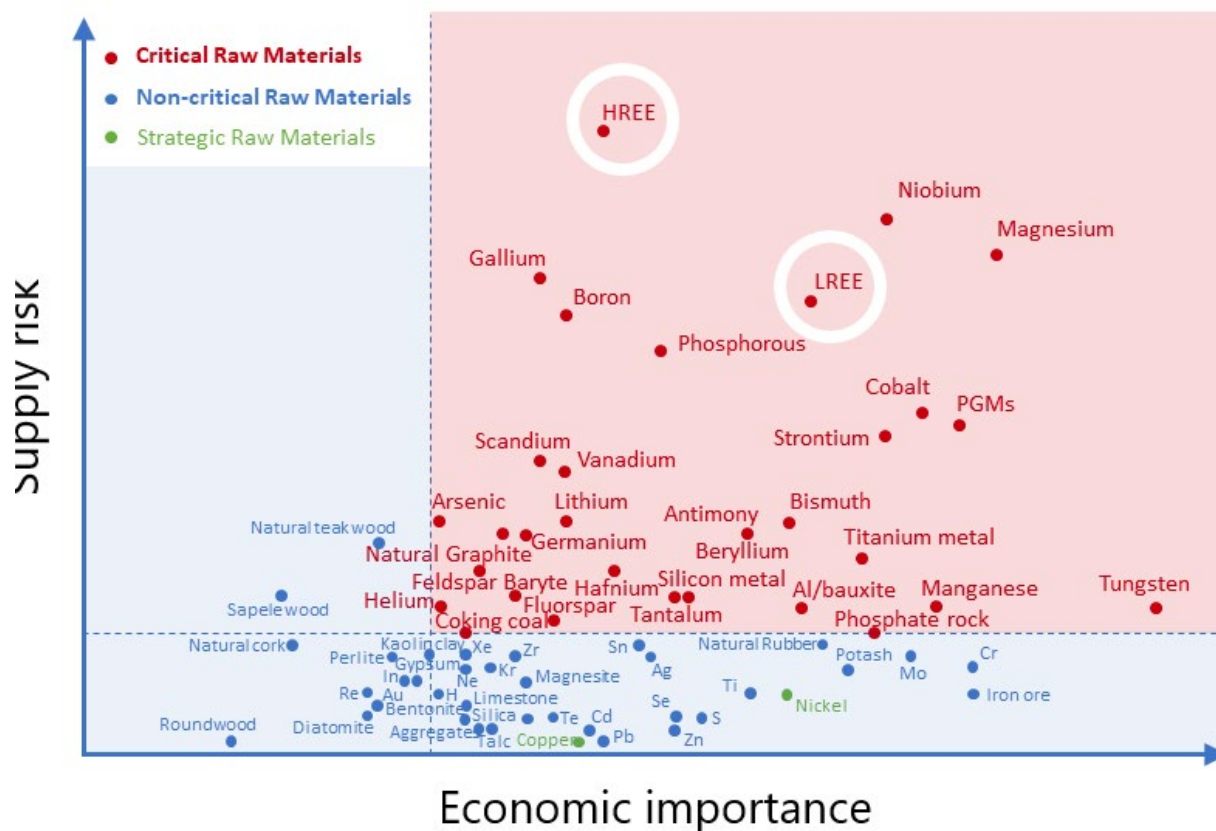


Figure 8 : Assessment of the criticality of various elements. HREE and LREE refer to heavy and light rare earth elements respectively. Diagram adapted from the European CRMA (Study on the Critical Raw Materials for the EU 2023 — Final).

I.5 Objectives and plan

The demand for REEs is currently regarded as essential for the energy transition, military and digital sectors. This demand for resources cannot be met solely by a revival of extraction within Europe, as the majority of supplies still originate from China, raising issues of sovereignty for nations. Thus, more responsible uses, which reduce our dependence on foreign supplies, can help address these challenges. The scientific literature identifies three levers in this regard (Figure 9):

- 1 • reducing REE consumption (Chapter II) ;
- 2 • recycling them (Chapter III) ;
- 3 • extract them differently, under social, political and environmental conditions that are more democratically acceptable — throughout the value chain (Chapter IV).

The aim of this synthesis document is to provide access to a vast body of scientific publications from a variety of disciplines, compiled on the basis of a rigorous protocol developed chapter by chapter and detailed in the appendix to the CSA report (in french). It thus provides solid scientific evidence for public debate and decision-making, whilst highlighting the uncertainties that remain in relation to these three levers.

REDUCE, RECYCLE, EXTRACT DIFFERENTLY REEs

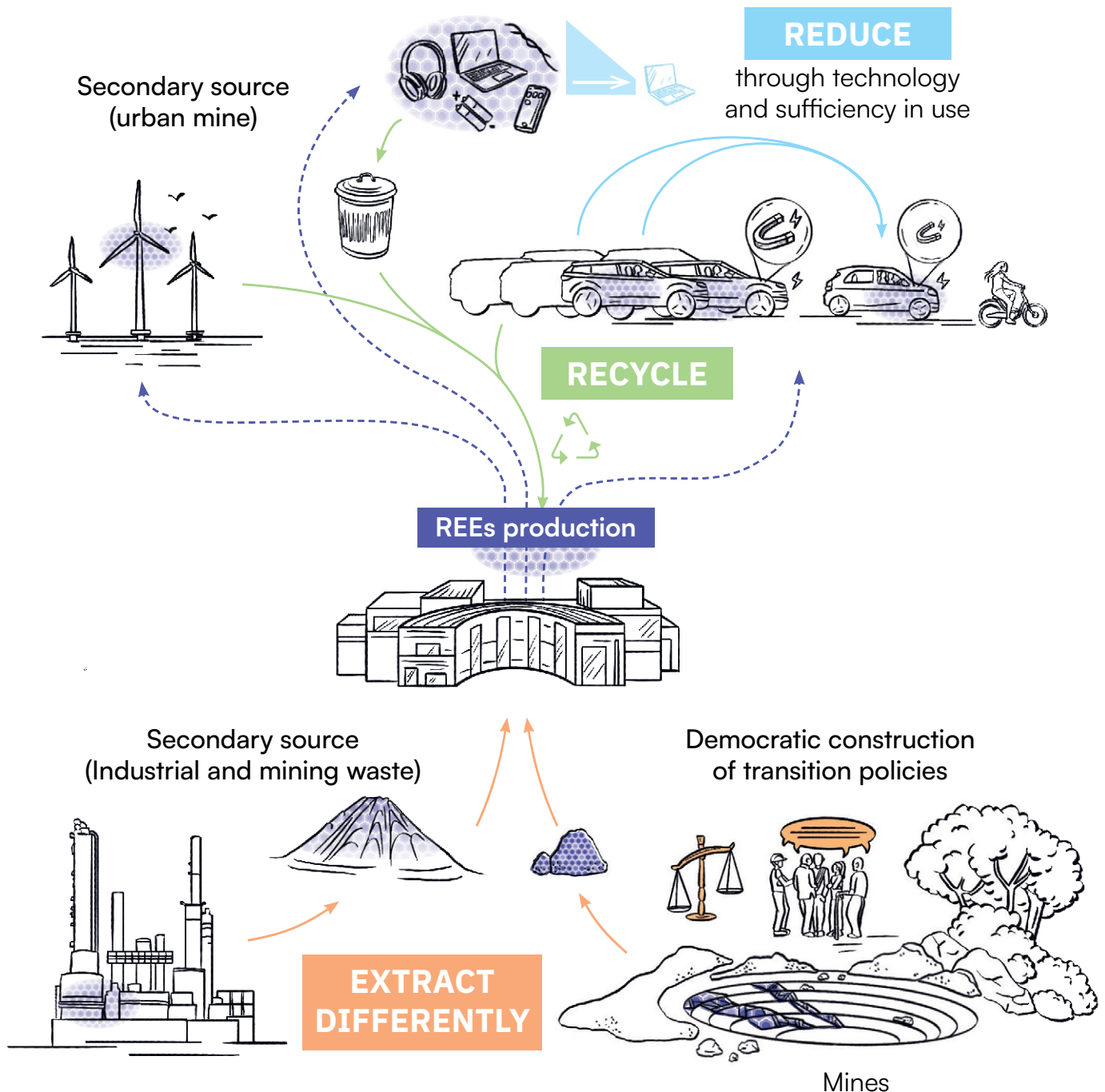


Figure 9 : The three pillars of this assessment: 1. Reduce, 2. Recycle and 3. Extract REEs differently. 1. Eco-design and sufficiency in use (here, cars and electrical and electronic waste have been selected to represent usage) 2. Circularity enabled by recycling (here, for example, wind turbines) 3. Extracting REEs from mining and industrial waste (here, coal ash) or through REE mining projects carried out under conditions of social and environmental justice.

II. Reducing

COLLECTIVE SCIENTIFIC ASSESSMENT

**Towards a responsible use
of rare earth elements
throughout their life cycle**

What are the prospects
in terms of sufficiency, recycling
and production methods?

II. Reducing

There are many ways to reduce REE consumption. These include **replacing** REEs with less critical materials, **improving the efficiency of devices that use them**, and **reducing the quantity of products that consume REE**. This reduction in REE consumption can be part of the circular economy, notably through eco-design and extending the lifespan of products, as well as the sharing economy, which prioritises use over ownership through the sharing of equipment. These two approaches help to reduce demand for raw materials whilst maintaining the expected service. Finally, resource sufficiency aims to reduce the uses themselves and questions their relevance. Some of these approaches are not specific to REEs and offer broader environmental benefits than simply securing resources (energy consumption and the use of other resources).

The academic literature is incomplete regarding certain uses. The reduction of REE-intensive uses in some materials (polishing, catalysis, etc.) is rarely the subject of academic publications: it appears to fall mainly under industrial secrecy and/or intellectual property. A review of the literature reveals a high proportion of incremental or iterative studies presenting few conceptual breakthroughs. For a systemic perspective, there appears to be a need to integrate assumptions of resource sufficiency and substitutability from the outset in approaches drawing on materials science. Meanwhile, the literature in the humanities and social sciences provides little insight into the relationship between the use of devices and the fact that these devices contain REEs.

II.1 Overview of uses and possibilities for reducing or substituting REEs

Key points

Generally speaking, REEs can be substituted in most applications, but often at the cost of compromising on the performance of materials and devices. However, in some cases, technological innovation has made possible to create high-performance devices with fewer or no REEs, such as :

- optimised electric vehicle motors designed to reduce the quantity of REE-containing permanent magnets whilst maintaining equivalent performance,
- the development of LED technology to replace phosphor lamps, significantly reducing the amount of REE-rich phosphor powder required per lighting device, whilst maintaining equivalent performance,
- the development of REE-free Li-ion batteries to replace NiMH batteries, made possible to eliminate REEs entirely, but shifted dependence to other critical metals (lithium, cobalt, manganese).

However, technological innovation today remains more focused on improving performance than on a genuine approach of sufficiency in REE uses.

The uses of REEs, as briefly introduced in Chapter I, are so numerous and varied that it is difficult to be exhaustive; the overview presented in this Chapter II focuses on those applications that account for a significant proportion of REE use (e.g. permanent magnets) and/or those representing academic research efforts resulting in numerous

scientific publications (e.g. contrast agents). The majority of publications report results that do not necessarily point towards a rise in TRL (*Technology Readiness Level*)¹⁰ or market applications. Studies that have reached or are likely to reach a TRL level close to commercial use are given priority here.

Materials with high REE content

Permanent magnets

From in-ear headphones to offshore wind turbines, from fridge seals to drones, magnets are used in a wide range of applications to perform a variety of functions.

The use of permanent magnets is most widely documented in the **electric vehicle** sector (1 to 2 kg of magnets in a EV drive) and the wind turbine sector (over a tonne of magnets in a wind turbine). Although the proportion by mass of magnets produced for these two applications is currently modest, forward-looking studies suggest that it is set to grow significantly in the coming decades (IEA, 2024).

Other uses are either less demanding in terms of performance, or relate to products for which the cost of the magnet is negligible. The vast majority of REE magnets are dispersed in the form of small magnets, sometimes weighing just a few tens of milligrams, hidden within a device and which will eventually become waste electrical and electronic equipment (WEEE): speakers and autofocus mechanisms in mobile phones, earphones, styluses and charging connectors for tablets, etc.

Magnets are divided into two main families: ferrite-type magnets and REE-based magnets, which account for 50% and 40% of the market respectively. The latter offer unrivalled performance in terms of their ability to generate a permanent magnetic flux. Their use is sometimes essential (quadcopter drone motors, mobile phone speakers, etc.), sometimes useful for minimising the mass of electrical machinery (wind turbines, electric vehicles, micro-mobility devices, etc.), and sometimes trivial (chalkboard magnets, handbag fastenings, etc.). Three-quarters of REE-based magnets are composed of approximately 30% neodymium: these are NdFeB magnets. They account for the vast majority of scientific literature on magnets because their application potential is very high and the associated technology is evolving significantly.

Commercial NdFeB magnets are currently available in 72 energy and temperature grades.

For low energy applications or use at room temperature, a blended approach may be considered. This involves **replacing part of the neodymium with less critical REEs** (mainly praseodymium and, more recently, cerium). However, the substitution rate must remain low to avoid degrading the properties, unless a trade-off between performance and cost is accepted. For high temperatures, neodymium is substituted with heavy REEs (dysprosium and possibly terbium). Given its criticality, current research

FOCUS : The electric car : its reliance on REEs

In an electric car, the battery supplies coils via an electronic converter. These coils produce a rotating magnetic field that drives the rotation of the motor's moving part (the rotor), to which magnets are usually attached, thereby generating the mechanical force needed to drive the transmission and revolve the car's wheels. Magnets are not essential for operation; it is possible to produce the excitation field using copper windings, but these will consume energy to operate, placing a greater strain on the battery. REE-based magnets can also be replaced by non-REE magnets, but for equivalent performance, the mass of magnets required will be significantly greater. Whichever solution is chosen, the REE-based option will always result in a lower total motor mass. In addition to its traction motor, an electric car may contain over thirty NdFeB magnet-based components for various actuators and sensors.

is focused on reducing dysprosium. The most direct reduction method identified in the scientific literature operates at the **material's structural** level. It involves infiltrating dysprosium into the grain boundaries of the magnet rather than within the grains themselves at the synthesis stage. This reduces its proportion by a factor of approximately 2, whilst maintaining constant performance (Wu et al., 2023).

These two main strategies can be combined and are already being implemented on an industrial scale.

For applications at room temperature, at the constituent level, a large number of articles address the search for **constituents that are inherently lower in REE** (e.g., instead of a ratio of one REE atom to seven non-critical metal atoms (e.g., $\text{Nd}_2\text{Fe}_{14}\text{B}$), a ratio of 1 to 12 is achieved (e.g. NdFe_{12}N)). However, the structural stability of these compounds remains a significant obstacle to their development. The search for new REE-free magnets has also generated a substantial body of literature, but the vast majority of this work consists of simulations. Although interesting compounds have been identified by calculation, no compound with equivalent properties appears to have been synthesised yet. On the experimental side, manganese alloys (without REE) remain the main compounds studied, but no real progress has been noted for decades in terms of performance¹⁰, which is inferior to, or equal to, that of ferrites.

10 - The TRL scale is a tool for measuring the maturity of a technology by mapping the critical milestones in a product's development, from its initial concept to its industrial deployment. A technological breakthrough generally occurs with the discovery of new components, leading to new materials and subsequently devices that are better suited to the intended use. For example, the emergence of visible-light-emitting semiconductors ('materials') has enabled the creation of light-emitting diodes (LEDs) ('components'), which in turn have allowed the design of LED lamps ('devices') that are now predominant in lighting applications.

11 - Certain magnets are not used in high-temperature conditions and therefore do not need to be composed of heavy rare earth elements such as dysprosium to maintain their performance.

Another way, that of ‘ α ’ iron nitride Fe_{16}N_2 , shows greater potential for development, with some advances observed over the past 10 years. Whilst it is unlikely that this alloy could replace NdFeB, it could, in the near future, compete with a family of REE-free magnets containing cobalt: AlNiCo. Nevertheless, the performance claims made by companies producing these iron nitride-based magnets should be appreciated with caution. Finally, ‘hexagonal ferrites’ (composed of iron and strontium oxides in a hexagonal structure) remain the only REE-free magnets that can be used, if AlNiCo is excluded due to the criticality of cobalt. However, their performances, which are significantly lower than that of NdFeB (eight times lower in terms of energy), implies a reduction in power density that is not acceptable in all applications due to technical, economical or marketing constraints. Hexagonal ferrites have very limited potential for further development.

In the context of electrical machines, the most common approach involves working on the **arrangement of magnets and magnetic flux barriers**. Numerous variants exist, but all aim to better channel the flux produced by the magnets to achieve the same induction with lower magnet volume and thus less REE. Another principle allows magnets to be eliminated by exploiting ‘reluctance torque’ (an effect that interacts with the magnetic flux path), but this solution alone does not achieve the desired performance. The combination of these two principles has been favoured by car manufacturers for several years.

The use of a **combination of magnets** is also being considered by replacing some of the NdFeB with ferrites (Y. Chen et al., 2020; Zhu et al., 2019). A more innovative solution frequently appears in the literature, particularly for generators and traction applications : the flux switching machines. These are machines in which the magnets are this time arranged in the stator of the motor, which allows for better cooling of the magnets and thus reduces the need for heavy REE (Raminosoa et al., 2015). Although still **far from industrial application**, these machines are nevertheless very promising. Current studies suggest that this concept could achieve **power** levels **close** to those of NdFeB-based motors used in the automotive industry today, using only ferrites (Tahanian et al., 2020 ; Mohammadi et al., 2023). This would entail an additional weight of around 5 kg, but with no real impact on a 2-tonnes SUV carrying a 500 kg battery. The use of magnet-free machines, whilst predominant in energy generation (thermal power stations, onshore wind farms, etc.) and the rail sector, remains for the time being limited to entry-level models in the automotive industry; however, in reality, there is no technological barrier to eliminating magnets for automotive traction.

Polishing powder

Polishing powders, mainly based on cerium and lanthanum, are used for polishing hard and transparent materials requiring a high-gloss finish, such as optical glass (lenses, flat screens, smartphones, etc.) or semiconductors.

Although polishing powders account for a significant proportion of REE use (14% by mass of all REEs consumed worldwide in 2020, i.e. 23 kt), no academic articles concerning the reduction or substitution of REEs have been identified. The low cost and low criticality of the two REEs involved, cerium and lanthanum, certainly explain the lack of enthusiasm for identifying alternatives to their use. However, as polishing is a key step in some industrial sectors, it cannot be ruled out that recent developments may be covered by trade secrets or intellectual property rights.

Electrodes

REEs are present in anodes of NiMH batteries used in hybrid cars (5% by mass of REE usage in 2020, or 8 kt), but not in Li-ion batteries, which account for most of the usage growth of battery for electric vehicles. Whilst replacing NiMH batteries with Li-ion batteries reduces REE consumption for this application, the sustainability of such a technological shift is questionable given the criticality of lithium and cobalt and the environmental impacts associated with their extraction and purification.

Luminescent materials (phosphors)

REEs are used in several types of photonic applications, including white LED lighting devices, known as ‘W-LEDs’. Luminescent materials accounted for 2% of REE usage in 2020, or 3.6 kt, but with a sharp downward trend (see Figure 4) linked to the replacement of phosphor lamps by LED devices. Indeed, the quantities of REEs required in an LED are one to two orders of magnitude lower than those required to produce an equivalent amount of light with phosphor lamps (Ku, et al., 2015). The most common systems are devices in which the blue radiation from a chip is ultimately converted by a cerium-based luminescent material into white light. The scientific community has proposed a very wide variety of alternative compounds to REE-based luminescent materials for W-LED applications. Nevertheless, studies remain most often at an early stage of development and few credible devices have emerged from the literature, notably due to the degradation of luminous properties or thermal instability under operating conditions. However, the use of nanoscale REE-based luminescent materials in existing devices appears to be an effective approach for maximising the performance of W-LEDs (Cesaria and Baldassare Di Bartolo, 2019; Cesaria et al., 2018). Furthermore, approaches using ‘quantum dots’ (semiconductor nanocrystals without REEs that allow control of the light spectrum at the nanoscale) appear to be promising (e.g. Chen et al., 2020). Conversely, certain organic LEDs, known as ‘OLEDs’ (used in particular in smartphone and television screens), which initially did not contain REEs, now contains some of them to improve the colour quality and lifespan of the screens (Utochnikova, 2021).

Materials with low REE content

In most materials with low REE content, REEs are used in trace amounts (referred to as ‘doping’) and up to a few per cent by mass, and significantly improve the intended application, or are even essential to it.

Glass

Although used in **trace amounts**, the proportion of REE consumption in glass accounted for 6% of total REE consumption in 2020, or 10.7 kt. It is clear that the addition of REE is effective in protecting glass (or ensuring its protective function) from damage caused by radiation. However, the number of scientific publications is low compared to known applications; alternatives to REEs are not considered therein. Yet the primary application of REEs in glass relates to telecommunications. To extend signal transmission over long distances (>50 km), telecommunications optical fibres use REE-doped amplifiers. The literature shows that the most efficient devices are based on erbium-doped fibre amplifiers (EDFA) and erbium-doped waveguide amplifiers (EDWA). They require only a **small amount of erbium, and no reasonable alternative** has been found in the scientific literature reviewed. The trend in use appears to be modest, with a preference for EDWAs as they are more compact and easier to integrate. The impact and applicability of alternative devices without REEs—such as SOAs (Semiconductor Optical Amplifiers, based on GaAs/AlGaAs, InP/InGaAs semiconductors, etc.) and Raman amplifiers—are difficult to assess based on scientific publications.

Active materials for lasers

Despite the widespread use of lasers containing REEs in various fields (e.g. materials manufacturing, nuclear fusion), the only comparative analyses focus on the healthcare sector. Two specific applications involve the substitution of one REE for another: lithotripsy (the treatment of kidney stones) and prostate adenomectomy (removal of the prostate in cases of benign hyperplasia). Holmium-doped lasers (YAG:Ho) are gradually being replaced by thulium-doped lasers (YAG:Tm) in these applications. Thulium is a REE that is no less critical or cheaper, but these lasers reduce recovery times and post-operative complications for the patient (Petov et al., 2022), as well as the cost and frequency of equipment maintenance (Wilson et al., 2016).

Contrast agents for medical imaging

During a MRI scan, contrast agents may be injected into patients to improve image quality and thus facilitate diagnosis. The use of gadolinium-based contrast agents (GBCAs) is widespread and is supported by a solid clinical evidences. The amount of gadolinium consumed annually for these contrast agents is marginal compared to the total

amount of REE consumed worldwide. However, the search for alternative compounds containing less or no REE is the topic of a significant number of publications (around a hundred publications analysed for this report). In France, the increase in demand for GBCAs directly follows the increase in the number of MRI scans (Chazot et al., 2020). Current research on GBCAs focuses primarily on reducing their use in patients with renal impairment. Several avenues are being explored: reducing the GBCA dose by developing more effective agents — such as Gadopiclenol, which would allow half the amount of product to be injected — or replacing GBCAs with alternative agents based on manganese or, in particular, iron (Ferumoxytol) (e.g. Gupta et al., 2020). Furthermore, research is developed for another type of contrast agent, CESTs (Chemical Exchange Saturation Transfer), currently based on REEs, but for which certain transition metals have recently been proposed as an alternative to REEs (Morrow et al., 2017). Nevertheless, these approaches remain at a relatively low TRL. The most advanced alternative to GBCAs lies in modifying MRI parametrization sequences, as well as in the use of artificial intelligence, enabling, for example, in certain applications, image analysis in 1 second instead of 15 minutes (Zhang et al., 2021). Overall, articles on clinical trials are under-represented compared to fundamental studies.

Metal alloys

The incorporation of REEs into metal alloys (used particularly in the aerospace industry for their resistance to extreme conditions) improves many of their physicochemical properties, and in particular mechanical properties and corrosion resistance. The addition is often less than 1% by mass but accounts for a significant proportion of REE consumption in 2020 (8%, or 13.7 kt). Reliable and relevant publications, selected from a vast number of articles, compare alloys with and without REE. They consistently demonstrate the high effectiveness of adding REE. While none of the analysed articles demonstrate that this doping is accompanied by any undesirable negative effects with small quantities of lanthanum, cerium or yttrium, the addition of other REEs, on the other hand, is less conclusive.

Catalysts

REEs are used as catalysts for numerous chemical reactions on an industrial scale (petroleum cracking during refining, particularly for fuel production; exhaust gas catalysis; synthesis of organic compounds, etc.). There is, however, a significant discrepancy between the proportion of REE used for this application (17% of REE consumed in 2020, i.e. 27.8 kt) and the number of publications identified on the subject (only 18 relevant articles out of the 39 analysed); this is likely due to reasons similar to those for polishing (trade secrets and intellectual property). Most of the publications analysed relate to fundamental research with limited short-term application potential. The use of REEs often offers a significant advantage. In the case of catalysts

for crude oil cracking (FCC), there is a trend towards reducing the use of REEs as stabilisers, in favour of mixtures of REEs and phosphorus. Conversely, nickel catalysts used in many reactions are being replaced by REE-based catalysts, which demonstrate significant increases in yield. However, a study shows that this yield gain is not desirable when other sustainability criteria are taken into account, such as environmental and health impacts, waste production or the overall cost of the process (Omodara et al., 2020)

The use of materials containing low levels of REE does not particularly stimulate research efforts into substitution or reduction, as the volumes involved and/or the associated costs are limited, whilst the functional benefits provided justify their continued use in systems. This is a significant issue for recycling, where short loops* remain possible, but where long loops are complex and costly (see Chapter III).

FOCUS : Reducing REE consumption in electric mobility

The objective of reducing REE consumption in electric mobility is not limited to the manufacturing phase of magnets or vehicles. At the end of a car's life, two strategies can also be implemented to extend the lifespan of permanent magnets, thereby helping to limit demand for REE :

- **the reuse of vehicle motors**, made easier by the fact that a manufacturer will have only two or three models of electric motors (compared to dozens of internal combustion engines) and that an electric motor is particularly simple and extremely robust compared to internal combustion engines. Furthermore, the lifespan of an electric motor is of the order of thousands of hours, whereas that of the vehicle housing it is less than 3,000 hours on average ;

- **the reuse of magnets**, although this solution can be complex to implement as the recovered magnet must have the same dimensions as those required for the new application ;

As a last resort, recycling may be considered (see Chapter III). For now, recycling streams are being established and it is difficult to predict which recovery methods will be prioritized in the future (reuse, recycling). However, given the limitations of magnet reuse and those of short-cycle recycling (currently, the properties are significantly inferior), the reuse of motors and long-cycle recycling will likely be prioritized for the automotive sector. Short-cycle recycling* could be directed towards other, less demanding sectors. As for wind turbines, their operating life (around 30,000 hours) and performance requirements currently mean that only long-cycle recycling* is feasible.

II.2 The legal framework applicable to REEs: from security of supply to the circular economy

Key points

The legislation governing critical metals (the EU Regulation on Critical Raw Materials, 2024) is primarily based on the imperative of security of supply. In this context, some authors fear that the desire to strengthen the independence of European industries may take precedence over sobriety concerns, particularly in the event of a relocation of mining activities. The Regulation does indeed emphasise increasing supply rather than reducing demand, which calls into question the adequacy of the sustainability measures, despite their prominent presence in the text. Furthermore, to facilitate the short-term 'relocation' of extraction, this may entail a departure from the principles of environmental democracy, such as a reduction in public consultation periods for so-called 'strategic' projects.

The considerations of resource sufficiency present in French and European legislation on the circular economy, which propose a waste hierarchy emphasising levers for sufficiency, are nevertheless, to a certain extent, aligned with the regulations on REE. The circular economy, widely promoted by the Critical Raw Materials Regulation, thus plays a direct role in securing supply.

The European framework for the production and supply of REEs through the prism of security

Regulation (EU) 2024/1252 establishes a framework aimed at ensuring a secure and sustainable supply of critical raw materials (including REEs). Security lies at the heart of this Regulation's provisions, which might at first glance seem somewhat removed from considerations of sufficiency, which would instead call for action on the demand side characterised by a reduction in the extraction and use of metals. Although rooted in a circular economy objective, it thus focuses on supply rather than demand reduction (Baldassarre, 2025). Indeed, the regulation sets the following targets for Member States by 2030 :

- the EU's **extraction** capacity must cover 10% of annual consumption of critical raw materials;
- the EU's **processing** capacity must cover 40% of annual consumption;
- the EU's **recycling** capacity must be sufficient to process 25% of annual consumption and thereby increase waste recycling;
- no **third country** should account for more than 65% of **imports** intended for the EU's annual consumption.

To achieve these objectives, the regulation defines, not only **strategic raw material** and **critical raw materials** but also in particular, **strategic projects*** which should benefit from an especially favourable regulatory conditions. Furthermore, the regulation provides for the implementation of national measures on the **recovery of extractive waste** and the **improvement of the recyclability of permanent**

magnets. It also provides for the recognition of **sustainability certification** schemes and the creation of environmental footprint declarations. Project promoters are required to make public all information relating to compliance with the requirements of the regulation. A European Committee on Critical Raw Materials is established. It is tasked with advising the Commission and carrying out the necessary tasks to oversee the implementation of the Regulation's obligations. A 'Critical Raw Materials Club' is also established, serving as a tool for European 'mineral' diplomacy to coordinate the actions of REE-consuming states, as well as to negotiate supply agreements with exporting states (Hool et al., 2023).

Given the recent nature of the renewal of regulations governing critical metals in Europe, the literature has not yet addressed this subject extensively, and even less so from the perspective of sufficiency. Around thirty articles were consulted for this section, with a number of studies currently being published given the topicality of this issue at the time of the research. This initiative has nevertheless given rise to some analyses and criticisms. Firstly, these are of a democratic nature: the potential restriction of public consultation — or political debate — during priority strategic projects could run counter to the imperative of social acceptance and **environmental democracy** (see also section IV.3, below). Secondly, these analyses highlight a push for the relocation of activities linked to the critical metals supply chain without anticipating the environmental and social consequences of such relocation within the European territory (Bogojević, 2024; Koese et al., 2025): although it enshrines the principles of the circular economy, the regulation places little emphasis on reducing resource use. Finally, some authors note that the regulation on critical metals does not yet organise the **governance**

of global value chains in a sufficiently comprehensive manner, i.e. their political institutionalisation (Radley, 2024). If the European Union does not implement stricter policies aimed at reducing the consumption of REEs, it will continue to depend on external sources for its essential industries. Some of the research therefore highlights the need for greater transparency and oversight.

In this context, the introduction of a **digital passport — a product's 'digital identity card' — is advocated by the 2024 European Regulation** establishing a framework for setting eco-design requirements for sustainable products ('Eco-design Regulation', which entered into force on 18 July 2024). **Its aim is to promote traceability, transparency and the democratisation of value chains.** It seeks to make essential information on a product's carbon footprint, chemical composition, origin of metals, reparability and recycled content accessible in digital form. This approach, standardised by ISO 14040 and 14044, has become widespread but remains underutilised in public policy and existing regulations, if only because it does not yet have fully operational legal status — in most cases, it remains voluntary. **The 'Environmental Product Declaration' (EPD),** for example, is complementary in that it presents a product's environmental impacts throughout its life cycle, from the extraction of raw materials to eventual recycling. **The EPD is not yet mandatory but is almost always required by industrial buyers.** The digital passport, meanwhile, will enable stakeholders and consumers to be informed about the origin and manufacturing conditions of products (Adisorn et al., 2021; Jansen et al., 2023). Certain products, such as batteries and electronic goods, are expected to be subject to this passport from 2027, as well as products containing critical raw materials from 2028.

To address the weaknesses mentioned, some of the literature proposes regulating the governance of REEs through traditional international conventions (e.g. Ali et al., 2022; Christmann, 2021). Other proposals are based on improving transnational regulations — combining national or European rules with corporate rules currently being developed: France's accession to the Extractive Industries Transparency Initiative (EITI — see Chapter IV), the creation of a major European and Chinese market through the harmonisation of European and Chinese rules on value chains to exclude companies, such as American ones that do not apply these environmental and social transition rules (recycling, etc.). Finally, **the creation of a European preference in public procurement, known as the 'Buy European and Sustainable Act' (BESA), could contribute to the regulation of REEs, as is the case in the United States and China.** This would involve regulating how public authorities in EU Member States award contracts for goods, services and works by introducing additional criteria relating to the environment, carbon footprint and local production. The

scientific literature generally does not address this issue; one must instead turn to grey literature to access analyses and concrete proposals on this point¹². The National Council of Industry (CNI) in France took up this proposal in an opinion dated 13 June 2025 entitled 'Making European preference a lever for reindustrialisation'. Nevertheless, as the law currently stands, such a proposal conflicts with international and European non-discrimination rules.

The relationship between regulations on REEs and the principles of the circular economy

Reducing the use of objects containing REEs is part of a circular approach, which takes into account the various stages of a product's life cycle. In order to move away from an economy that is still 90% linear (Bhatnagar et al., 2024) and to transition from waste law to circularity law (Boul and Radiguet, 2021), the principles of the circular economy propose implementing the '6R method of sustainability' in a hierarchical order (from most to least desirable): Reduce, Reuse, Repair, Rebuild, Recycle and Recover¹³. The initial impetus for their incorporation into law lies in the establishment of an integrated approach to sustainable waste management (Halkos and Aslanidis, 2024) with a view to recycling waste and preventing it through eco-design.

To achieve the objective of making product sustainability the new norm through circularity and material efficiency, particularly for products derived from REEs, **eco-design, as set out in Regulation (EU) 2024/1781 of 13 June 2024 (ESPR), has become one of the key elements of the Extended Producer Responsibility (EPR)* framework,** alongside waste prevention, end-of-life management and recovery. Eco-design "aims to minimise the environmental impacts of products and services from the design stage onwards and throughout their value chains" (ADEME). It appears to be a key driver of the circular economy in that it requires products to be sustainable, maintained, upgraded or improved, reused, repaired, reconditioned and ultimately recycled (Bundgaard et al., 2024). Legislation relating to eco-design, as well as to the various facets of the circular economy, applies to products and waste containing REEs.

The concept of sobriety, moreover, was incorporated into the French Environmental Code by the Act of 17 August 2015 on the energy transition for green growth in Article L.110-1-1, in the context of transposing the principles of the circular economy into law:

"The transition to a circular economy aims to achieve a neutral ecological footprint within the framework of respecting planetary boundaries (...) by calling for **the frugal and responsible consumption of natural resources and primary raw materials**, as well as, in order of priority, the prevention

12 - For example: Hughes-Marie Aulanier, Alain Grandjean, Antoine Crépel and Jori Damond, in Buy European and Sustainable Act: accelerating the transition to a low-carbon European economy, Carbone 4, 2024.
<https://www.carbone4.com/publication-buy-european-and-sustainable-act>

13 - To these '6 Rs' incorporated into circular economy law, a further three 'Rs' are added in the literature (Hunger et al., 2024): refuse, rethink, renovate, bringing the concept of the circular economy more closely into line with that of 'sobriety'.

FOCUS : The principles of the circular economy

Optimising the consumption of mineral resources is an issue that recurs periodically in economic research, engineering sciences and public debate. Formalised and popularised in the 2010s, the concept of the circular economy has brought together under a single term a wide range of actions and conceptualisations aimed at optimising the use of energy and materials and reducing the amount of waste. In France, the ADEME's conceptual framework serves as a reference (with its three domains and seven pillars of the circular economy). The scientific literature, for its part, lists or documents dozens of concrete circular economy initiatives led by various actors: individual consumers, of course, but also local authorities, public authorities and industry (Govindan and Hasanagic, 2018). For example, Nakajima and Vanderburg (2005) list certain circular economy approaches that manufacturers can adopt and rank them from the most environmentally virtuous to the least (see also below, section II.3):

- 1 • the functional economy, i.e. the approach of selling a service rather than a product (*selling services instead of products*, “*product-as-a-service*”)
- 2 • *product take-back*
- 3 • eco-design (basic design for the environment)
- 4 • *material and energy substitution*
- 5 • changes to production processes (*process modification*)
- 6 • recycling of manufacturing residues (*in-process recycling*) or consumer waste
- 7 • industrial symbiosis (*industrial eco-park design*)

of waste generation, in particular through the reuse of products, and, in accordance with the hierarchy of waste treatment methods, to *reuse, recycling or, failing that, the recovery of waste*. The promotion of industrial and territorial ecology and eco-design of products, the use of materials derived from sustainably managed renewable natural resources and from recycling, (...) the extension of product life cycles, and waste prevention (...) contribute to this new prosperity” (emphasis added).

This very general provision, particularly with regard to sobriety, is intended to serve as a guide, whilst being legally binding and therefore mandatory and enforceable in court. In the same vein, Article 191(1) of the Treaty on the Functioning of the European Union provides for ‘the prudent and rational utilisation of natural resources’. Within the general framework of this ‘circularity law’¹⁴ currently taking shape (Baudouin, 2024), **there is no specific regime concerning products containing REEs**. Apart from the Ecodesign Framework Regulation, to be read in conjunction with the Waste Framework Directive, there are numerous scattered sector-specific texts that apply on a case-by-case basis, product by product (batteries, etc.), with no current mention of whether or not REEs are present in the composition of these products.

The development of a **reparability** requirement, through the introduction of a commercial durability guarantee, generally helps to extend the lifespan of products and limit waste. At the same time, **life cycle assessment** (LCA), as set out in the 2008 Waste Directive (2008/98/EC), offers a holistic approach that could help to better quantify the overall environmental impacts (extraction, production, use, end-of-life) of products containing REEs. To address these challenges, the European Commission has recommended since 2021 the implementation of a harmonised method to assess the environmental performance of products throughout their life cycle, for example via the EPD. However, products containing REEs are rarely covered by EPDs (the data is complex to gather as it is often confidential or unavailable). As mentioned above, the Critical Raw Materials¹⁵ Act does not yet systematically incorporate EPDs or LCA data into its monitoring and evaluation mechanisms.

The surge in global demand for REEs thus calls into question the foundations of the circular economy, which is supposed to promote the prudent and sustainable management of resources. For some authors, **the regulation of REEs — or critical metals in general — establishes a new link between security and sustainability** (Marty and Ruel, 2025). Metal extraction and its inevitable environmental and social consequences are now justified by the industrial imperatives of the environmental transition, and the imperative of independence for national defence industries or innovation sectors. However, this discourse also revives a conception of sustainability justified by national security: reducing material use (circularity) reduces the dependence

¹⁴ - Sometimes analysed as a law of sobriety, the two terms are often associated with one another even though they do not entirely overlap.

¹⁵ - The text is currently being drafted: Commission Implementing Regulation (EU) .../... listing the products, components and waste streams considered as having a relevant critical raw materials recovery potential under Regulation (EU) 2024/1252.

of national economies. The circular economy thus becomes an element of sovereignty and defence policy, and the specific legislation on the supply of critical metals must be integrated into the general framework of circular economy law, which is gradually expanding (Baldassarre and Carrara, 2025). **Strengthening the link between these two legal frameworks is now a priority for the European Union**, as evidenced by the forthcoming draft implementing regulation on critical raw materials for the application of the CRMA, which will list the products, components and waste with high potential for the recovery of critical raw materials. Here again, the topicality of the subject and the recent nature of these developments mean there are few publications directly related to these issues. Nevertheless, the literature on the law applicable to the circular economy as a whole is extensive, and the concept of sobriety is also increasingly addressed by researchers (around a hundred selected publications dealt with these aspects and are analysed in section II.3 of the report).

FOCUS : The case of electric vehicles : when ‘critical metals law’ and eco-design are redefining the sector

The European legal framework arising from **the 2024 regulations on critical materials (EU 2024/1252)** and on **ecodesign (EU 2024/1781)** imposes new constraints on electric vehicle manufacturers. In practical terms, manufacturers will gradually have to:

- **better track and document** the composition of their vehicles using the digital passport, which must indicate the presence of critical metals and their environmental footprint,
- **design more durable**, repairable and recyclable **vehicles** in line with eco-design requirements: this involves making technical choices right from the design phase (see II.1),
- **adapt to recyclability standards** by developing supply chains capable of recovering up to 25% of the critical metals used, in line with the targets set by the Critical Materials Regulation,
- **comply with transparency requirements**, in particular by publishing certain environmental data on products and obtaining certifications, such as ISO 14040 and 14044, which provide a framework for product life-cycle analysis across the entire value chain,
- **reduce their dependence on external supply chains**, which may encourage them to relocate certain stages of electric car production or to secure partnerships with certified suppliers.

Thus, manufacturers are no longer subject merely to general environmental constraints, but to **a specific ‘critical metals law’**, currently being developed, which redefines the conditions for placing electric vehicles on the market in Europe.

II.3 Designing, consuming and owning differently

Key points

Changing design, manufacturing and consumption patterns (demand-side measures) is central to optimising consumption and securing supplies.

The literature on the circular economy does not, for the most part, specifically mention REEs. Nevertheless, its general principles are likely to be applicable to devices containing them, which are themselves the subject of studies. This literature focuses in particular on eco-design, the functional economy and consumer preferences.

Designing and manufacturing differently

The literature on eco-design is extensive but pays only marginal attention to the issue of material criticality. Several themes nevertheless emerge.

Within the framework of **eco-design**, promoting the sustainable development of materials requires the integration of sustainability metrics right from the design stage. For example, although refrigerators containing REE-based magnets (NdFeB) have a lower environmental impact during the use phase, taking into account the extraction and refining stages of REEs reveals that these refrigerators emit 13% more greenhouse gases than conventional refrigerators over their entire life cycle (Monfared et al., 2014). Comparative LCA studies of magnet manufacturing thus point to optimisation depending on the choice of :

- components — e.g. between 13 and 23% lower environmental impact by using Sr-ferrite for motor construction rather than NdFeB magnets (Nordelof et al., 2019),
- and methods — e.g. an 11% reduction in environmental impact by using 3D printers rather than moulds¹⁶ (Kulkarni et al., 2023).

The introduction of minimum performance standards enables the transformation of industries through the gradual replacement of obsolete products (Siderius, 2013). Over the past 40 years, the European Union has thus introduced minimum performance standards to be achieved progressively for various product groups (e.g. electric motors or lighting). Lighting and household appliances account for around 60% of final household electricity consumption in Europe: the literature establishes that these policies, which have been in place since 2010, have led to substantial reductions (around 15%) in electricity consumption for the same service provided (de Almeida et al., 2017; Gonzalez-Torres et al., 2023; Schleich et al., 2021).

However, the success of innovations does not stem solely from their technical qualities, but also depends on complex strategies and circumstances, which include a significant element of *product branding* (a marketing process based on the creation of a unique and recognisable identity for a product in order to differentiate it and appeal to consumers). In their analysis of Tesla's success, Palmie et al. (2024) show that the brand's success stems from the product's intrinsic qualities (which include REEs), but also from a structured and thoughtful approach aimed at diverting attention from criticism that might be levelled at it on environmental grounds, for example by pointing out that the product will be all the more virtuous as the electricity it uses will be of solar origin (*blame avoidance*).

Whilst **the circular economy framework** is widely invoked when considering the eco-design of products containing REEs, it is deemed insufficient by several authors, notably because it **does not adequately take into account social issues and the local context**. Alternative approaches could enable a qualitative assessment of the circular economy approach in relation to environmental, social and democratic issues (Ralph, 2021)

Ownership differently

The functional economy, also referred to as product-service system in the literature, is an approach that emphasises the use of a product rather than its ownership. This involves, for example, purchasing a certain number of kilometres to be travelled rather than an entire vehicle or tyres. This approach enables resource optimisation as well as improved eco-efficiency and reparability of the product, insofar as the burden of maintenance falls on the producer rather than the consumer (Lanzilotti et al., 2022). It is thus a pillar of the circular economy as a lever for sufficiency (Sakao et al., 2023).

The functional economy features **much less prominently than the other pillars of the circular economy in the literature analysed on the use of REE mechanisms** (notably

¹⁶ - Additive manufacturing (Big Area Additive Manufacturing, BAAM) rather than injection moulding (Injection Moulding, IM).

eco-design and recycling). The studies considered focus primarily on the determinants of social acceptability for individual practices, as well as on productivity and profitability gains for industrial practices. Conversely, the benefits (in terms of money, time, etc.) associated with the functional economy for individuals, and the drivers of acceptability and desirability for manufacturers, have not yet been extensively explored by academic research (Golinska-Dawson et al., 2025; Hidalgo-Crespo et al., 2024).

Whilst none of the 16 scientific publications analysed on the functional economy explicitly mention REEs, all of them, however, draw on case studies of objects containing REEs or critical materials and are therefore readily transferable. Some studies analyse the reasons why the functional economy model is struggling to take hold. Among the factors, two attract particular attention. On the one hand, **the legal framework** (see above: the law focuses more on eco-design, reparability, recycling, etc., rather than on the levers for sharing usage that require significant behavioural changes) and **the policy support** for the functional economy (incentive policies promoting sufficiency), which are under-invested in by public actors (Neramballi et al., 2024). On the other hand, **consumer buy-in** is sometimes difficult to achieve. Most studies focus on the field of mobility, particularly various forms of car-sharing rather than individual car ownership. Social acceptability appears to be a key factor to consider. According to a study in Germany (Kannstatter and Meerschiff, 2015), the 'price signal' appears to be of little significance: only 15% of the 120 people surveyed believed that a lower price would increase their use of the electric car-sharing service. In contrast, other studies reveal three determining factors:

- the age of users (Julsrud et al., 2023; Thurner et al., 2022) : those over 45 are more heavily reliant on the private car culture,
- environmental awareness,
- and the perception of social and environmental benefits: these last two factors have a positive impact on young adults' uptake of the service (Vatamanescu et al., 2023).

In industry (machining), the sharing economy enables both significant time savings in replacing parts and increased profitability. In the example by Lanzilotti et al. (2022), the analysis focuses on the provision of machining services by a contractor within a diesel engine parts manufacturing site in Brazil: the contractor's direct management of a new machine tool system significantly reduces the time required to replace a faulty tool (20 minutes vs 1 week). The time saved explains the rapid return on investment for the new system (9 months). Furthermore, in this example, the economy of functionality facilitates the recycling or remanufacturing of worn cutting tools containing critical metals.

Consuming differently

The eco-design approach faces challenges not only from consumer behaviour, but also from the ability of eco-designed products to disrupt established markets and replace other products with poorer environmental performance (Dijk et al., 2016). The transition to electric cars depends on the interplay between technological innovation, consumer adoption and regulatory support. Without explicitly mentioning the presence of REE, a review of the literature (Secinaro et al., 2022) identifies **three main determinants for consumers: purchase price, environmental awareness, and consumer perception and personality** (e.g. novelty seeking). In a study of Polish consumers (Sobiech-Grabka et al., 2022), purchase price is the most significant barrier for 77% of respondents. A Norwegian study (Gehlmann et al., 2024) shows, however, that a third of respondents would be willing to pay more for an electric vehicle manufactured under conditions presented as more responsible. Recent literature also highlights that consumers remain uncertain and wary due to the lack of charging points and the actual environmental benefits that electric vehicles may offer compared to internal combustion engine vehicles (Wicki et al., 2022).

Whilst these issues are relevant to a better understanding of possible shifts in demand for metals, and more specifically for REEs, they do not account for the findings of more general research in the humanities and social sciences on sufficiency or the social acceptability of alternative consumption patterns. For example, Paulson and Büchs (2022) estimate that 60% of the European population are in favour of a reduction in individual consumption (post-growth society). In the same vein, Wiedmann et al. (2020) highlight the scale of the negative environmental impact of the wealthiest households in rich countries, which is not, or only minimally, offset by technological innovation. The authors identify reduced consumption as the main lever. As this research may have a direct impact on the consumption of items containing REEs, it had to be added to our initial corpus of scientific publications.

This tension suggests **a silo effect in research practices**, with, on the one hand, a small number of studies—some of which are not particularly robust—that specifically and explicitly address REE consumption, and, on the other, studies from numerous disciplinary fields offering varied methodologies and relevant results, but which do not explicitly state the impact of their conclusions on demand for REEs. One challenge for future research is addressing this gap.

II.4 Putting things into perspective

Different disciplines tackle the issue of sufficiency from varied perspectives, which do not necessarily overlap. Materials science focuses on the technical performance

of materials and devices, whilst the social sciences explore forms of sufficiency based on changes in usage, which may be more radical.

In materials science, the study of sufficiency mainly involves research into substitutability or the reduction of REE content in materials containing the most critical REEs — which does not apply to industrial applications relying primarily on lanthanum and cerium, such as catalysis and polishing. For permanent magnets, the dysprosium content can be halved without affecting their performance. Neodymium can be partially substituted with less critical rare earths, such as praseodymium or neodymium, but at the cost of reduced magnetic performance. However, at the device level, particularly in electric motors, several technological approaches can reduce the quantity of REE-based permanent magnets, for example through optimisation of the rotor design or combination with ferrite magnets. Beyond magnets and for the majority of applications, REE are often still essential to material's performance, and the proposed alternatives sometimes require the use of other critical or toxic elements. For example, the shift from NiMH batteries to Li-ion batteries eliminates the need for REE, but shifts the issue to other critical metals such as lithium and cobalt. Analysis of past case studies shows that genuine gains in sufficiency stem less from the substitution of components or materials than from technological changes (innovation). Thus, the replacement of phosphor-based fluorescent lamps with LEDs, which consume far fewer REEs, constitutes a successful form of substitution. However, in the majority of cases, reducing the use of REEs is not the main driver of these transitions: it is rather a consequence. These changes have primarily been driven by performance gains or compliance with new standards. **At this stage, there are few examples where REE sufficiency is the genuine driving force for technological innovation.**

Circular economy legislation calls for more cautious consumption of natural resources, including critical materials, and has led to the development of regulations on eco-design, waste prevention and recovery, and energy efficiency. Nevertheless, with regard to products containing critical materials, this must be aligned to secure the supply of REEs, as set out in particular by the European Critical Raw Materials Act (CRMA): sufficiency then becomes a vehicle for sovereignty and a means of meeting demand in the face of fluctuating or uncertain supply.

In social sciences, sufficiency is approached through the lens of changing patterns of use, notably through behavioural change, and thus the optimisation of demand via circular economy initiatives. By emphasising use rather than ownership, the functional economy allows, for example, for the maintenance of usage patterns whilst reducing the quantity of devices and thus materials used. However, the number of research in the social sciences on these topics is very limited and focuses almost exclusively on electric cars.

Finally, the levers of sufficiency corresponding to the pillars 'Refuse, Reduce or Reuse' are still under-researched in the literature, which instead focuses on the technical levers of the circular economy, with recycling leading the way (57% of the literature). This imbalance prevents a full understanding of the cultural, institutional or regulatory barriers that hinder the full implementation of a circular economy.

The literature reviewed lacks a systemic, integrated perspective on the issue of sufficiency, which could bring together insights from the intersection of materials science and the social sciences. In particular, there is no literature that questions the 'right' level of technological need in relation to uses, with a view to reducing REE consumption. For example, the following question could be raised: **which magnet(s) for which use(s)?** Many applications require small magnets (in electronics, for example). Replacing them with REE-free magnets would lead to an increase in the size of devices, which does not align with current market dynamics or practical consumer s (e.g. earphones), as the latter are not independent of how markets are structured by economic actors. On the other hand, when considering electric vehicles, the need for an REE magnet (NdFeB) may be questioned, as equivalent performance can be achieved with larger SrFeO or AlNiCoFe magnets. Taking a 1 kg NdFeB magnet—which is common in electric vehicle motors—as an example, 3.7 kg of SrFeO magnet would be required to achieve the same performance. At the scale of an electric vehicle, this additional weight appears negligible relative to the vehicle's total weight, and such a substitution would significantly reduce **the demand for REE in electric mobility. According to the literature, there are currently no major technical obstacles to the complete elimination of REE magnets in automotive traction motors.**

Similarly, consideration could be given to prioritising uses by incorporating physical, economic and social criteria and drawing on the development of dedicated indicators. The approach adopted in this CSA, which involves examining REEs through the lens of reduction potential based on applications, thus raises a broader question—one that goes beyond the scope of this report—regarding the identification of priority applications and, ultimately, the associated societal choices. These considerations have not yet been explored in the literature and go beyond the simple scope of research to form part of a democratic debate.

REDUCING REEs IN THE MOBILITY SECTOR: ECO-DESIGN AND SUFFICIENCY IN USE

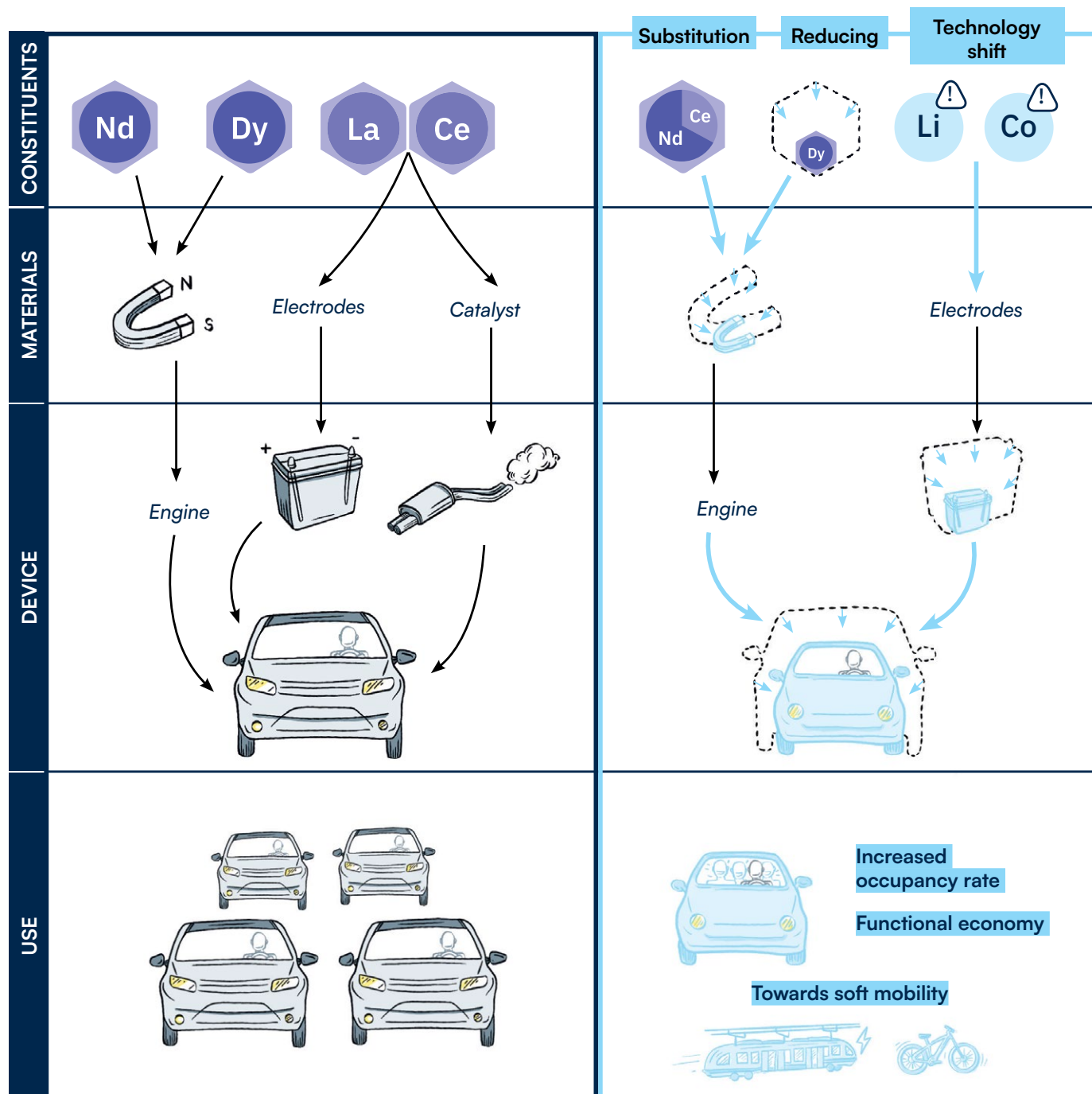


Figure 10 : Summary infographic of Chapter II 'Reduce', focusing on the mobility sector. The levers are shown in light blue.

FOCUS : Reducing the use of REEs in the mobility sector (Figure 10)

Electric cars use REEs mainly for motors (NdFeB permanent magnets) and NiMH batteries — though Li-ion batteries are increasingly replacing these. There are also auxiliary uses (screens, speakers, etc.). **Reducing the quantity of REEs in the mobility sector relies mainly on :**

1 • The eco-design of vehicles, which may involve :

- a. **technological changes** (e.g. from NiMH batteries to Li-ion batteries). However, this risks simply shifting environmental and sovereignty issues to other materials (in this case, lithium and cobalt);
- b. **reduction** (e.g. injecting dysprosium into grain boundaries rather than into the bulk of the magnets for the same efficiency);
- c. **substitution** (e.g. replacing part of the neodymium with cerium or praseodymium (less critical REEs), with a possible loss of magnet performance which may nevertheless be sufficient for lighter vehicles. The complete replacement of REE magnets is also feasible and has already been achieved or is under development by some manufacturers);
- d. **optimisation of material efficiency** (e.g. optimising motor geometry to reduce the size of permanent magnets whilst maintaining the same performance);

d.**reducing vehicle size** (small city-type electric cars do not use REE in their motors).

2 • A reduction in the number of vehicles, envisaged through :

- a. **increasing the occupancy rate**. The average occupancy rate of a vehicle in France was 1.4 occupants for local travel and 2.25 for long-distance travel (over 80 km) in 2019¹⁷,
- b. **the development of the sharing economy**: increasing usage through car-sharing. Today, a car is used on average for 1 hour per day,
- c. **the modal shift** towards sustainable transport modes¹⁸ (public transport, cycling, walking). It is worth noting that 42% of French people whose workplace is less than 1 km from their home travelled there by car in 2020¹⁹.

Forecast scenario: in France in 2024, 39.3 million private cars will be on the road. It is, of course, essential to take various factors into account, such as regional specificities. However, assuming that, on average, the occupancy rate were to double (from 1.67 to 3.34 people per car) and the intensity of use were to triple (to 3 hours of use per day per car), thanks to the sharing economy, then, the number of cars on the road in France could be, assuming constant usage (without technological disruption or additional modal shift), 6.5 million vehicles.

17 - https://www.ecologie.gouv.fr/sites/default/files/documents/DE_4p_covoiturage-v4-050722_SH_OK.pdf

18 - Soft mobility refers to modes of transport that have a low environmental impact.

19 - <https://www.insee.fr/fr/statistiques/5013868>

III. Recycling

COLLECTIVE SCIENTIFIC ASSESSMENT

**Towards a responsible use
of rare earth elements
throughout their life cycle**

What are the prospects
in terms of sufficiency, recycling
and production methods?

III. Recycling

In line with the circular economy approach (Chapter II), when products containing REEs reach the end of their life, these materials are intended to be recycled. The stock of REEs constitutes a **secondary resource** (unlike primary resources, which are extracted from the ground) and corresponds to the concept of an **'urban mine'** (Figure 11). The recycling of REEs is currently far from being an economic and industrial reality: **globally, less than 1% are recycled**. This figure has remained stagnant since the early 2010s. **Primary production predominates over recycling in every country in the world, whether in countries with REE deposits such as China** (Ge et al., 2022) **or in countries without such deposits**. The opening in 2025 of several plants dedicated to REE

recycling in Europe has not yet been sufficient to reverse the trend, although it does demonstrate the development of initiatives aimed at addressing this low rate.

It is important to investigate the reasons for the slow development of REE recycling, given the role it could play in supporting primary production (Jowitt et al., 2018). By way of illustration, **global consumption of primary dysprosium could increase by a factor of 10 to 30 by 2050 compared to 2011. This figure would be reduced by a factor of 1.5 or 2 with the implementation of recycling** (Hoenderdaal et al., 2013). But how can this be organised and encouraged? What are the barriers hindering its full development?

III.1 Institutionalisation of recycling

Key points

The main challenge is transforming stocks of technical objects into a resource (an 'urban mine'), i.e. developing the collection and sorting of these objects.

In the absence of economic incentives from the market (which faces sharp price fluctuations detrimental to industrial investment), the development of recycling relies on the possibility of establishing legal obligations (but using what metrics?).

Recycling is not capable of fully meeting REE needs in the context of ever-increasing demand, even though it can meet certain demands whilst minimising the *balance problem*.

Recycling: a systemic activity

Recycling operates within a systemic framework (Hagelüken et al., 2016) : it is governed by a multitude of interacting factors that can be divided into internal and external factors. Internal factors refer to everything relating to the recycled product itself: the value of the materials it contains, the complexity or heterogeneity of the product (which will make it more or less difficult to dismantle), the presence or absence of hazardous substances, the type of economic model to which it belongs (consumer goods or industrial products) and the social context in which it is used (for example, is it likely to be passed on from one consumer to another?). **External factors** relate to the physical, economic and legal infrastructure for recycling: collection schemes, material or economic incentives (e.g. deposits), legislation on end-of-life products and waste, and finally, social practices — for example, consumer engagement (Hagelüken et al., 2016).

The institutionalisation of recycling thus refers to **the set of political and legal initiatives adopted by stakeholders to 'institute' recycling**. In sociology, 'instituting' refers to the process by which social practices, norms or values become institutions, that is to say, enduring and recognised structures within a society (through the law but not only). The institutionalisation of recycling is necessary for it to gain significant scale. A distinction must indeed be made between the technical feasibility of recycling and its actual implementation: just because a technical process exists does not mean it will necessarily be used and scaled up to an industrial level. It is therefore necessary to create the conditions (including economic ones) that make recycling possible by influencing external and, possibly, internal factors.

These conditions are explored in this section. Firstly, the social science literature in economics, sociology, geography, management and administration (approximately 500 articles)

POTENTIAL REE SOURCES: REE QUANTITIES IN GLOBALLY GENERATED OBJECTS (2020)

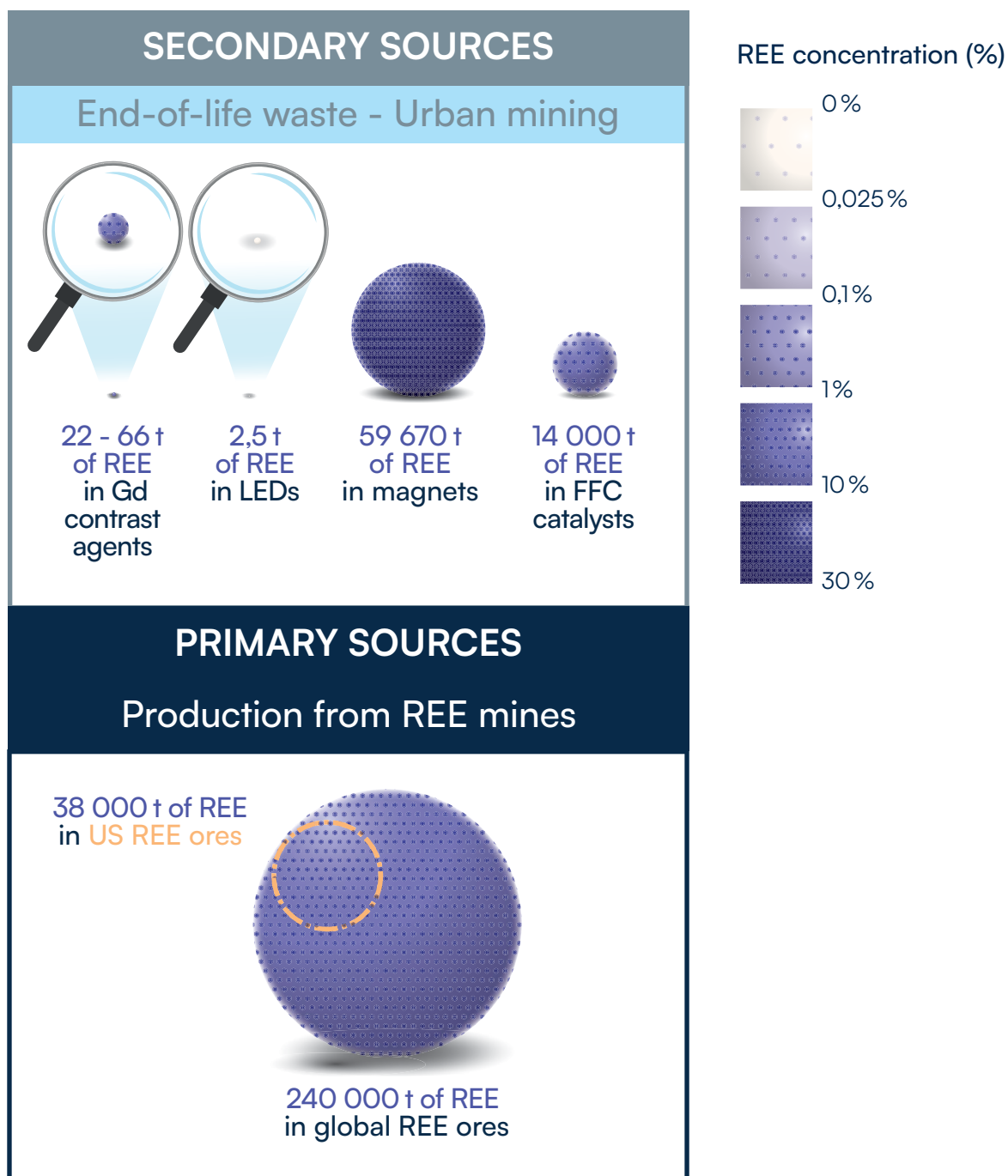


Figure 11 : Comparison of the quantity of REE present in objects generated worldwide in 2020 (which may constitute urban mines) with the quantity of REE present in rock extracted from REE mines in 2020. Whilst the mass of magnets generated in 2020 is similar to that of LEDs (170,000 and 114,000 tonnes respectively), the high concentration of REE in magnets (26.6% compared to 0.022% for LEDs) makes them a far more significant source of REE.

enables us to identify the barriers to the development of a large-scale REE recycling system at European or French level. Next, the legal literature (around 100 publications) describes the legal framework for the recycling of products containing REEs in France and Europe.

The need for a cross-cutting vision of the barriers to REE recycling

Recycling relies on the creation of reverse *logistics*, that is, a reversal of material and information flows compared to the production of goods (Wilson and Goffnett, 2022). Recycling involves organising these flows through technical infrastructure, legal regulations, public policies and mechanisms for consultation between stakeholders (Zhang et al., 2017). Literature reviews on the recycling of electrical and electronic waste highlight the complexity of these systems, in terms of their design, implementation and operation (Islam and Huda, 2018; van Nielen et al., 2022). **The reason why REEs are still so rarely recycled is that the functioning of this system results in them being discarded** (Horta Arduin et al., 2020). The literature (around forty publications) analysing the possibility of establishing and exploiting stocks of consumer goods for recycling (the urban mine) (e.g. Jones et al., 2013; Xavier et al., 2023) **highlights five challenges: dispersion/dilution, variability in the composition of objects, hibernation phenomena, regional variability in deposits and, finally, the accessibility of recycling infrastructure.**

A range of technological, market, organisational and legal factors thus explain the lack of recycling. Among the technological factors (internal factors), the literature highlights, on the one hand, **the highly dispersed use of REEs, the complexity of disassembling items, and the current low economic viability of the process** for a number of electronic waste streams (such as LEDs, Nikulski et al., 2021). On the other hand, the possibility of recycling REEs, particularly those contained in permanent magnets or mobile phones, **depends on the accumulation of sufficiently large stocks of items from the ‘urban mine’.** However, this is not independent of technological developments either: the obsolescence of certain REEs means they end up in the urban mine with no credible prospect of future use, in the absence of demand. Finally, the existence of losses during recycling operations, linked to the efficiency of each stage of the recycling chain (collection, disassembly, processing, etc.) must not be overlooked. The **case of hard drives** is a good example of the difficulties involved in recycling (Sprecher et al., 2014). Hard drives represent a potential source of REEs due to their neodymium-iron-boron (NdFeB) permanent magnets. Studies by Jin and Sutherland (2018, 2019) and Nguyen et al. (2017) highlight that, although technically feasible, recycling hard disk drives only recovers around 1% of global demand for REEs. Their average lifespan of around five years makes these flows regular. They will be the first to kick-start the recycling industry, but they are too small to have a significant impact. For a true circular economy to emerge, **the recycling scope must therefore include the more concentrated and durable sources represented by magnets**

in wind turbines and electric vehicle motors (Jin et al. 2018, Nguyen et al. 2017, Bandara et al. 2015). At the end of their life, these represent a strategic potential for closing the loop on the circularity of REEs.

In any case, recycling is subject to the imperative of profitability — and, more generally, to economic factors. This point is sometimes downplayed in the literature, which views recycling as an ethical, obligatory act signifying a form of environmental virtue. In reality, the viability of recycling is strongly linked to the **strength of demand, the price of virgin resources and the quality of recycled materials.** The profitability of recycling critical metals depends closely on market prices and technological costs. Bhuwalka et al. (2023) show that long-term metal prices are determined by a complex balance between innovation, substitution and resource availability. Applying this to REEs, most of these are only marginally substitutable, making their recycling potentially strategic but economically fragile. Economic analyses of batteries and hard drives (Jin et al., 2018; Kampker et al., 2023; Nguyen et al., 2017) converge: **recycling is only profitable at high price thresholds or with targeted subsidy policies.** Zhong et al. (2023) analyse the lighting sector: the replacement of compact fluorescent lamps with LEDs will lead to a drastic reduction (of between 87% and 100%) in demand for europium, yttrium and terbium in China by 2060, making recycling a very unattractive proposition.

Cost analyses of recycling processes reveal significant variations depending on the material recovered. For example, a life-cycle cost assessment for mobile phone recycling estimated the costs of extracting high-tech metals (HTM), such as cobalt, palladium and neodymium, with notable differences between conventional phones and smartphones (He et al., 2020). **Whilst the economic challenge of recycling RBMs lies in the combination of low collection rates and fluctuating metal prices, which can discourage investment** in pre-treatment and refining technologies (Thiebaud et al., 2018), some research highlights the potential economic benefits of REEs from secondary sources such as fluorescent powder and permanent magnets (Amato et al., 2019). The results, summarised in Table 2, confirm that secondary production of REEs significantly reduces overall costs based on 2017 market prices. This potential for cost savings underscores the importance of developing effective recycling strategies to improve resource sustainability and reduce dependence on primary extraction methods.

However, manufacturers are often reluctant to commit to recycling initiatives and investments given the **high volatility of REE prices.** Bandara et al. (2015) modelled the effects of a high recycling rate on price volatility: even at a 40% recycling rate, the impact remains low, as the global market is dominated by China and characterised by significant inertia. **The benefits of recycling therefore lie more in security of supply and reduced geopolitical dependence than in price stabilisation.** Calls for recycling are therefore often in vain, insofar as, without adjustments to market conditions, the conditions for recycling to succeed cannot be met, even if the price of certain REEs

Source of REE	Target metal	Cost of metal compounds from secondary production (€/kg)	Price of metal oxide from primary production (€/kg)
Fluorescent powder process	Y	0,04	2,9
	Eu	1	77
	Ce	0,03	2,1
	Gd	0,5	37
	La	0,03	2,1
	Tb	7	513
FCC catalytic processes	La	14	2,1
	Ce	14	2,1
Permanent magnet processes	Nd	8	57
	Pr	11	74

Table 2 : Comparison between the cost of metals from the described recovery processes and the price of the same elements from primary production in 2017 (Amato et al., 2019).

is very high. The literature places great emphasis on the relationship between the development of recycling and the price of secondary raw materials. If this price is too low, recycling cannot establish itself as a profitable economic activity (Beylot et al., 2020). Consequently, recycling is also highly dependent on demand, and its profitability is linked to a variety of factors: ‘Profitability must be considered from a systemic perspective rather than from a purely material perspective; however, process costs, energy requirements and environmental impacts must also be taken into account within this same systemic perspective.’ (Nlebedim and King, 2018).

The systemic perspective also extends to the organisational factors that constrain recycling: the methods of collecting items (particularly WEEE), the nature of the *business model* (B2B — business-to-business — or B2C — business-to-consumer), consumer behaviour, and the geographical distribution of recycling facilities (Prats Raspini et al., 2022). **Building up a stock of items** is all the easier when the supply chains involve only B2B, whether this involves the recycling of manufacturing waste or item take-back schemes (via deposits or the retention of ownership rights). For B2C models, the initial collection of electronic waste involves the local level, but the literature shows that the subsequent stages of recycling require increasingly large and centralised facilities, which are therefore less numerous and more distant from the local level. For example, the catchment area for Solvay’s phosphor recycling plant in Saint-Fons was the whole world. It is, in fact, this case

that we analyse in the report: the **recycling of phosphors from fluorescent lamps**, which in the 2010s was the subject of an industrial sector led by Solvay, since closed due to a lack of profitability. Around ten articles examine this case in order to draw lessons from it: it emerges that the rapid obsolescence of the fluorescent lamp sector was not sufficiently anticipated by the manufacturer, which calls for a degree of caution regarding innovation dynamics and their consequences for investment in recycling (e.g. ; Bin-nemans and Jones, 2014; Machacek et al., 2015).

The existence of a general legal framework applicable to the recycling of products containing REEs in France and Europe

As with all materials or substances legally classified as waste, recycling as a method of recovery must be prioritised. This priority was clearly consecrated by the 2008 Waste Framework Directive (2008/98/EC) in relation to the concept of a ‘**European recycling society**’. It states that “in order to move towards a European recycling society with a high level of resource efficiency, targets should be set for the preparation for reuse and recycling of waste” (Article 21). The law places at the heart of waste recycling organisation the requirement for a strong link with eco-design (see Chapter II) as well as the issue of highlighting **new priority waste streams — for example, waste electrical and electronic equipment** (Directive 2012/19/EU)

and electric vehicle batteries (Regulation (EU) 2023/1542). The applicable legislation does, of course, treat products containing REEs in the same way as all other products and aims to prevent them from becoming waste. Nevertheless, **there is currently no legislation requiring the presence of REEs to be mentioned or specific recycling measures to be indicated for them, whether for dispersed or concentrated uses, and legal literature has so far paid very little attention to this issue.** The 2024 European directives on Critical Raw Materials and on Eco-design (see II.2) do, however, point towards a mandatory recycling requirement for products containing critical metals and could lead in the short term to the adoption of specific European regulations concerning the recovery of REEs (e.g. regarding offshore wind turbines that will reach the end of their life in the 2030s–2040s and are not yet regulated in this regard).

Generally speaking, the legal framework for recycling is based on ‘**extended producer responsibility**’ (EPR), which consists of the obligation for any producer or holder of waste to ensure its management or to have it managed, in accordance with the polluter pays principle (Article L541-10 of the Environmental Code: “The producer is responsible for the management of the product they place on the market until the end of its life”). For producers of certain listed products, this entails covering the costs of preventing and managing waste arising from these products at the end of their life (Micheaux, 2023; Wilts et al., 2011). Funding is provided either through contributions paid to an eco-organisation or by setting up an individual waste management system.

The European extended producer responsibility scheme for **waste electrical and electronic equipment (WEEE)** is considered a pioneer, as it is the oldest. It stems from Directive 2002/96/EC of 27 January 2003, revised by Directive 2012/19/EU. This directive sets overall targets for separate collection and recovery or recycling, by broad categories of equipment (large appliances, small appliances, displays, lamps, etc.). Member States must ensure that collected WEEE is treated by separating certain components to facilitate the recovery of hazardous or rare substances. The WEEE Directive remains, however, general in nature: it mandates recycling by category of appliance but does not set specific quotas or obligations, including therefore for REEs. Furthermore, at the international level, **the case of WEEE highlights the contradictions in current legal regimes, which fail to establish an effective collection system for this waste.** The Basel Convention, which regulates the transboundary movement of hazardous waste, does indeed contain loopholes: used equipment intended for ‘direct reuse’ falls outside the scope of the regulations, facilitating the illegal transfer of electronic waste to developing countries (Khan, 2016; Ngom, 2022). This phenomenon undermines the effectiveness of Extended Producer Responsibility (EPR*) policies and jeopardises the recycling of critical metals.

The 2023 **Battery Regulation** (EU 2023/1542) serves as a model for metal recovery, with quantified targets set over time. Article 8 stipulates, for example, that by 2028, electric vehicle batteries must contain a minimum proportion of

cobalt (16%), lithium (6%) or nickel (6%) derived from the recovery of battery manufacturing waste or post-consumer waste. Similarly, a minimum proportion of lead (85%) must come from waste recovery for each battery model, per year and per unit produced. These rates are set to increase by 2036, except for lead. However, REEs in NiMH batteries are not mentioned in this regulation (which could extend the list of components to be recycled by 2027) and most other products destined to become waste containing REEs are not yet subject to specific legislation.

Current approaches, based on recycling targets expressed in terms of mass rather than quality, therefore do not promote the optimal recycling of end-of-life vehicles (Wilts et al. 2011). For example, the End-of-Life Vehicles Directive 2000/53/EC of 18 September 2000 stipulates that 85% of the mass of an end-of-life vehicle must be reused and recycled: **it is therefore the components with the highest density, in particular steel or aluminium, that will be the focus of recycling efforts.** However, the legal literature addresses these issues only to a limited extent, particularly with regard to the reuse of products. **A shift towards a comprehensive EPR scheme that takes into account the entire product life cycle, develops new metrics and incorporates specific requirements for critical metals—and in particular for REEs—is presented by some authors as an interesting option for enhancing the circularity of these strategic resources on a global scale** (Campbell-Johnston et al., 2023). EPR applied more specifically to REE would entail an obligation for producers to finance the collection, sorting and recycling of products containing REE, the establishment of an accredited eco-organisation through a ‘rare earth’ sector similar to those for WEEE or batteries, an obligation regarding traceability and the reporting of quantities placed on the market, as well as obligations relating to eco-design. For end users, an EPR scheme applied to REEs would notably entail an obligation to return end-of-life products to the accredited scheme and a monitoring requirement.

At national and regional levels, several studies (Gu et al., 2018; Huiyun et al., 2019; Mazzarano, 2022; Qiu and Suh, 2019; Wakolbinger et al., 2014; Wan and Yang, 2024) thus show that **effective policies for tapping into the urban mine rely on a balance between legal regulation, economic incentives and innovation, and above all on collaboration between the various actors in the chain.** Centralised models led by manufacturers, when combined with an extended producer’s responsibility scheme, offer better collection and traceability performance. The literature also argues that, to succeed in its role of securing resources, recycling must be conceived on a regional basis, which restricts exports of WEEE (Wang et al., 2024). Manhart (2011), whilst operating within a general framework and not focusing solely on REEs, emphasises, for example, the need for extensive international cooperation, combining manual pre-treatment in the Global South and industrial refining in the Global North, in order to optimise costs and limit illegal exports. These approaches are part of a coordinated circularity framework, where collaboration between producers, recyclers, distributors and consumers becomes a key driver of success. Furthermore, the study by Li et al.

(2023), although applied to electric vehicle batteries that do not contain REEs, introduces a transferable idea: the use of blockchain-based incentive systems and ‘tokens’²⁰. This hybrid mechanism combines market incentives with public regulation and could be applied to the recycling of REEs to improve transparency, consumer participation and the recovery of recycled materials.

In conclusion, legislation relating to circular economy could facilitate the organisation of REE recycling by relying, amongst other things, on extended producer responsibility to structure a sector, or on eco-design to ensure that manufacturers consider the production of more easily recyclable objects at an early stage (see Chapter II). An analysis of a wide range of social science literature also highlights the current obstacles to organising large-scale recycling. Firstly, it points **to the difficulty of building up sufficient stocks of items to recycle in an economically viable manner** (whilst emphasising the possibility of achieving such viability for certain types of electronic waste). International law concerning the ban on exports of hazardous electronic waste from the Global North to the Global South (the 1989 Basel Convention) is not sufficiently effective, which, in addition to having harmful environmental and social consequences for countries in the Global South, makes the collection of electronic items for recycling REE in the North more difficult and less profitable. European regulations treat electronic waste as both a source of danger and a source of value, creating conflicting imperatives (Kama, 2015). At present, the costs involved in terms of information, material organisation and human resources required to establish a recycling sector offer little incentive for economic actors to invest in setting up such a system. Moving from the concept of extended producer responsibility to its practical implementation requires the development of a highly complex collection and treatment system (e.g. in the state of Washington: Gui et al., 2013). **The literature highlights the important role of public authorities in structuring the sector through the use of legal and financial instruments and incentives for consumers** (returning their end-of-life electronic devices to the market).

Finally, because the literature on the recycling of REEs mainly analyses the issue from the perspective of electronic waste, a number of issues remain to be explored. Indeed, as REEs from electronic devices are highly dispersed, their recycling may require collection and storage methods that conflict with the way electronic waste is currently collected. **Treatment centres located relatively close to collection points (as is currently the case) may not have sufficient volume to process in order to recycle REEs profitably.** The role and structure of eco-organisations in situations where they collect waste for REE recycling, without these organisations ending up with excessive market power (i.e. by purchasing items at very low costs thanks to their central role in organising the sector), have not yet been studied in the literature. There would also be significant

scientific and public policy value in **learning lessons from failed attempts to establish certain REEs recycling centres**, such as the closure of the Rhodia-Solvay facilities in Saint-Fons and La Rochelle in 2016. No such studies currently exist in the literature. Conversely, a French company, Caremag, announced in March 2025 its intention to commence its REEs (permanent magnet) recycling operations by the end of 2026. Given the major economic, political and scientific implications of such an undertaking, studies in the economics and sociology of innovation could be conducted to monitor the project and draw lessons for the structuring of a broader sector.

By highlighting the difficulties companies face in organising the recycling of electronic waste, the literature points to the need for a proactive structuring of the sector, led by industry, but more certainly by the State. This, in turn, requires the ability to produce reliable data on stocks of items to be recycled, to fund the sector to kick-start a large-scale initiative, or to guide consumer behaviour to encourage recycling through information, subsidies or the organisation of collection schemes.

20 - Blockchain is a distributed digital ledger system, and tokens are the assets traded via this ledger. Tokens can be linked to physical objects (batteries in this case) and to collection and return schemes.

III.2 Practical organisation and stages of recycling

Key points

Recycling appears to be a more responsible alternative for the production of REEs. Life Cycle Assessment (LCA), in conjunction with Material Flow Analysis (MFA), shows that recycling processes have a lower carbon footprint than primary extraction.

The recycling of end-of-life vehicles (ELVs) is organised into three stages: dismantling and pre-treatment to separate out the recoverable fractions; the application of thermal, chemical or biological processes to concentrate the metals; and final conversion or shaping.

The main obstacles to dismantling relate to the heterogeneity of assemblies and the complexity of fastenings, which limit the automation of operations. Profitability also depends on the joint recovery of the entire 'metal cocktail'. Existing pre-treatment processes demonstrate proven technical feasibility, although optimisations still need to be implemented.

As for the core process, pyrometallurgical processes offer simplicity and relative durability, but are energy-intensive and poorly suited to diluted streams, whilst hydrometallurgy and its variants (liquid-liquid extraction, selective adsorption, electrochemistry) form the basis of separation. Unconventional approaches (solvometallurgy, ionometallurgy, biometallurgy) as well as short loops (such as the 'magnet-to-magnet' route) open up more sustainable pathways, although they still require validation at industrial scale.

Analytical methods such as Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) enable the quantification of the environmental benefits of recycling and the identification of exploitable secondary resources. Emerging technologies show **strong potential for reducing environmental impact** (Magrini and Jagodzinska, 2022). Multi-criteria planning tools such as those proposed by Yeh and Xu (2013) or Jin et al. (2019) enable the simultaneous optimisation of the economic and environmental performance of logistics networks. The uptake of these solutions will, however, depend on an appropriate regulatory framework, investment in R&D, and coordinated industrial strategies at European level. Economic data confirm the benefits of recycling, with **secondary production costs significantly lower than those of primary extraction** for key metals such as neodymium or terbium. Waste from electrical and

electronic equipment (WEEE) offers recovery potential in the medium term, with projections of a significant increase in the volumes available in waste streams (Habib et al., 2014; Wang et al., 2022).

The following sections outline the main stages of recycling, highlighting the most innovative and promising techniques in this field: (i) the front-end of the process, comprising the dismantling/disassembly of waste and the mechanical/physical processes to isolate components containing REE, and (ii) the core of the process relating to the extraction of metals via thermal, chemical or biochemical extractive metallurgy processes. The end of the process (iii), an optional stage involving the conversion of REE oxides and the final purification of the resulting metal, is covered in Section IV.2, which is dedicated to extraction processes²¹.

21 - The end of the process is covered in Chapter IV, which examines primary sources and mining and industrial residues, as this final stage applies systematically in that context. Whereas for recycling, if we consider both short and long pathways, there is not necessarily a need to purify REEs into metallic form (as in the case of phosphors, polishing powders, etc.).

FOCUS : Key metrics for assessing recyclability

The concept of 'recyclability' was defined by Henstock in 1988: it refers to 'the technical ease and economic feasibility of recovering materials from products that would otherwise be considered as waste'. The work of Graedel et al. (2011) defined the main parameters and metrics for assessing the efficiency of metal recycling. They distinguish between recycling at the end of an object's life (*End-Of-Life Recycling*) and recycling during the production process (production scraps). In the first category, the most important metric is the EOL-RR (*End-of-Life Recycling Rate*): this is the product of collection efficiency and the efficiency of the technical recycling process (i.e. the process yield, also known as

the recovery rate). The EOL-RR always refers to *functional* recycling, i.e. recycling that preserves the metal's functional qualities. *Non-functional* recycling refers to the situation where the metal is recycled but mixed with another material, causing it to lose its functional properties.

For the same material (in this case, permanent magnets concentrated in REE, the impact of concentrated versus dispersed use on recyclability is significant when comparing the quantity of NdFeB magnets present in a wind turbine with that found in vehicles or everyday consumer goods.

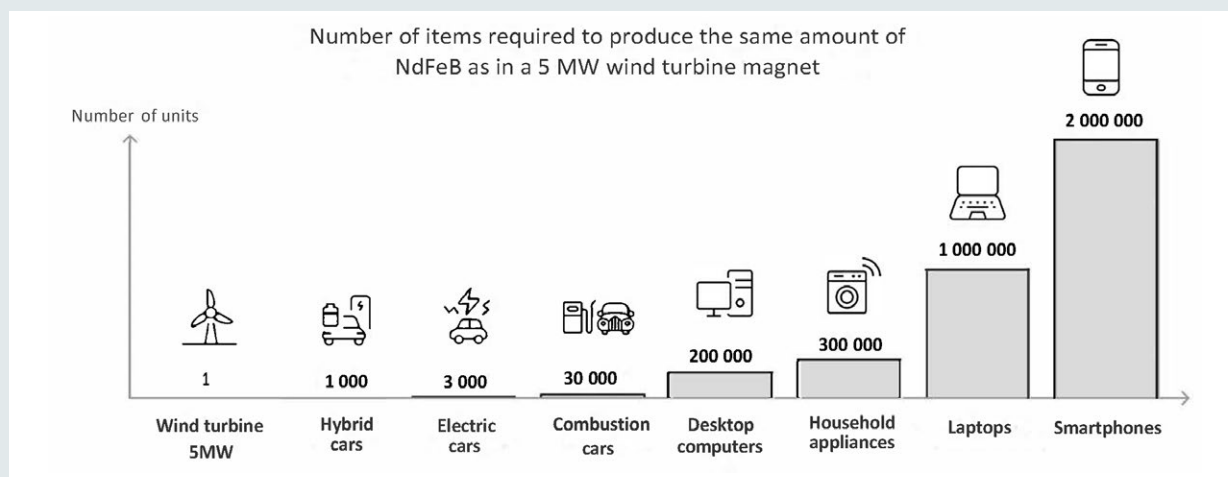


Figure 12 : Quantitative comparison of items to be recycled to obtain the same quantity of REEs

Recycling Steps

Process front-end	Waste Preparation	Dismantling
		Grinding/Compaction
	Materials preparation	Deposit characterization
		Materials sorting
Core process	Metal Extraction	Metal dissolution in liquid or solid phase
		Chemical separation
End of process	Purification	

Technologies

Manual Dismantling		
Mechanical Dismantling		
Grinding/Compaction		
Sampling		
Analytical technologies		
Magnetic separation		
Eddy current separation		
Others (gravity, electrostatic...)		
Hydrometallurgy/Biohydrometallurgy/Solvometallurgy		Pyrometallurgy
Leaching	Acid or alkaline	Melting, gas-phase reaction
	Bioleaching	
Liquid/liquid extraction	Solvation	
	Ion exchange	
Adsorption	Ionic liquids /DES	
	Supercritical fluids	
Precipitation		Refining
Adsorption		
Electrolysis/electrodeposition		
Others		

Figure 13 : The various stages of recycling processes and their associated technologies.

Process front-end: dismantling and pre-treatment

Studies in the field of dismantling published between 2020 and 2024 (reviewed through 30 publications) all highlight the same tension: high concentrations of strategic metals coexist with still low collection or recycling rates due to a lack of suitable supply chains and processes. Regarding pre-treatment, the literature confirms that there is currently a limited range of processes for REEs recycling. More than a hundred original articles, supplemented by around fifteen reviews published between 2018 and 2024, converge to show **that a recovery rate of over 80% for REEs is technically achievable through pre-treatment stages**. However, these results are often based on laboratory-scale experimental series that are still modular and not readily comparable.

For NdFeB magnets, the life cycles of devices suggest that waste from magnets in the automotive and energy sectors will peak from 2030 onwards. Current magnet recycling processes still focus on **hard drives**, notably through the industrial example set by Hitachi. This demonstrates that semi-automated dismantling of small magnets from computer hard drives is feasible on a large scale (Baba et al., 2013). Among pre-treatment processes, hydrogen decrepitation (HD) has emerged, according to a dozen studies published since 2020, as the shortest ‘magnet-to-magnet’ pathway²² (Burkhardt et al., 2023; Habibzadeh et al., 2023) through which approximately 90% of the initial magnetic properties are retained.

In a **fluorescent lamp**, the luminescent material (phosphors) accounts for barely 1% of the total mass, yet they concentrate six REEs (lanthanum, cerium, europium, gadolinium, terbium and yttrium). In France, Solvay processed up to 2,000 tonnes per year of phosphor powders between 2012 and 2018. Abroad, recycling rates vary (4–28% depending on the country). Emerging solutions are demonstrating their ability to overcome some issues, such as mercury dispersion. Around twenty studies (2001–2024) agree on recovery rates exceeding 90%, achieved through certain pre-treatment processes. Three reviews (Chenna Rao Borra et al., 2018; Lu and Liang, 2024; Wu et al., 2021) present a process (regeneration of CeO₂ powder) enabling two additional polishing cycles without loss of performance.

The volume of **NiMH batteries** (with REE) will decline with the rise of Li-ion batteries (without REE). Around twenty studies recommend the manual dismantling of hybrid vehicle modules. Mechanical processes already achieve nickel recovery rates of 90%, but still face challenges in the cost-effective purification of light REEs. Two recent literature reviews (Cassayre et al., 2022; Innocenzi et al., 2017), covering around 200 references, confirm that **the hydrometallurgical route** (dissolving the battery, after pulverisation, before carrying out separations) **dominates the pre-treatment options**; this allows for the recovery of over 90% of REEs.

Other waste streams attract less research interest. The residual market for cathode-ray tubes is declining rapidly, with six recent publications deeming a dedicated processing route unprofitable. Processes for treating polishing powders already make it possible to increase the REE content five-fold, but the presence of fluorine (3–5%) and heavy metals complicates recovery. Regarding FCC catalysts (petroleum cracking), the lack of added value of lanthanum limits recovery (Chen and Yang, 2024). Cerium from automotive exhaust catalysts remains concentrated in the pyrometallurgical residues from precious metal extraction, due to a lack of profitability. Finally, the recycling of REEs from optical glass (containing up to 40% La₂O₃), which is scarcely described in the literature, is hampered by the lack of collection schemes. However, according to two pilot studies, it is possible to recover 1,600 tonnes per year of high-purity REE oxides, and a handful of studies (around five) demonstrate the feasibility of a concentrated NaOH (55%) pre-treatment, with yields of 99–100%.

In conclusion, waste rich in REEs constitutes both a strategic resource and an operational barrier to circularity. Two converging factors stand out. **On the one hand, the intrinsic value of these waste streams offers tangible economic leverage. On the other hand, collection rates**

FOCUS : The example of mobile phone magnet recycling

Mobile phones are a relatively dispersed application (small quantities of magnets in a very large number of devices) and are therefore difficult to recycle. 16 billion devices were in use in 2022, with an average lifespan of less than three years (Vats and Singh, 2015), but only 1 in 10 is recycled, according to a European Commission study. One tonne of end-of-life phones contains 35% metals, including 3.3 kg of REE (mainly neodymium, praseodymium, dysprosium and erbium). Although a few studies have demonstrated the feasibility of semi-automatic disassembly based on the development of *machine learning*, the ten studies on dismantling published since 2018 confirm that manual sorting remains the most effective method for separating components. However, its cost still limits large-scale industrial implementation. To date, there is therefore no recovery chain for NdFeB magnets in consumer electronics. However, the recovery circuit for soft magnetic materials (electrical steels) is highly developed, both in the energy and automotive sectors, and could easily be adapted to recover magnets as well.

22 - A technique aimed at recovering a magnet with one or few processing steps from one device to another.

and the industrial maturity of processes remain insufficient to capture this value. The bottlenecks lie mainly upstream: the heterogeneity and complexity of assemblies (chemical, mechanical or magnetic fastening of components) still necessitate manual dismantling. This is effective but costly, whilst automation remains limited to a few niche areas. Similarly, profitability depends less on the REE content alone than on the ability to identify and recover the entire ‘cocktail’ of metals contained in the collected equipment. For example, studies on NiMH batteries show that profitability depends as much on the nickel, copper or precious metal content as on the REEs themselves. Finally, the associated environmental risks necessitate the integration of early decontamination stages. These findings highlight approaches such as the widespread adoption of modular design²³ to facilitate sorting and the pooling of treatment sites in order to achieve profitability thresholds. The few industrial successes demonstrate that an integrated logistics-process-market approach is technically feasible when volumes and co-products justify it. Finally, the body of data provides arguments in favour of a phased roll-out based on the informed selection of the process best suited to each type of waste and on the controlled scaling up from laboratory trials to semi-industrial demonstrators.

Core process

Following the dismantling and pre-treatment stages, three main categories of processes exist to extract metals from waste streams: pyrometallurgy, operating at high temperatures to melt and separate metals; hydrometallurgy, which uses chemical solutions to dissolve and separate metals; and biohydrometallurgy, employing microorganisms as physico-chemical agents.

Pyrometallurgy

Pyrometallurgical processes, whether in a molten metal environment, by chlorination/distillation, by molten salt electrolysis or by the ‘glass slag’ method, achieve yields ranging from 80 to 99.7% and each has its own specific constraints. They are particularly used for the recycling of permanent magnets. These processes are simple, generate little or no acidic effluents and are relatively clean. They can directly produce alloys composed of REEs or compounds intended for purification for industrial production (Assefi et al., 2020; Deng et al., 2025). These processes usually require feedstock rich in REE; they are not suitable for low-grade resources. They also involve energy-intensive calcination, which increases the carbon footprint and may produce harmful organic compounds. The sustainability of pyrometallurgical processes therefore depends heavily on the rigorous control of gaseous and particulate emissions, as well as on the energy efficiency of thermal operations.

Their optimisation thus involves improving energy efficiency, utilising waste heat, and implementing systems for the capture, filtration and treatment of effluents, ensuring a significant reduction in the environmental footprint. An analysis of some thirty leading articles highlights the growing interest in the optimisation of pyrometallurgical processes. The various pyrometallurgical routes, along with their main advantages and limitations, are listed in Table 3. **Their integration into hybrid recycling chains (combining pyrometallurgy, hydrometallurgy and electrochemical stages) appears essential** to meet the technical, environmental and economic requirements of future industrial sectors.

Hydrometallurgy

According to an analysis of around 300 publications, hydrometallurgy is currently **the most widely explored approach for REEs recycling**. This process relies on a sequence of operations (dissolution, followed by separation and purification) and a variety of approaches combining conventional and innovative strategies, tailored to the specific characteristics of the materials being processed. This diversity is neither accidental nor merely technological: it reflects the extreme variability of secondary sources of REEs and their composition, and the need to combine performance, selectivity, robustness and environmental sustainability.

The first key step, **dissolution or ‘leaching’**, is carried out using strong mineral acids to solubilise the REEs. The high recoveries already achieved over 30 years ago (>95% according to Lyman and Palmer, 1992) continue to be optimised (e.g. Ni’am et al., 2020). The literature highlights the value of systematically adapting leaching parameters to the target material and the REEs present, rather than adopting a generic approach. Furthermore, it provides arguments in favour of a reasoned intensification of pre-treatments to improve process selectivity. Moreover, the recovery of REEs is generating growing interest in more sustainable processes. Certain methods present themselves as promising alternatives to conventional leaching using aggressive mineral acids. They utilise organic acids, which have been the subject of numerous studies (around twenty of which have been considered here). Some achieve 90% recovery (Belfqueh et al., 2023), or even close to 100% (Behera et al., 2019; Tanvar et al., 2020), while others confirm the possibility of selectively separating iron from magnets (Niskanen et al., 2022). In addition, ‘supercritical’ CO₂²⁴ is proposed as a non-toxic, recyclable and efficient co-solvent for organic acids. For example, such an extraction medium enabled the recovery of 99.4% of neodymium from NdFeB magnet powder in just 30 minutes (Reisdörfer et al., 2020), compared to 900 minutes using conventional leaching. Challenges remain, however, regarding selectivity towards iron. Ionic liquids and eutectic solvents²⁵ are also emerging, with literature

²³ - A modular design refers to an engineering approach that involves structuring a system into autonomous and interconnected sub-assemblies, in order to facilitate the maintenance, upgrading and reuse of components whilst ensuring the coherence of the whole.

²⁴ - A substance brought to very high temperatures and pressures, exhibiting properties intermediate between those of liquids and gases.

highlighting the benefits of their low volatility, recyclability and the ability to tailor their selectivity based on ionic composition or structure (nature of the cation and anion) or molecular composition (nature of the hydrogen donor and acceptor) (Binnemans and Jones, 2017; El Maangar et al., 2024; Pateli et al., 2020; Riano et al., 2017).

From the leachate obtained by leaching, **liquid-liquid extraction (LLE)** remains the most widely used method for separating REEs from other elements. This technique relies on the transfer of REEs from the aqueous phase to another liquid phase called the solvent, consisting of an extractant and a diluent, which has a chemical affinity for the REEs. This method is particularly applied to the selective separation of REEs from one another (e.g. differentiating dysprosium from neodymium, or dysprosium from praseodymium), yet it still requires the fine-tuning of certain parameters, such as extractant concentration, pH, and extraction cascades by altering the nature of the extraction... (Liu and Chen, 2021; Traore et al., 2023). However, LLE often requires multiple steps to achieve a purity of over 99%, and the solvents used pose environmental risks (flammability, toxicity). Current research therefore aims to develop extractant formulations that are less polluting, more efficient and recyclable. In particular, the use of liquid filtration membranes offers a promising alternative to LLE, providing rapid, energy-efficient separation and integrating the various steps into a single device. **Solid-liquid adsorption** is an alternative to LLE, particularly for dilute solutions or complex wastes (urban mine tailings, ash, effluents). Reviews such as those by Artiushenko et al. (2023) classify the numerous adsorbent materials according to their structures, active sites and performance (yield, selectivity, recyclability). The best materials achieve adsorption rates exceeding 90% even at acidic pH (<2), a key criterion for adapting to industrial leachates. Some can also exhibit selectivity amongst REEs.

Electrochemical processes are another approach that stands out for their ability to combine dissolution, separation and purification under controlled conditions. The work of Venkatesan et al. (2018a, 2018b) shows that the application of oxidative electrolysis enables the selective precipitation of REEs and their separation from iron. Other processes have also demonstrated high yields (>99%) with a final REE purity exceeding 99%. Whether through electro-leaching, electro-dialysis (using selective membranes), electro-deposition or electro-sorption, these electrochemical approaches, which are still in their infancy for REEs, offer great flexibility and make it possible to partially overcome the complexity of conventional pyrometallurgical or hydrometallurgical processes.

Recent scientific literature on hydrometallurgy is ultimately converging towards an approach that combines leaching optimisation, improved separation techniques and the

increasing integration of electrochemical processes. This literature demonstrates a growing interest in **less polluting processes**²⁶, **with high selectivity, adaptable to complex waste streams** (such as NdFeB magnets, fluorescent lamps or batteries). Whilst technological maturity varies depending on the route, **the complementary nature of these methods offers solid prospects for developing sustainable industrial pathways for the recovery of REEs**. Consequently, current research is actively exploring these so-called 'green' pathways (i.e. sustainable, eco-compatible). Around a hundred recent studies between 2017 and 2024 confirm the strategic importance of these technologies for the selective, rapid and sustainable recycling of REEs.

Biohydrometallurgy

Beyond these physico-chemical processes, biohydrometallurgy offers promising solutions based on the activity of microorganisms, notably bacteria, microfungi and archaea.

Bioleaching relies on microorganisms capable of solubilising metals through their metabolism. This process produces organic acids (e.g. gluconic acid, citric acid) and inorganic acids (e.g. sulphuric acid, nitric acid), which enable the solubilisation of REEs by lowering the pH (acidolysis) or produce organic molecules that form soluble [metal-organic molecule] compounds (complexolysis). For example, the bacterium *G. oxydans* has demonstrated remarkable efficacy in extracting REEs such as lanthanum, cerium or neodymium from used NiMH batteries (Rasoulnia et al., 2023, 2022, 2021b, 2021a). Bioleaching can also be implemented through the reuse of spent media containing leaching bacteria. This process offers considerable advantages in terms of cost and environmental impact. However, certain limitations remain, such as the slowness of the process, the sensitivity of microorganisms to substrate toxicity, and the difficulty in achieving consistent industrial yields. Research is underway to optimise operating conditions and to select or genetically modify more robust and selective microbial strains. In this context, containment and regulatory compliance could also become significant issues.

Biosorption uses biomass²⁷ (living or dead) such as bacteria, algae or fungi to capture REEs via physical and chemical interactions (electrostatic, ion exchange, complexation, precipitation). The results reported from 12 studies on innovative biosorbents are promising. Some systems, via proteins and peptides²⁸, are capable of selectively recovering REEs even from chemically complex leaching solutions (Ye et al., 2024). Functionalised biomaterials are designed to be stable, reusable and effective in continuous processes. Despite these advances, technical challenges remain to be resolved for sustainable industrial application.

25 - A mixture with a lower melting point than that of its individual components. Most of these solvents are therefore liquid at room temperature, which makes them easier to use.

26 - Fewer acids, fewer solvents, non-polluting bio-based solvents...

27 - Organic matter of plant, animal, bacterial or fungal (mushroom) origin.

28 - Protein fragments. A molecule composed of 2 to 50 amino acids.

Biomineralisation is a microbial process that precipitates REEs into insoluble compounds in the form of carbonates or phosphates. Various microorganisms are capable of accumulating and transforming REEs with very high yields (e.g. (Kang et al., 2023)). To date, few studies have explored this environmentally friendly, selective and sustainable process.

These biotechnologies have the potential to solve problems related to the extraction and recycling of REEs thanks to their concentration and separation capabilities. **They have shown good results at the laboratory scale, but only one study to date has addressed the issue of scaling up to an industrial level** (Good et al., 2023). In addition to scalability, **technical-economic** and life-cycle analyses will be required to demonstrate that these biotechnologies can compete with existing extraction methods, both economically and environmentally.

III.3 Putting things into perspective

The European Union, in its quest for climate neutrality by 2050, is committed to developing a circular economy and reducing greenhouse gas emissions, notably by relying on green technologies using REEs. Studies on REE recycling highlight a growing potential for recovery in the medium term, with projections of a significant increase in the volumes available in waste streams (Habib et al., 2014; Wang et al., 2022). Life Cycle Assessment (LCA), in conjunction with Material Flow Analysis (MFA), shows that recycling processes generally have a lower carbon footprint than primary extraction. Recycling technologies, such as hydrometallurgy, bioleaching or direct 'magnet-to-magnet' processes, can significantly reduce the environmental impact compared to primary extraction (Magrini & Jagodzinska, 2022).

Compared to primary production, the recycling of REEs offers advantages, the most significant is that it avoids the difficulties associated with separating the radioactive elements commonly found in natural deposits, thereby reducing their environmental impact (Gkika et al., 2024). However, emissions of harmful substances during the recycling of REEs can be similar to those generated during their primary extraction and processing, and can also lead to environmental and health problems. **There are still very few publications examining the impact of REE recycling on environmental and human health, particularly in electronic waste dismantling areas,** even though the use of recycling methods similar to those used in ore processing may have more significant repercussions on humans and the environment. Publications

addressing the environmental impact of WEEE recycling focus on numerous organic and inorganic pollutants but rarely address REEs specifically. The expansion of the REE industry raises concerns regarding occupational health issues, as prolonged exposure to REEs (cerium > neodymium > lanthanum > samarium > yttrium > terbium > europium > lutetium) has been associated with conditions such as pneumoconiosis and pulmonary fibrosis, although the progression of these conditions may be due to the radioactivity of certain REEs. *In vitro* studies also demonstrated a pulmonary toxicity, including potential fibrosis induced by cerium and neodymium. Cutaneous fibrosis (nephrogenic systemic fibrosis) has been reported as an effect of gadolinium used in early forms of contrast agents for magnetic resonance imaging.

Further research is needed to assess the **risks to workers**, in particular to determine the REE levels at which health problems may arise. Indeed, only occupational exposure limits for yttrium and cerium are currently regulated at 1 and 5 mg/m³ respectively, but more comprehensive regulations are needed as methods of handling REEs can vary depending on the raw material used and the finished product, and the substances produced may also differ for each process.

Furthermore, it should be noted that sufficiency strategies (such as substitution or reducing usage) are at odds with the aim of building up a stockpile of items containing REEs: "Substitution efforts can help reduce the criticality of heavy REEs as recycling can, but substitution and recycling are also competing strategies, since the alleviated supply shortage achieved by reduction or substitution can make recycling less economically viable, and *vice versa*." (Schulze and Buchert, 2016, p. 23)

Technologies for recycling permanent magnets from hybrid electric vehicles

Dismantling/disassembly

Equipment	Technique	Advantages	Main obstacles
Rotors of synchronous motors in electric vehicles. Main REEs contained in the extracted magnets: Nd, Pr, Dy REE mass: 1 kg EV and HEV	1) manual 2) semi-automated	1) separation of the different elements 2) energy and time savings, efficient separation of the various components and purity of the recovered magnets	1, 2) heterogeneity of the streams, risk of damage to the magnets

Pre-treatment

Equipment	Technique	Advantages	Main obstacles
NdFeB magnets Main REEs : Nd, Pr, Dy	1) demagnetisation, hydrogenation/dispersion (HD) 2) Demagnetisation, hydrogenation/dispersion/desorption/recombination (HDDR) 3) calcination	1, 2) short-path recycling in a magnet-to-magnet strategy 2) production of powders finer than those obtained by HD 3) suitable for subsequent hydro-metallurgical stages, as REE oxides leach more readily than other metal oxides, including Fe_2O_3	1, 2) inerting of the medium

Core process

Pyrometallurgy	Technique	Advantages	Main obstacles
Chlorination	1) using Cl_2 / AlCl_3 followed by vapour transport 2) by carbochlorination following oxidative calcination of the magnets 3) using MgCl_2 4) via NH_4Cl	1) selective production of gaseous REAlnCl_{3+3n} 2) gradual distillation of chlorides other than RECl_3 condensed in the solid residue 3) solid Fe-B removed from the mixture of $\text{RECl}_3/\text{MgCl}_2/\text{Mg}$. NdCl_3 and DyCl_3 recovered after distillation of residual Mg and MgCl_2 4) production of RECl_3 at 400°C , directly soluble in aqueous phase	1) AlCl_3 , gaseous Cl_2 , slow migration kinetics 2) Gaseous Cl_2 , temperature $> 1000^\circ\text{C}$ 3) Average yield due to loss via the formation of NdOCl and DyOCl in the presence of O_2 in the medium 4) Generation of gaseous HCl

Molten metal	Mainly Mg but also Cu or Ag	Formation of a distilled Mg-REE alloy	High temperatures
Molten salts	Solubilisation in eutectics such as $\text{MgCl}_2\text{—KCl}$, LiCl—KCl or $\text{AlF}_3\text{—NaF}$, followed by recovery of Mg-REE or Al-REE alloys or electrolysis	Applicable to NdFeB and SmCo	Appropriate control of bath composition, temperature and atmosphere
Glass slag	Melting of the magnet in the presence of a flux under an oxygen flow to obtain leachable slags	Pyro-hydro combination	High temperatures, non-leachable slag

Conventional hydrometallurgy	Technique	Advantages	Main obstacles
Leaching	Inorganic acids: HCl, H_2SO_4 , HNO_3 . Influence of concentration, temperature, agitation, time, solid-liquid ratio, activation (ultrasound, microwaves)	Varies depending on the conditions applied	Corrosive acids, low selectivity, high environmental footprint
Liquid-liquid extraction	Extraction by contact of extractant/diluent formulations with a leachate	Wide variety of extractants, rapid kinetics, high selectivity, low energy consumption	Toxicity of formulations, volatility, flammability, solvent volume, third-phase formation, emulsion stability, re-extraction dependent on the nature and strength of the extraction ligand, carry-over loss
Membrane systems	Liquid membrane, supported liquid membrane, solid membranes	Low waste production, high selectivity, low energy consumption, extraction/re-extraction	Toxicity of formulations, flammability, membrane stability
Adsorption	Inorganic, organic, organic/inorganic hybrid materials	No organic solvents, recyclability	No organic solvents, recyclability
Electrochemical processes	Electroleaching, electrosorption, electrodeposition	Combination of dissolution and separation, high selectivity, minimal waste	Complex processes, high potential

Innovative hydrometallurgy	Technique	Advantages	Main obstacles
Leaching	1) Organic acids 2) DES, ILs	1) Selectivity (depends on magnet pre-treatment) 2) Water savings, selectivity 1, 2) Low environmental footprint	1) Kinetics, yield 2) Viscosity, cost
Extraction using ion exchange resins and/or DES	1) Cationic, neutral or anionic extractant in DES or ILs 2) Pure DES or TSILs	1, 2) low volatility, high capacity, selectivity, possibility of electrodeposition	1, 2) Viscosity, cost, stability, recyclability
Supercritical fluids	Extractant dissolved in supercritical CO ₂ (74 bar, 31°C)	Low toxicity, non-flammability, easy separation	pressure, selectivity, solubility of extractants

End of process			
Reduction	Technique	Advantages	Main obstacles
From anhydrous chlorides	- preparation of REE trichlorides - Reduction of REE trichlorides with Ca or Li, followed by sublimation, distillation or vacuum fusion	Reduction with Ca is effective for light REEs with Pr Reduction by Li is effective for all REEs	Hygroscopicity of chlorides
Of anhydrous fluorides	- Preparation of fluorides by hydrofluorination of REE oxides with HF or calcination in the presence of NH ₄ HF ₂ - Reduction of REEF ₃ by Ca or by Li-LiF in the presence of Mg, followed by vacuum melting or distillation	Reduction effective for all REEs	Cost of fluorination reagents
Of REE oxides	Reduction by addition of lanthanum (lanthanothermy), cerium, or sodium in a NaCl-CaCl ₂ medium, followed by sublimation, distillation or vacuum melting	Effective reduction for heavy REEs	
Molten salt electrolysis	Technique	Advantages	Main obstacles
Of REE chlorides	Electrolysis	Less expensive than metallothermic methods	High temperatures, corrosion
Oxyfluorides	Electrolysis	Less expensive than metallothermic methods	high temperatures, corrosion, low solubility of oxides in molten fluorides, current density limitations

Table 3 : As a summary table of recycling processes, the focus has been on permanent magnets from electric cars (also applicable to permanent magnets from wind turbines, except for the dismantling stage).

DECISION FLOWCHART FOR REE **RECYCLING**

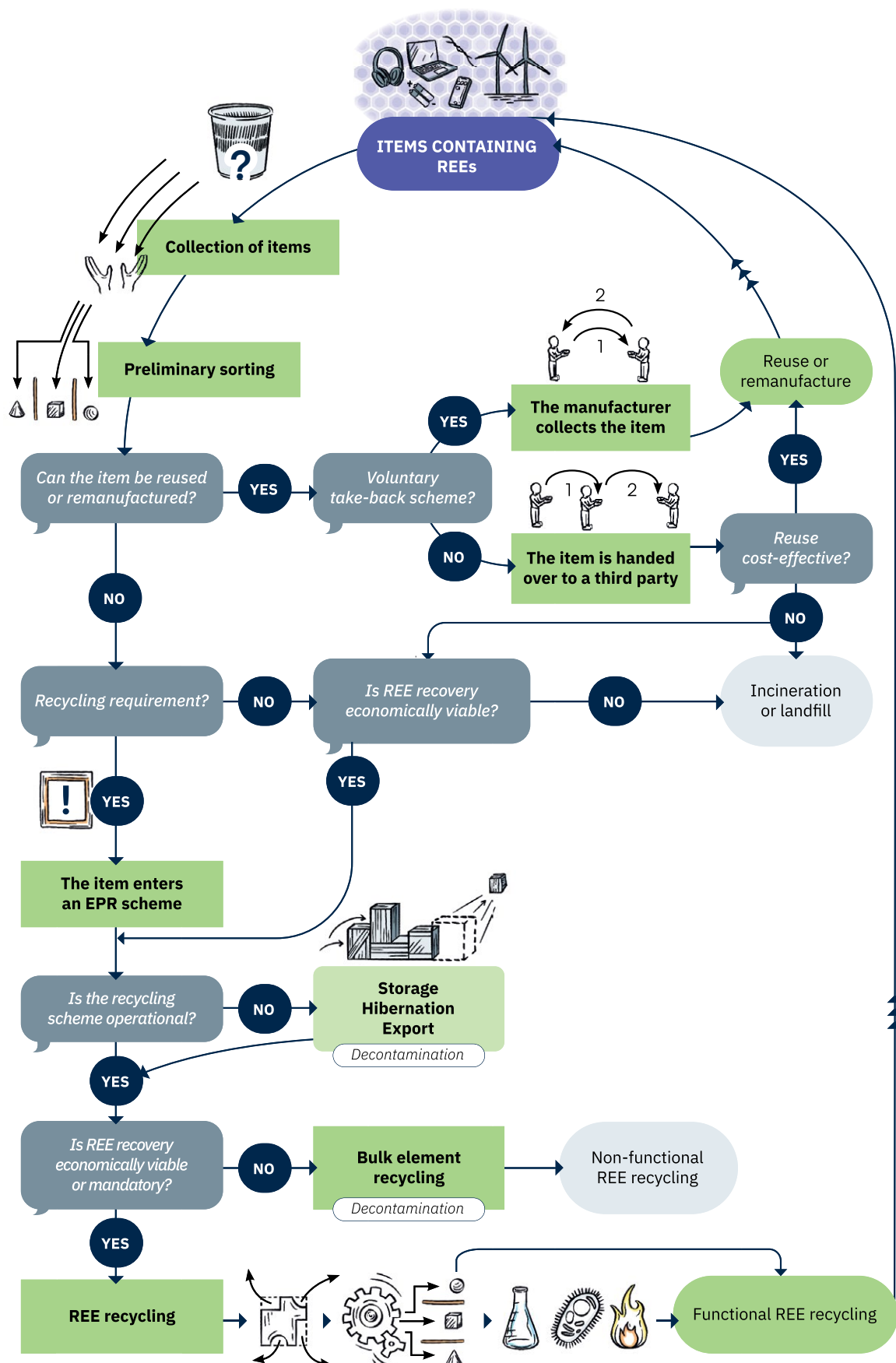


Figure 14 : Conclusion of Chapter III — Recycling through a flowchart of its stages.

IV. Extracting differently

COLLECTIVE SCIENTIFIC ASSESSMENT

**Towards a responsible use
of rare earth elements
throughout their life cycle**

What are the prospects
in terms of sufficiency, recycling
and production methods?

IV. Extracting differently

Sobriety based on the principles of the circular economy can only significantly meet demand if that demand is regulated (Grosse, 2023, 2014). In the case of REEs, annual demand is growing strongly, and the consumption reduction or recycling discussed in Chapters II and III will not be sufficient to meet growing needs. It is therefore necessary to

consider **other forms of supply**: beyond efforts to reduce consumption of REEs and to recycle them, **tangible possibilities for ‘relocalisation’ are being explored, as well as the conditions under which these REEs may be extracted, produced and imported.**

IV.1 The development of primary and secondary resources in France and Europe: resources mapping

Key points

In Europe, the main high-grade deposits, and therefore those with significant potential, are located in northern Europe (Greenland, Sweden, Norway, Finland). Deposits with low concentrations (<1%) are fairly numerous and have been well identified in Europe, particularly in France. In France and southern Europe, deposits are generally located in the superficial envelopes of the Earth’s crust.

Although it appears that there is no significant geological potential for REEs in France, specific alternative sources of REEs may be of considerable interest. Nevertheless, their exploitation remains subject to several uncertainties:

Firstly, as France is the world’s second-largest maritime territory as it owns the maritime areas off its overseas territories (11 million km²), the associated offshore mineral resources may constitute a source of REEs supply. Estimates, however, vary widely, and their exploitation presents numerous technical, economic and environmental challenges and uncertainties, as documented in the literature. This has led some states to call for a moratorium on offshore mining activities and is currently the subject of significant controversy.

Furthermore, secondary sources of REEs are identified in the literature (mining waste: bauxite residues, coal ash, phosphogypsum). Their potential is very significant, but the available data on their stocks and characteristics remain limited. Operating conditions, particularly social and environmental ones, could be similar to those of a primary mine, but these are not discussed in the literature.

Primary deposits that formed under deep geological conditions

World-class primary deposits are well identified and located in very ancient igneous rocks in northern Europe (Greenland, Sweden, Norway, Finland). These rocks result from the partial melting of the deep Earth’s layers (the mantle or the Earth’s crust). The main REE-bearing minerals are also rich in phosphorus, carbonate or silica²⁹.

Greenland has eight large to very large undeveloped REE deposits, with estimated resources of ca. 34.79 Mt (Jonsson et al., 2023). As a comparison, global REE production in 2024 stood at 0.39 Mt according to the USGS. Norway has three medium to large-sized unexploited deposits (0.70 Mt), two of which are located in the magmatic rocks of the Oslo Rift in the south of the country. **Sweden has two large deposits associated with active mines (0.46 Mt) and two medium-sized unexploited deposits (0.49 Mt).** The two

29 - Three chemical substances used for their specific properties. Phosphorus, a structural element of living organisms, is crucial for agriculture. Carbonates are widely used in industry, particularly in iron smelting. Silica possesses optical transparency and electrical insulation properties.

largest are located in active iron and phosphorus mines (IOA type) at Kiruna and Malmberget in the north of the country (Decrée et al., 2023).

Furthermore, occurrences with low concentrations ($1 < \%$) are quite numerous and have been well identified in Europe, particularly in France. These include granitic magmas found throughout the Variscan orogen, in the Massif Central and the Armorican Massif in France.

Rare-metal granites, such as the Beauvoir granite (Echassières), are currently the subject of detailed research for their lithium content, but could be re-examined for their REE content (Dehaine et al., 2019). Finally, in this type of primary deposit, as with other types, there is a lack of knowledge regarding REEs as by-products. REEs have chemical affinities with base metal deposits of tin (Sn), titanium (Ti) and iron (Fe) (Nassar et al., 2015). Nevertheless, very few case studies are available. These types of magmatic rocks with low concentrations have not been, or have been only minimally, characterised economically.

Deposits that formed under shallow geological conditions

Shallow-type deposits, formed near the Earth's surface, are the most significant in France and southern Europe. There are two main types:

- palaeoplacers, formed by the accumulation of sediment³⁰, found notably in the Armorican Massif. Their concentrations are fairly high (0.4–0.8% REE oxide) (Charles et al., 2022), but their occurrences are disseminated and form only small deposits (3,000 t);
- bauxites, formed by rock weathering, mostly found in southern Europe. They are less concentrated ($<0.2\%$), but the volumes are very significant ($>> \text{Mt}$). REEs could also be by-products of other deposits, such as the 'phosphorite' rocks of the Czech Republic (Al-Bassam et al., 2021) or the 'pyrite' bearing-rocks of the Iberian belt (Costis et al., 2021; Ruiz et al., 2002), but with lower concentrations ($<0.05\%$).

Shallow-type deposits are therefore quite abundant in France and Europe, but in the form of **small, highly concentrated occurrences** (palaeoplacers), **or large, weakly concentrated occurrences** (bauxites, phosphorites, pyrite-bearing Iberian belt). A major advantage of bauxites is that they are already mined for aluminium and may contain high concentrations of other critical metals (titanium, gallium, nickel, cobalt). However, these deposits require a better understanding of the metal environment to verify whether *in-situ* leaching protocols, such as those used for ion-adsorption deposits (Moldoveanu and Papangelakis, 2016), which minimise separation steps, could be adapted.

'Avenues for the future'

Extraterrestrial sources

Meteorites and asteroids are sources considered by a number of scientific articles. These agree that they would be less abundant than those found in deposits currently being mined on Earth (Luszczek and Przylibski, 2019; McLeod and Krekeler, 2017; McLeod and Shaulis, 2018) and that their exploitation is, at present, not a convincing option. Nevertheless, some lunar basalts are enriched in heavy REEs. Despite the seemingly distant prospects for such mining, some authors have already considered space mining techniques. This is the case, for example, with Jiang et al. (2020), who have identified electrodes capable of removing lunar dust.

Despite these distant horizons, an **international legal framework** is gradually taking shape with a view to highlighting the common nature of these resources. As early as 1967, the United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, stipulated that 'The exploration and use of outer space (...) shall be for the benefit and in the interests of all countries (...); they are the prerogative of all mankind'. Whilst the principle of non-appropriation is enshrined in Article 2, the Treaty simultaneously proclaims that the Moon and other celestial bodies may be freely explored and used by all States, without discrimination, whether or not those States are parties to the Treaty. This Treaty has been ratified by a significant number of countries, which attests to its legal standing. Nevertheless, the focus is now more on the individual regulation of extraterrestrial mining activities, as demonstrated by the legislation adopted by the United States, Luxembourg, Japan and the United Arab Emirates on the status of asteroids, in anticipation of future exploration (with projects such as NASA's Psyche Mission to explore an asteroid having been launched) and in contradiction to the spirit of the multilateral framework, although the latter lacks precision.

Although **extraterrestrial resources from outer space are generally not considered a convincing potential source** in the short term in the literature, their exploitation is being studied from geological, technical and legal perspectives. As summarised by Merle et al. (2023), the perception of this type of extraction appears to be the culmination of hyper-capitalism seeking to free itself from the finitude of planet Earth. Whether positive or negative, the potential impacts of the exploitation of space resources could profoundly change society, as the technological progress this would represent offers hope for solutions to the overexploitation of resources and future wealth.

30 - Placers are deposits formed by the accumulation of high-density sands under the effect of gravity. These deposits result from separation and sorting through the processes of erosion, transport and deposition as the flow of water slows down. These deposits are called palaeoplacers when they were formed in past geological eras.

Seabed: potential, impacts and legal framework

The **seabed** constitutes a potential source for the supply of metals, including REEs (Menendez et al., 2018), whether in sediments or in nodules formed by the agglomeration of minerals. These nodules, known as ‘polymetallic nodules’, account for between 2.1 and 12.1 Mt of REE worldwide. The most promising regions for this resource are the North-West Atlantic (1.1 to 3.8 Mt — with an average concentration of 0.39%), the East Atlantic (0.47 to 1.6 Mt — 0.34%), the South-West Pacific (0.32 to 3.1 Mt — 0.27%) and the Clarion-Clipperton Zone, located in the Pacific Ocean off the coast of Mexico (0.1 to 3.4 Mt — 0.1%). Nodules formed by the chemical precipitation of elements from seawater (‘hydrogenetic’ nodules) can be enriched in REE due to the slow nature of the process.

Deep-sea sediments and muds can also be enriched in REEs, with an average concentration of $0.12\% \pm 0.02$. Kato et al. (2011) estimate a quantity of $9,110 \pm 1,460$ tonnes of REE oxides per km² for a thickness of 10 m. If all sediments in the Pacific Ocean located at depths of more than 4 km were dredged to a depth of one metre (over 1.1 million km²), the resource would amount to 450 Mt of REE oxides (Hong et al., 2024). However, the enormous volumes involved and their limited accessibility mean that the exploitation of this resource remains highly uncertain.

As France is the **world’s second-largest maritime territory** thanks to the maritime areas off its overseas territories (almost 11 million km²), the offshore mineral resources it harbours could, in theory, constitute a credible source for REE supply. Generally speaking, the seabed can be considered to contain deposits of low concentration (< 0.2%) and potentially large volume (> 100 Mt).

However, **the exploitation of seabed mineral resources to extract REEs presents numerous challenges, particularly regarding the environmental impact of the techniques that could be used, and is currently highly controversial in the literature.** Some authors are indeed seeking to compare the advantages and benefits of these activities with those of land-based extraction (Miller et al., 2021; Paulikas et al., 2022). Conventional methods are thought to cause significant impacts by generating turbidity plumes and sediment-laden currents, as the force of gravity acts differentially on the water-sediment mixture, which is denser than the surrounding fluid (see in particular Elerian et al., 2022). The extent of the damage, as well as the biodiversity found on the seabed, is still very poorly understood. We do, however, know that it is home to numerous endemic species. It is not currently possible to determine whether the seabed could return to equilibrium following exploitation. The studies analysed as part of this assessment agree that the ecological impacts mainly include:

- 1 • alteration of the sedimentary habitat and its communities,
- 2 • the discharge of sediments and plumes,
- 3 • the discharge of toxic compounds,

- 4 • the generation of light and
- 5 • noise,
- 6 • thermal pollution,
- 7 • atmospheric emissions,
- 8 • discharges into water,
- 9 • withdrawal of ambient water, and
- 10 • destruction of marine genetic resource.

As for the **legal framework** governing the exploration and exploitation of offshore mineral resources, it varies depending on whether the area in question falls under national jurisdiction or is an international area. The 1982 United Nations Convention on the Law of the Sea provides that a State has sovereign and exclusive rights regarding the exploration and exploitation of mineral resources on its continental shelf, i.e. on the seabed and subsoil adjacent to its coastline up to a distance of 200 nautical miles offshore. Within this area (territorial waters, then the exclusive economic zone and the continental shelf), it is therefore up to each country to determine the appropriateness and methods of exploring and exploiting these resources. **France has taken a stance in favour of banning their exploitation in international waters**, but not in waters under national jurisdiction, where its mining law applies. Conversely, French Polynesia and New Caledonia, as well as Wallis and Futuna, have introduced a temporary ban on all mineral resource exploration and exploitation activities. The European Union, in Regulation 2024/1252 (Critical Raw Materials Act), has also declared itself in favour of refraining from any activity relating to the exploration and exploitation of offshore metals, until the absence of harmful effects from such activities has been demonstrated. Although Norway announced plans to commence mining on its continental shelf — before temporarily abandoning them — and with a few exceptions (Petterson and Tawake, 2019; Tassin Campanella, 2024) the literature reviewed addresses the issue of exploiting REEs located in areas under the national jurisdiction of States (the continental shelf) relatively little, focusing to a greater extent on the issue of exploiting mineral resources in the international seabed (the ‘Area’). In this ‘Area’, mineral resources are regarded as the **‘common heritage of mankind’** and are subject to a specific regime which involves, in particular, the redistribution to developing countries of a percentage of the profits to be derived from the commercial exploitation of these resources, as well as the centralised management of these resources by an international organisation representing the interests of mankind: the International Seabed Authority (UNCLOS, Part XI; (Dingwall, 2020)). Currently, 31 mineral exploration contracts have been awarded by the Authority, including two to IFREMER, in the Clarion-Clipperton Zone, identified for its high potential for polymetallic nodules — and therefore promising in terms of REEs. Exploitation, however, has not yet begun. The Authority is finalising the regulations that will apply to these activities (Dingwall 2020), unless a moratorium on mining in the Area is decided, as requested by some forty States, NGOs united within the Deep Sea Conservation Coalition, and certain companies including Eramet,

Ford, General Motors and Microsoft. The executive order adopted by the United States on 24 April 2025, aimed at encouraging the exploitation of offshore mineral resources both within and beyond the limits of national jurisdiction, thus runs counter to the multilateral legal framework that has been under development since the 1980s. A Canadian company, The Metals Company, could soon become a pioneer in this field, having submitted in April 2025 the **first application for mining in international waters**, based on the US executive order, after criticising the slowness of the multilateral process within the International Seabed Authority, whilst planning, through its subsidiary NORI and the sponsoring state of Nauru, to submit a parallel application to the Authority, building on its existing exploration licence — a move that raises numerous legal questions.

The scientific studies analysed agree that **significant uncertainties remain** regarding the exploitation of mineral resources (including, therefore, REEs) on the seabed, **not only in terms of their mapping, concentration and volume, but also regarding the effects of mining on the marine environment and its economic viability**. Furthermore, according to Merle et al. (2023), the technological challenges are extremely significant, and the development of offshore REE mining would not necessarily circumvent current geopolitical issues.

Secondary sources

The literature identifies and characterises secondary sources with low REE enrichment derived from industrial waste and waste from mining operations other than those intended for REE production (Figure 15). This includes **coal ash** from industrial combustion, as well as **bauxite residues** and **phosphogypsum** produced during the mining of aluminium and phosphates respectively. In Europe and France, **these could represent the greatest potential source of REE**. The interest in these three residues for REE extraction is reflected in the analysed literature by more than 100 articles published on the subject since 2015. However, very few studies (fewer than 5) have attempted to estimate the stocks of these secondary sources in Europe. They are often regionalised (Sajn et al., 2024) ; the overall stock in France and Europe is uncertain and generally estimated indirectly (calculated from the consumption of primary ores, for example). For example, Dedy et al. (2016) estimate that 100 to 270 kt of REE could be extracted from bauxite residues produced in Europe between 1972 and 2013, assuming a recovery rate of 50%.

The concentration and chemical form ('speciation') of REEs in industrial residues vary depending on the geological origin of the primary ore. The vast majority of speciation studies are carried out on residues produced outside Europe and are therefore not directly applicable to those of European origin (with a few exceptions, notably for bauxite residues; Couturier et al., 2024; Vind et al., 2018). Finally, the specific characteristics of each residue are important to consider when estimating their potential: (1) the stock (particularly in Europe and France) and its current use in other applications (mainly

construction materials), which could compete with the use of these secondary sources for REE production, (2) the concentration of scandium, a high-cost REE that can make the extraction process profitable (particularly in the case of bauxite residues), (3) the relative concentrations of the most critical REE (such as neodymium, europium, terbium, dysprosium, yttrium and erbium); and finally (4) radioactivity, which may limit certain recovery pathways following REE extraction (zero-waste approaches in particular).

In addition to these industrial residues, studies are examining the potential of mining residues in Europe resulting from the extraction of other metals (silver, lead, zinc, copper, gold). These studies are still very fragmented, and extraction yields depend heavily on the nature of the residues (Balassone et al., 2021; Peelman et al., 2016; Rosario-Beltre et al., 2023). Furthermore, some tailings produce sulphuric acid effluents that could be potential sources of REE (acid mine drainage).

The **legal framework governing the recovery and recycling of mining waste for the purpose of extracting REEs exists** and is based primarily on the Directive of 15 March 2006 on waste from the extractive industries. In this context, Member States of the European Union must, in particular, ensure that 'operators in the sector draw up appropriate waste management plans to prevent or minimise, treat, recover and dispose of extractive waste'. The directive is primarily based on a logic of **prevention** and risk management due to the hazardous nature of some of this waste. Nevertheless, although such waste accounts for one-third of the waste produced in the European Union, the Directive has not set any targets regarding the volumes of waste from the extractive industry. Furthermore, it does not form part of the regulations relating to the circular economy, even though this could enable better prevention, management and recycling of mining waste. The literature reviewed would therefore benefit from being updated, in particular by considering the setting of targets based on a life-cycle analysis.

Integrating the extraction of secondary raw materials into strategies for managing these residues could help reduce the environmental impact of storage whilst generating added value within a circular economy approach. The analysis shows that very few studies have attempted to estimate the stocks of secondary resources in Europe. Significant efforts are still required in research and development to identify effective and efficient solutions that integrate the social, economic and legal dimensions outlined in IV.3. Furthermore, for these solutions to be viable and compatible with credible sustainable development, it is essential that they are based on contextual knowledge of each mining site or mining project under consideration (Tayebi-Khorami et al., 2019).

POTENTIAL REE SOURCES: REE QUANTITIES IN GLOBALLY GENERATED OBJECTS (2020)

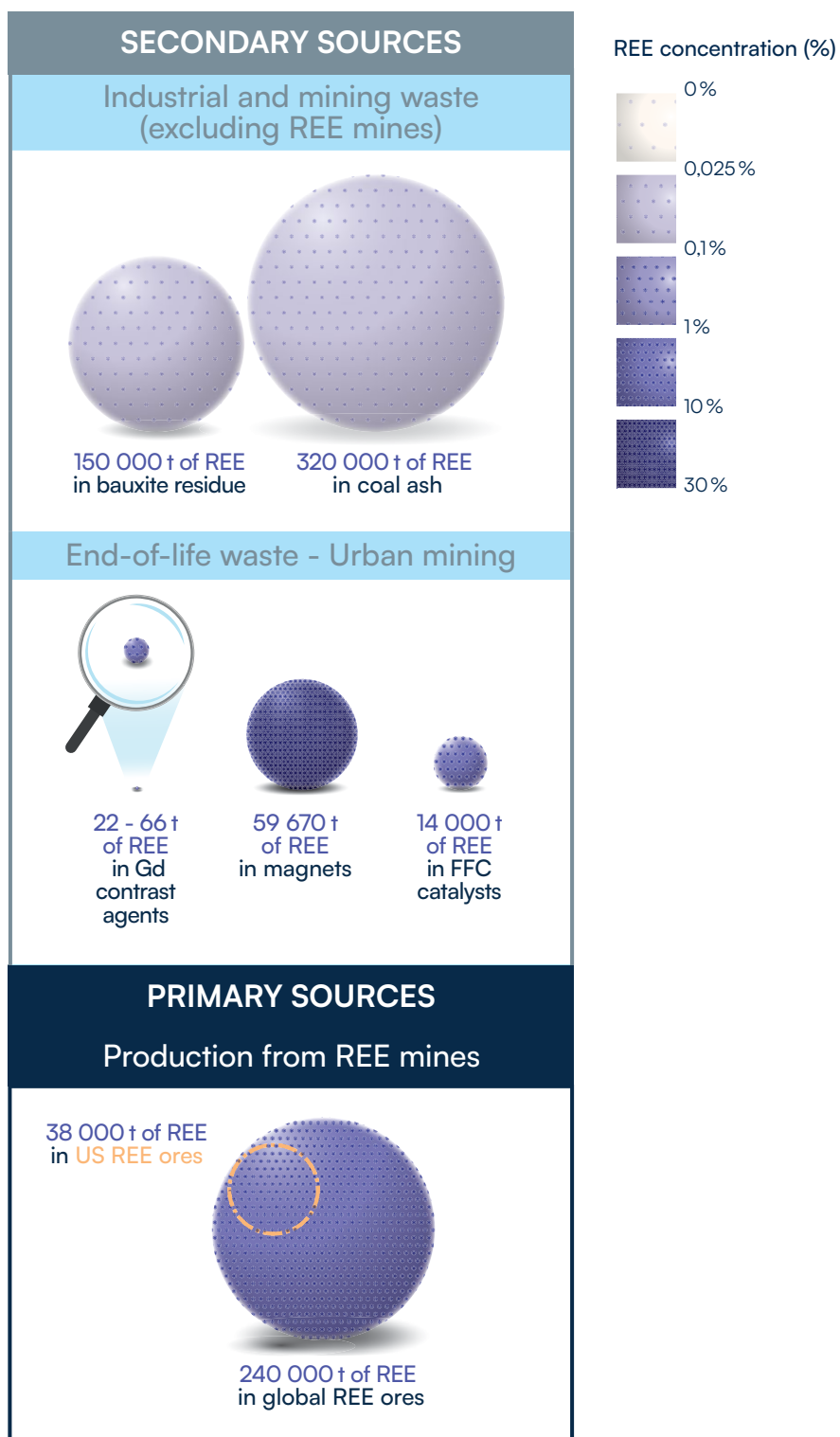


Figure 15 : Comparison of the quantity of REE present in mining and industrial waste (bauxite residues and coal ash) generated worldwide in 2020, with that present in objects generated in 2020 that could be used to create urban mines, and that in rocks extracted from REE mines in 2020. The coal ash and bauxite tailings produced annually worldwide represent very large volumes (800,000,000 tonnes and 150,000,000 tonnes) with low concentrations of REE (0.04% and 0.1%).

IV.2 The existence of innovative, more environmentally friendly processes

New exploration technology pathways

Key points

The extraction of REEs relies on a close match between the mineralogy of the deposit and a process chain combining enrichment, physico-chemical and chemico-metallurgical treatments. The selection of these processes requires integrated ‘resource—process—environment’ optimisation, based on circular hydrometallurgy and the internal recycling of reagents (Binnemans and Jones, 2023), in order to reconcile security of supply with sustainability requirements.

Beyond extraction from primary ores, the experimental scientific literature analysed identifies innovative solutions, such as the recovery of secondary sources like mining waste (coal, bauxite, phosphogypsum), or the use of more environmentally friendly processes such as bioleaching, phytomining and zero-waste approaches. These secondary sources, which are abundant in France and/or Europe, could limit the need for primary extraction by promoting circular practices.

However, these technologies are still relatively immature and have not been extensively tested in an industrial setting, making their deployment uncertain without a clear commitment from the mining sector.

Exploration technologies for **discovering and characterising new REE deposits** rely on a range of geological³¹, geophysical³², geochemical³³ and mineralogical³⁴ methods. They are constantly evolving, improving analytical resolution in detecting concentrations, in spatial and volumetric scales, as well as in the speed of measurements (Balaram, 2022). The scales of analysis vary greatly depending on the methods used. They can cover vast regions using remote sensing or airborne measurements, but can also pinpoint the location of metals at the microscopic scale of a single mineral. **Geophysical methods** are essential for the initial detection of deposits and for revealing the geometry of deep-seated discontinuities that delineate the deposits. They must then be supplemented by a range of **geochemical and mineralogical analyses** to characterise concentrations and confirm the potential for metal recovery. Among the most notable developments in recent years is the trend towards the miniaturisation of analytical tools, which can thus be taken into the field and which approach the resolutions of traditional laboratory methods (Balaram, 2019). One of the main objectives of these methods is to discover new deposits (Malainine et al.,

2022), particularly carbonatites, which are the geological formations with the highest potential for REE (Simandl and Paradis, 2018), but also to refine the mineralogy in order to improve extraction efficiency.

The various methods provide complementary information that constitutes vast datasets (Nykanen et al., 2008). Integrating these methods is essential, as no single method can determine both the concentrations and volumes of a deposit and the REE-mineral hosts. **By combining these geological, geophysical, geochemical and mineralogical data within geographic information systems, artificial intelligence can recognise complex spatial and mineral signatures associated with REE deposits** — for example, distinguishing a bastnäsite-enriched carbonatite from a barren one — and thus improve the prediction and prioritisation of exploration targets. With its rapid rise, it is becoming difficult to anticipate the extent of its impact on new deposit discoveries and associated separation processes, and thus the revolution it could bring about in the REE exploration and exploitation, in the coming years (Katiyar et al., 2024).

31 - Tectonic structures, presence of rocks associated with the target deposits.

32 - Magnetic, gravimetric, electromagnetic anomalies, etc.

33 - Abnormal concentrations of elements indicative of the presence of REE.

34 - Identification of minerals containing the target metals.

Extraction of REEs from primary sources

The scientific literature is consistent in indicating that **the extraction of REE relies on a fine balance between the mineralogy of the deposit and a sequence of processes combining physical and physico-chemical beneficiation as well as chemometallurgical treatments, with a focus on essential circularity** (over 120 articles, including 35 focused studies between 2020 and 2023). Unlike the process front-end for recycling (see III.2), the process front-end for mining extraction involves enrichment stages comprising grinding, gravimetry, desliming, magnetic separation and/or particle flotation, prior to the core process stages involving thermal treatment and/or leaching followed by separation/purification, which are highly similar regardless of the resource's origin (mine or end-of-life equipment). Reference articles on minerals derived from carbonatites (bastnäsite and monazite) (Cen et al., 2021; Demol et al., 2019) highlight that a compromise must be found between metallurgical yields, reagent consumption and the management of fluorinated or radioactive effluents (toxic and polluting substances).

Whilst conventional approaches remain robust, a dozen studies (2020–2023) show that pre-treatment steps combining microwaves, the use of 'green' chemical agents³⁵ or the recovery of recoverable by-products (CaF_2 , Na_3PO_4) can reduce the reagent load and associated emissions by 20–40% and fit within a circularity framework³⁶. The selection of processes is driven by the nature of the deposit, which calls for integrated 'resource—process—environment' optimisation, based on circular hydrometallurgy (Binnemans and Jones, 2023) and the internal recycling of reagents. A dozen studies focusing on ionic clays capable of retaining REE deposits indicate that conventional ammonium sulphate-based solutions, whilst effective, now require alternatives with a lower environmental impact (Luo et al., 2022), such as the use of magnesium sulphate (Xiao et al., 2015) or its combinations with ascorbic acid or a mixture of ammonium chloride and calcium chloride.

Life cycle assessment methods enable the environmental impacts of REE production to be documented and quantified at various scales, from local to global. However, current studies show discrepancies due to disparate databases and often incomplete methods and data, particularly for Chinese supply chains (Wulf et al., 2017). Research shows that European deposits, such as Norra Kärr in Sweden, offer a more environmentally friendly alternative with up to 40% lower impacts than the Chinese Bayan Obo mine (Schreiber et al., 2016). Environmental performance depends heavily

on the type of ore extracted: bastnäsite and monazite, for example, require large amounts of chemical reagents and energy, whereas eudialyte, found at Norra Kärr, offers better results (Bailey et al., 2020; Zapp et al., 2018). New practices, such as the use of hydroelectricity in processes, enable a significant reduction in CO_2 emissions. Finally, recent studies highlight the limitations of purely environmental approaches, emphasising the **need to integrate socio-economic and geopolitical dimensions into sustainability assessments**. Recent models incorporating geopolitical supply constraints reveal that environmental gains can sometimes shift the burden towards new economic vulnerabilities³⁷, thus highlighting the need to integrate socio-economic and geopolitical dimensions into sustainability assessments (Gemetchu et al., 2017). Tools such as the GeoPolRisk indicator³⁸ offer promising avenues for addressing this gap, by linking environmental impacts to the economic vulnerabilities of markets. Nevertheless, further efforts are required to harmonise LCA methodologies, expand data inventories (particularly for emerging deposits) and develop forward-looking scenarios that incorporate changes in energy and trade policies. Ultimately, a combined approach, integrating environmental, social and economic considerations within the framework of life-cycle sustainability analysis, appears essential to support the development of a more sustainable and resilient REE supply chain.

Bioleaching

Like the bioleaching process used for the urban mine (section III.2), this approach also represents **an emerging and promising route for the sustainable extraction of REEs from various sources, whether primary ores or mining and industrial waste**. These processes utilise microorganisms that facilitate the solubilisation of REEs by attacking the mineral matrix (Brisson et al., 2016; Castro et al., 2023; Fathollahzadeh et al., 2018). It offers a more environmentally friendly alternative to conventional chemical processes by reducing the quantity of leaching agents, requiring less energy, and generating less polluting waste (Chen et al., 2024; McGaughey et al., 2025). A mineral such as monazite presents challenges due to the co-presence of thorium, a radioactive element, but it remains one of the most studied minerals due to its high concentration of cerium, lanthanum and neodymium (He et al., 2024). Significant progress has been made in optimising biological and operational parameters, such as pH, temperature, and the co-cultivation of microorganisms, to increase extraction yields (Fathollahzadeh et al., 2018; McGaughey et al., 2025). Furthermore, combining

35 - A 'green chemical' is a substance (reagent, solvent, catalyst or additive) used in a chemical process whose production, use and degradation minimise the negative impact on human health and the environment, whilst maintaining chemical and economic efficiency equivalent to or superior to conventional alternatives. In other words, it aims to reduce toxicity, hazard, waste production and the consumption of non-renewable resources.

36 - Some of the waste produced is disposed of by utilising its properties: CaF_2 (fluorite) as a source of fluorine or a material for optics (IR, UV) and Na_3PO_4 as a source of phosphorus for fertilisers.

37 - Economic vulnerability expresses the probability that a country's economy may be hampered by unforeseen events external to the economic system.

38 - GeoPolRisk is a method for quantifying geopolitical risks to the supply of a raw material based on the concentration of global production of that raw material and the trading partner's import shares, weighted by their political instability.

these approaches with the use of other techniques, such as hydrometallurgy, increases the process's efficiency (e.g. Vera et al., 2022). As with all extraction processes, the efficiency of bioleaching depends on the mineralogical nature of the deposit. Whilst certain raw materials, such as ionic clays, demonstrate recovery rates of up to 95–100% (Meng et al., 2023, 2022), others, such as bastnäsite, still exhibit low yields, requiring further research (Zhang et al., 2018). Thus, although bioleaching is still in the development phase, it represents a **strategic technological pathway towards a more environmentally friendly and efficient exploitation of REE primary resources**.

Phytomining

Phytomining, or agromining, is also a promising ecological strategy (Dinh et al., 2022; Rabbani et al., 2024). This method relies on the use of 'hyperaccumulator' plants³⁹ capable of absorbing high concentrations of REEs without apparent toxicity (Chour et al., 2020; Grosjean et al., 2024). After harvesting, the plant biomass is processed to extract the metals (Chour et al., 2018; Jally et al., 2021; Xie et al., 2023). This process, which is **more environmentally friendly** than conventional mining techniques, also enables the **utilisation of secondary sources** such as fly ash or mining residues (Peiravi et al., 2021), whilst contributing to the rehabilitation of degraded soils (van der Ent et al., 2015). The complex mechanisms used by these plants are still poorly understood and require in-depth research into the role of their root microbiota as well as the genetic selection of high-performing plants (Jalali and Lebeau, 2021 ; McGaughey et al., 2025 ; Grosjean et al., 2024). Although primarily focused on light REEs, this research must also extend to heavy REEs, which are rarer and of strategic importance (Grosjean et al., 2020). Still at a **pre-industrial stage**, this approach could become economically viable in a context of geopolitical tensions and high prices, particularly if it is integrated into regional biorefineries and validated by large-scale trials and life-cycle analyses (Rabbani et al., 2024).

Separation and purification of REEs

Recent work on the separation and purification of REEs reveals a highly structured technical field, enriched by decades of industrial optimisation of proven processes and by the emergence of more sustainable solutions. The modularity of extraction circuits, the diversification of extractants and the synergistic combinations of chemical families make it possible to refine separations without compromising either yield or purity, even when dealing with deposits of variable composition. This operational flexibility is now emerging as a strategic lever, not only for **reducing the number of processing steps**, but also for **adapting processes to the specific constraints** of each sector.

Furthermore, emerging solvents introduce new design principles based on **the selectivity of REEs and the minimal use of reagents** (e.g. Alemrajabi et al., 2022; Arrachart et al., 2021; Zeng et al., 2023). Recent studies highlight their potential to significantly reduce fluorinated or radioactive emissions, while maintaining acceptable recovery rates. These approaches, still limited to the laboratory scale, nevertheless offer credible prospects in the medium term, particularly for the treatment of secondary sources. Their integration into existing recovery chains requires sustained efforts at technical and economic optimisation and a better understanding of the molecular and supramolecular mechanisms involved.

The current literature also converge on the importance of integrating **locally adapted** innovations. Research carried out in Europe, for example, highlights the benefits of **integrated processing chains** combining flotation, leaching and hybrid processes, in order to recover resources from regional deposits that have hitherto been under-exploited. Far from being an obstacle, increasing technical complexity is becoming a source of opportunity: it encourages the diversification of solutions, the customisation of processes, and the emergence of more resilient strategies. This evolving field calls for **greater coordination** between academic research, industry and public policy, in order to establish an REE sector that is efficient, clean and strategically self-sufficient.

Reduction, final purification and metal production

The processes described above yield REE oxides. To finally convert these into REE metals, they must be 'reduced' (the oxygen removed). This process is complex due to their chemical stability and physical properties (high melting point, low vapour pressure). Common methods involve using calcium or lithium as reducing agents, or conductive molten salts. The use of fluorine, although energetically favourable and suitable for obtaining very pure products, remains costly. For certain volatile REEs (lanthanum), direct thermal reduction is a viable option. Finally, hybrid processes such as reduction-extraction in a salt bath or recovery in the form of alloys offer prospects for techno-economic optimisation for large-scale production.

Reduced REEs are generally 98–99% pure, but cutting-edge research and certain technological applications require 'ultra-pure' REEs (99.99%). An additional treatment sequence, notably 'pyrovide'—which involves heating the metal to temperatures close to its melting point under vacuum—enables these purity levels to be achieved.

The trade-off between purity, yield, energy cost and industrial feasibility determines the choice of reduction routes. Whilst some methods appear better suited to niche production, others seem to hold the greatest promise for large-scale implementation. This development nevertheless requires rigorous monitoring of scientific advances and industrial parameters, in order to steer future innovations towards solutions that are truly scalable to an industrial level.

39 - For example, *Dicranopteris linearis* or *Phytolacca americana*.

Extraction of REEs from secondary sources

As mentioned previously, bauxite residues, phosphogypsum and coal ash are three secondary sources described by numerous studies as having high potential for the extraction of REEs (see IV.1). Although the **concentrations of REEs are relatively low** (0.04—0.25%) compared to a primary deposit or certain end-of-life products (e.g. permanent magnets), **the quantities of these residues generated annually on a global scale are very significant**, thus representing a substantial stock of REEs which is, however, difficult to quantify based on the literature. Furthermore, **these residues have already been extracted and crushed, thereby limiting the most energy-intensive stages of ore preparation**. Finally, the global distribution of these stocks makes them particularly strategic secondary sources for countries lacking primary REE ores.

Numerous so-called ‘conventional’ approaches to REE extraction have been developed in the literature for these three types of residue, the vast majority of which combine **hydrometallurgical and pyrometallurgical methods**. Nevertheless, these processes, historically developed for primary ores, are not always suited to this type of more diluted deposit and generate numerous negative externalities (significant consumption of mineral acids and toxic organic solvents, generation of large quantities of waste, high energy consumption for the pyrometallurgical stages, etc.).

However, over the last 15 years, a number of innovative studies have been carried out to reduce the overall environmental impact of extraction. Most studies aim to **increase yields and selectivity, thereby limiting the number of stages and reagents used**. A second strategy involves **developing zero-waste approaches** with the aim of avoiding the numerous costs (economic, social, environmental) associated with the storage of tailings.

The main conclusions of these studies show that:

- Pre-treatment approaches are not very effective, probably due to the fine particle size of these residues and their heterogeneity (which varies depending on geological origin).
- The use of unconventional extractants, such as organic acids as a substitute for mineral acids, yields similar recoveries (Borra et al., 2015). The extraction conditions are then less extreme (in terms of pH for example) and better selectivity can be achieved. Pyrometallurgy improves the extraction yield of the most refractory phases prior to the use of hydrometallurgical processes. This combination also allows for better selectivity (tested mainly with coal ash and bauxite residues). The pyrometallurgical stage also enables the release of Sc, the price of which is on a par with the most expensive REEs (Lu, Tb) (\$700—900/kg in March 2025), but

with concentrations 2 to 3 orders of magnitude higher than the latter in bauxite residues (150 g/t, Zhang et al., 2016). Its extraction could contribute to improved profitability of the extraction process.

- Yields and selectivities are sometimes difficult to compare across studies, as they depend heavily on the origin of the residue and thus on the chemical form of the REEs.
- Bioleaching is also effective for the sustainable and selective recovery of REEs from these industrial wastes.
- The feasibility of multi-element recovery (REEs, iron, titanium, vanadium, etc.) from residues has been technically demonstrated (Zinoveev et al., 2021). However, these processes are complex and involve numerous pre-treatment, hydrometallurgical and pyrometallurgical stages, and are not designed to have a low environmental impact.
- Even without multi-element extraction, the valorization of the residue itself after extraction also represents a promising alternative. For example, phosphogypsum can be used as an additive in cement following the extraction of REEs, thereby reducing operating costs. However, studies on this subject remain very limited.

Ultimately, the body of literature analysed highlights significant advances in terms of (1) **improving the recovery rates and selectivity of REE extraction** and (2) **developing processes for the complete valorization of residues using innovative zero-waste approaches**.

However, the literature identifies several obstacles to the large-scale development of these processes:

- **Their development remains mostly at the laboratory scale** (sometimes even at the conceptual stage) and, in the vast majority of cases, studies focus on a single stage of the process. Process engineering approaches are virtually non-existent in the literature reviewed, even though pilot trials are emerging worldwide.
- **Environmental and economic considerations for such processes are still limited** (Zinoveev et al. 2021) and have been little or not at all studied in relation to current practices. Comparative techno-economic and environmental impact studies between these approaches and the current scenario of storing these residues are lacking to identify the most effective pathways. Although a few very incomplete attempts have been made (e.g. Borra et al. 2016), such studies are complex to conduct for technologies that are not yet mature (low TRL).

IV.3 Integrating human and environmental considerations into extraction

Key points

The literature reviewed in the humanities and social sciences emphasises the social, political and territorial dimensions of extraction, highlighting the importance of public participation, co-construction of projects, and of the consideration of impacts and externalities. The analysed literature confirms that energy transition objectives only take root locally if they are shared.

Mining law is undergoing significant changes that are tightening the corporate social and environmental responsibility (CSR) requirements for mining companies. Such stricter requirements are intended to enable more responsible mineral extraction throughout the value chain. This development concerns not only the relocation of mines within Europe, but also the conditions under which critical raw materials are produced or extracted in other countries for subsequent import into Europe.

Nevertheless, an analysis of the literature on the social acceptability of mines highlights that protests frequently arise from the absence of a prior, sincere and open debate on the very appropriateness of developing new mines: mines for what purpose, and for whose benefit? Research on mining controversies shows that they are not resolved by mere educational or compensatory measures aimed at the affected local populations. Indeed, it highlights the need to link decisions on extraction to the actual uses and needs of the extracted metals. This is why securing the supply of REEs is difficult to envisage without a democratic debate on which uses to encourage, reduce or abandon.

The literature in the humanities and social sciences concerning the integration of human and environmental considerations into mining does not directly and specifically address the case of REEs. Indeed, **although REEs have specific characteristics, the rules governing their extraction are the same as those for other metals.** Moreover, they are often extracted as 'by-products', meaning they are associated with other metals during extraction. As was done in Chapter II, a consideration of the relevance and possible **application** of the general literature to the specific case of REEs had to be undertaken: the state of the art presented in this Chapter IV of the synthesis and in the report necessarily focuses on the regulatory framework and context applicable to the mine and the associated value chain in general, **as literature focusing exclusively on the case of REEs is very rare.**

The emergence of 'corporate social responsibility' and 'sustainability' requirements: limited slogans for mining differently.

Since the 1990s, the mining sector has undergone a transformation in its regulatory frameworks, with the rise of **Corporate Social Responsibility (CSR)** (Jenkins, 2004).

This dynamic is based on voluntary norms, self-regulatory mechanisms and **international standards that are incentivising, non-binding and primarily derived from the extractive sector itself.** These norms and standards enable companies to demonstrate (particularly to their investors) a commitment to social and environmental issues and an awareness of the social dimension, whilst retaining control over how this commitment is implemented.

Beyond these sustainability frameworks, initiatives are being proposed to **try to highlight the issues related to social relations in mining projects.** For example, Bergeron et al. (2016) developed an analytical framework aimed at objectively assessing the conditions for the social acceptability of mining projects, in order to make tangible the 'social risk' that conflicts pose to projects. Their 'social risk index' comprises four dimensions: 1. the host community, 2. the project developer, 3. the nature of the project and the natural environment, and 4. the communication dynamics between stakeholders. Each dimension comprises variables (proximity of communities, social history, credibility, transparency, environmental sensitivity, etc.) assigned specific weights according to their relative importance in the Quebec context. One of the cases analysed is that of the Canadian Malartic mine (Osisko-Malartic). This open-pit project, located in the immediate vicinity

of the town of Malartic, required the relocation of several homes, the reconfiguration of parts of the urban area, and generated nuisances (noise, dust, vibrations, increased traffic). Applying the index to this case demonstrated that several social risk indicators were high: the mine's close proximity to residential areas, the history of community concern regarding the mine's environmental and health impacts, communication perceived as insufficiently transparent in the early phases, as well as the significant spatial changes that took place (relocations, demolition of buildings). These combined factors gave rise to psychological effects, community tensions, polarisation (between supporters and opponents), and a sense of loss or disruption to the living environment, which are not reflected in the social risk indicator. Efforts towards transparency, consultation and compensation helped to stabilise the social climate, although, as the project had already been launched, it was not modified in response to feedback from residents. The study highlights in particular that projects perceived as imposed or opaque provoke strong opposition, whilst those based on consultation and open communication enjoy greater acceptance. This initiative has been **heavily criticised in the literature** as it is part of the mining investment perspective, which **views society as a risk to the project**. From the perspective of project promoters and investors, this risk can be measured by a series of indicators and can be anticipated. The example provided by Bergeron et al. (2016) illustrates a method of measuring social risk that incorporates numerous parameters and is intended to be applied at the early stages of projects. Designed for mining companies, it operates solely within the scope of a project whose viability is not in question.

This initiative forms part of a **broader trend that has made CSR an integral part of mining projects**. It is based on several non-binding tools and principles (e.g. the ISO 26000 standard, the UN and OECD principles on due diligence) and includes approaches such as transparency, traceability, impact mapping, remediation plans and dispute resolution mechanisms. These principles are often implemented through sector-specific guidelines aimed at defining 'best practices'.

Beyond CSR, **other key initiatives have emerged to create international indicators and standards, such as the Mining, Minerals and Sustainable Development project (1999), which is now widely used**. Frameworks such as the 'Seven Questions to Sustainability' or those developed by the Mining Association of Canada propose assessment grids based on community engagement, governance, the local economy and environmental protection (Fonseca et al., 2013). These indicators are oriented towards the now central concept of the **social licence to operate (SLO)**, in which acceptance by local communities has become as crucial as the legal licence issued by the state (Komnitsas, 2020; Prno and Scott Slocombe, 2012; Roche et al., 2023).

However, numerous studies highlight the limitations of the norms, standards and 'best practices' used in the extractive sector, based on case studies that go beyond the scope of REEs (Dou et al., 2023; Fonseca et al., 2013; Kamenopoulos et al., 2015). The literature shows that existing frameworks often suffer from a lack of systemic integration, a difficulty in

taking long-term effects into account (e.g. pollution inherent in extraction) and an overly narrow focus on organisational performance, which in practice generally fails to account for territorial specificities. Critics also highlight the **exclusionary effects produced by participatory mechanisms, which tend to oversimplify the complexity of local situations and impose interlocutors deemed legitimate by companies, sometimes to the detriment of existing social structures** (Murrey and Jackson, 2020). Some of the articles analysed highlight that initiatives carried out in the name of CSR can generate economic dependence among local populations or mask the root causes of social opposition (Bezzola et al., 2022; Jenkins and Obara, 2006). Furthermore, some authors (including Kamenopoulos et al., 2015) question the adaptation of indicators and standards to the specific characteristics of REEs (presence of radioactive elements, differences between various REEs, market characteristics, the Chinese monopoly, etc.). Similarly, these 'best practices' are often universally applicable, even though environmental and social issues may differ depending on the region or the mineral products in those regions, raising the question of how well they are adapted to local specificities. Consequently, **approaches taken in the name of responsibility or sustainability remain contested** (Laurent, 2023; Merlin et al., 2021; Weszkalnys, 2014).

Whilst the extractive industries have embraced the concepts of responsibility and sustainability to introduce mechanisms aimed at voluntarily addressing the environmental and social impacts of mining projects, through 'soft law' (i.e. non-binding) widely promoted by international institutions such as the World Bank, **this development remains fundamentally ambivalent**. Indeed, extractive industry actors have fully integrated requirements for responsibility and sustainability, sometimes even promoting concepts such as 'sustainable mining' or 'responsible mining'; however, the lack of genuine monitoring and sanctions in the event of failure to implement the resulting recommendations in practice prevents truly effective application and does not encourage robust action.

The studies analysed criticise the normalisation of the terms 'responsibility' and 'sustainability', and highlight the problem of treating them as neutral or consensual. They call for these terms to be scrutinised, placed within their political and social context, and for **ways to be explored towards mining that fully acknowledges its challenges and implications, by explicitly addressing the contentious nature of mining projects**.

The 'tightening' and adaptation of the legal framework in response to the shortcomings of CSR

Recent developments in international law are leading to its direct application to companies without going through States (d'Ambrosio, 2021; Lhuillier, 2022). The European Directive on **due diligence** (EU 2024/1760), although currently undergoing a relaxation at European level, embodies this shift by requiring companies to **comply with international**

FOCUS : The harmful impacts of a weak regulatory framework: the example of certain REE extraction mines

The environmental impacts of mining can be exacerbated in areas where it is poorly regulated (Harpprecht et al., 2024; Langkau and Erdmann, 2021). REE extraction leads to pollution from radioactive substances and various metals. Some extraction sites use processes based on polluting chemicals, such as acid leaching, which causes severe contamination of soil and watercourses. Furthermore, illegal mining accounts for approximately 22–25% of China's REE extraction volume, contributing to social risks such as corruption, unfair competition, lack of worker protection and child labour (Werker et al., 2019). For example, the Chinese Bayan Obo mine recorded a risk of public corruption twice as high as that of Mount Weld (Australia-Malaysia) and five times higher than Mountain Pass (US-Japan). The Chinese Rare Earths Law, enacted on 22 June 2024 (State Council Order No. 785) aims, in this context, to strengthen the fight against this phenomenon by stipulating that rare earth resources belong to the state, imposing penalties for illegal activities throughout the value chain, and establishing a product traceability system (companies must record product flows in a tracking system).

standards throughout their value chain, including in third countries. The directive effectively requires companies to comply with a list of international conventions or obligations arising from these conventions, including in States that have not ratified them. It thus refers to the Paris Agreement (1992), the International Covenant on Civil and Political Rights and the International Covenant on Economic, Social and Cultural Rights (1966), as well as the Convention on Biological Diversity (1992). Negative environmental impacts must be subject to preventive or remedial measures throughout the whole value chain. This marks a significant break with traditional international law, which is exclusively inter-state in nature. The company becomes both a subject and an agent of international law, within a framework of the extraterritorial application of fundamental rights, which implies that it may be sanctioned in the event of a breach of these obligations.

States also incorporate into their national law the principles of environmental democracy derived from international law (e.g. the 1992 Rio Declaration or the 1998 Aarhus Convention), such as access to information, public participation and access to justice. In France, these principles consecrated in Article 7 of the Environmental Charter have a constitutional status. Since 1976, several laws have established mechanisms for public participation, such as public consultation and participation schemes.

The renewal of the ambition for corporate (social) responsibility and sustainability through the energy transition, a source of new asymmetries

The energy transition is reviving interest in mining, including that of REEs (Roche et al. 2023). It lies at the heart of the discourse on the mining revival in Europe, but this association has mixed consequences due to the environmental and social tensions generated by extraction (Martinez-Allier, 2002). Policies such as the European Green Deal, although framed by sustainability standards, reveal **contradictions between ecological objectives and the realities of extraction** (see Chapter II). The case of lithium in Portugal, as analysed in several articles within the studied corpus, shows that the revival of extraction in the name of energy sovereignty faces local opposition and a lack of environmental and social safeguards deemed sufficient by the affected communities (Dunlap and Riquito, 2023; Zhou and Brown, 2024). There is no objective reason to believe that the extraction of REEs (including through secondary resources) would give rise to different social and environmental tensions.

On a global scale, the energy transition exacerbates long-standing inequalities, where populations — often indigenous — bear the consequences of extractivism without reaping its benefits. This phenomenon is termed '**green colonialism**': a dynamic in which the interests of dominant countries or groups take precedence over those of the territories where mining operations are located (Burton et al., 2024; Dunlap & Riquito 2023). Canelas and Carvalho (2023) show that local populations, and in particular Indigenous communities, face the reproduction of historical inequalities inherent in the colonial extractive model. Similarly, Ash (2024) and Dou et al. (2023) highlight the fact that the social burden of the energy transition is borne disproportionately by Indigenous populations. In Greenland, Sweden and Chile, mining conflicts reveal how mining projects are likely to **marginalise local knowledge and rights**, even when they are part of transition-related objectives and seek to apply standards of accountability and sustainability. Local communities therefore criticise the way in which mining companies present REEs as global commodities, erasing colonial history and local realities by assigning them a purely capitalist value from the moment of extraction.

In response, numerous social movements are emerging (protests, mine blockades), driven by local communities who condemn the instrumentalisation of the ecological transition to justify the continuation of destructive extractive models, throughout the entire value chain (Peet and Watts, 2010; Pim, 2021). These struggles, rooted in a history of rural and popular resistance, call for a post-extractivist vision centred on environmental justice, the defence of the commons and territorial autonomy. Canelas and Carvalho (2023) also show that concerns regarding environmental justice in the critical metals industry are not limited to local impacts, but extend **beyond borders and value chains**. Thus, these struggles challenge the notion that 'green growth' necessarily requires the intensification of natural resource exploitation, including that of REEs.

In conclusion, whilst the energy transition currently appears to be a key driver of the renewed interest in mining, it is accompanied by profound ambivalence. By invoking objectives linked to sovereignty and concepts such as ‘green growth’, the transition justifies new extractive dynamics without resolving the social, political and ecological tensions they generate. Far from easing conflicts, this context of transition tends to exacerbate them by reproducing old asymmetries and provoking local resistance to the instrumentalisation of an ecological imperative. **Yet the goal of transition could pave the way for a radically different approach to extraction wherever it takes place, provided that the choices it entails are re-politicised: what should be extracted, for what purposes, for whose benefit, and at what social and environmental cost?** The literature examined invites us to address these

FOCUS : The example of the rejection of lithium extraction in Portugal

Dunlap and Riquito (2023) examine how pro-mining authorities and companies attempt to gain the acceptance of local communities by employing techniques of social warfare and infrastructural colonisation. The Barroso lithium mine project in Portugal, set to become one of the largest open-pit lithium mines in Western Europe, forms part of the European Union’s energy transition strategy. This initiative, which aims to reduce Europe’s dependence on lithium imports, is coming up against the environmental and social concerns of local communities, particularly in the rural region of Barroso, renowned for its global agricultural heritage and biodiversity. The Portuguese authorities, backed by the EU, are promoting lithium extraction as a green solution, but the local community perceives this project as a threat to its traditional way of life and its environment. Institutional and corporate actors use the concept of ‘green mining’ to legitimise mining projects, whilst marginalising the needs and voices of local populations. To facilitate acceptance of the project, Savannah Resources has manipulated local perceptions through intermediaries by employing local residents as liaison officers. The region, designated by the Food and Agriculture Organisation of the United Nations as an agricultural system of global importance, is home to rich biodiversity, including endangered species (Canelas and Carvalho, 2023). The authors note that habitat fragmentation, caused by the construction of mining infrastructure, could lead to the extinction of certain local species sensitive to changes in water quality. Furthermore, the Barroso region relies on agriculture and livestock farming for its livelihood. Local residents fear that mining will destroy not only their land but also their way of life.

questions in order to move beyond existing frameworks of responsibility or sustainability and thus imagine forms of governance capable of making decisions regarding resource extraction truly collective and democratic.

How can we do better to extract differently?

To put it another way, the literature highlights the need to consider ways of ensuring social, environmental and epistemic justice. The latter requires, first and foremost, taking into account traditional knowledge, which is deeply rooted in an understanding of ecosystems, yet is rarely taken into account in mining governance (Zhou & Brown 2024; Canelas & Carvalho 2023; Ash 2024). Beyond financial compensation, restoration programmes based on local knowledge could be proposed. The recognition of this knowledge, as well as transparency of information, are described as essential to enable the active participation of affected communities and prevent the reproduction of inequalities. This may involve the use of technological tools providing public data to monitor the environmental assessment of extractive projects (such as Copernicus satellites monitoring gold mining in the Republic of the Congo; (Buschke et al., 2023)) or through the establishment of regulatory frameworks requiring companies to disclose their environmental and social impacts (e.g. by standardising the use of the EITI standard 2023).

More generally, recognising that ‘extracting differently’ must take into account **the economic, social and material questions that matter to the affected populations** (whether they live near mining sites or use the extracted resources) would lead mining projects to form part of a shared transition policy — in the sense that projects would be linked to shared decisions on the objectives and means of the transition, but also on the positive and negative implications of extractive projects. The literature reviewed suggests avenues in this direction (e.g. Zhou & Brown 2024; Burtseva and Bysyina, 2019; Laurent 2023). These involve **rethinking environmental assessment, addressing data production and access, and taking into account the entire value chain**, which in part aligns with recent legal developments in the sector. Beyond these suggestions, the analysed literature converges on the need to rethink the decision-making processes regarding mining projects in order to design extraction that is integrated into a **shared transition** policy. This ‘alternative’ form of extraction would require a collective capacity to identify needs and agree on the best ways to meet them, thereby bringing extraction into the public debate beyond the scope of individual mining projects.

In conclusion, the analysis of contemporary developments in the extractive sector highlights a fundamental tension: that between the imperative of sustainability and social responsibility on the one hand, and the persistence of logics of dispossession and asymmetry on the other.

The use of more binding legal instruments, such as the duty of care for companies, reflects a growing recognition of the systemic impacts of supply chains. Nevertheless, these regulatory advances remain largely characterised by top-down governance approaches, which struggle to fully integrate the knowledge, priorities and rights of the affected communities at the local level. The energy transition, sometimes described as the driving force behind ‘green growth’ and pursued in the name of sovereignty, nevertheless often tends to perpetuate old forms of extractivism, disguised under renewed discursive forms. Far from achieving consensus, it reignites conflicts, both over the use of resources and over decision-making processes. Furthermore, the literature pays very little attention to the human and environmental dimensions of the other stages of the value chain, namely processing or refining, generally remaining focused on the issue of extraction, wherever it

takes place (and therefore including cases where it occurs abroad but involves raw materials intended for import into France or the EU).

Conceiving of truly responsible and sustainable extraction requires moving beyond the current regulatory framework to question the very purposes of extraction: **why extract, for whom, and at what cost?** This entails recognising the diversity of knowledge and ways of life affected, and collectively debating the transition pathways to be developed. Such a perspective calls not only for legal reform, but also for a rethinking of the governance models for strategic minerals, and more specifically for REEs, capable of restoring effective decision-making power to the communities concerned.

In other words, **a review of the literature shows that ‘extracting differently’ is not merely a matter of improving existing practices: it involves a profound transformation of our relationship with the land, resources, science and decision-making.** This transformation is described as possible only by embedding extractive projects within a policy of democratic transition, grounded in the requirements of social, environmental and epistemic justice, and within a jointly developed and ambitious legal framework capable of meeting these requirements. To be coherent and effective, such a policy can only address the value chain as a whole, and not merely European production, and should be rolled out globally. Whilst this remains complex, it is gradually taking shape, for example through the development of transparency and material tracking requirements with the Digital Product Passport (see above, Chapter II).

FOCUS : The case of Greenland

Boetzkes and Diamanti (2023) demonstrate how the Australian company Greenland Minerals Ltd (GML) attempts to appropriate Greenlandic resources through the exploitation of the Kuannersuit mountain, despite protests from the local population. The latter denounce the desire to impose a Western worldview on territories where resources are perceived differently. The authors refer to the subtleties of oppression, where seemingly harmless bureaucratic and scientific processes mask violence against the environment and local inhabitants. This violence is perpetrated through consultations, environmental impact assessments and technical reports, which neutralise local concerns whilst validating mining projects. The concept of geo-fetishism helps to illustrate these mechanisms. It is defined as the way in which mining companies present REEs as commodities, erasing colonial history and local realities. In the context of Kuannersuit, this fetishistic view transforms the mountain into a mere reservoir of precious minerals, where the potential market value of the minerals is emphasised, to the detriment of ecological risks and cultural significance for the local inhabitants. The rock ‘lujavrite’ is described by GML as a ‘host rock’ in their environmental impact assessment, which normalises extraction by portraying it as a purely geological process. In response, the Urani Naamik group is campaigning against the mining project due to environmental risks and to protect Greenlanders’ rights over their resources. In 2021, following protests, the Greenlandic parliament imposed a five-year moratorium on uranium mining. Urani Naamik is conducting counter-analyses to demonstrate the flaws in GML’s impact assessment and expose the biases in their calculations, particularly regarding radioactive dust emissions, which were assessed by British consultants who have never visited Narsaq.

IV.4 Putting things into perspective

Adopting alternative extraction methods with the aim of strengthening national and European sovereignty *ultimately* requires identifying the metal potential of primary deposits (geological subsoil) and secondary deposits (industrial waste and waste from mines other than REE mines) on French and European soil, and placing them in a societal context. In this context, it is nevertheless crucial to consider resources by linking geological deposits and their economic potential to territorial data (social, geographical, demographic, political). Indeed, the exploitation of a resource requires political support and social acceptance, beyond the mere presence of an economically viable deposit.

Producing REEs differently involves far more than a technological transition. The literature reviewed in the humanities and social sciences emphasises the social, political and territorial dimensions of extraction, highlighting the importance of citizen participation, the co-construction of projects, and the consideration of impacts and externalities. The analysed literature confirms that energy transition objectives can only take root locally if they are shared, but does not provide practical solutions to ensure this connection.

The literature analysed in the experimental sciences identifies innovative technical solutions, such as the recovery of mining waste (coal, bauxite, phosphogypsum) as secondary resources, or the use of processes such as bioleaching, which are more environmentally friendly. These wastes, which exist in large quantities across France and/or Europe, could limit the need for primary extraction by promoting circular practices. However, these technologies are still relatively immature and have not been extensively tested in an industrial setting, making their deployment uncertain without a clear commitment from the mining sector. Furthermore, the significant potential associated with the development of artificial intelligence-based tools (discovering new deposits and mapping them) has not yet been addressed.

The integration of interdisciplinary approaches shows that these alternatives cannot be viable without being embedded in clear regional projects, developed with local stakeholders, supported by long-term public policies and an institutional framework that allows for the discussion of

transition policy objectives. In France, sites of secondary deposits, such as the bauxite tailings in places like Gardanne or former coal mining sites, offer concrete opportunities to test a more inclusive regulatory framework, based on shared governance and the recognition of environmental liabilities. This requires moving beyond a strictly technical view of extraction to consider it as a collective and evolving project, capable of improving certain situations inherited from the past. The issue of exploiting these secondary resources also represents a promising field for research, whether in the experimental sciences or in the humanities and social sciences.

Finally, a critical reflection on the economic value of REEs is necessary. The construction of this value, discussed at the regional level, would foster a democratic debate on uses, redistribution and benefits within a framework of shared sustainability. This issue, at the intersection of political economy, economic geography and anthropology, remains largely unexplored.

EXTRACT DIFFERENTLY

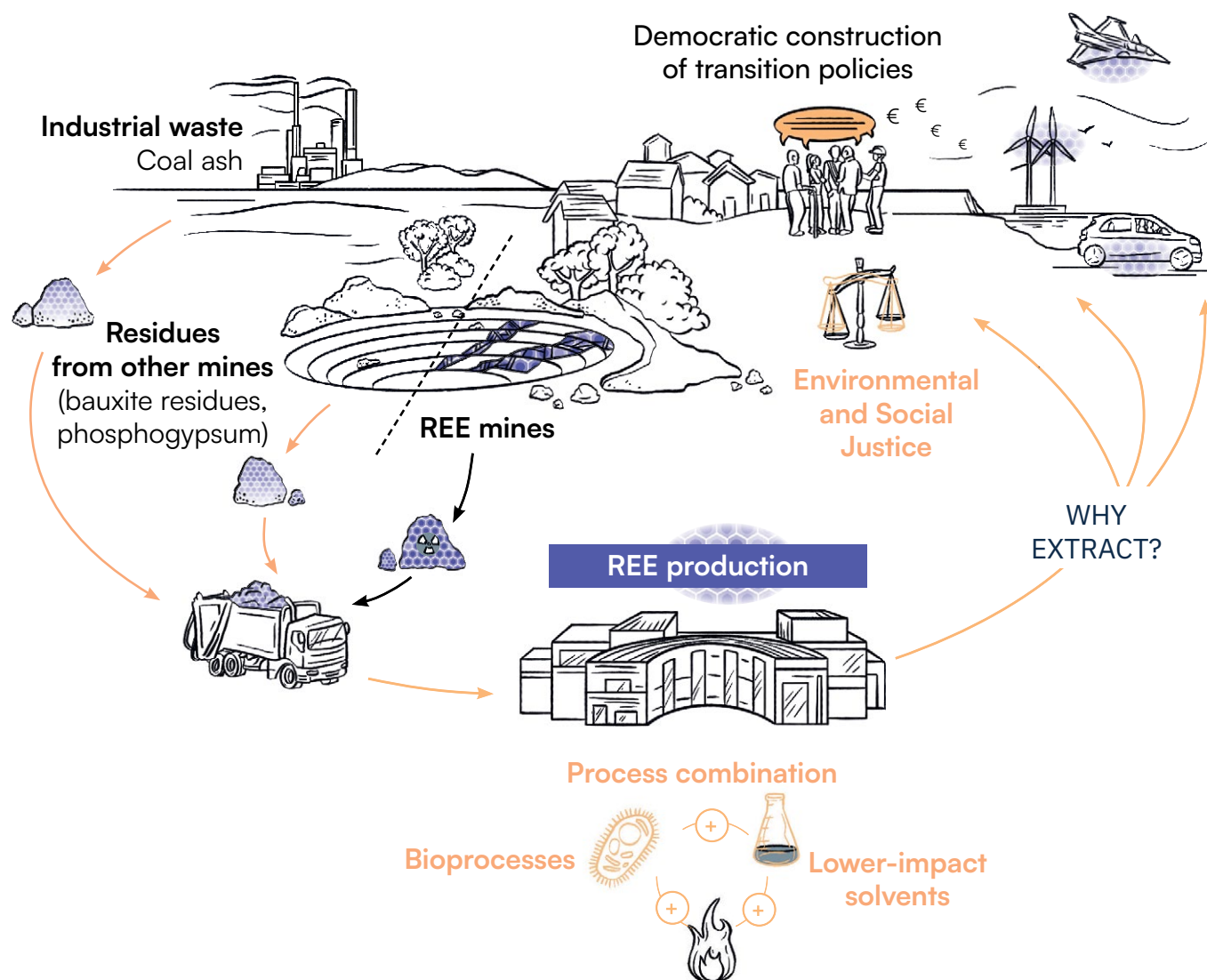


Figure 16 : Conclusion of Chapter IV 'Extracting Differently'. The levers are shown in orange.

General conclusion

REEs are highly specific metals. Their characteristics — their ubiquity and dispersion across technologies and uses, as well as the fact that they can only be extracted together, amongst other things — create a complexity that requires a truly multidisciplinary and cross-cutting approach. Access to these resources is becoming problematic due to geo-political tensions, economic barriers and growing demand. These challenges are not new, but are taking on renewed relevance with the development of applications linked to carbon-free energy production technologies.

In this context, any consideration of needs must therefore include a reflection on the sufficiency in use.

Reducing reliance on REEs through technology and sufficiency in use presents an opportunity, and highlights a need for reflection—beyond research—to determine what is essential.

The literature offers insights into possible levers for action in terms of reduction:

- reducing REE consumption through more efficient use of materials and the technologies that depend on them, as described for permanent magnets;
- developing materials using alternative technologies that require fewer or none of these resources, as described for lighting (LEDs);
- considering the uses of objects containing REEs and ways to reduce or adapt these uses;
- or adopting a legal and public policy framework capable of substantially influencing the development of certain sectors.

Levers for action on demand for REEs are much less studied in the literature than levers for action on supply (primary and secondary production, recycling, and recovery of mining and industrial REEs waste). When these levers are specifically studied, they do not focus precisely on REEs but on the devices that contain them. These gaps highlight the need to explicitly identify REEs as a key issue in themselves regarding France's vulnerability, beyond the objects and devices that contain them. The lack of traceability of REEs also appears to be a constraint on sufficiency and collection for recycling. Circularity could indeed contribute to security of supply, but it requires technical innovations and changes to the rules governing economic activity (traceability of resources and waste, recycling obligations for critical materials).

In materials science, research efforts focus on improving performance rather than on REE sufficiency. Indeed, the literature lacks a truly systemic and interdisciplinary approach to sufficiency. Research across all disciplines fails to address the 'appropriate technological need' according to specific uses, in order to reduce REE consumption. Although

certain cases, such as the use of NdFeB magnets in electric vehicles, show that substitution with REE-free magnets may be feasible, in many cases reduction or substitution leads to a drop in performance. In the case of electric vehicles, this could be offset by reducing the vehicle's weight or by developing less powerful vehicles.

France has potentially significant secondary sources in the form of both waste from consumer products (urban mining) and from the mining and industrial sectors.

Technological opportunities exist, but the recycling sector relies on a collection system, infrastructure and an economy that needs to be stabilised:

There is a particularly large body of literature on the optimisation of recycling processes for urban mining (over 1,000 articles have been identified). Existing pre-treatment processes demonstrate solid technical feasibility, although several avenues for optimisation remain to be explored. In particular, the heterogeneity of urban mining makes the automation of dismantling complex. As for the core processes, pyrometallurgical methods stand out for their simplicity and robustness, but are energy-intensive and not always suitable for diluted streams. Conversely, hydrometallurgy and its variants (liquid-liquid extraction, selective adsorption, electrochemistry) form the basis of separation processes. Finally, so-called non-conventional approaches (solvometallurgy, ionometallurgy, biometallurgy) offer more sustainable prospects, but still require validation at pilot or industrial scale.

Although the technical feasibility of recycling has been demonstrated, the actual recycling rate has remained below 1% for several years. The literature indicates that it is possible to establish a recycling chain for REEs in France, but that certain obstacles remain. Whilst, initially, the supply from the 'urban mine' would not be sufficient to meet France's growing needs (particularly in view of the energy transition towards renewable energies), this recycling chain could, in the medium term, provide a significant quantity of REEs, particularly when the first generations of wind turbines will be recycled. From a technical perspective, it is possible to establish this recycling chain: France possesses the necessary scientific and technological expertise. It is from an organisational, legal and political perspective that numerous challenges arise. Firstly, regarding more dispersed applications, the low concentration of REEs in objects greatly complicates their collection and undermines the profitability of recycling. The level and volatility of REE prices relative to other metals (notably gold and copper) are not high enough to encourage economic actors to invest in the sector. The literature shows that the establishment of a market enabling the organisation of such a sector, and thus the reduction of production costs, can only be achieved through the creation of legal frameworks and the development of incentive policies by public authorities.

Exploiting mining and industrial waste presents an opportunity that must be balanced against the mining controversies often arising from the absence of prior and sincere debate on environmental impacts, the purpose of the project, and the sharing of benefits with local communities:

As for the potential of primary REE deposits, it appears relatively modest in France, with the exception of resources found on the seabed. Nevertheless, many uncertainties regarding the potential of the latter remain. Furthermore, the literature highlights deep-seated controversies regarding the advisability of exploiting the seabed, given the significant environmental consequences that such exploitation would entail, as well as its technical and economic feasibility. In the medium term, economic and geopolitical alliances with countries other than China are being considered as options for France to diversify its supplies, notably through resources in Northern Europe or those of other countries such as Brazil.

Furthermore, a potentially very significant secondary source of REE exists in France and Europe in mining waste and certain industrial waste. Whilst the stocks of bauxite residues in France and Europe are poorly understood, they are currently not being utilised and could represent up to nearly 270,000 tonnes of REE, thereby significantly meeting European needs, at least in the short term. The environmental benefit of recycling bauxite tailings, or other mining waste, lies in the fact that these materials have already undergone the crushing and grinding stages, which are particularly energy-intensive during primary extraction. Furthermore, extracting REEs using zero-waste approaches would help reduce the environmental impacts associated with their storage.

On the other hand, the exploitation of mining residues raises difficulties that overlap with those of primary mining in technical, economic and democratic terms. The literature on social acceptability issues shows that limited consultation with stakeholders, coupled with the presentation of technical and economic projects that are too advanced, tends to increase controversy and tensions surrounding the projects. Beyond safety considerations, the literature questions the methods of extraction wherever it takes place. Mining activities in themselves raise significant environmental and social issues. Numerous studies on mining controversies show that these issues cannot be resolved solely through educational initiatives and compensation schemes aimed at affected local communities. The literature agrees on the need to link decisions regarding extraction with questions of the use and needs for the extracted minerals, which implies

that public debates on REEs should not be confined to the scope of extractive projects. The strengthening of social and environmental standards, particularly through corporate due diligence, as well as the increasingly close link between security objectives and those of sufficiency and the circular economy, are very recent developments and have not yet been properly assessed in the literature. A lack of studies on the traceability of REEs in products and on the implementation of European preference policies (similar to those in China or the United States) can be noted.

In conclusion, France and Europe have significant potential for the production of secondary REEs, derived from both mining and industrial waste and the urban mining sector. However, the recovery of these resources requires overcoming several technical, economic and regulatory barriers, which calls for greater support from public policy, through schemes for support, innovation and the structuring of supply chains.

At the same time, this issue is intrinsically linked to a democratic debate on sufficiency in use and an integrated vision of the energy transition, bringing together technological, social and environmental dimensions to ensure the coherence and sustainability of collective choices regarding the consumption of critical resources.

Glossary

Bauxite: a rock formed by the accumulation of sediments and characterised by its high aluminium content. The mining of bauxite is therefore the main source of global aluminium production. Bauxite residues, also known as ‘red mud’ when hydrated, contain concentrations of REE of up to 0.2% by mass.

Critical metal/material: metal/material that play an important economic role, are difficult to substitute, and pose supply risks. REEs belong to this group, which also includes other metals.

EPR: the principle of Extended Producer Responsibility, recognised in the European Waste Framework Directive, whereby producers, i.e. those who place certain products on the market, may be held responsible for financing or organising the prevention and management of waste arising from these products at the end of their life.

Extraction: the physical act of removing ore from the ground (in a geological sense) or the physico-chemical process of separating metallic compounds from other compounds (in a process engineering sense).

Leaching: a process involving the dissolution of a substance in a liquid to extract its soluble components. Bioleaching relies on microorganisms capable of carrying out this solubilisation.

Long-loop recycling: a recycling process involving complex transformations that allow the recycled material to be used for purposes other than its original applications.

Material performance: the ability of a material’s properties to effectively meet the requirements of a given application. For example, the performance of a magnet is the maximum energy it is capable of storing (and therefore delivering) relative to its volume, as well as the maximum temperature threshold at which it loses its magnetisation.

Mining: the organisation of activities aimed at extracting and processing metals.

Permanent magnet: a material that produces a permanent magnetic field without consuming energy. The relative movement of a magnet in relation to a copper coil (or another conductive metal) induces an electric current in the coil. Conversely, applying an alternating current to the coil generates a force that moves the magnet. This principle is used, for example, in electric vehicle motors. These can generate the force to move the vehicle and produce electrical energy during braking to recharge the battery.

Phosphogypsum: mining waste generated during the production of fertiliser from rock resulting from the extraction of phosphates intended for the production of fertiliser or phosphoric acid. The storage of this waste poses certain environmental and health risks due to its toxicity. This waste contains REEs.

Processing: the set of physico-chemical or metallurgical operations designed to transform the sorted material (ore or material) into a metal concentrate of varying purity.

Refining: a physico-chemical process used to obtain a metal or compound of high purity by removing the final impurities present in the product resulting from processing. This final stage is necessary for most applications, but not all, depending on the desired performance.

Reserve: part of a resource that can be extracted in an economically viable manner using available techniques and in accordance with current legal and environmental conditions.

Resource: the total quantity of an ore or material present in the subsoil, whether or not it is exploitable at a given time.

Secondary source: sources of REE other than primary production from REE mining. These sources include waste from other mines (e.g. bauxite tailings, phosphogypsum), industrial waste (e.g. coal ash, scrap from the manufacture of permanent magnets) and end-of-life products containing REEs, also known as the urban mine (e.g. smartphones, electric cars, wind turbines, contrast agent solutions, etc.)

Separation: mechanical and/or physical processes designed to concentrate metals of interest within the material or the ore by isolating them from other components.

Short-loop recycling: a recycling process aimed at reducing the number of waste recovery and treatment stages, without returning to the original component.

Strategic metal/material: metal/material associated with certain strategic sectors such as defence or those involved in transition policies (energy, mobility, etc.). Certain REEs belong to this group, which also includes other metals (lithium, cobalt, etc.).

Strategic project : project that makes a significant contribution to the EU's secure supply of strategic raw materials, is technically feasible, has an expected production volume that can be estimated with sufficient confidence, and is implemented sustainably.

Sobriety (or sufficiency): this “involves questioning our needs and satisfying them whilst limiting their impact on the environment” (ADEME). In the context of this report, sobriety (or sufficiency) has been addressed in three different ways : (i) an approach aimed at reducing the consumption of REEs through more efficient use of materials and the technologies that depend on them; (ii) the development of alternative technologies that require fewer or none of these resources; (iii) a consideration of the uses of objects containing REEs and the levers for reducing these uses.

Urban mine: a mass of waste originating from urban areas (end-of-life objects) that may represent a reserve, particularly of metals, for reuse or recycling.

Appendix: Summary of the methodology

Formation of the expert group

A preliminary phase involving four experts identified around ten disciplinary issues relating to REEs. The scientific leads were then selected on the basis of their expertise and scientific output to provide a systemic and multidisciplinary response to the question of the responsible use of REEs in the face of geopolitical challenges for France and Europe. The experts were identified on the basis of their fields of expertise and their scientific output, in collaboration with the scientific leads from CSA (Collective Scientific Assessment) and with the support of the monitoring committee comprising representatives from the relevant CNRS institutes. They were selected from among French authors featured in the initial lists of publications compiled using keywords. **A core group of 17 experts was thus formed.** Each declared any conflicts of interest they might have in relation to the subject. These declarations were analysed by a committee chaired by the CNRS Ethics Officer to establish the absence of any conflicts of interest concerning them. The CNRS did not disclose their identities until the results were published, in order to protect them from attempts to influence them and from any form of pressure they might face regarding the sensitive subjects of the expert assessment. Conversely, the experts did not disclose their participation in this CSA outside their own organisational hierarchies.

The CSA called upon a second group of **13 contributing experts** to shed light on a limited number of publications and on areas where the first group's expertise was limited.

Establishment of the scientific resource base

The aim of compiling the corpus of scientific publications on which the CSA was based was to provide an overview of the international state of the art on the issue of 'Towards the responsible use of rare earth elements throughout their life cycle - What are the prospects in terms of sufficiency, recycling and production methods?'. The Mission for Scientific Expertise (MPES - CNRS) called upon the Institute of Scientific and Technical Information (INIST — CNRS) for this purpose, implementing a so-called 'funnel' method, moving from an expanded corpus to the final corpus.

Expanded corpus. For each chapter, the core group experts and the INIST collectively determined a list of keywords (see the methodological appendix of the full report) and

defined combinations to identify relevant references within five scientific publication databases (Web of Science, Scopus, CorHAL/Conditor, Istex and OpenAlex). Modifications were made to the keyword queries by testing their ability to retrieve publications from a control list compiled by the scientific leads, until a coverage rate of over 98% was achieved with this list. This procedure was followed to ensure the completeness of coverage of relevant publications (no gaps). **This search ultimately resulted in an initial corpus of nearly 14,000 scientific publications.**

Intermediate corpus. The expert group then sorted the publications based on their titles, abstracts and keywords to eliminate irrelevant publications (noise). Exclusion criteria (e.g. publications on scandium or those not mentioning a point of comparison in materials science for the 'Reduce' chapter) and inclusion criteria (e.g. publications on metals similar to REEs in the 'Extract differently' chapter) were defined collectively. The sorting of references was carried out indiscriminately by any expert within either of the two groups (experimental sciences and humanities and social sciences) using the shared criteria, which were specified in the form of tags using the Rayyan software (see the report's full methodology). At the end of this sorting process, the corpus consisted of nearly **4,600 scientific publications.**

Final corpus. The references from this intermediate corpus were uploaded to a shared digital library (Zotero) to enable distribution among experts, classification according to the outline, and the importation of the full-text publications. A final sorting process was carried out based on the full texts, and just over 1,000 articles were excluded. Conversely, publications that had been overlooked during the process or published after the corpus was compiled (2023–2024) were added by the expert group. **The final scientific resource base on which the CSA report is based contains over 4,100 publications. The synthesis does not cite them all but is based on a review of them.** The references cited in this document are listed at the end of the document.

This process of compiling a traceable corpus of publications adheres to the principle of **transparency** set out in the **CNRS Charter on Scientific Expertise** and enables the results of the state-of-the-art review to be linked to its scope and to the compiled **scientific resource base.**

³⁷With regard to grey literature, certain studies (quantitative studies produced by the USGS, IEA, etc., and legal texts) have been included where necessary as contextual data.

Writing and working methods

In accordance with the **principle of impartiality**, drafting **relied on the scientific resources gathered for the report and not solely on the opinions of experts**. The connections made between the publications enabled the report's structure to be organised in order to produce the state of knowledge and its analysis. Any scientific controversies and gaps in knowledge were highlighted throughout the argument and at the end of sections and chapters.

The report and the synthesis were written collectively: each section was drafted on a secure collaborative workspace. Two coordinators were appointed for each chapter to oversee the writing process, organise working groups and identify the key elements and interdisciplinary aspects. The synthesis cites only certain publications, but it was drafted on the basis of 4,100 publications and the report, which contains more detailed arguments and technical elements.

A peer-review process was put in place: the sections were reviewed by at least two other experts, in order to comply with the **principle of impartiality** set out in the CNRS charter. In addition to the experts from the core group and the scientific leads, the project manager, the MPES and the CSA monitoring committee are involved in the review process for the synthesis and the summary.

Monthly plenary meetings brought together the scientific leads, the expert group and the MPES to agree on a common direction, methodologies and the scientific content emerging from the expert work.

References

- Adisorn, T., Tholen, L., Gotz, T., 2021. Towards a Digital Product Passport Fit for Contributing to a Circular Economy. *Energies* 14. <https://doi.org/10.3390/en14082289>
- Al-Bassam, K., Rambousek, P., Cech, S., 2021. REE-Rich Turonian Phosphates in the Bohemian Cretaceous Basin, Czech Republic: Assessment as Source of Critical Elements and Implications for Future Exploration. *Minerals* 11. <https://doi.org/10.3390/min11030246>
- Alemrajabi, M., Ricknell, J., Samak, S., Rodriguez Varela, R., Martinez, J., Hedman, F., Forsberg, K., Rasmuson, Å.C., 2022. Separation of Rare-Earth Elements Using Supported Liquid Membrane Extraction in Pilot Scale. *Ind. Eng. Chem. Res.* 61, 18475 — 18491. <https://doi.org/10.1021/acs.iecr.2c03268>
- Ali, S.H., Kalantzakos, S., Eggert, R., Gauss, R., Karayannopoulos, C., Klinger, J., Pu, X., Vekasi, K., Perrons, R.K., 2022. Closing the Infrastructure Gap for Decarbonization: The Case for an Integrated Mineral Supply Agreement. *Environ. Sci. Technol.* 56, 15280 — 15289. <https://doi.org/10.1021/acs.est.2c05413>
- Alonso, E., Pineault, D.G., Gambogi, J., Nassar, N.T., 2023. Mapping first to final uses for rare earth elements, globally and in the United States. *J. Ind. Ecol.* <https://doi.org/10.1111/jiec.13354>
- Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., Kirchain, R.E., 2012. Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies. *Environ. Sci. Technol.* 46, 3406 — 3414. <https://doi.org/10.1021/es203518d>
- Amato, A., Becci, A., Birloaga, I.P., De Michelis, I., Ferella, F., Innocenzi, V., Ippolito, N.M., Jiménez-Gómez, C.P., Veglio, F., Beolchini, F., 2019. Sustainability analysis of innovative technologies for the rare earth elements recovery. *Renew. Sustain. Energy Rev.* <https://doi.org/10.1016/j.rser.2019.02.029>
- Arrachart, G., Couturier, J., Dourdain, S., Levard, C., Pellet-Rostaing, S., 2021. Recovery of Rare Earth Elements (REEs) Using Ionic Solvents. *Processes* 9, 1202. <https://doi.org/10.3390/pr9071202>
- Artiushenko, O., Raphael Freire da Silva, Zaitsev, V., 2023. Recent advances in functional materials for rare earth recovery: A review. *Sustain. Mater. Technol.* <https://doi.org/10.1016/j.susmat.2023.e00681>
- Ash, J., 2024. Social impacts of critical mineral exploration on Indigenous peoples' lands: A case study from Solomon Islands. *Extr. Ind. Soc.* 17. <https://doi.org/10.1016/j.exis.2024.101439>
- Assefi, M., Maroufi, S., Yamauchi, Y., Sahajwalla, V., 2020. Pyrometallurgical recycling of Li-ion, Ni-Cd and Ni-MH batteries: A minireview. *Curr. Opin. Green Sustain. Chem.* <https://doi.org/10.1016/j.cogsc.2020.01.005>
- Baba, K., Hiroshige, Y., Nemoto, T., 2013. Rare-earth magnet recycling. *Hitachi Rev.*
- Bailey, G., Joyce, P.J., Schrijvers, D., Schulze, R., Sylvestre, A.M., Sprecher, B., Vahidi, E., Dewulf, W., Van Acker, K., 2020. Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite. *Resour. Conserv. Recycl.* 155, 104675. <https://doi.org/10.1016/j.resconrec.2019.104675>
- Balaram, V., 2022. Rare Earth Element Deposits: Sources, and Exploration Strategies. *J. Geol. Soc. India* 98, 1210 — 1216. <https://doi.org/10.1007/s12594-022-2154-3>
- Balassone, G., Manfredi, C., Vasca, E., Bianco, M., Boni, M., Aldo Di Nunzio, Lombardo, F., Mozzillo, R., Marino, A., Mormone, A., Mura, G., Trifuoggi, M., Mondillo, N., 2021. Recycling REEs from the Waste Products of Silius Mine (SE Sardinia, Italy): A Preliminary Study. *Sustainability.* <https://doi.org/10.3390/su132414000>
- Baldassarre, B., 2025. Circular economy for resource security in the European Union (EU): Case study, research framework, and future directions. *Ecol. Econ.* 227, 108345. <https://doi.org/10.1016/j.ecolecon.2024.108345>
- Baldassarre, B., Carrara, S., 2025. Critical raw materials, circular economy, sustainable development: EU policy reflections for future research and innovation. *Resour. Conserv. Recycl.* 215, 108060. <https://doi.org/10.1016/j.resconrec.2024.108060>

- Bandara, H.M.D., Mantell, M.A., Darcy, J.W., Emmert, M.H., 2015. Rare Earth Recycling : Forecast of Recoverable Nd from Shredder Scrap and Influence of Recycling Rates on Price Volatility. *J. Sustain. Metall.* <https://doi.org/10.1007/s40831-015-0019-3>
- Barakos, G., Gutzmer, J., Mischo, H., 2016. Strategic evaluations and mining process optimization towards a strong global REE supply chain. *J. Sustain. Min.* 15, 26 — 35. <https://doi.org/10.1016/j.jsm.2016.05.002>
- Barteková, E., Kemp, R., 2016. National strategies for securing a stable supply of rare earths in different world regions. *Resour. Policy* 49, 153 — 164. <https://doi.org/10.1016/j.resourpol.2016.05.003>
- Baudouin, V., 2024. Sobres perspectives - La sobriété à l'assaut du droit. *VertigO - Rev. Électronique En Sci. Environ.* <https://doi.org/10.4000/12eqw>
- Behera, S.S., Panda, S.K., Mandal, D., Parhi, P.K., 2019. Ultrasound and Microwave assisted leaching of neodymium from waste magnet using organic solvent. *Hydrometallurgy.* <https://doi.org/10.1016/j.hydromet.2019.02.003>
- Belfqueh, S., Seron, A., Chapron, S., Arrachart, G., Menad, N., 2023. Evaluating organic acids as alternative leaching reagents for rare earth elements recovery from NdFeB magnets. *J. Rare Earths* 41, 621 — 631. <https://doi.org/10.1016/j.jre.2022.04.027>
- Bergeron, K., Jébrak, M., Yates, M., Séguin, S., Lehmann, C., Meur, V., Le, Angers, P.-Y., Durand, P., Gendron, C., 2016. Indice du risque social : un outil pour mieux saisir les enjeux, risques et opportunités des projets miniers. *L'acceptabilité sociale et les projets miniers : essai de modélisation et validation. Éthique Publique* 18.
- Beylot, A., Menad, N., Seron, A., Delain, M., Bizouard, A., Ménard, Y., Villeneuve, J., 2020. Economic assessment and carbon footprint of recycling rare earths from magnets : Evaluation at lab scale paving the way toward industrialization. *J. Ind. Ecol.* <https://doi.org/10.1111/jiec.12943>
- Bezzola, S., Günther, I., Brugger, F., Lefoll, E., 2022. CSR and local conflicts in African mining communities. *World Dev.* 158, 105968.
- Bhatnagar, A., Härrä, A., Levänen, J., Niinimäki, K., 2024. Exploring the role of social life cycle assessment in transition to circular economy : A systematic review. *Resour. Conserv. Recycl.* 207, 107702. <https://doi.org/10.1016/j.resconrec.2024.107702>
- Bhuwalka, K., Kirchain, R.E., Olivetti, E.A., Roth, R., 2023. Quantifying the drivers of long-term prices in materials supply chains. *J. Ind. Ecol.* 27, 141-154 — 154. <https://doi.org/10.1111/jiec.13355>
- Binnemans, K., Jones, P.T., 2023. The Twelve Principles of Circular Hydrometallurgy. *J. Sustain. Metall.* 9, 1 — 25. <https://doi.org/10.1007/s40831-022-00636-3>
- Binnemans, K., Jones, P.T., 2017. Solvometallurgy : An Emerging Branch of Extractive Metallurgy. *J. Sustain. Metall.* 3, 570 — 600. <https://doi.org/10.1007/s40831-017-0128-2>
- Binnemans, K., Jones, P.T., 2014. Perspectives for the recovery of rare earths from end-of-life fluorescent lamps. *J. Rare Earths* 32, 195 — 200. [https://doi.org/10.1016/S1002-0721\(14\)60051-X](https://doi.org/10.1016/S1002-0721(14)60051-X)
- Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M., 2013. Recycling of rare earths: a critical review. *J. Clean. Prod.* 51, 1-22 <http://dx.doi.org/10.1016/j.jclepro.2012.12.037>
- Boetzkes, A., Diamanti, J., 2023. Geofetishism and the Tender Violence of Rare Earths. *Sub-STANCE* 52. <https://doi.org/10.1353/sub.2023.a913888>
- Bogojević, S., 2024. The European Green Deal, the rush for critical raw materials, and colonialism. *Transnatl. Leg. Theory* 15, 600 — 615. <https://doi.org/10.1080/20414005.2024.2399408>
- Borra, C.R., Pontikes, Y., Binnemans, K., Van Gerven, T., 2015. Leaching of rare earths from bauxite residue (red mud). *Sustain. Miner.* 76, 20 — 27. <https://doi.org/10.1016/j.mineng.2015.01.005>
- Boudia, S., 2019. Quand une crise en cache une autre : la « crise des terres rares » entre géopolitique, finance et dégâts environnementaux : *Crit. Int.* N° 85, 85 — 103. <https://doi.org/10.3917/crit.085.0085>
- Boul, M., Radiguet, R., 2021. Du droit des déchets au droit de l'économie circulaire : regards sur la loi du 10 février 2020, *Colloques & essais. Institut francophone pour la justice et la démocratie*, Bayonne.
- Brisson, V.L., Wei-Qin Zhuang, Lisa Alvarez-Cohen, 2016. Bioleaching of rare earth elements from monazite sand. *Biotechnol. Bioeng.* 113, 339 — 348. <https://doi.org/10.1002/bit.25823>

- Bundgaard, A.M., Huulgaard, R.D., Remmen, A., 2024. Getting the Priorities Right in Material Efficiency: From the Ecodesign Directive to the Ecodesign for Sustainable Products Regulation, in: 2024 Electronics Goes Green 2024+ (EGG). Presented at the 2024 Electronics Goes Green 2024+ (EGG), IEEE, Berlin, Germany, pp. 1–7. <https://doi.org/10.23919/EGG62010.2024.10631182>
- Bünzli, J.-C.G., 2022. Applications of Rare Earths, in: The Lanthanides and Actinides. WORLD SCIENTIFIC (EUROPE), pp. 633–685. https://doi.org/10.1142/9781800610163_0017
- Bünzli, J.-C.G., 2019. Lanthanide Photonics: Shaping the Nanoworld. Trends Chem. 1, 751–762. <https://doi.org/10.1016/j.trechm.2019.05.012>
- Burkhardt, C., Van Nielen, S., Awais, M., Bartolozzi, F., Blo mgren, J., Ortiz, P., Xicotencatl, M.B., Degri, M., Nayebossadri, S., Walton, A., 2023. An overview of Hydrogen assisted (Direct) recycling of Rare earth permanent magnets. J. Magn. Magn. Mater. 588, 171475. <https://doi.org/10.1016/j.jmmm.2023.171475>
- Burton, J., Kemp, D., Barnes, R., Parmenter, J., 2024. A socio-spatial analysis of Australia's critical minerals endowment and policy implications. Resour. Policy 88. <https://doi.org/10.1016/j.resourpol.2023.104448>
- Burtseva, E., Bysyina, A., 2019. Damage Compensation for Indigenous Peoples in the Conditions of Industrial Development of Territories on the Example of the Arctic Zone of the Sakha Republic. Resour.-Basel 8. <https://doi.org/10.3390/resources8010055>
- Buschke, F.T., Estreguil, C., Mancini, L., Mathieux, F., Eva, H., Battistella, L., Peedell, S., 2023. Digital Storytelling Through the European Commission's Africa Knowledge Platform to Bridge the Science-Policy Interface for Raw Materials. Circ. Econ. Sustain. 3, 1141–1154. <https://doi.org/10.1007/s43615-022-00198-2>
- Butler, C., 2014. Rare Earth Elements: China's Monopoly and Implications for U.S. National Security. The Fletcher Forum of World Affairs 38, 23–39.
- Campbell-Johnston, K., Erik Roos Lindgreen, Mondello, G., Teresa Maria Gulotta, Vermeulen, W.J.V., Salomone, R., 2023. Thermodynamic rarity of electrical and electronic waste: Assessment and policy implications for critical materials. J. Ind. Ecol. 27, 508–521–521. <https://doi.org/10.1111/jiec.13374>
- Canelas, J., Carvalho, A., 2023. The dark side of the energy transition: Extractivist violence, energy (in) justice and lithium mining in Portugal. Energy Res. Soc. Sci. 100. <https://doi.org/10.1016/j.erss.2023.103096>
- Cassayre, L., Guzhov, B., Zielinski, M., Biscans, B., 2022. Chemical processes for the recovery of valuable metals from spent nickel metal hydride batteries: A review. Renew. Sustain. Energy Rev. <https://doi.org/10.1016/j.rser.2022.112983>
- Castro, L., Gomez-Alvarez, H., Carmona, M., Gonzalez, F., Munoz, J.A., 2023. Influence of biosurfactants in the recovery of REE from monazite using Burkholderia thailandensis. Hydrometallurgy. <https://doi.org/10.1016/j.hydromet.2023.106178>
- Cen, P., Bian, X., Liu, Z., Gu, M., Wu, W., Li, B., 2021. Extraction of rare earths from bastnaesite concentrates: A critical review and perspective for the future. Miner. Eng. 171. <https://doi.org/10.1016/j.mineng.2021.107081>
- Cesaria, M., Baldassare Di Bartolo, 2019. Nanophosphors-Based White Light Sources. Nanomaterials 9. <https://doi.org/10.3390/nano9071048>
- Cesaria, Maura, Baldassare Di Bartolo, DiBartolo, B., Silvestri, L., Cesaria, M., Collins, J., 2018. Nanophosphors: From Rare Earth Activated Multicolor-Tuning to New Efficient White Light Sources. Quantum Nano-Photonics 26–77. https://doi.org/10.1007/978-94-024-1544-5_3
- Charles, N., Tuduri, J., Lefebvre, G., Pourret, O., Gaillard, F., Goodenough, K., 2022. Ressources en terres rares de l'Europe et du Groenland : potentiel minier et enjeux, in: Ressources métalliques 1. ISTE Group, pp. 1–137. <https://doi.org/10.51926/ISTE.9135.ch1>
- Chazot, A., Barrat, J.-A., Gaha, M., Jomaah, R., Ognard, J., Ben Salem, D., 2020. Brain MRIs make up the bulk of the gadolinium footprint in medical imaging. J. Neuroradiol. 47, 259–265. <https://doi.org/10.1016/j.neurad.2020.03.004>
- Chen, B., Li, D., Wang, F., 2020. InP Quantum Dots: Synthesis and Lighting Applications. Small 16, 2002454. <https://doi.org/10.1002/smll.202002454>
- Chen, Y., Cai, T., Zhu, X., Fan, D., Wang, Q., 2020. Analysis and Design of a New Type of Less-Rare-Earth Hybrid-Magnet Motor With Different Rotor Topologies. IEEE Trans. Appl. Supercond. 30. <https://doi.org/10.1109/tasc.2020.2965879>
- Chen, Y.-C., Yang, W.-X., 2024. Recycling of a spent residue-fluid-catalytic cracking catalyst into an adsorbent for the removal of copper(II) ions from wastewater. J. Environ. Chem. Eng. 12, 114566. <https://doi.org/10.1016/j.jece.2024.114566>

Chen, Z., Han, Z., Gao, B., Zhao, H., Qiu, G., Shen, L., 2024. Bioleaching of rare earth elements from ores and waste materials: Current status, economic viability and future prospects. *J. Environ. Manage.* 371, 123217.

<https://doi.org/10.1016/j.jenvman.2024.123217>

Chenna Rao Borra, Vlugt, T.J.H., Yang, Y., S. Erik Offerman, 2018. Recovery of Cerium from Glass Polishing Waste: A Critical Review. *Metals*.

<https://doi.org/10.3390/met8100801>

Chour, Z., Laubie, B., Morel, J.L., Tang, Y., Qiu, R., Simonnot, M.-O., Muhr, L., 2018. Recovery of rare earth elements from *Dicranopteris dichotoma* by an enhanced ion exchange leaching process. *Chem. Eng. Process. - Process Intensif.* 130, 208 — 213.

<https://doi.org/10.1016/j.cep.2018.06.007>

Chour, Z., Laubie, B., Morel, J.L., Tang, Y.-T., Simonnot, M.-O., Muhr, L., 2020. Basis for a new process for producing REE oxides from *Dicranopteris linearis*. *J. Environ. Chem. Eng.* 8, 103961.

<https://doi.org/10.1016/j.jece.2020.103961>

Christmann, P., 2021. Mineral Resource Governance in the 21st Century and a sustainable European Union. *Miner. Econ.* 34, 187 — 208.

<https://doi.org/10.1007/s13563-021-00265-4>

Costis, S., Mueller, K.K., Coudert, L., Carmen Mihaela Neculita, Reynier, N., Blais, J.-F., 2021. Recovery potential of rare earth elements from mining and industrial residues: A review and cases studies. *J. Geochem. Explor.* 221.

<https://doi.org/10.1016/j.gexplo.2020.106699>

Couturier, J., Pierre Tamba Oulare, Collin, B., Lallemand, C., Kieffer, I., Longerey, J., Chaurand, P., Rose, J., Borschneck, D., Angeletti, B., Criquet, S., Podor, R., Pourkhorsandi, H., Arrachart, G., Levard, C., 2024. Yttrium speciation variability in bauxite residues of various origins, ages and storage conditions. *J. Hazard. Mater.* 464.

<https://doi.org/10.1016/j.jhazmat.2023.132941>

d'Ambrosio, L., 2021. Le devoir de vigilance : une innovation juridique entre continuités et ruptures: *Droit Société* N° 106, 633 — 647.

<https://doi.org/10.3917/drs1.106.0633>

de Almeida, A.T., Fong, J., Falkner, H., Bertoldi, P., 2017. Policy options to promote energy efficient electric motors and drives in the EU. *Renew. Sustain. Energy Rev.* 74, 1275 — 1286.

<https://doi.org/10.1016/j.rser.2017.01.112>

de Koning, A., Kleijn, R., Huppel, G., Sprecher, B., van Engelen, G., Tukker, A., 2018. Metal supply constraints for a low-carbon economy? *Resour. Conserv. Recycl.* 129, 202 — 208.

<https://doi.org/10.1016/j.resconrec.2017.10.040>

De Young, J., John H., McCartan, L., Gambogi, J., 2017. What's Been (and What Will Be) Strategic—My Metal or Your Paint? in *Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34*, North Carolina Geological Survey, (Proceedings edited by Jeffrey C. Reid), Professional Paper.

Deady, É.A., Mouchos, E., Goodenough, K., Williamson, B.J., Wall, F., 2016. A review of the potential for rare-earth element resources from European red muds: examples from Seydişehir, Turkey and Parnassus-Giona, Greece. *Mineral. Mag.* 80, 43-43 — 61.

<https://doi.org/10.1180/minmag.2016.080.052>

Decrée, S., Coint, N., Debaille, V., Hagen-Peter, G., Leduc, T., Schiellerup, H., 2023. The potential for REEs in igneous-related apatite deposits in Europe. *Geol. Soc. Lond. Spec. Publ.* 526, 219 — 249.

<https://doi.org/10.1144/SP526-2021-175>

Dehaine, Q., Filippov, L.O., Glass, H.J., Rollinson, G., 2019. Rare-metal granites as a potential source of critical metals: A geomettallurgical case study. *Ore Geol. Rev.* 104, 384 — 402.

<https://doi.org/10.1016/j.oregeorev.2018.11.012>

Demol, J., Ho, E., Soldenhoff, K., Senanayake, G., 2019. The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. *Hydrometallurgy* 188, 123 — 139.

<https://doi.org/10.1016/j.hydromet.2019.05.015>

Deng, C., Zhang, X., Guo, F., Wang, S., Wang, X., 2025. The current status of recycling technology for waste NdFeB resources. *J. Mater. Cycles Waste Manag.* 27, 796 — 811.

<https://doi.org/10.1007/s10163-025-02162-2>

Deng, X., Ge, J., 2020. Global wind power development leads to high demand for neodymium praseodymium (NdPr): A scenario analysis based on market and technology development from 2019 to 2040. *J. Clean. Prod.* 277.

<https://doi.org/10.1016/j.jclepro.2020.123299>

Dijk, M., Wells, P., Kemp, R., 2016. Will the momentum of the electric car last? Testing an hypothesis on disruptive innovation. *Technol. Forecast. Soc. Change* 105, 77 — 88.

<https://doi.org/10.1016/j.techfore.2016.01.013>

Dingwall, J., 2020. Commercial Mining Activities in the Deep Seabed beyond National Jurisdiction: the International Legal Framework, in: *Publications on Ocean Development*. pp. 139 — 162.

https://doi.org/10.1163/9789004391567_009

- Dinh, T., Dobo, Z., Kovacs, H., 2022. Phytomining of rare earth elements - A review. *Chemosphere* 297. <https://doi.org/10.1016/j.chemosphere.2022.134259>
- Dobransky, S., 2015. The Curious Disjunction of Rare Earth Elements and US Politics: Analyzing the Inability to Develop a Secure REE Supply Chain, in: Kiggins, R.D. (Ed.), *The Political Economy of Rare Earth Elements*. Palgrave Macmillan UK, London, pp. 85 — 105. https://doi.org/10.1057/9781137364241_5
- Dou, S., Xu, D., Zhu, Y., Keenan, R., 2023. Critical mineral sustainable supply: Challenges and governance. *Futures* 146. <https://doi.org/10.1016/j.futures.2023.103101>
- Dunlap, A., Riquito, M., 2023. Social warfare for lithium extraction? Open-pit lithium mining, counterinsurgency tactics and enforcing green extractivism in northern Portugal. *Energy Res. Soc. Sci.* 95. <https://doi.org/10.1016/j.erss.2022.102912>
- El Maangar, A., Fleury, C., Pellet-Rostaing, S., Zemb, T., 2024. Leaching and recycling of NdFeB permanent magnets using ionic non-toxic hydrotropes instead of extractants. *Front. Chem. Eng.* 6. <https://doi.org/10.3389/fceng.2024.1420008>
- Elerian, M., Cees van Rhee, Helmons, R., 2022. Experimental and Numerical Modelling of Deep-Sea-Mining-Generated Turbidity Currents. *Minerals* 12. <https://doi.org/10.3390/min12050558>
- Fan, X., Xiang, J., Zhang, D., Nie, Z., Liu, Y., Zhang, L., Zhang, D., 2022. Highly-efficient and sequential recovery of rare earth elements, alumina and silica from coal fly ash via a novel recyclable ZnO sinter method. *J. Hazard. Mater.* 437, 129308. <https://doi.org/10.1016/j.jhazmat.2022.129308>
- Fathollahzadeh, H., Hackett, M.J., Khaleque, H.N., Eksteen, J.J., Kaksonen, A.H., Watkin, E.L.J., 2018. Better together: Potential of co-culture microorganisms to enhance bioleaching of rare earth elements from monazite. *Bioresour. Technol.* 3, 109 — 118. <https://doi.org/10.1016/j.biortech.2018.07.003>
- Figueiredo, F.M.J., M. Fatima Araujo, Marcalo, J., Leal, J.P., Sardinha, J.P., 2024. Determination of rare earth elements in CRT phosphors and NdFeB magnets residues using an ED-XRF portable spectrometer to assist field semi-quantitative screening. *Microchem. J.* <https://doi.org/10.1016/j.microc.2024.110136>
- Fu, B., Hower, J.C., Zhang, W., Luo, G., Hu, H., Yao, H., 2022. A review of rare earth elements and yttrium in coal ash: Content, modes of occurrences, combustion behavior, and extraction methods. *Prog. Energy. Comb. Sci.* 88, 100954. <https://doi.org/10.1016/j.pecs.2021.100954>
- Fonseca, A., Mary Louise McAllister, Fitzpatrick, P., 2013. Measuring what? A comparative anatomy of five mining sustainability frameworks. *Miner. Eng.* 46, 180 — 186. <https://doi.org/10.1016/j.mineng.2013.04.008>
- Gavin, B., 2015. Sustainable development of China's rare earth industry within and without the WTO. *J. World Trade* 49, 495 — 516. <https://doi.org/10.54648/trad2015020>
- Ge, Z., Geng, Y., Dong, F., Liang, J., Zhong, C., 2022. Towards carbon neutrality: Improving resource efficiency of the rare earth elements in China. *Front. Environ. Sci.* 10. <https://doi.org/10.3389/fenvs.2022.962724>
- Gehlmann, F., Haustein, S., Klockner, C.A., 2024. Willingness to pay extra for electric cars with sustainably produced batteries. *Transp. Res. Part - Transp. Environ.* 128. <https://doi.org/10.1016/j.trd.2024.104110>
- Gemechu, E.D., Sonnemann, G., Young, S.B., 2017. Geopolitical-related supply risk assessment as a complement to environmental impact assessment: the case of electric vehicles. *Int. J. Life Cycle Assess.* 22, 31-39 — 39. <https://doi.org/10.1007/s11367-015-0917-4>
- Gholz, E., Hughes, L., 2021. Market structure and economic sanctions: the 2010 rare earth elements episode as a pathway case of market adjustment. *Rev. Int. Polit. Econ.* 28, 611 — 634. <https://doi.org/10.1080/09692290.2019.1693411>
- Gkika, D., Chalari, M., Kyzas, G.Z., 2024. Review of Methods for Obtaining Rare Earth Elements from Recycling and Their Impact on the Environment and Human Health.
- Goldman, J.A., 2014. The U.S. Rare Earth Industry: Its Growth and Decline. *J. Policy Hist.* 26, 139 — 166. <https://doi.org/10.1017/s0898030614000013>
- Golinska-Dawson, P., Sakao, T., Sundin, E., Werner-Lewandowska, K., 2025. How can OEMs scale up remanufacturing in product-as-a-service (PaaS)? — challenges and enablers from a theoretical and industrial perspective. *Int. J. Prod. Res.* 63, 3854 — 3883. <https://doi.org/10.1080/00207543.2024.2423798>
- Gonzalez-Torres, M., Bertoldi, P., Castellazzi, L., Perez-Lombard, L., 2023. Review of EU product energy efficiency policies: What have we achieved in 40 years? *J. Clean. Prod.* 421, 138442. <https://doi.org/10.1016/j.jclepro.2023.138442>

- Good, N.M., Kang-Yun, C.S., Su, M.Z., Zytick, A.M., Barber, C.C., Vu, H.N., Grace, J.M., Nguyen, H.H., Zhang, W., Skovran, E., Fan, M., Park, D.M., Norma Cecilia Martinez-Gomez, 2023. Scalable and Consolidated Microbial Platform for Rare Earth Element Leaching and Recovery from Waste Sources. *Environ. Sci. Technol.* <https://doi.org/10.1021/acs.est.3c06775>
- Govindan, K., Hasanagic, M., 2018. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. *Int. J. Prod. Res.* 56, 278 — 311. <https://doi.org/10.1080/00207543.2017.1402141>
- Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What Do We Know About Metal Recycling Rates? *J. Ind. Ecol.* 15, 355 — 366. <https://doi.org/10.1111/j.1530-9290.2011.00342.x>
- Granvik, P., Hanski, J., Lähdesmäki, S., Jokilaakso, A., Huttunen-Saarivirta, E., 2025. Critical raw materials for green transition: Key parameters and feasibility index for sufficiency. *Resour. Conserv. Recycl.* 218, 108197. <https://doi.org/10.1016/j.resconrec.2025.108197>
- Grosjean, N., Blaudez, D., Chalot, M., Gross, E.M., Le Jean, M., 2020. Identification of new hardy ferns that preferentially accumulate light rare earth elements: a conserved trait within fern species. *Environ. Chem.* 17, 191 — 200. <https://doi.org/10.1071/EN19182>
- Grosjean, N., Purwadi, I., Sirguey, C., Chalot, M., Le Jean, M., van der Ent, A., Blaudez, D., 2024. Chapter Two - Rare earth elements in plants: transfer, transport, accumulation, impacts and perspectives, in: Chalot, M. (Ed.), *Advances in Botanical Research*. Academic Press, pp. 19 — 61. <https://doi.org/10.1016/bs.abr.2023.10.005>
- Grosse, F., 2023. Croissance soutenable? la société au défi de l'économie circulaire. PUG, Fontaine.
- Grosse, F., 2014. Les limites du recyclage dans un contexte de demande croissante de matières premières: *Ann. Mines - Responsab. Environ.* N° 76, 58 — 63. <https://doi.org/10.3917/re.076.0058>
- Gu, X., Ieromonachou, P., Zhou, L., Tseng, M.-L., 2018. Developing pricing strategy to optimise total profits in an electric vehicle battery closed loop supply chain. *J. Clean. Prod.* 203, 376-385 — 385. <https://doi.org/10.1016/j.jclepro.2018.08.209>
- Gui, L., Atasu, A., Ergun, Ö., L. Beril Toktay, 2013. Implementing Extended Producer Responsibility Legislation. *J. Ind. Ecol.* 17, 262-276 — 276. <https://doi.org/10.1111/j.1530-9290.2012.00574.x>
- Gupta, A., Caravan, P., Price, W.S., Platas-Iglesias, C., Gale, E.M., 2020. Applications for Transition-Metal Chemistry in Contrast-Enhanced Magnetic Resonance Imaging. *Inorg. Chem.* 59, 6648 — 6678. <https://doi.org/10.1021/acs.inorgchem.0c00510>
- Habib, K., Hansdottir, S.T., Habib, H., 2020. Critical metals for electromobility: Global demand scenarios for passenger vehicles, 2015-2050. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2019.104603>
- Habib, K., Schibye, P.K., Vestbo, A.P., Dall, O., Wenzel, H., 2014. Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach. *Environ. Sci. Technol.* <https://doi.org/10.1021/es501975y>
- Habibzadeh, A., Kucuker, M.A., Gökelma, M., 2023. Review on the Parameters of Recycling NdFeB Magnets via a Hydrogenation Process. *ACS Omega* 8, 17431 — 17445. <https://doi.org/10.1021/acsomega.3c00299>
- Hagelüken, C., Lee-Shin, J.U., Carpentier, A., Heron, C., 2016. The EU Circular Economy and Its Relevance to Metal Recycling. *Recycling* 1, 242 — 253. <https://doi.org/10.3390/recycling1020242>
- Halkos, G.E., Aslanidis, P.-S.C., 2024. Reviewing the integrated institutional waste-related framework for circular economy in the European Union. *Waste Manag. Bull.* 2, 28 — 35. <https://doi.org/10.1016/j.wmb.2024.06.002>
- Hanauer, L., Morris, L.J., 2014. Chinese Engagement in Africa: Drivers, Reactions, and Implications for U.S. Policy
- Harpprecht, C., Brenda Miranda Xicotencatl, Sander van Nielen, Marc van der Meide, Li, C., Li, Z., Tukker, A., Steubing, B., 2024. Future environmental impacts of metals: A systematic review of impact trends, modelling approaches, and challenges. *Resour. Conserv. Recycl.* 205. <https://doi.org/10.1016/j.resconrec.2024.107572>
- Hatakeyama, K., 2015. Rare Earths and Japan: Traditional Vulnerability Reconsidered, in: Kiggins, R.D. (Ed.), *The Political Economy of Rare Earth Elements*. Palgrave Macmillan UK, London, pp. 43 — 61. https://doi.org/10.1057/9781137364241_3
- He, P., Feng, H., Hu, G., Hewage, K., Achari, G., Wang, C., Sadiq, R., 2020. Life cycle cost analysis for recycling high-tech minerals from waste mobile phones in China. *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2019.119498>
- He, Y., Ma, L., Liang, X., Li, X., Zhu, J., He, H., 2024. Resistant rare earth phosphates as possible sources of environmental dissolved rare earth elements: Insights from experimental bio-weathering of xenotime and monazite. *Chem. Geol.* 661, 122186. <https://doi.org/10.1016/j.chemgeo.2024.122186>

- Hidalgo-Crespo, J., Riel, A., Golinska-Dawson, P., Peeters, J.R., Werner-Lewandowska, K., Dufflou, J.R., 2024. Facilitating circularity: challenges and design guidelines of Product-as-a-Service (PaaS) business model offers for electrical and electronic equipment. *Procedia CIRP*, 34th CIRP Design Conference 128, 567 – 572. <https://doi.org/10.1016/j.procir.2024.03.037>
- Hoenderdaal, S., Luis Tercero Espinoza, Marscheider-Weidemann, F., Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies? *Energy*. <https://doi.org/10.1016/j.energy.2012.10.043>
- Hong, S.K., Kim, Y., Kim, Y.-M., 2024. Assessment of REY resource potential in deep-sea sediments with Fe – Mn (oxyhydr)oxides in the Pacific Ocean. *J. Geochem. Explor.* 267, 107581. <https://doi.org/10.1016/j.jexplo.2024.107581>
- Hool, A., Helbig, C., Wierink, G., 2023. Challenges and opportunities of the European Critical Raw Materials Act. *Miner. Econ.* <https://doi.org/10.1007/s13563-023-00394-y>
- Horta Arduin, R., Mathieux, F., Huisman, J., Blengini, G.A., Charbuillet, C., Wagner, M., Baldé, C.P., Perry, N., 2020. Novel indicators to better monitor the collection and recovery of (critical) raw materials in WEEE: Focus on screens. *Resour. Conserv. Recycl.* 157, 104772. <https://doi.org/10.1016/j.resconrec.2020.104772>
- Huiyun, J., Xu, M., Zhou, L., 2019. Collaborative collection effort strategies based on the “Internet plus recycling” business model. *J. Clean. Prod.* 241. <https://doi.org/10.1016/j.jclepro.2019.118120>
- Humphreys, D., 1995. Whatever happened to security of supply? Minerals policy in the post-cold war world. *Resour. Policy* 21, 91 – 97. [https://doi.org/10.1016/0301-4207\(95\)00057-w](https://doi.org/10.1016/0301-4207(95)00057-w)
- Ikhlal, M., 2017. Evaluation of the environmental impacts of rare earth elements production. *Int. J. Environ. Stud.* <https://doi.org/10.1080/00207233.2017.1341737>
- Innocenzi, V., Nicolo Maria Ippolito, Ida De Michelis, Prisciandaro, M., Medici, F., Veglio, F., 2017. A review of the processes and lab-scale techniques for the treatment of spent rechargeable NiMH batteries. *J. Power Sources*. <https://doi.org/10.1016/j.jpowsour.2017.07.034>
- Islam, M.T., Huda, N., 2018. Reverse logistics and closed-loop supply chain of Waste Electrical and Electronic Equipment (WEEE)/E-waste: A comprehensive literature review. *Resour. Conserv. Recycl.* 137, 48-75 – 75. <https://doi.org/10.1016/j.resconrec.2018.05.026>
- Jalali, J., Lebeau, T., 2021. The Role of Microorganisms in Mobilization and Phytoextraction of Rare Earth Elements: A Review. *Front. Environ. Sci.* 9, 688430. <https://doi.org/10.3389/fenvs.2021.688430>
- Jally, B., Laubie, B., Chour, Z., Muhr, L., Qiu, R., Jean Louis Morel, Tang, Y., Simonnot, M.-O., 2021. A new method for recovering rare earth elements from the hyperaccumulating fern *Dicranopteris linearis* from China. *Miner. Eng.* 166. <https://doi.org/10.1016/j.mineng.2021.106879>
- Jansen, M., Meisen, T., Plociennik, C., Berg, H., Pomp, A., Windholz, W., 2023. Stop Guessing in the Dark: Identified Requirements for Digital Product Passport Systems. *Systems* 11. <https://doi.org/10.3390/systems11030123>
- Jenkins, H., 2004. Corporate social responsibility and the mining industry: conflicts and constructs. *Corp. Soc. Responsib. Environ. Manag.* 11, 23 – 34. <https://doi.org/10.1002/csr.50>
- Jenkins, H., Obara, L., 2006. Corporate Social Responsibility (CSR) in the mining industry – the risk of community dependency, in: *Corporate Responsibility Research Conference*, Dublin. CiteSeer, pp. 4 – 5.
- Jiang, J., Lu, Y., Yan, X., Wang, L., 2020. An optimization dust-removing electrode design method aiming at improving dust mitigation efficiency in lunar exploration. *Acta Astronaut.* 166, 59 – 68. <https://doi.org/10.1016/j.actaastro.2019.10.004>
- Jin, H., Byung Duk Song, Yih, Y., Sutherland, J.W., 2019. A bi-objective network design for value recovery of neodymium-iron-boron magnets: A case study of the United States. *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2018.11.101>
- Jin, H., Yih, Y., Sutherland, J.W., 2018. Modeling operation and inventory for rare earth permanent magnet recovery under supply and demand uncertainties. *J. Manuf. Syst.* <https://doi.org/10.1016/j.jmsy.2017.11.002>
- Jones, P.T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., Hoekstra, N., 2013. Enhanced Landfill Mining in view of multiple resource recovery: a critical review. *J. Clean. Prod.* 55, 45-55 – 55. <https://doi.org/10.1016/j.jclepro.2012.05.021>

- Jonsson, E., Törmänen, T., Keiding, J.K., Bjerkgård, T., Eilu, P., Pokki, J., Gautneb, H., Reginiussen, H., Rosa, D., Sadeghi, M., Sandstad, J.S., Stendal, H., 2023. Critical metals and minerals in the Nordic countries of Europe: diversity of mineralization and green energy potential. *Geol. Soc. Lond. Spec. Publ.* 526, 95 — 152.
<https://doi.org/10.1144/SP526-2022-55>
- Jowitt, S.M., Werner, T.T., Weng, Z., Mudd, G.M., 2018. Recycling of the rare earth elements. *Curr. Opin. Green Sustain. Chem.*
<https://doi.org/10.1016/j.cogsc.2018.02.008>
- Julsrud, T.E., Kallbekken, S., Aasen, M., 2023. Can shared autonomous vehicles become a sustainable mode of mobility in the future? Insights from a practice-based study of urban dwellers in Norway. *J. Environ. Policy Plan.* 25, 703 — 722.
<https://doi.org/10.1080/1523908x.2023.2251923>
- Kama, K., 2015. Circling the economy: resource-making and marketization in EU electronic waste policy. *Area* 47, 16–23 — 23.
<https://doi.org/10.1111/area.12143>
- Kamenopoulos, S.N., Shields, D., Agioutantis, Z., 2015. Sustainable Development Criteria and Indicators for the Assessment of Rare Earth Element Mining Projects, in: *Rare Earths Industry: Technological, Economic, and Environmental Implications*. pp. 87 — 109.
<https://doi.org/10.1016/b978-0-12-802328-0.00006-1>
- Kampker, A., Heimes, H.H., Offermanns, C., Friege, M.H., Graaf, M., Natalia Soldan Cattani, Spaeth, B., 2023. Cost-Benefit Analysis of Downstream Applications for Retired Electric Vehicle Batteries. *World Electr. Veh. J.* 14.
<https://doi.org/10.3390/wevj14040110>
- Kang, X., Csetenyi, L., Gadd, G.M., 2023. Fungal biorecovery of cerium as oxalate and carbonate biominerals. *Fungal Biol.* 127, 1187 — 1197.
<https://doi.org/10.1016/j.funbio.2022.07.006>
- Kannstatter, T., Meerschiff, S., 2015. Launching an E-carsharing system in the polycentric area of Ruhr. *Green Energy Technol.* 203, 187 — 208.
https://doi.org/10.1007/978-3-319-13194-8_11
- Katiyar, N., Kulshreshtha, A., Singh, P.K., 2024. A Review of Integration Techniques of Multi-Geoscience Data-Sets in Mineral Prospectivity Mapping. *Earth Sci.* 13, 127 — 140.
<https://doi.org/10.11648/j.earth.20241304.12>
- Kato, Y., Fujinaga, K., Nakamura, K., Takaya, Y., Kitamura, K., Ohta, J., Toda, R., Nakashima, T., Iwamori, H., 2011. Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements. *Nat. Geosci.* 4, 535 — 539.
<https://doi.org/10.1038/ngeo1185>
- Khan, S.A., 2016. E-products, E-waste and the Basel Convention: Regulatory Challenges and Impossibilities of International Environmental Law. *Rev. Eur. Comp. Int. Environ. Law* 25, 248–260 — 260.
<https://doi.org/10.1111/reel.12163>
- Kiggins, R.D. (Ed.), 2015. *The Political Economy of Rare Earth Elements*. Palgrave Macmillan UK, London.
<https://doi.org/10.1057/9781137364241>
- Kleijn, R., van der Voet, E., 2010. Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renew. Sustain. Energy Rev.* 14, 2784 — 2795.
<https://doi.org/10.1016/j.rser.2010.07.066>
- Klinger, J.M., 2018a. *Rare Earth Frontiers*. Cornell University Press.
- Klinger, J.M., 2018b. Rare earth elements: Development, sustainability and policy issues. *Extr. Ind. Soc.* 5, 1 — 7.
<https://doi.org/10.1016/j.exis.2017.12.016>
- Koese, M., Parzer, M., Sprecher, B., Kleijn, R., 2025. Self-sufficiency of the European Union in critical raw materials for E-mobility. *Resour. Conserv. Recycl.* 212, 108009.
<https://doi.org/10.1016/j.resconrec.2024.108009>
- Komnitsas, K., 2020. Social License to Operate in Mining: Present Views and Future Trends. *Resour.-Basel* 9.
<https://doi.org/10.3390/resources9060079>
- Kraus, C., 2010. Creating a Soviet “Semi-Colony”? Sino-Soviet Cooperation and its Demise in Xinjiang, 1949–1955. *Chin. Hist. Rev.* 17, 129 — 165.
<https://doi.org/10.1179/tcr.2010.17.2.129>
- Ku, A., Setlur, A., Loudis, J., 2015. Impact of Light Emitting Diode Adoption on Rare Earth Element Use in Lighting: Implications for Yttrium, Europium, and Terbium Demand. *Electrochem. Soc. Interface*.
<https://doi.org/10.1149/2.F04154if>
- Kulkarni, S., Zhao, F., Nlebedim, I.C., Fredette, R., Paranthaman, M.P., 2023. Comparative Life Cycle Assessment of Injection Molded and Big Area Additive Manufactured NdFeB Bonded Permanent Magnets. *J. Manuf. Sci. Eng.-Trans. Asme*.
<https://doi.org/10.1115/1.4056489>
- Langkau, S., Erdmann, M., 2021. Environmental impacts of the future supply of rare earths for magnet applications. *J. Ind. Ecol.*
<https://doi.org/10.1111/jiec.13090>

- Lanzilotti, C.O., Pinto, L.F.R., Facchini, F., Digiesi, S., 2022. Embedding Product-Service System of Cutting Tools into the Machining Process: An Eco-Efficiency Approach toward Sustainable Development. *Sustainability* 14. <https://doi.org/10.3390/su14031100>
- Laurent, B., 2023. Quelle politique du territoire face à l'extraction minière?, in: Cerceau, J., Laurent, B. (Eds.), *Quand La Mine Déborde. Enquêtes Sur La Fabrique Des Territoires Extractifs*. Presses des Mines, pp. 157 — 178.
- Lhuillier, G., 2022. The Proposal for a European Directive on Duty of care of company with regard to sustainability / La proposition de directive sur le devoir de vigilance des entreprises en matière de durabilité, in *International Business Law Journal*, Sweet & Maxwell, issue 2022, .N°5, pp. 422-455.
- Li, J., Peng, K., Wang, P., Zhang, N., Feng, K., Guan, D., Meng, J., Wei, W., Yang, Q., 2020. Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions. *One Earth* 3, 116-125 — 125. <https://doi.org/10.1016/j.oneear.2020.06.009>
- Li, Z., Zhong, X., Xu, X., 2023. The mechanism of retired power batteries recycling through blockchain token incentives. *J. Clean. Prod.* 415. <https://doi.org/10.1016/j.jclepro.2023.137560>
- Liang, Y., Kleijn, R., Voet, E. van der, 2023a. Increase in demand for critical materials under IEA Net-Zero emission by 2050 scenario. *Appl. Energy*. <https://doi.org/10.1016/j.apenergy.2023.121400>
- Liang, Y., Kleijn, R., Voet, E. van der, 2023b. Increase in demand for critical materials under IEA Net-Zero emission by 2050 scenario. *Appl. Energy*. <https://doi.org/10.1016/j.apenergy.2023.121400>
- Liu, T., Chen, J., 2021. Extraction and separation of heavy rare earth elements: A review. *Sep. Purif. Technol.* 276, 119263. <https://doi.org/10.1016/j.seppur.2021.119263>
- Lovik, A.N., Hagelueken, C., Wager, P., 2018. Improving supply security of critical metals: Current developments and research in the EU. *Sustain. Mater. Technol.* 15, 9-18 — 18. <https://doi.org/10.1016/j.susmat.2018.01.003>
- Lu, G., Liang, H., 2024. Review and test on rare earths recovery from polishing powder waste. *Heliyon* 10, e40785. <https://doi.org/10.1016/j.heliyon.2024.10.101>
- Luo, X., Zhang, Y., Zhou, H., He, K., Luo, C., Liu, Z., Tang, X., 2022. Review on the Development and Utilization of Ionic Rare Earth Ore. *Minerals* 12, 554. <https://doi.org/10.3390/min12050554>
- Luszczek, K., Przylibski, T.A., 2019. Potential deposits of selected metallic resources on L chondrite parent bodies. *Planet. Space Sci.* 168, 40 — 51. <https://doi.org/10.1016/j.pss.2019.02.005>
- Lyman, J.W., Palmer, G.R., 1992. Scrap treatment method for rare earth transition metal alloys. *US 5,129,945 (US 5129945A)*.
- Machacek, E., Fold, N., 2018. Competitors contained? Manufacturer strategies in the global rare earth value chain: Insights from the magnet filament. *Extr. Ind. Soc. - Int. J.* 5, 18 — 27. <https://doi.org/10.1016/j.exis.2017.12.012>
- Machacek, E., Richter, J.L., Habib, K., Klossek, P., 2015. Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties. *Resour. Conserv. Recycl.* 104, 76 — 93. <https://doi.org/10.1016/j.resconrec.2015.09.005>
- Magrini, C., Jagodzinska, K., 2022. Can bioleaching of NIB magnets be an answer to the criticality of rare earths? An ex-ante Life Cycle Assessment and Material Flow Cost Accounting. *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2022.132672>
- Malainine, C.-E., Raji, O., Ouabid, M., Bodinier, J.-L., Hicham El Messbahi, 2022. Prospectivity mapping of carbonatite-associated iron oxide deposits using an integration process of ASTER and Sentinel-2A multispectral data. *Int. J. Remote Sens.* 43, 4951 — 4983. <https://doi.org/10.1080/01431161.2022.2121189>
- Manhart, A., 2011. International Cooperation for Metal Recycling From Waste Electrical and Electronic Equipment. *J. Ind. Ecol.* 15, 13-30 — 30. <https://doi.org/10.1111/j.1530-9290.2010.00307.x>
- Marty, J., Ruel, S., 2025. Unpacking the interconnected challenges of rare metals supply chains: A systematic literature network analysis and conceptual framework. *Resour. Policy* 106, 105624. <https://doi.org/10.1016/j.resourpol.2025.105624>
- Marx, J., Schreiber, A., Zapp, P., Walachowicz, F., 2018. Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits. *Acs Sustain. Chem. Eng.* <https://doi.org/10.1021/acssuschemeng.7b04165>
- Mazzarano, M., 2022. Material governance and circularity policies: How waste policies and innovation affect household appliances? accumulation. *Ecol. Econ.* 200. <https://doi.org/10.1016/j.ecolecon.2022.107538>
- McGaughey, S.A., Iqbal, S., De Rosa, A., Caley, J.A., Kaksonen, A.H., Villa-Gomez, D., Byrt, C.S., 2025. Interactions of rare earth elements with living organisms and emerging biotechnical applications. *PLANTS PEOPLE PLANET* 7, 1251 — 1274. <https://doi.org/10.1002/ppp3.70010>

- McLeod, C.L., Krekeler, Mark.P.S., 2017. Sources of Extraterrestrial Rare Earth Elements: To the Moon and Beyond. *Resour.-Basel* 6. <https://doi.org/10.3390/resources6030040>
- McLeod, C.L., Shaulis, B.J., 2018. Rare Earth Elements in Planetary Crusts: Insights from Chemically Evolved Igneous Suites on Earth and the Moon. *Minerals* 8. <https://doi.org/10.3390/min8100455>
- Medeiros, C.A.D., Trebat, N.M., 2017. Transforming natural resources into industrial advantage: the case of China's rare earths industry. *Braz. J. Polit. Econ.* 37, 504 — 526. <https://doi.org/10.1590/0101-31572017v37n03a03>
- Menendez, A., James, R., Shulga, N., Connelly, D., Roberts, S., 2018. Linkages between the Genesis and Resource Potential of Ferromanganese Deposits in the Atlantic, Pacific, and Arctic Oceans. *Minerals* 8. <https://doi.org/10.3390/min8050197>
- Meng, X., Zhao, H., Zhang, Y., Shen, L., Gu, G., Qiu, G., Zhang, X., Yu, H., He, X., Liu, C., 2022. Simulated bioleaching of ion-adsorption rare earth ore using metabolites of biosynthetic citrate: An alternative to cation exchange leaching. *Miner. Eng.* 189. <https://doi.org/10.1016/j.mineng.2022.107900>
- Meng, X., Zhao, H., Zhao, Y., Shen, L., Gu, G., Qiu, G., 2023. Heap leaching of ion adsorption rare earth ores and REEs recovery from leachate with lixiviant regeneration. *Sci. Total Environ.* 898. <https://doi.org/10.1016/j.scitotenv.2023.165417>
- Merle, R., Troll, V.R., Hook, M., Kuchler, M., Byrne, P.K., Donoso, G., 2023. Extra-terrestrial resources: A potential solution for securing the supply of rare metals for the coming decades? *Geol. Today* 39, 225 — 230. <https://doi.org/10.1111/gto.12454>
- Merlin, J., Laurent, B., Gunzburger, Y., 2021. Promise engineering: Investment and its conflicting anticipations in the French mining revival. *Econ. Soc.* 50, 590 — 617.
- Micheaux, H., 2023. L'évolution de la responsabilité élargie du producteur : de la fin de vie des produits à l'économie circulaire : *Entrep. Hist.* n° 110, 87 — 104. <https://doi.org/10.3917/eh.110.0087>
- Miller, K.A., Brigden, K., Santillo, D., Currie, D., Johnston, P., Thompson, K.F., 2021. Challenging the Need for Deep Seabed Mining From the Perspective of Metal Demand, Biodiversity, Ecosystems Services, and Benefit Sharing. *Front. Mar. Sci.* 8. <https://doi.org/10.3389/fmars.2021.706161>
- Mohammadi, A., Badewa, O.A., Chulaee, Y., Ionel, D.M., Essakiappan, S., Manjrekar, M., leee, 2023. Design Optimization of a Direct-drive Wind Generator with Non-rare-earth PM Flux Intensifying Stator and Reluctance Rotor. 2023 leee Int. Electr. Mach. Drives Conf. *Iemdc*. <https://doi.org/10.1109/iemdc55163.2023.10238962>
- Moldoveanu, G.A., Papangelakis, V.G., 2016. An overview of rare-earth recovery by ion-exchange leaching from ion-adsorption clays of various origins. *Mineral. Mag.* 80, 63 — 76. <https://doi.org/10.1180/minmag.2016.080.051>
- Monfared, B., Furberg, R., Palm, B., 2014. Magnetic vs. vapor-compression household refrigerators: A preliminary comparative life cycle assessment. *Int. J. Refrig.-Rev. Int. Froid.* <https://doi.org/10.1016/j.ijrefrig.2014.02.013>
- Morrow, J.R., Tsitovich, P.B., McMahon, M., Gilad, A., Bulte, J., VanZijl, P., 2017. Transition Metal paraCEST Probes as Alternatives to Lanthanides. *Chem. Exch. Satur. Transf. Imaging Adv. Appl.* 257 — 282.
- Murrey, A., Jackson, N.A., 2020. A decolonial critique of the racialized "localwashing" of extraction in Central Africa. *Ann. Am. Assoc. Geogr.* 110, 917 — 940.
- Nakajima, N., Vanderburg, W.H., 2005. A Failing Grade for Our Efforts to Make Our Civilization More Environmentally Sustainable. *Bull. Sci. Technol. Soc.* 25, 129-144 — 144. <https://doi.org/10.1177/0270467605274856>
- Nassar, N.T., Graedel, T.E., Harper, E.M., 2015. By-product metals are technologically essential but have problematic supply. *Sci. Adv.* 1, e1400180. <https://doi.org/10.1126/sciadv.1400180>
- Neramballi, A., Milios, L., Sakao, T., Matschewsky, J., 2024. Toward a policy landscape to support the product-as-a-service design process for a circular economy. *J. Ind. Ecol.* 28, 1045 — 1059. <https://doi.org/10.1111/jiec.13535>
- Ngom, A., 2022. Les terres rares d'Afrique, un potentiel recours pour l'Union européenne dans le respect du droit international: *Rev. Int. Droit Économique t.XXXVI*, 5 — 27. <https://doi.org/10.3917/ride.361.0005>
- Nguyen, R.T., Diaz, L.A., D. Devin Imholte, Lister, T.E., 2017. Economic Assessment for Recycling Critical Metals From Hard Disk Drives Using a Comprehensive Recovery Process. *Jom.* <https://doi.org/10.1007/s11837-017-2399-2>
- Ni'am, A.C., Wang, Y.-F., Chen, S.-W., Chang, G.-M., You, S.-J., 2020. Simultaneous recovery of rare earth elements from waste permanent magnets (WPMs) leach liquor by solvent extraction and hollow fiber supported liquid membrane. *Chem. Eng. Process. - Process Intensif.* 148, 107831. <https://doi.org/10.1016/j.cep.2020.107831>

- Nikulski, J.S., Ritthoff, M., Nadja von Gries, 2021. The Potential and Limitations of Critical Raw Material Recycling: The Case of LED Lamps. *Resour.-Basel*. <https://doi.org/10.3390/resources10040037>
- Niskanen, J., Lahtinen, M., Perämäki, S., 2022. Acetic acid leaching of neodymium magnets and iron separation by simple oxidative precipitation. *Clean. Eng. Technol.* 10, 100544. <https://doi.org/10.1016/j.clet.2022.100544>
- Nlebedim, I.C., King, A.H., 2018. Addressing Criticality in Rare Earth Elements via Permanent Magnets Recycling. *Jom*. <https://doi.org/10.1007/s11837-017-2698-7>
- Nordelof, A., Grunditz, E., Lundmark, S., Tillman, A.-M., Alatalo, M., Thiringer, T., 2019. Life cycle assessment of permanent magnet electric traction motors. *Transp. Res. Part - Transp. Environ.* <https://doi.org/10.1016/j.trd.2018.11.004>
- Nykanen, V., Groves, D.I., Ojala, V.J., Eilu, P., Gardoll, S.J., 2008. Reconnaissance-scale conceptual fuzzy-logic prospectivity modelling for iron oxide copper-gold deposits in the northern Fennoscandian Shield, Finland. *Aust. J. Earth Sci.* 55, 25 – 38. <https://doi.org/10.1080/09692290.2019.1693411>
- Omodara, L., Turpeinen, E.M., Pitkaaho, S., Keiski, R.L., 2020. Substitution potential of rare earth catalysts in ethanol steam reforming. *Sustain. Mater. Technol.* 26. <https://doi.org/10.1016/j.susmat.2020.e00237>
- Palmie, M., Mieke, L., Mair, J., Wincent, J., 2024. Valuation entrepreneurship through product-design and blame-avoidance strategies: How Tesla managed to change the public perception of sustainable innovations. *J. Prod. Innov. Manag.* 41, 644 – 676. <https://doi.org/10.1111/jpim.12732>
- Pateli, I.M., Abbott, A.P., Binnemans, K., Nerea Rodriguez Rodriguez, 2020. Recovery of yttrium and europium from spent fluorescent lamps using pure levulinic acid and the deep eutectic solvent levulinic acid-choline chloride. *Rsc Adv.* <https://doi.org/10.1039/d0ra05508e>
- Paulikas, D., Katona, S., Ilves, E., Ali, S.H., 2022. Deep-sea nodules versus land ores: A comparative systems analysis of mining and processing wastes for battery-metal supply chains. *J. Ind. Ecol.* 26, 2154 – 2177. <https://doi.org/10.1111/jiec.13225>
- Paulson, L., Büchs, M., 2022. Public acceptance of post-growth: Factors and implications for post-growth strategy. *Futures* 143, 103020. <https://doi.org/10.1016/j.futures.2022.103020>
- Peelman, S., Sun, Z.H.I., Sietsma, J., Yang, Y., Alam, S., Kim, H., Neelameggham, N., Ouchi, T., Oosterhof, H., 2016. Hydrometallurgical Extraction Of Rare Earth Elements From Low Grade Mine Tailings. *Rare Met. Technol.* 2016 17 – 29
- Peet, R., Watts, M. (Eds.), 2010. *Liberation ecologies: environment, development, social movements*, 2. ed., digital print. ed. Routledge, London.
- Peiravi, M., Dehghani, F., Ackah, L., Baharlouei, A., Godbold, J., Liu, J., Mohanty, M., Ghosh, T., 2021. A Review of Rare-Earth Elements Extraction with Emphasis on Non-conventional Sources: Coal and Coal Byproducts, Iron Ore Tailings, Apatite, and Phosphate Byproducts. *Min. Metall. Explor.* 38, 1 – 26. <https://doi.org/10.1007/s42461-020-00307-5>
- Peiro, L.T., Mendez, G.V., 2013. Material and Energy Requirement for Rare Earth Production. *Jom*. <https://doi.org/10.1007/s11837-013-0719-8>
- Petov, V., Babaevskaya, D., Taratkin, M., Chuvalov, L., Lusuardi, L., Misrai, V., Sukhanov, R., Scoffone, C.M.M., Enikeev, D., 2022. Thulium Fiber Laser Enucleation of the Prostate: Prospective Study of Mid- and Long-term Outcomes in 1328 Patients. *J. Endourol.* 36, 1231 – 1236. <https://doi.org/10.1089/end.2022.0029>
- Petterson, M.G., Tawake, A., 2019. The Cook Islands (South Pacific) experience in governance of seabed manganese nodule mining. *Ocean Coast. Manag.* 167, 271 – 287. <https://doi.org/10.1016/j.ocecoaman.2018.09.010>
- Piguet, C., 2019. Set Aside when Building the Periodic Table 150 Years ago, are Rare Earths any better considered by Chemists in the 21st Century? *Chimia* 73, 165. <https://doi.org/10.2533/chimia.2019.165>
- Pim, J.E., 2021. “Galiza is (not) a mine”: rural responses to pro-extractivist policies. *Araucaria-Rev. Iberoam. Filos. Polit. Humanidades* 23, 441 – 466. <https://doi.org/10.12795/araucaria.2021.i48.20>
- Prats Raspini, J., Canal Bonfante, M., Rossetti Cunico, F., Alarcon, O.E., Campos, L.M.S., 2022. Drivers and barriers to a circular economy adoption: a sector perspective on rare earth magnets. *J. Mater. Cycles Waste Manag.* <https://doi.org/10.1007/s10163-022-01424-7>
- Prno, J., Scott Slocombe, D., 2012. Exploring the origins of ‘social license to operate’ in the mining sector: Perspectives from governance and sustainability theories. *Resour. Policy* 37, 346 – 357. <https://doi.org/10.1016/j.resourpol.2012.04.002>
- Qiu, Y., Suh, S., 2019. Economic feasibility of recycling rare earth oxides from end-of-life lighting technologies. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2019.104432>

- Rabbani, M., Taqi Rabbani, M., Muthoni, F., Sun, Y., Vahidi, E., 2024. Advancing phytomining: Harnessing plant potential for sustainable rare earth element extraction. *Bioresour. Technol.* 401, 130751. <https://doi.org/10.1016/j.biortech.2024.130751>
- Radley, B., 2024. Conflict Minerals Inc.: War, Profit and White Saviourism in Eastern Congo. *Afr. Aff.* 123, 419 — 421. <https://doi.org/10.1093/afraf/adae023>
- Ralph, N., Assoc., 2021. A conceptual merging of circular economy, degrowth and conviviality design approaches applied to renewable energy technology. *J. Clean. Prod.* 319. <https://doi.org/10.1016/j.jclepro.2021.128549>
- Raminosoa, T., El-Refaie, A.M., Pan, D., Huh, K.-K., Alexander, J.P., Grace, K., Grubic, S., Galioto, S., Reddy, P.B., Shen, X., 2015. Reduced Rare-Earth Flux-Switching Machines for Traction Applications. *IEEE Trans. Ind. Appl.* 51, 2959 — 2971. <https://doi.org/10.1109/tia.2015.2397173>
- Rasoulnia, P., Barthen, R., Lakaniemi, A.-M., Ali-Loytty, H., Puhakka, J.A., 2022. Low residual dissolved phosphate in spent medium bioleaching enables rapid and enhanced solubilization of rare earth elements from end-of-life NiMH batteries. *Miner. Eng.* <https://doi.org/10.1016/j.mineng.2021.107361>
- Rasoulnia, P., Barthen, R., Puhakka, J.A., Lakaniemi, A.-M., 2021a. Leaching of rare earth elements and base metals from spent NiMH batteries using gluconate and its potential bio-oxidation products. *J. Hazard. Mater.* <https://doi.org/10.1016/j.jhazmat.2021.125564>
- Rasoulnia, P., Barthen, R., Valtonen, K., Lakaniemi, A.-M., 2021b. Impacts of Phosphorous Source on Organic Acid Production and Heterotrophic Bioleaching of Rare Earth Elements and Base Metals from Spent Nickel-Metal-Hydride Batteries. *Waste Biomass Valorization*. <https://doi.org/10.1007/s12649-021-01398-x>
- Rasoulnia, P., Hajdu-Rahkama, R., Puhakka, J.A., 2023. High-rate and-yield continuous fluidized-bed bioconversion of glucose-to-gluconic acid for enhanced metal leaching. *Chem. Eng. J.* <https://doi.org/10.1016/j.cej.2023.142088>
- Reisdörfer, G., Bertuol, D.A., Tanabe, E.H., 2020. Extraction of neodymium from hard disk drives using supercritical CO₂ with organic acids solutions acting as cosolvents. *J. CO₂ Util.* 35, 277 — 287. <https://doi.org/10.1016/j.jcou.2019.10.008>
- Riano, S., Petranikova, M., Onghena, B., Tom Vander Hoogerstraete, Banerjee, D., Foreman, M.R.S.J., Ekberg, C., Binnemans, K., 2017. Separation of rare earths and other valuable metals from deep-eutectic solvents: a new alternative for the recycling of used NdFeB magnets. *Rsc Adv.* <https://doi.org/10.1039/c7ra06540j>
- Roche, L., Arendt, R., Bach, V., Finkbeiner, M., 2023. The social impacts of resource extraction for the clean energy transition: A qualitative news media analysis. *Extr. Ind. Soc.* 13. <https://doi.org/10.1016/j.exis.2023.101213>
- Rosario-Beltre, A.J., Sanchez-Espana, J., Rodriguez-Gomez, V., Francisco Javier Fernandez-Naranjo, Bellido-Martin, E., Adanez-Sanjuan, P., Julio Cesar Arranz-Gonzalez, 2023. Critical Raw Materials recovery potential from Spanish mine wastes: A national-scale preliminary assessment. *J. Clean. Prod.* 407. <https://doi.org/10.1016/j.jclepro.2023.137163>
- Ruiz, C., Antonio Arribas, Antonio Arribas, 2002. Mineralogy and geochemistry of the Masa Valverde blind massive sulphide deposit, Iberian Pyrite Belt (Spain). *Ore Geol. Rev.* 19, 1 — 22. [https://doi.org/10.1016/s0169-1368\(01\)00037-3](https://doi.org/10.1016/s0169-1368(01)00037-3)
- Sager, M., Wiche, O., 2024. Rare Earth Elements (REE): Origins, Dispersion, and Environmental Implications—A Comprehensive Review. *Environments* 11, 24. <https://doi.org/10.3390/environments11020024>
- Sajn, R., Alijagic, J., Ristic, I., 2024. Secondary Deposits as a Potential REEs Source in South-Eastern Europe. *Minerals* 14. <https://doi.org/10.3390/min14020120>
- Sakao, T., Golinska-Dawson, P., Vogt Duberg, J., Erik, S., Hidalgo-Crespo, J., Riel, A., Peeters, Jef, Green, Aaron, Mathieux, Fabrice, 2023. Product-as-a-service for critical raw materials: challenges, enablers, and needed research.
- Schleich, J., Durand, A., Brugger, H., 2021. How effective are EU minimum energy performance standards and energy labels for cold appliances? *Energy Policy* 149, 112069. <https://doi.org/10.1016/j.enpol.2020.112069>
- Schreiber, A., Marx, J., Zapp, P., Hake, J.-F., Voßenkaul, D., Friedrich, B., 2016. Environmental impacts of rare earth mining and separation based on eudialyte: A new European way. *Resources*. <https://doi.org/10.3390/resources5040032>

- Schulze, R., Buchert, M., 2016. Estimates of global REE recycling potentials from NdFeB magnet material. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2016.05.004>
- Secinaro, S., Calandra, D., Lanzalonga, F., Ferraris, A., 2022. Electric vehicles? consumer behaviours: Mapping the field and providing a research agenda. *J. Bus. Res.* 150, 399 – 416. <https://doi.org/10.1016/j.jbusres.2022.06.011>
- Siderius, H.-P., 2013. The role of experience curves for setting MEPS for appliances. *Energy Policy* 59, 762–772 – 772. <https://doi.org/10.1016/j.enpol.2013.04.032>
- Simandl, G.J., Paradis, S., 2018. Carbonatites: related ore deposits, resources, footprint, and exploration methods. *Appl. Earth Sci.* 127, 123 – 152. <https://doi.org/10.1080/25726838.2018.1516935>
- Sobiech-Grabka, K., Stankowska, A., Jerzak, K., 2022. Determinants of Electric Cars Purchase Intention in Poland: Personal Attitudes v. Economic Arguments. *Energies* 15. <https://doi.org/10.3390/en15093078>
- Sprecher, B., Kleijn, R., Gert Jan Kramer, 2014. Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives. *Environ. Sci. Technol.* <https://doi.org/10.1021/es501572z>
- Tahanian, H., Aliahmadi, M., Faiz, J., 2020. Ferrite Permanent Magnets in Electrical Machines: Opportunities and Challenges of a Non-Rare-Earth Alternative. *IEEE Trans. Magn.* 56. <https://doi.org/10.1109/tmag.2019.2957468>
- Tanvar, H., Barnwal, A., Dhawan, N., 2020. Characterization and evaluation of discarded hard disc drives for recovery of copper and rare earth values. *J. Clean. Prod.* 249, 119377. <https://doi.org/10.1016/j.jclepro.2019.119377>
- Tassin Campanella, V., 2024. *Routledge Handbook Of Seabed Mining And The Law Of The Sea*, Routledge Handbook of Seabed Mining and the Law of the Sea. <https://doi.org/10.4324/9780429426162>
- Tayebi-Khorami, M., Edraki, M., Corder, G., Golev, A., 2019. Re-Thinking Mining Waste through an Integrative Approach Led by Circular Economy Aspirations. *Minerals* 9, 286. <https://doi.org/10.3390/min9050286>
- Thiebaud, E., Hilty, L.M., Schlupe, M., Boni, H.W., Faulstich, M., 2018. Where Do Our Resources Go? Indium, Neodymium, and Gold Flows Connected to the Use of Electronic Equipment in Switzerland. *Sustainability*. <https://doi.org/10.3390/su10082658>
- Thomsen, H.S. 2017. Are the increasing amounts of gadolinium in surface and tap water dangerous? *Acta Radiologica* 58(3), 259–263. <https://doi.org/10.1177/0284185116666419>
- Turner, T., Fursov, K., Nefedova A., 2022. Early adopters of new transportation technologies: Attitudes of Russia's population towards car sharing, the electric car and autonomous driving. *Transp. Res. Part - Policy Pract.* 155, 403 – 417. <https://doi.org/10.1016/j.tra.2021.11.006>
- Traore, M., Gong, A., Wang, Y., Qiu, L., Bai, Y., Zhao, W., Liu, Yang, Chen, Y., Liu, Ying, Wu, H., Li, S., You, Y., 2023. Research progress of rare earth separation methods and technologies. *J. Rare Earths* 41, 182 – 189. <https://doi.org/10.1016/j.jre.2022.04.009>
- Utochnikova, V.V., 2021. Chapter 318 - Lanthanide complexes as OLED emitters, in: Bünzli, J.-C.G., Pecharsky, V.K. (Eds.), *Handbook on the Physics and Chemistry of Rare Earths*. Elsevier, pp. 1 – 91. <https://doi.org/10.1016/b.sbpcre.2021.05.001>
- V. Balaram, 2019. Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geosci. Front.* <https://doi.org/10.1016/j.gsf.2018.12.005>
- van der Ent, A., Baker, A.J.M., Reeves, R.D., Chaney, R.L., Anderson, C.W.N., Meech, J.A., Erskine, P.D., Simonnot, M.-O., Vaughan, J., Morel, J.L., Echevarria, G., Fogliani, B., Rongliang, Q., Mulligan, D.R., 2015. Agromining: Farming for Metals in the Future? *Environ. Sci. Technol.* 49, 4773 – 4780. <https://doi.org/10.1021/es506031u>
- van Nielen, S.S., Kleijn, R., Sprecher, B., Miranda Xicotencatl, B., Tukker, A., 2022. Early-stage assessment of minor metal recyclability. *Resour. Conserv. Recycl.* 176, 105881. <https://doi.org/10.1016/j.resconrec.2021.105881>
- Vatamanescu, E.-M., Nicolescu, L., Gazzola, P., Amelio, S., 2023. Integrating smart mobility and electric car sharing adoption in a common framework: Antecedents and mediators. *J. Clean. Prod.* 418. <https://doi.org/10.1016/j.jclepro.2023.138254>
- Vats, M.C., Singh, S.K., 2015. Assessment of gold and silver in assorted mobile phone printed circuit boards (PCBs): Original article. *Waste Manag.* 45, 280 – 288. <https://doi.org/10.1016/j.wasman.2015.06.002>
- Vaughan, J., Gontijo, V., Valenta, R., Alonso, E., 2023. Rare earth element sources, end-use demand trends, and hydrometallurgical separations.
- Venkatesan, P., Tom Vander Hoogerstraete, Hennebel, T., Binnemans, K., Sietsma, J., Yang, Y., 2018a. Selective electrochemical extraction of REEs from NdFeB magnet waste at room temperature. *Green Chem.* <https://doi.org/10.1039/c7gc03296j>

- Venkatesan, P., Vander Hoogerstraete, T., Binnemans, K., Sun, Z., Sietsma, J., Yang, Y., 2018b. Selective Extraction of Rare-Earth Elements from NdFeB Magnets by a Room-Temperature Electrolysis Pretreatment Step. *ACS Sustain. Chem. Eng.* 6, 9375 — 9382. <https://doi.org/10.1021/acssuschemeng.8b01707>
- Vera, M., Schippers, A., Hedrich S., Sand, W., 2022. Progress in bioleaching: fundamentals and mechanisms of microbial metal sulfide oxidation — part A. *Appl. Microbiol. Biotechnol.* 106, 6933 — 6952. <https://doi.org/10.1007/s00253-022-12168-7>
- Verrax, F., 2014. Governance of mineral resources: Towards the end of national states' supremacy? The WTO and the case of rare earth elements as an illustrative example. *Etikk Praksis* 8, 41 — 51.
- Vind, J., Malfliet, A., Blanpain, B., Tsakiridis, P.E., Tkaczyk, A.H., Vassiliadou, V., Papias, D., 2018. Rare Earth Element Phases in Bauxite Residue. *Minerals* 8. <https://doi.org/10.3390/min8020077>
- Wakolbinger, T., Toyasaki, F., Nowak, T., Nagurny, A., 2014. When and for whom would e-waste be a treasure trove? Insights from a network equilibrium model of e-waste flows. *Int. J. Prod. Econ.* 154, 263-273 — 273. <https://doi.org/10.1016/j.ijpe.2014.04.025>
- Wan, Y., Yang, L., 2024. Differential recycling strategies and government intervention in a closed-loop supply chain. *Comput. Ind. Eng.* 187. <https://doi.org/10.1016/j.cie.2023.109816>
- Wang, C., 2018. WTO rare earths case's influence on China's domestic regulatory changes. *J. World Trade* 52, 307 — 330. <https://doi.org/10.54648/trad2018014>
- Wang, P., Yang, Y.-Y., Heidrich, O., Chen, L.-Y., Chen, L.-H., Fishman, T., Chen, W.-Q., 2024. Regional rare-earth element supply and demand balanced with circular economy strategies. *Nat. Geosci.* 17, 94 — 102. <https://doi.org/10.1038/s41561-023-01350-9>
- Wang, Y., Sun, B., Gao, F., Chen, W., Nie, Z., 2022. Life cycle assessment of regeneration technology routes for sintered NdFeB magnets. *Int. J. LIFE CYCLE Assess.* <https://doi.org/10.1007/s11367-022-02081-6>
- Werker, J., Wulf, C., Zapp, P., Schreiber, A., Marx, J., 2019. Social LCA for rare earth NdFeB permanent magnets. *Sustain. Prod. Consum.* 19, 257-269 — 269. <https://doi.org/10.1016/j.spc.2019.07.006>
- Weszkalnys, G., 2014. Anticipating oil: the temporal politics of a disaster yet to come. *Sociol. Rev.* 62, 211 — 235.
- Wicki, M., Bruckmann, G., Bernauer, T., 2022. How to accelerate the uptake of electric cars? Insights from a choice experiment. *J. Clean. Prod.* 355. <https://doi.org/10.1016/j.jclepro.2022.131774>
- Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. *Nat. Commun.* 11, 3107. <https://doi.org/10.1038/s41467-020-16941-y>
- Wilson, C.R., Hardy, L.A., Irby, P.B., Fried, N.M., Choi, B., Kollias, N., Zeng, H., Kang, H., Wong, B., Ilgner, J., Tearney, G., Gregory, K., Marcu, L., Skala, M., Campagnola, P., Mandelis, A., 2016. Proximal Fiber Tip Damage during Holmium: YAG and Thulium Fiber Laser Ablation of Kidney Stones. *Photonic Ther. Diagn.* Xii 9689. <https://doi.org/10.1117/12.2207895>
- Wilson, M., Goffnett, S., 2022. Reverse logistics: Understanding end-of-life product management. *Bus. Horiz.* 65, 643-655 — 655. <https://doi.org/10.1016/j.bushor.2021.10.005>
- Wilts, H., Bringezu, S., Bleischwitz, R., Lucas, R., Wittmer, D., 2011. Challenges of metal recycling and an international covenant as possible instrument of a globally extended producer responsibility. *Waste Manag. Res.* 29, 902 — 910. <https://doi.org/10.1177/0734242x11415311>
- Wu, T., Cao, S., Kou, M., Xie, Y., Ding, G., Guo, S., Zheng, B., Chen, R., Zhong, M., Yan, A., 2023. Magnetic performance and microstructure of NdFeB sintered magnet by diffusing Tb10Pr90-x(Cu,Al,Ga)x alloys. *J. Alloys Compd.* 934. <https://doi.org/10.1016/j.jallcom.2022.167888>
- Wu, Y., Song, M., Zhang, Q., Wang, W., 2021. Review of rare-earths recovery from polishing powder waste. *Resour. Conserv. Recycl.* 171, 105660. <https://doi.org/10.1016/j.resconrec.2021.105660>
- Wulf, C., Zapp, P., Schreiber, A., Marx, J., Schloer, H., 2017. Lessons Learned from a Life Cycle Sustainability Assessment of Rare Earth Permanent Magnets. *J. Ind. Ecol.* 21, 1578-1590 — 1590. <https://doi.org/10.1111/jiec.12575>
- Xiao, Y., Feng, Z., Hu, G., Huang, L., Huang, X., Chen, Y., Li, M., 2015. Leaching and mass transfer characteristics of elements from ion-exchange adsorption type rare earth ore. *Rare Met.* 34, 357—365. <https://doi.org/10.1007/s12598-015-0481-x>
- Xavier, L.H., Ottoni, M., Abreu, L.P., 2023. A comprehensive review of urban mining and the value recovery from e-waste materials. *Resour. Conserv. Recycl.* 190, 106840. <https://doi.org/10.1016/j.resconrec.2022.106840>

- Xie, C., Xiao, Y., He, C., Liu, W.-S., Tang, Y.-T., Wang, S., Antony van der Ent, Jean Louis Morel, Simonnot, M.-O., Qiu, R.-L., 2023. Selective recovery of rare earth elements and value-added chemicals from the *Dicranopteris linearis* bio-ore produced by agromining using green fractionation. *J. Hazard. Mater.* 443. <https://doi.org/10.1016/j.jhazmat.2022.130253>
- Ye, Q., Wang, D., Wei, N., 2024. Engineering biomaterials for the recovery of rare earth elements. *Trends Biotechnol.* 42, 575 — 590. <https://doi.org/10.1016/j.tibtech.2023.10.011>
- Yeh, C.-H., Xu, Y., 2013. Sustainable planning of e-waste recycling activities using fuzzy multicriteria decision making. *J. Clean. Prod.* 52, 194-204 — 204. <https://doi.org/10.1016/j.jclepro.2013.03.003>
- Yin, X., Martineau, C., Demers, I., Basiliko, N., Fenton, N.J., 2021. The potential environmental risks associated with the development of rare earth element production in Canada. *Environ. Rev.* 29, 354 — 377. <https://doi.org/10.1139/er-2020-0115>
- Zapp, P., Marx, J., Schreiber, A., Friedrich, B., Vossenkaul, D., 2018. Comparison of dysprosium production from different resources by life cycle assessment. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2017.12.006>
- Zeng, Z., Gao, Y., Ni, S., Zhang, S., Fu, X., Sun, X., 2023. Investigation on the recovery of thorium and rare earth from radioactive waste residue by functionalized ionic liquids. *Sep. Purif. Technol.* 317, 123901. <https://doi.org/10.1016/j.seppur.2023.123901>
- Zhang, L., Dong, H., Liu, Y., Bian, L., Wang, X., Zhou, Z., Huang, Y., 2018. Bioleaching of rare earth elements from bastnaesite-bearing rock by actinobacteria. *Chem. Geol.* 483, 544 — 557. <https://doi.org/10.1016/j.chemgeo.2018.03.023>
- Zhang, N., Li, H.-X., Liu, X.-M., 2016. Recovery of scandium from bauxite residue—red mud: a review. *Rare Met.* 35, 887 — 900. <https://doi.org/10.1007/s12598-016-0805-5>
- Zhang, Q., Burrage, M.K., Lukaschuk, E., Shanmuganathan, M., Popescu, I.A., Nikolaidou, C., Mills, R., Werys, K., Hann, E., Barutcu, A., Polat, S.D., Salerno, M., Jerosch-Herold, M., Kwong, R.Y., Watkins, H.C., Kramer, C.M., Neubauer, S., Ferreira, V.M., Piechnik, S.K., Hypertrophic Cardiomyopathy Regis, 2021. Toward Replacing Late Gadolinium Enhancement With Artificial Intelligence Virtual Native Enhancement for Gadolinium-Free Cardiovascular Magnetic Resonance Tissue Characterization in Hypertrophic Cardiomyopathy. *Circulation* 144, 589 — 599. <https://doi.org/10.1161/circulationaha.121.054432>
- Zhang, S., Ding, Y., Liu, B., Chang, C., 2017. Supply and demand of some critical metals and present status of their recycling in WEEE. *Waste Manag.* <https://doi.org/10.1016/j.wasman.2017.04.003>
- Zhong, C., Geng, Y., Ge, Z., Rui, X., Liang, J., Wei, W., 2023. Promoting future sustainable utilization of rare earth elements for efficient lighting technologies. *Environ. Res. Lett.* 18. <https://doi.org/10.1088/1748-9326/acdf74>
- Zhou, B., Li, Z., Chen, C., 2017. Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies. *Minerals* 7, 203. <https://doi.org/10.3390/min7110203>
- Zhou, R., Brown, D., 2024. Epistemic justice and critical minerals-Towards a planetary just transition. *Extr. Ind. Soc.* 18. <https://doi.org/10.1016/j.exis.2024.101463>
- Zhu, X., Fan, D., Xiang, Z., Quan, L., Hua, W., Cheng, M., 2019. Systematic multi-level optimization design and dynamic control of less-rare-earth hybrid permanent magnet motor for all-climatic electric vehicles. *Appl. Energy* 253. <https://doi.org/10.1016/j.apenergy.2019.113549>
- Zinoveev, D., Pasechnik, L., Fedotov, M., Dyubanov, V., Grudinsky, P., Alpatov, A., 2021. Extraction of Valuable Elements from Red Mud with a Focus on Using Liquid Media-A Review. *Recycling* 6. <https://doi.org/10.3390/recycling6020038>



**Centre national
de la recherche scientifique
CNRS**

Mission Pour l'Expertise Scientifique - MPES
3, rue Michel-Ange - 75794 Paris Cedex 16
+ 33 1 44 96 40 00

Join us on :



cnrs.fr