The role of research and innovation in ensuring a safe and sustainable supply of critical raw materials in the EU

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The role of research and innovation in ensuring a safe and sustainable supply of critical raw materials in the EU

This study aims to illuminate the role of research and innovation (R&I) in ensuring a safe and sustainable supply of critical raw materials (CRM). It provides background information on CRMs, related EU policies, sustainability issues, and public controversy, tying all these in with their respective R&I needs. The study reviews the role of R&I and cooperation in securing the EU's raw material supply, highlighting the significance of R&I along the value chain and analysing patenting activities and international cooperation. It concludes by presenting 11 policy options on EU institutional and R&I capacities, international collaboration and legitimacy and regulation, assessing each against a list of dimensions (e.g. costs, benefits and feasibility).

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Executive summary

Raw materials are so deeply intertwined with human history that they gave names to the stone and iron ages. Raw materials are as necessary today as they were then. While European prosperity is based on knowledge (among other things), much of that knowledge is about making useful things and these useful things are made of raw materials. The green and digital transitions are particularly materials-intensive and will drive future demand for many raw materials.

Critical raw materials

Critical raw materials (CRM) are crucial for the EU economy but are characterised by a high risk of supply disruption. The definition of CRM varies, based on the perspective of the assessment team and the characteristics of the materials themselves, leading to the development of different methodologies worldwide. The EU methodology for assessing CRM is based on the likelihood of supply disruption (termed 'supply risk') and the impact such a supply disruption would have (termed 'economic importance'). The EU criticality assessment ranks candidate raw materials based on these dimensions. Materials scoring above the designated threshold for both dimensions are considered critical.

In addition, the Critical Raw Materials Act (CRMA) introduced the concept of strategic raw materials (SRM), which are characterised by their importance to strategic technology fields (green and digital transition, aerospace, defence), the forecasted demand outstripping supply, and expected production scaling difficulties. Most strategic raw materials are already identified as critical, but nickel and copper are classified as strategic without being critical, due to their broad supplier base. All SRM are treated as CRM under the Critical Raw Materials Act. However, some of the provisions of the CRMA only apply to SRM (see below).

The supply of critical and strategic raw materials to the EU is not a single chain, but different for each material. The concentration of supply is a key factor in assessing the risk of possible supply constraints for CRM supply chains. A distinction between extraction and processing stages is important because constraints can occur at either stage, affecting downstream manufacturers. Extraction and processing often take place in different regions, and some CRM are by-products recovered during processing. This means that extraction in one jurisdiction does not guarantee availability of the processed form in the same place. This has enabled China to emerge as a major processing centre for critical raw materials, even those not mined within its borders, such as lithium and cobalt. The EU relies on imports of both extracted and processed materials for most CRM. Even if the EU is independent at the processing stage for certain materials, it may still depend on imports of raw materials at the extraction stage. Conversely, independence at the extraction stage does not guarantee independence at the processing stage. The EU has a more developed processing industry compared to mining, providing opportunities for growth at both stages for most CRM.

Addressing the risks of supply constraints is possible from different angles. The methodology for identification of CRM and SRM already provides several approaches: action to reduce the factors identified as increasing the probability of supply disruption; or strengthening the factors that make such a supply disruption less likely or its impact less severe. Such 'mitigation measures' – aimed at increasing security of supply, reducing demand or increasing resilience towards supply disruption – along the supply and value chains of CRM include:

- Supply diversification: this involves finding and securing alternative sources of critical raw materials, both domestically and internationally.
- Increased domestic supply: while limited by the geological availability of raw materials in the EU, efforts can be made to enhance exploration and mine development activities within the region.

- Substitution: substitution can occur through different mechanisms, including material-for-material or technology-for-material changes.
- More efficient use in manufacturing: design and process innovations that reduce scrap generation can lead to a decrease in raw material demand for producing the same products, thereby reducing pressure on supply.
- Recycling: functional recycling of post-consumer scrap within Europe provides a domestic source of raw materials independent of mining.
- Circularity strategies beyond recycling: strategies like sharing, reusing, repairing, refurbishing, and remanufacturing aim to keep the value of raw materials in the economic cycle for longer periods, reducing the demand for critical raw materials and easing the pressure on supply.

The CRMA addresses many of these points, including provisions for defining and monitoring critical and strategic raw materials, strategic partnerships with third countries (i.e., securing and diversifying supply), facilitating financing and permitting for raw materials production projects (i.e., increasing domestic supply), and increasing circularity in all its scope (from product design to recycling). The targets of the CRMA are very specific regarding domestic production and dependence on dominant foreign suppliers, namely, it stipulates that by 2030, the EU will cover:

- at least 10 % of the EU's annual consumption for extraction,
- at least 40 % of the EU's annual consumption for processing,
- at least 25 % of the EU's annual consumption for recycling,

from domestic sources for strategic raw materials. Furthermore, the EU will source no more than 65 % of the Union's annual consumption of any strategic raw material at any stage from a single third country.

The further EU policy framework on CRM includes legislation, EU communications, and regulations. We categorise EU CRM policies based on the degree of generality and policy target/field. The degree of generality distinguishes between general policies applicable to all CRMs and specific policies related to certain CRMs, product groups or countries. The policy targets/fields are supply security and social and environmental sustainability. Documents and action reviewed include the raw materials initiative of 2008, the latest report on 'Critical Raw Materials for the EU', and the European action plan on critical raw materials, the European Raw Materials Alliance, and the RePowerEU plan.

Alongside general CRM policies focusing on supply security, the EU policy framework also includes policies that address other aspects relevant to CRM supply and use, specifically social and environmental sustainability. These policies cover areas such as human health, environmental protection, circular economy, conflict minerals, social responsibility, and due diligence.

The visibility and funding for the raw materials sector have significantly increased in the past 20 years due to these policies. Initiatives such as the establishment of the Knowledge and Innovation Community on Raw Materials (EIT RawMaterials), the ERA-MIN network, and the inclusion of raw materials topics in Horizon 2020 and Horizon Europe programmes demonstrate this increase.

The EU policy framework is complemented by bilateral agreements and product/raw-material specific policies. Bilateral agreements include strategic partnerships on sustainable raw material value chains established with various countries. Product-specific policies include the establishment of the European Battery Alliance and the EU Sustainable Batteries Regulation, which targets CRMs used in batteries, and the EU regulation on supply chain due diligence for minerals from conflict-affected and high-risk areas.

Role of R&I and cooperation in securing CRM supply

We analyse the role of R&I and cooperation in securing a safe and sustainable CRM supply for the EU following a simplified and generic supply chain for raw materials, including critical raw materials. The general steps in this chain and related R&I topics are:

- Exploration, where ore deposits are identified and characterised. R&I in exploration focuses on improving data collection and prediction, leveraging big data and earth observation technologies, and developing new technologies to enhance the efficiency, safety, and sustainability of mineral resource exploration. Earth observation (EO) and artificial intelligence (AI) technologies play a significant role in current projects at the exploration stage funded through Horizon Europe.
- Mining, where material is extracted and prepared for further processing. R&I for mining involves the development and adaptation of technologies to specific deposit (types), increasing process efficiencies, addressing environmental considerations, ensuring health and safety, using mine tailings, and understanding social impacts. R&I in deep-sea mining is nascent and fraught with uncertainties and the prospect of unknown environmental damage. As for exploration, EO models also play a role in current projects funded through Horizon Europe at the extraction stage. Further projects develop methods for sustainable and safer extraction, novel approaches for selective blasting and bioleaching. Digitisation and automation are being implemented to reduce carbon footprint. Further work focuses on framework conditions, including permits, policies, and social aspects of mining.
- Processing of ores and concentrates, comprising both pyrometallurgical and hydrometallurgical processes. Prevailing themes are reducing costs, optimising resource use, reducing energy consumption and carbon emissions through improved unit operations and whole facility optimisation, as well as developing, adapting and adopting digital solutions. Some projects funded through Horizon Europe combine processing with mining and extraction, while others explore new technologies for processing specific CRM. More sustainable practices (e.g. using alternative chemicals or digitalisation as a tool for increasing efficiency or generating insights) are being developed in processing projects.
- Manufacturing: the transformation of refined minerals or metals into end-use products. R&I topics at this stage include improving the efficiency of raw materials use, reducing energy use and carbon emissions, as well as designing products with explicit consideration of circularity aspects. In current Horizon Europe projects, the manufacturing stage is embedded in projects focused on processing, recycling, and recovery, with a trend towards introducing circular economy principles. Substitution projects cluster into three main groups: catalysts, capacitors, and batteries, with a focus on developing technologies with low or no CRM content. Usage optimisation projects aim to lower CRM content or make manufacturing more sustainable.
- Use phase, where products are used by consumers and businesses. R&I topics relevant to this phase include usage optimisation (e.g., sharing concepts) and prolonging product life span, thereby reducing demand.
- Recycling of manufacturing and post-consumer scrap. Common R&I themes in recycling are enhancing efficiency of known processes, developing recycling routes for increasingly complex products, and reducing costs. In addition to technologies, the establishment of collection infrastructures, understanding consumer behaviour and effective regulation are crucial for enhancing raw material recovery through recycling. Current Horizon Europe projects at the recycling and recovery stage focus on e-waste, specific end-of-life technologies (such as solar panels and batteries), and bioremediation and bio-based technologies. Digitalisation plays a crucial role in tackling recycling challenges and facilitating the tracking of CRM through the supply chain.

The EU's import dependency on CRM has increased as domestic mining and processing have declined. The European Commission has recognised this issue in various policy documents and forward-looking reports, including supply chain analyses and demand forecasts. Reports by the Joint Research Centre (JRC), the International Energy Agency (IEA) and others indicate a general consensus that raw materials demand will increase rapidly to achieve the green and digital transitions, in addition to global drivers such as economic and population growth. In light of the EU's current dependence on third countries for its critical raw materials supply, there is a need for strategic planning and policies to address the increasing demand for CRM while reducing dependence on external sources. R&I can play an important role in achieving these goals.

Different R&I policy instruments are implemented at various stages of the innovation cycle, ranging from fundamental research to market readiness. The ERA-MIN network supports the European Innovation Partnership on Raw Materials and funds smaller-scale collaboration projects, complementing Horizon Europe. Topics include resource efficiency, recycling, policy, and public perception. ERA-MIN funds projects between technology readiness level (TRL) 2-6. EIT RawMaterials functions as an innovation platform and accelerator, fostering the entire ecosystem for the RM industry. It focuses on bringing economically self-sustaining products and services to the market, primarily at TRL 6 and above. However, it also supports lower TRL projects, particularly start-ups emerging from university research. The EU's R&I framework programmes also support research related to CRM. The results of a review of ongoing projects funded through Horizon Europe are summarised above along a generic CRM supply and value chain. An analysis of the reviewed projects showed a focus on recycling and recovery, with comparatively limited attention paid to the exploration stage and sustainable mining practices. Batteries, catalysts, and capacitors are the most researched technologies, while magnets for wind turbines and solar panels appear under-represented. The most represented CRM in the reviewed projects are cobalt, lithium, platinum group metals, nickel, and manganese. Cooperation with non-European countries is minimally targeted, with only Zambia and South Africa mentioned. Finland, Greece, and Portugal are the most targeted European countries for demonstration sites or pilot technologies.

We use a quantitative analysis of patents filed at the World Intellectual Property Organization (WIPO) or the European Patent Office (EPO) to outline the relative positioning and collaboration patterns of the EU-27, as well as selected EU-27 Member States in the domain of technologies relevant for raw materials up to 2021. We find that mining industry innovations are strongly influenced by the oil and gas industry at the exploration stage, with the USA being the dominant player internationally. This strong influence follows from the similarity of technologies required to survey and probe the subsurface in search of valuable mineral or hydrocarbon deposits. Beyond exploration, the EU has a strong position in most of the remaining CRM supply chain, including mining and processing technologies, mining-specific transport technologies, environmental technologies and recycling. The patenting level of the EU-27 as a whole matches or surpasses that of the USA in all these categories. China shows the fastest increase in internationally filed patents, matching the USA and EU-27 for extraction technologies, the USA but not the EU in processing and environmental technologies, and surpassing both in recycling technologies. Japan led the field of recycling technologies until recently, with the EU-27 at a slightly lower level. Both were surpassed by China in 2021.

In addition to absolute levels of patenting, we examined the occurrence of co-patents (patents submitted by institutions from more than one country) as a measure of international cooperation. International cooperation appears more pronounced in mining and processing technologies compared to the average of all technologies: Mid-size (many EU Member States) and large nations (i.e., USA) exhibit 15-20 % co-patents in mining and processing. The level of cooperation in recycling technologies is higher still (EU approximately 30 %, US approximately 15 %). By comparison, the level of co-patenting across all technologies is close to 10 %. Based on these results, we conclude that the EU is solidly embedded into international innovation chains, with US-European collaboration one of the primary axes of cooperative R&D in the global innovation system for raw materials technologies, from exploration to recycling technology. Conversely, China and Japan stand largely apart in terms of patent filings.

We further examined the current state of R&I cooperation with partners outside the EU and the role of science and raw materials diplomacy in fostering international relations in the field of raw materials. Ideally, international collaboration can contribute to prosperity of both producing and consuming countries in mutually beneficial partnerships. However, critics argue that the current setup is not yet beneficial to all parties. Established forums for international cooperation, such as the Conference on Critical Materials and the Minerals Security Partnership aim to reduce supply risks, diversify sources, and manage dependence on specific resources: a clear buyer perspective. However, the ERA-MIN framework facilitates R&I collaboration by coordinating calls for proposals through research funding organisations in participating member states, including non-European countries. And the EU Global Gateway initiative aims to develop sustainable infrastructure projects and stimulate public-private partnerships to enhance supply chain resilience for CRM, also benefiting producing countries. Finally, R&I plays a clear bridging role in EU raw materials diplomacy. R&I topics are part of agreements with Canada (through the Comprehensive Economic and Trade Agreement – CETA), Ukraine, Kazakhstan, Namibia (including hydrogen), Argentina, Chile, Zambia, the Democratic Republic of the Congo, Rwanda, Greenland and Serbia. These agreements emphasise a broad array of R&I areas, explicitly targeting crucial issues such as the harmonisation of standards, technology and information exchange, and participation in Horizon Europe.

Conclusions

Critical raw materials are essential for the EU economy and diverse in their nature and challenges. High-level methodologies are in place to assess and monitor risks and possible impacts of supply disruption. Despite remaining challenges regarding access to timely, high-quality data, these methodologies address both the status quo (critical raw materials, CRM) and future developments (SRM) regarding supply and demand for raw materials. The outcome of the CRM assessments has changed over time due to changing supply and demand realities. This will continue to also apply to the assessment of SRM. These assessments and the accompanying background work provide a view of the entire supply chain for CRM, which is necessary for the development of action to minimise risks and increase resilience.

The EU has tackled the issue of raw material criticality with a variety of actions, including strong engagement in research and innovation (R&I) for critical raw materials. The role of R&I is stressed in policy documents, from the Raw Materials Initiative (2008) to the recent CRMA. In parallel with this political attention, funding has increased significantly in EU programmes, including Framework Programmes, Horizon 2020, Horizon Europe, and EIT RawMaterials (now reaching the end of the funding period however). The EU as a whole is an important actor in patenting in mining/processing and recycling, with strong international ties, especially to the US. Continued funding and policy support will be key to maintaining and profiting from this position.

Overarching themes in R&I and sustainability challenges for CRM are:

- Reducing costs and impacts of mining, processing and recycling;
- Managing complexity (from mining and processing complex ores to recycling complex products);
- Understanding and engaging with stakeholders, securing public acceptance;
- Covering the entire chain, from exploration to recycling, including circularity strategies;
- Ensuring access to data and creating transparency along supply chains.

Policy options

The areas set out below may be of interest for further action at the European level:

- Own institutional and R&I capacities
  - **Retain and reinforce own capacities, develop modern and more effective solutions for technologically mature fields**. EU institutions tasked with the implementation of the CRMA will require additional resources for establishing effective assessment and monitoring methodologies and for maintaining an up-to-date overview of CRM supply chains in the EU. Furthermore, EU mining and processing firms and equipment and technology providers require support to provide competitive solutions to the world market. Under existing State aid rules, this will primarily relate to reinforced investment in research and development efforts, alone and in collaboration with research institutions.
  - **Build capacities and lead in dynamic fields; secure a key position in evolving future areas along the entire cycle (from mining to recycling)**. To defend and extend the EU's leading position in fields where it retains a cutting-edge, granular support for single projects will not be enough. The domain of CRM research deserves attention as a key area of 'common European interest'.
  - **Encourage smaller, innovative change agents (small and medium-sized enterprises (SMEs) and citizen initiatives) outside established structures throughout the entire cycle**. If all support and attention were focused on established, large corporates, the EU would risk consolidating the status quo and achieve merely incremental innovation. Hence particular attention should be paid to young, dynamic firms with disruptive ideas.
- International collaboration
  - **Collaborate with the best to learn faster – regardless of whether Europe leads or needs to catch-up**. In research and innovation, collaborations with leading players are needed to maintain or regain a cutting edge. In the CRM domain, intensified collaboration with the US, Japan, but increasingly also China, appear therefore advisable – in addition to joint intra-European efforts.
  - **Develop bridgeheads in raw materials supplying nations by collaborating with the best local research partners**. While many nations with a focus on extraction may not count among the scientific leaders, they have specific knowledge of site conditions and practical experience that are essential to making European solutions technologically and commercially viable at home and abroad.
  - **Combine strategic materials diplomacy with existing science diplomacy efforts**. The embedding of CRM-related activity, also related to R&I, into a robust political fabric is essential. Science diplomacy should be extended to key nations in the CRM supply and waste chains.
- Legitimacy and regulation
  - *Identify and assess social and environmental conflicts arising from the development of new or the re-activation of old mines. Potential investors in mining operations are not necessarily dismissive but may lack contextualized knowledge of the problems that the (re-)opening of processing or extraction sites causes to the local population. These problems need to be duly acknowledged and precisely analysed, ideally by neutral third parties.*
  - *Develop procedures to facilitate new mining operations while taking into account justified grievances. Societal conflicts will arise if the resulting impacts are real and substantive. Hence, the political task should be neither to avoid them entirely nor to seek to talk stakeholders into compliance. Instead, means must be found – and agreed – that allow for actions that secure Europe's CRM sovereignty.*
  - *Develop a sound, evidence-based foundation for standards in future international partnership agreements (methods & data). While within the Union,*

political processes can be implemented to ascertain that local interest groups are duly consulted, this is not always possible in the case of operations outside Europe. Hence, there is a need to define exactly what European corporations are expected to do in concert with local governments.

Following these general areas, the following R&I options were identified:

- Own capacities: EU institutions
  Achieving the goals of the CRM Act will require extensive data gathering, analysis and monitoring capacities beyond what is available to-date. This pertains both to methods and data, *e.g.*, for assessing criticality or conducting stress tests.
- Strengthening and bundling of internal expertise for analysis and evidence based policy making in European institutions. They need to remain in a position of 'qualified arbiters' in a dynamically changing environment.
- Better utilize existing capacities in the EU research ecosystem, e.g. by commissioning external analysis. Not all specialist expertise and capacity can and should be built within administration.
- Own capacities: EU research and innovation landscape
  The specific benchmarks on EU sourcing will require significant research and development efforts along the entire CRM and SRM supply chains, from exploration and mining to processing, use and recycling.
  - Increase funding allocated to raw materials topics in Horizon programmes; encourage work on "less popular" CRM
  - Continued funding for bringing research results to the market (EIT, EIC, ERA-MIN). This action also Supports build-up of SME capacity across EU countries
  - Strengthen R&I on demand reduction (reduced consumption, substitution and longevity).
- International collaboration
  The EU has strong R&I along the CRM supply chains. The opportunities and incentives for international collaboration, especially with raw materials supplying nations, could be improved and contribute to securing access to sustainably sourced raw materials.
  - Strengthen incentives for research collaboration with non-EU partners
  - Use international projects to generate data on opaque supply chains
  - Ensure funding for R&I aspects of strategic partnerships on raw materials

- Legitimacy and regulation
  Developing new raw materials projects – both primary and secondary – will likely lead to controversy. R&I can help to identifying and addressing the issues, thus contributing to achieving the goals of the CRM Act regarding self-sufficiency.
  - Support demo-cases and living labs for citizen engagement and responsible innovation around new or reactivated exploration, mining and processing sites
  - Encourage integration SSH aspects into technical R&I projects along the CRM supply chains, when relevant
  - Research into overcoming regulatory barriers and strengthening drivers to achieve the goals of the CRM Act, also addressing the retention and mobility of scrap within the EU

Each of these options has been assessed along the dimensions costs, benefits, feasibility, effectiveness, sustainability, risks and uncertainties, coherence with EU objectives, regulatory impacts, as well as social and ethical impacts. Finally, a list of more specific actions along the CRM supply chain (*e.g.*, addressing specific technological challenges) has been developed and is provided in the Annex.

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1. Introduction

While starting to read a report on raw materials, an industry we use to name ancient time periods such as the stone and iron ages, one could ask: "Why should we worry about raw materials in a knowledge society?" While European prosperity is based, among other things, on knowledge, what is often forgotten is that much of that knowledge is about making useful things and these useful things are made of raw materials. In particular, the green and digital transitions are materials-intensive and will drive demand for many raw materials for the years to come.

Critical raw materials (CRM) are materials that are essential for the EU economy but are at high risk of supply disruption. These materials are vital for a wide range of products, from basic necessities to advanced technologies. In light of the EU's current dependence on third countries for its CRM supply, there is a need for strategic planning and policies to address the increasing demand for CRMs while reducing dependence on external sources. Research and innovation (R&I) can play an important role in achieving these goals.

The goal of this study was to illuminate the role of R&I and provide policy options for strengthening the contribution of R&I to a safe and sustainable supply of raw materials in the EU. To achieve this, the report starts by providing background (both methods and data) into critical raw materials and their assessment in the EU since the mid-2000s. A focus of this part of the study is in providing an overview of supply and use across all critical raw materials, as well as actions commonly pursued to secure supply or mitigate the adverse effects of possible supply disruptions. This is accompanied by an overview of EU policies affecting CRMs – from the Raw Materials Initiative (RMI) to the Critical Raw Materials Act (CRMA). In addition, the report provides an overview of sustainability issues and public controversy around mining and processing of raw materials as these are key in the development of concrete raw materials projects and therefore central to the implementation of the Critical Raw Materials Act.

The main part of the report focuses on a review of R&I and cooperation in securing supply of raw materials for the EU. Here, we use a simplified value chain – stretching from exploration of mineral resources to recycling of post-consumer scrap – to highlight the importance of R&I and the diversity of themes covered in the current research landscape, using specific examples from a review of current funding schemes and projects, and paying special attention to sustainability aspects. This view of research is complemented by a quantitative analysis of patenting along the CRM value chain, placing the EU in the international context and analysing relative strengths and weaknesses. Finally, this part illuminates international cooperation in the field of raw materials through a quantitative analysis of co-patenting activity as well as a qualitative analysis of raw materials diplomacy, including strategic partnerships and established forums for international cooperation.

The above provides the basis for a set of policy options in the areas of (1) EU institutional and R&I capacities, (2) international collaboration, and (3) legitimacy and regulation. Each option is examined qualitatively along the dimensions costs, benefits, feasibility, effectiveness, sustainability, risks and uncertainties, coherence with EU objectives, regulatory impacts, and social and ethical impacts.

2. Methodology and resources used

The work presented in this report is based on the author's own knowledge, combined with extensive inputs from the literature, systematic reviews of projects and patents, as well as diffuse inputs from stakeholders in expert forums together with focused inputs through interviews.

2.1. Literature review

The main method in developing the study is desk research of both scientific and grey literature. This includes reports by the European Parliament / STOA, the European Commission, international organizations (e.g., World Bank, OECD, UN / UNECE, IEA), national governments and agencies (e.g., BGR/DERA, BRGM/OFREMI), industry associations (e.g. Eurometaux), and universities and research institutes either as reports or in the scientific literature. Furthermore, existing legislative texts were consulted. A full list of references used in given under the heading References starting on page 59.

We also consider research and innovation agendas for raw materials produced by the EU (e.g. relevant Horizon and EIT RawMaterials calls) as well as associations and ad-hoc groups (e.g. ERMA).

In addition, a qualitative descriptive analysis of current projects in Horizon Europe was carried out. The CORDIS database and the individual descriptions were used to establish a corpus of relevant projects and analyse their potential impacts. A total of 90 projects were selected based on their relevance to critical raw materials. Specific factors were considered during the qualitative analysis such as the projects' scope, which technologies or CRMs were addressed, expected impacts, geographic zones and general approach to the CRMs theme. The projects were clustered according to the stage of the CRM supply chain they targeted the most and general trends and elements were highlighted, in an attempt to draw pertinent conclusions about the role of Horizon Europe funding program for a safe and sustainable supply of CRM in the EU.

2.2. Patent analysis

The patent data for this study was extracted from the "EPO Worldwide Patent Statistical Database" (PATSTAT), which provides information about published patents collected from more than 80 patent authorities worldwide. The patents in our analyses are counted according to their year of worldwide first filing, which is commonly known as the priority year. This is the earliest registered date in the patent process and is therefore closest to the date of invention. As patents in this report are considered first and foremost to reflect the level of inventive activities resulting as an output of R&D processes referring to filing instead of grants is appropriate. Fraunhofer ISI runs a large in-house version of PATSTAT that has been extended by and matched with other datasets, now providing broader and deeper analytical potential than the publicly available raw version.

To advance work on the patent analysis, the project team has reviewed the available literature on definitions and delineations of specific technologies relevant for CRM. Primarily, the subsequent analysis will be grounded in a recent publication by the World Intellectual Property Organization (WIPO; Daly et al. 2019) that delineates different, relevant aspects of mining technologies, including exploration, mining, processing, transport, specific environmental technologies. However, as these publication does not separate mining technologies for CRM and those for mining other raw materials (in particular oil, gas and coal) the search strategies proposed by the WIPO have been reviewed in detail and, where needed, re-evaluated. In consequence, they have been complemented by additional keywords to exclude irrelevant patents and avoid classes primarily dedicated to activities relevant to oil, gas and coal, but not to the CRM mining industry. In a similar way, existing definitions and delineation for recycling patents have been reviewed and re-evaluated to exclude any recycling technologies primarily relevant for e.g. paper or plastic or other substance technically not alike to those CRM which, be it in raw or processed form, stand in the centre of this analysis.

Subsequent to this work on the definitions, first versions of the amended strategies were tested and the pertinence and validity of first results cross-checked with qualitative expert knowledge and, in consequence, fine-tuned and amended. As a result, the original version of the non-specific WIPO search strategy for mining as well as prior search strategies for recycling have been significantly amended and are now available for use. In the upcoming weeks, the required indicators concerning global competitiveness and collaboration will be produced.

2.3. Interviews and stakeholder inputs

Semi-structured expert interviews utilizing a questionnaire were conducted via video call and analysed using MaxQDA. The topics covered were EU- and national R&I policy and funding for Critical Raw Materials. In addition, input gathered from presentations and discussions at various expert forums was included. These forums include the Raw Materials Week with the Critical Raw Materials Event, the International Round Table on Materials Criticality, the European Conference on Corporate R&D and Innovation (CONCORDi), and the REIA REEsilience Conference.

3. Synthesis of the research results and findings

The Sections below present the key findings of the project, following the sequence (1) subject matter background, (2) role of R&I and cooperation for securing a sustainable CRM supply to the EU, and (3) positioning of the EU in the international R&I landscape for CRM. In general, the report follows a data-driven perspective, crucial for informed decision-making.

3.1. Critical raw materials (CRM)

The word "critical" has an intuitive meaning for each reader. Unfortunately, the meaning is likely different for different stakeholders and requires clarification in the context of raw materials security and sustainability of supply. This Section describes what is meant by "critical raw materials" (CRM) in EU publications and policy discussions, and provides necessary background on the current state of play for supply and use of CRM in the EU.

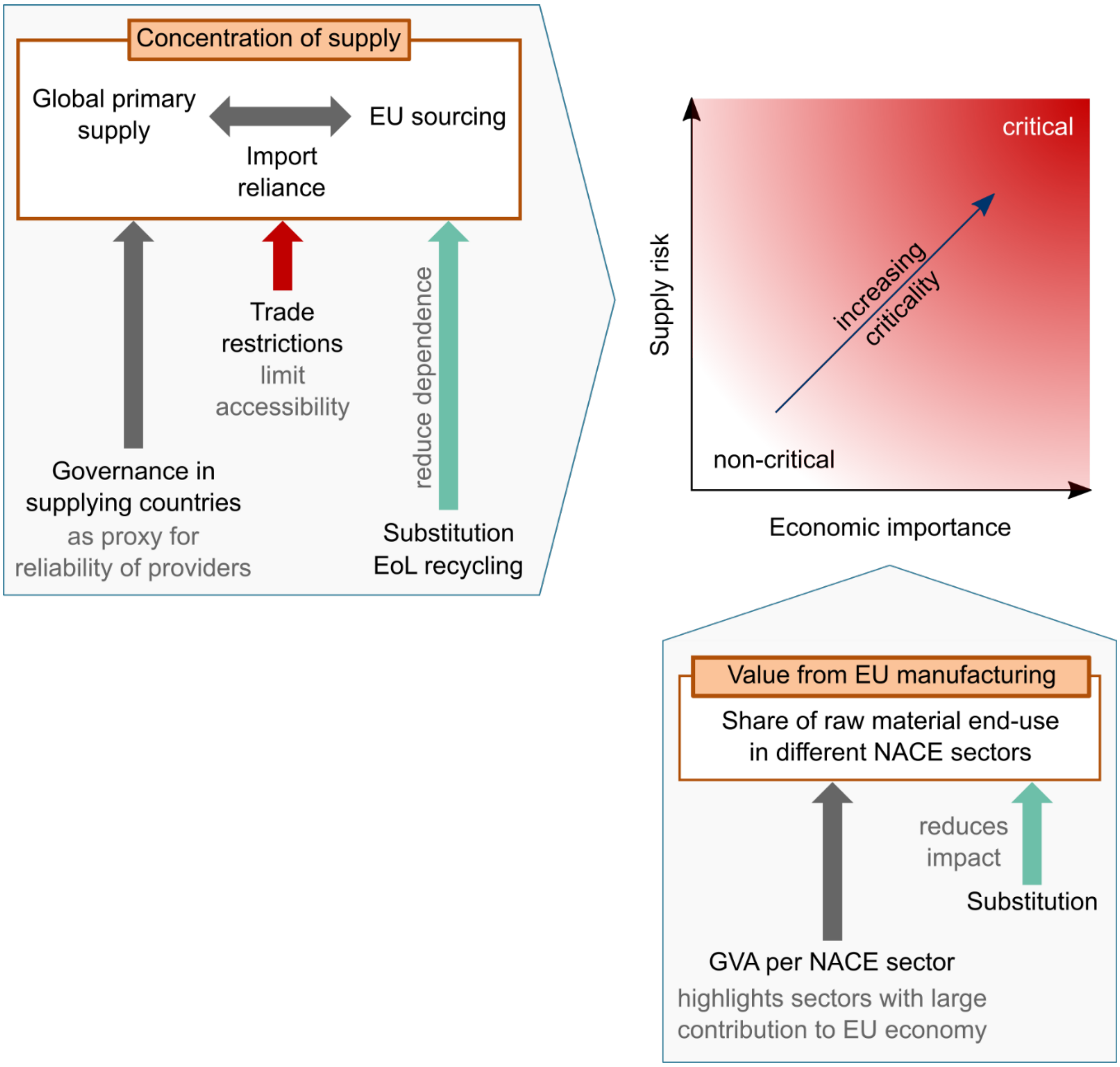
3.1.1. What are critical raw materials?

The definition of Critical Raw Materials depends on the positioning of the team carrying out the assessment in addition to the material and market characteristics of the raw materials themselves (Graedel et al. 2014; Schicho & Tercero Espinoza 2024). Thus, different methodologies have emerged to examine criticality of raw materials from different perspectives (different countries, sectors, companies; cf. Schrijvers et al. 2020). Contemporary reasoning on raw materials criticality was strongly influenced by the report "Minerals, critical minerals and the U.S. economy" (NRC 2008) and developed into a fully quantitative methodology by the Ad-hoc Working Group on defining Critical Raw Materials (European Commission 2010) triggered by the EU Raw Materials Initiative (Commission of the European Communities 2008).

The EU methodology is conceptually related to classical risk assessment (cf. Glöser et al. 2015), examining both the likelihood of a supply disruption and its potential impact on the EU economy (Blengini et al. 2017). However, significant disruptions to the supply of metals and minerals are fortunately rare events and very heterogeneous in their causes (Hatayama & Tahara 2018), encumbering their quantitative analysis due to lack of data. Therefore, the methodological challenge is to construct transparent scores for both likelihood and impact of supply disruptions using available data (Tercero Espinoza 2023).

In the EU methodology, the likelihood dimension is termed "supply risk" and the impact dimension "economic importance" (cf. European Commission 2010, Blengini et al. 2017). The key idea behind the "supply risk" dimension is that reliance on a dominant provider or small number of providers is inherently risky. Factors such as the degree of import reliance, trade restrictions, the availability of substitutes and the supply from recycling modify the scoring. Yet the central element remains the existence of monopolistic or oligopolistic supply structures. The key idea behind the "economic importance" dimension is that the value of the raw materials to the EU economy is tied to the products they enable rather than their tonnage or price. The possibility of providing the same function with a different material or technology (substitution) also plays a role (Blengini et al. 2017, Tercero Espinoza 2023). The EU criticality matrix and the construction of the scores are illustrated in Figure 1. For a more in-depth description of the contribution of each indicator to the criticality scores, see Tercero Espinoza 2023.

Figure 1 – Conceptual matrix and indicators used in the determination of Critical Raw Materials for the EU.



Source: Modified from Tercero Espinoza 2023.

The latest EU criticality assessment ranked more than 80 candidate raw materials (European Commission 2023b). Materials with scores higher than the designated threshold for both dimensions are considered critical. Figure 2 shows the results of this assessment.

Strategic raw materials (SRM)

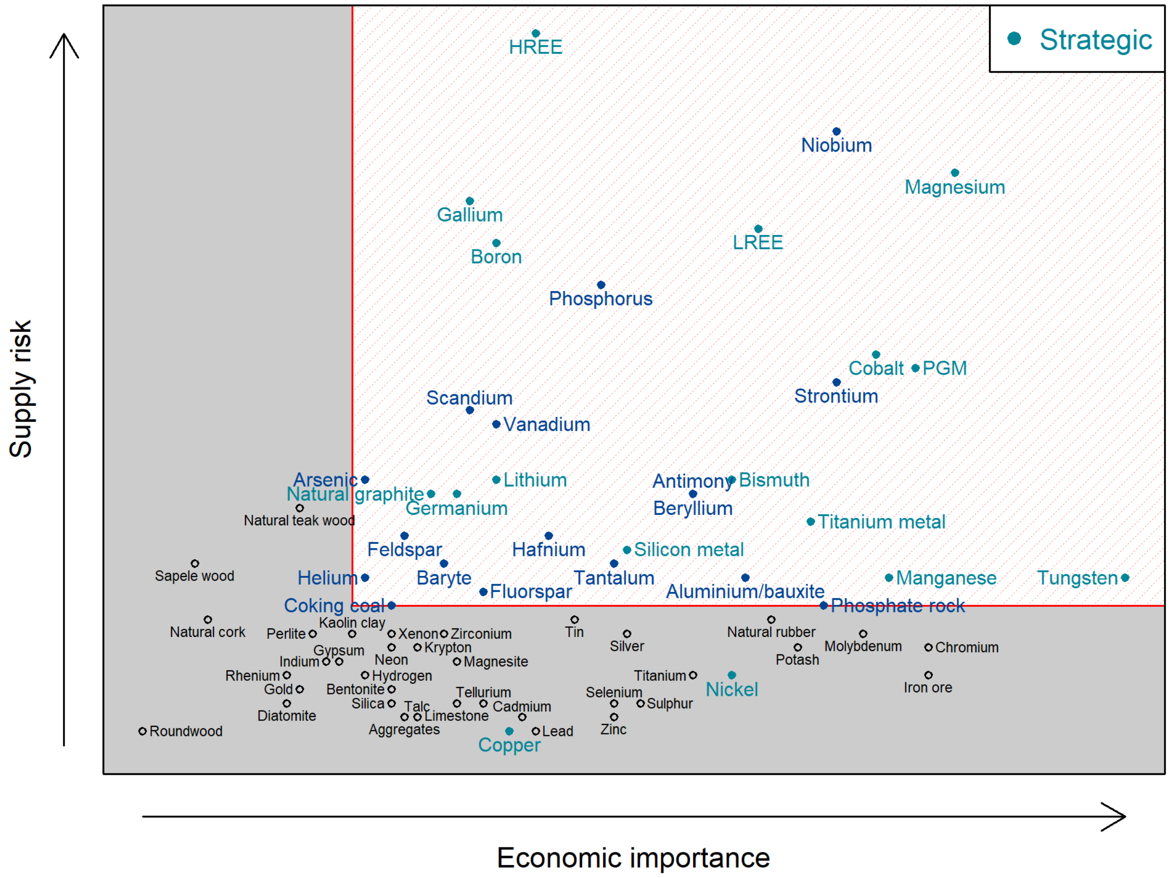
A key feature of the EU methodology for criticality assessment is its reliance on quantitative data. This makes the exercise reproducible and transparent. However, there is no data about the future. Therefore, the list of critical raw materials cannot account for trends or strategic policy goals. To counteract this limitation, the Critical Raw Materials Act (CRMA, Regulation (EU) 2024/1252) introduces the concept of "strategic raw materials" (SRM). SRM are characterized by (European Commission 2023a,b):

- being key to strategic technology fields (e.g. green and digital transition, aerospace, defence)
- showing a risk of forecasted demand outstripping supply, and
- expected difficulty to sufficiently scale up production.

Figure 2 shows the 2D criticality matrix for the EU and highlights strategic raw materials. Notice that most strategic raw materials are already identified as critical by the methodology outlined above (cf. Figure 1), meaning current supply is at risk and its importance is high. Note that nickel and copper are identified as strategic but are not critical on account of their current broad supplier base. Conversely, less than half of raw materials considered critical re also classified as SRM. Materials in the CRM list that are not SRM are: aluminium/bauxite, antimony, arsenic, baryte, beryllium, coking coal, feldspar, fluorspar, hafnium, helium, niobium, phosphate rock, phosphorus, scandium, strontium, tantalum and vanadium cf (Figure 2). The CRMA establishes that SRM are to be treated as CRM. Some provisions in the CRMA – in particular, the targets on EU production and supply diversification – only apply to SRM.

The two-dimensional matrix shown in Figure 2 has changed over time, for three main reasons: (1) the number of candidate raw materials has increased, from approx. 40 minerals and metals in 2011 to more than 80 minerals, metals, gases and bio-based materials in 2023; (2) due to changes in methodology introduced in 2017, and (3) due to changing realities in the markets for raw materials, including shifts in sourcing and technological change.

Figure 2 – Latest criticality matrix for the EU, including critical (in the top right quadrant, blue lettering) and strategic raw materials (marked separately in turquoise).

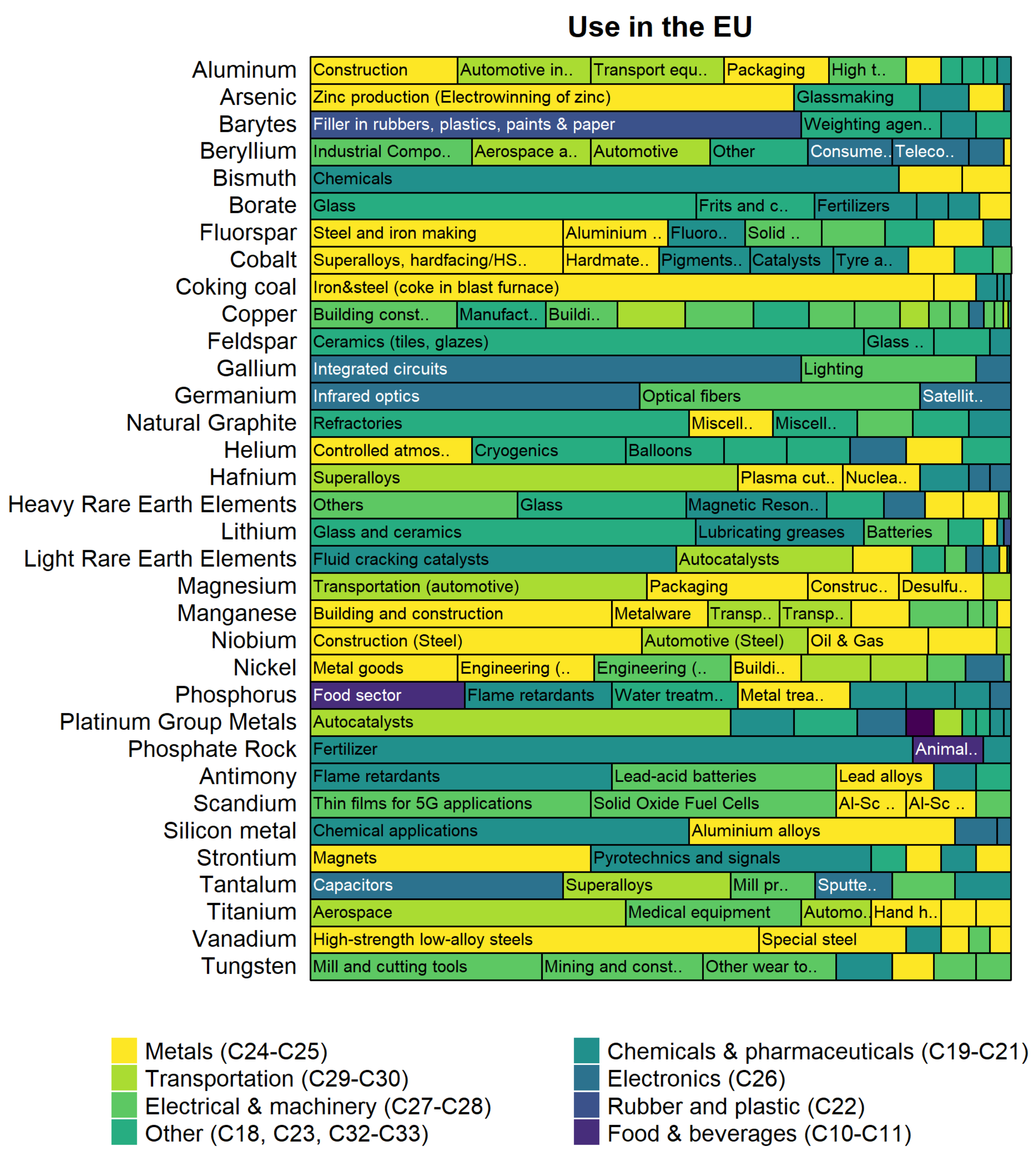


Source: Fraunhofer ISI based on data from European Commission 2023b.

3.2. Relevance of critical raw materials

European citizens do not directly demand critical raw materials. Instead, their needs are met by a wide variety of products which, in turn, are made possible by said raw materials. Figure 3 shows the different applications of critical raw materials in the EU. These range from basic needs such as food

Figure 3 – Use of critical and strategic raw materials in the EU. The length of the bars corresponds to the share in use by each application (named for share ≥ 10%) and the colours match applications to broad industries (defined by 2-digit NACE codes) following the latest EU criticality study.



Source: Fraunhofer ISI based on data from European Commission 2023b and https://scrreen.eu/crms-2023/.

and housing to everyday high-tech devices and infrastructures (everybody, everyday) to seldom used medical technologies and air transport.

Notice that the ranking of economic importance of raw materials for the EU is based on EU manufacturing and not on EU consumption (cf. Figure 1). Therefore, some products such as lithium-ion batteries, which are used extensively but not yet produced in large quantities in the EU, are not featured prominently in Figure 3. This will change as manufacturing capacities expand to meet EU demand. The same applies to electric motors using rare earth-based permanent magnets, which are key to the energy transition and electric mobility; yet minor in EU use for manufacturing.

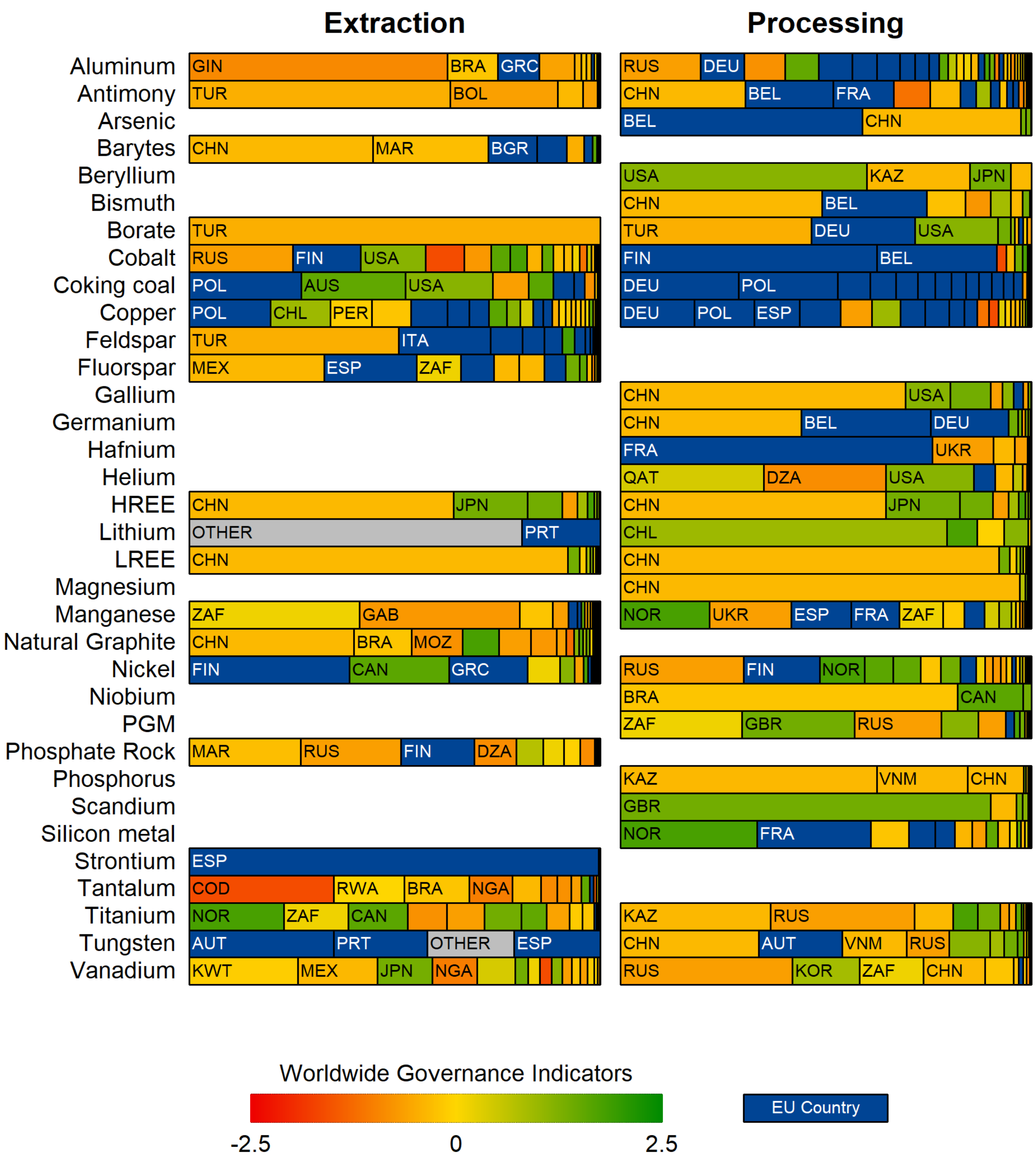
3.2.1. Supply of CRMs to the EU

The supply of critical raw materials to the EU cannot be seen as a single chain. Instead, each raw material exhibits its own characteristics. In terms of risk of possible supply constraints, a key element is the concentration of supply. This is shown for the extraction and processing stages in Figure 4.

This distinction (extraction vs. processing) is important because supply constraints may occur at either of these stages, leading to a constraint for manufacturers downstream. Furthermore, extraction and processing often occur in different regions and some critical raw materials are by-products recovered at the processing stage, i.e., their extraction does not imply their recovery. A consequence of the former is that extraction of a raw material in one jurisdiction does not necessarily lead to its availability in a processed form in that same place. Examples of the latter are gallium not recovered from bauxite and lead-zinc ores or hafnium not extracted during zirconium processing, which in turn depends on the mining of heavy mineral sands exploited mainly for titanium ore. In particular, China has emerged as a large processing centre even for raw materials not mined within its borders. Prominent examples of this are lithium and cobalt (SCRREEN Consortium 2023).

Figure 4 also highlights the aspect of import dependence of the EU (sourcing from EU countries is highlighted in blue). For most critical and strategic raw materials, the EU is largely or completely reliant on imports of either extracted or processed materials. Notice that this is a chain: material at the extraction stage feeds the processing stage and processed material is needed by downstream industries. Critical raw materials where the EU is largely independent at the processing stage may still largely depend on imports of raw materials at the extraction stage (e.g., cobalt, coking coal). Conversely, independence at the extraction stage does not exclude import-dependence at the processing stage (e.g. tungsten). Overall, Figure 4 points to a more developed processing than mining industry in the EU, with opportunities to grow at both stages for most critical raw materials.

Figure 4 – EU sourcing of critical and strategic raw materials at the extraction and processing stages. The length of the bars corresponds to the share in supply by each country (named for share ≥ 10% of EU sourcing) and the colours correspond to the Worldwide Governance Indicators published by the World Bank.



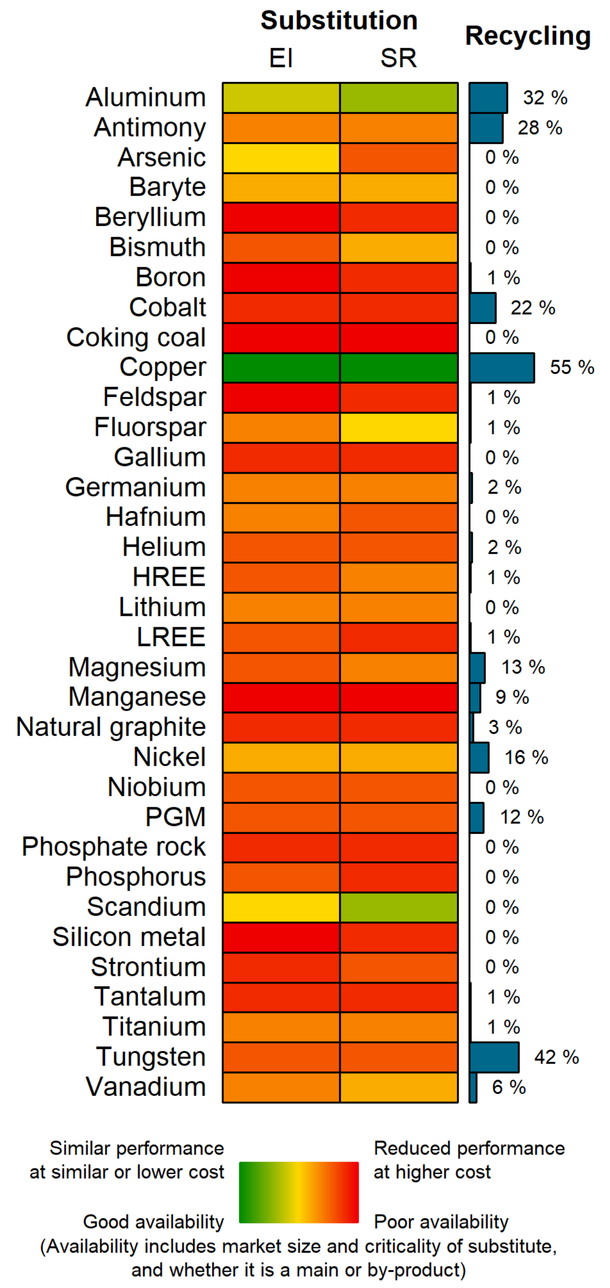
Source: Fraunhofer ISI based on data from European Commission 2023b, https://scrreen.eu/crms-2023/ and https://www.worldbank.org/en/publication/worldwide-governance-indicators.

3.2.2. Mitigation measures

Addressing the risks of supply constraints is possible from different angles along the CRM supply chain. The methodology for identification of CRM and SRM already imply several approaches, namely actions to reduce the factors identified as increasing the probability of supply disruption, or strengthening the factors that make such a supply disruption less likely or its likely impact less severe. Such "mitigation measures" along the supply and value chains of critical raw materials include:

- **Supply diversification**. This implies finding and securing alternative sources of critical raw materials, both domestically and abroad. Significant policy efforts are underway by the EU and Member States to achieve this (cf. Section 3.4.3 "Strategic partnerships outside the EU" starting on page 43 and Table 1).
- **Increased domestic supply**. This is ultimately limited by the geological endowment of the EU but at present mostly by a low level of exploration and mine development activities (cf. Eilu et al. 2023).
- **Substitution**. This may take different forms, including material-for-material (e.g. aluminium instead of copper in some electrical applications) without significant change in the product, and technology-for-material (e.g., digital instead of analogue cameras essentially eliminated the need for silver for photography) where the product changes so drastically that a different material basis is needed. The current status for available substitution options is shown in Figure 5.
- More **efficient use** in manufacturing. Reduced scrap through design or process innovation leads to reduced demand for raw materials for obtaining the same products. This, in turn, reduces the pressure on supply.
- **Recycling**. Functional recycling from European post-consumer scrap adds a domestic source of raw materials that is independent from mining. The current state of recycling is given in Figure 5 (cf. Tercero Espinoza 2021 for limitations of these data). It also contributes to energy savings / reducing CO_2 emissions, and to

Figure 5 – Current status of substitution and recycling in the EU. Column "EI" refers to the substitute cost-performance and column "SR" to substitute availability.



Source: Fraunhofer ISI based on data from European Commission 2023b.

reducing landfilling both in the EU and abroad. Factors preventing more extensive recycling are lack of adequate technologies to recover critical raw materials present only in small quantities in highly complex products, high costs of recycled materials compared to primary materials, lack of access to sufficient scrap, which in turn may result from the products being still in service during the ramp-up of technologies (physical or absolute scrap scarcity), from logistical constraints (inadequate collection systems), from an unwillingness to discard (e.g. retained electronics), or through the export of collected scrap (Tercero Espinoza 2012). Note that recycling of manufacturing scrap does not provide the level of independence that the recycling of post-consumer products does because the availability of manufacturing scrap immediately decreases if the supply of raw materials (largely from mining) is constrained whereas post-consumer scrap draws from a pool of products potentially produced several years earlier.

- **Circularity** strategies beyond recycling. A variety of strategies including sharing, reusing, repairing, refurbishing and remanufacturing that aim to keep the value of raw materials longer in the economic cycle (European Commission 2018). Cumulatively, these strategies lead to reduced demand for critical raw materials, which in turn eases the pressure on supply.

3.2.3. EU policy framework for CRMs

In this section, we briefly introduce the policy framework related to CRMs, starting with the Raw Materials Initiative (Commission of the European Communities 2008) and ending with the Critical Raw Materials Act (European Commission 2023a; Council of the EU 2024). The aim is not to give a complete or chronological overview of all policy acts constituting this framework (including all amended versions), but rather to give an overview of the building blocks of the framework that is now in force. Moreover, not only the legislation in force is reviewed, but also important EU communications and proposed regulations are reviewed, since they give important information about the policy aims at EU level and are important for understanding the evolution of the policy discussion over time. A good overview of EU-policy aspects related to CRMs is provided by European Commission 2024a,b and International Energy Agency 2024. The core of the following discussion is based on these three sources and classifies the EU's CRM policies upon the following categories:

- Degree of generality: general (*i.e.*, relevant for all CRM, all countries etc.; e.g., Critical Raw Materials Act) *vs.* specific (*i.e.*, related to specific CRMs, product groups, raw materials, countries etc.; *e.g.*, the EU Battery Directive, bilateral strategic partnerships)
- Policy target/field: supply security and social and environmental sustainability

Based on this systematization, the following discussion starts with the general policy framework elements that have a supply security context. It is followed by a discussion of the general policy elements that have sustainability as a policy target; finally, a brief discussion of the (country and product) specific framework elements is provided, which can be regarded as complementary to the general building blocks of the CRM-relevant EU policy framework. The different policy targets/fields are closely related to each other, and, in practice, the CRM supply is not only dependent on the policy measures targeting supply security, but also on policy measures targeting, e.g., sustainability. Thus, a discussion of policy framework elements going beyond mere supply security seems important.

Annex A lists the general CRM-relevant EU policies (neglecting product-specific or bilateral framework elements). Among these, only few focus on supply security: The 'Raw Materials Initiative'[1]

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52008DC0699

of 2008 targets supply security and sustainability, in particular, conditions of market access to raw materials, import and primary material dependencies, recycling and resource efficiency (Solar et al. 2012). The 'EU Critical Raw Materials List',[2] first published in 2011, seeks to provide an information basis for CRM-related policies. It defines a list of materials that are regarded as critical and provides accompanying information. The 2020 'European Action Plan on Critical Raw Materials'[3] targets supply security, in particular, resilience and (partial) autonomy of CRM supply by aims of circular economy, innovation, domestic sourcing and diversification among others. A part of this action plan is the 'European Raw Materials Alliance'[4], which seeks to provide a forum and investment channels for raw material projects. As a reaction to the changing market situation caused by the Ukraine war, the 2022 'RePowerEU Plan'[5] shows the intention of the European Commission to intensify the work/legislation on critical raw material supply. The 'Joint Communication to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the regions – EU External energy engagement in a changing world'[6] announces, among others, several measures targeting the supply of CRMs, e.g., further bilateral supply chain partnerships, cooperation with, e.g., the OECD regarding CRM supply chains and increased use of trade policy for access to global markets. Finally, the 2023 proposal of a 'European Critical Raw Materials Act'[7] includes an array of measures relevant for CRM supply security. They refer to:

- benchmarks for EU production of strategic raw materials
- periodical publication of strategic and critical raw material lists
- criteria for the selection of strategic CRM projects
- CRM risk monitoring and mitigation mechanisms
- improvement of collection and recycling of CRM-relevant waste
- greater coordination with member states for CRM-relevant foreign policies
- establishment of the European Critical Raw Materials Board for implementation of the act.

European Critical Raw Materials Board (ECRMB)

Articles 34 and 35 of the European Critical Raw Materials Act aim to set up the ECRMB composed of high-level representatives from the Member States and chaired by the European Commission. The tasks of the ECRMB, according to Article 35, include the advice to the European Commission and the assistance with the coordination, cooperation and information exchange to support the implementation of the European Critical Raw Materials Act. In particular, Article 35, requires the ECRMB to establish standing subgroups to contribute to the coordination or monitoring of

- financing of strategic projects (Article 15)
- national exploration programmes for CRMs (Article 18)
- CRM supply risks (Article 19)
- strategic stocks of strategic raw materials (Article 22).

Source: European Commission 2023a.

As previously explained, beside general CRM policies focusing on supply security, the EU policy framework contains (general CRM) policies focusing on other aspects that are, however, relevant for CRM supply. In general, these policies can be grouped under the term social and environmental sustainability. They refer to various aspects, such as human health, environmental protection,

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0474, p.2

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474, p.6

[4] https://erma.eu/

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=JOIN%3A2022%3A23%3AFIN&qid=1653033264976

[7] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160

circular economy, conflict minerals, social responsibility and due diligence. The regulations and actions related to these aspects form the supply (and demand) conditions imposed upon companies and other actors. The EU-policy framework elements belonging to these categories include:[8]

- 2010 Industrial Emissions Directive.[9] It covers the production and processing of raw materials among others and targets various forms of emissions.
- European partnership for responsible minerals.[10] Established in 2016, it targets small scale artisanal mines in conflict-affected and high-risk areas. The aim is to increase socially responsible mining.
- 2020 Green Deal (New) Circular Economy Action Plan.[11] The focus is on sustainability. Environmental aspects of raw materials and secondary materials are considered among others. Vehicles and batteries play a major role in this circular economy action plan. Thus, it could also be listed in the product-specific list of actions that is discussed below.
- 2021 European Commission Recommendation on the use of Environmental Footprint methods.[12] This is a recommendation related to assessment of life cycle environmental performance of products.
- 2022 EU Corporate Sustainability Reporting Directive.[13] It sets rules for companies regarding social and environmental sustainability reporting, which includes raw materials.
- Directive on Corporate Sustainability Due Diligence.[14] Announced in 2022 (adopted in 2024), it requires companies to identify and act against the negative environmental and social impacts of their operations and along their supply chains.
- 2023 Green Deal Industrial Plan for the Net-Zero Age[15] which seeks to complement the Circular Economy Action Plan among others. Besides references to aforementioned RePowerEU Plan and Critical Raw Materials Act, the plan – when directly referring to raw materials – announces the proposal of Net-Zero Industry Academies (up-skilling and re-skilling programmes) for raw material industries among others[16] and a Critical Raw Materials Club to "develop principles to bring together raw material 'consumers' and resource-rich countries and foster cooperation to allow resource-rich developing countries to move up the value chain". Thus, the 2023 Green Deal Industrial Plan can also be understood as part of the discussion of supply-security related framework elements (see above).
- EU Generalised Scheme of Preferences (GSP).[17] Updated version for the period 2024-2034. Via the withdrawal mechanism, tariff preferences and commitments are, to some extent, dependent upon the social sustainability conditions (e.g., human rights) in beneficiary countries.

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[8] This list is not exhaustive. Further policy framework elements related to raw material supply in a, more or less, indirect way are, e.g., the Strategic Technologies for Europe Platform (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023PC0335), the Ecodesign Directive (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02009L0125-20121204) and the Zero Pollution Action Plan (https://eur-lex.europa.eu/resource.html?uri=cellar:a1c34a56-b314-11eb-8aca-01aa75ed71a1.0001.02/DOC_1&format=PDF).

[9] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0075-20110106

[10] https://europeanpartnership-responsibleminerals.eu/

[11] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[12] https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en

[13] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022L2464

[14] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0071

[15] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023DC0062

[16] See also Article 23 of the Net Zero Industry Act (https://eur-lex.europa.eu/resource.html?uri=cellar:6448c360-c4dd-11ed-a05c-01aa75ed71a1.0001.02/DOC_1&format=PDF).

[17] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0426

- As a result of the policies listed above, the area of raw materials saw a significant increase in visibility and funding in the past twenty years. The establishment of the Knowledge and Innovation Community on Raw Materials within the European Institute of Technology (EIT RawMaterials), co-funding of ERA-MIN (a pan-European network of research funding organizations dedicated to raw materials since 2011), and increased inclusion of raw materials topics in Horizon 2020 (Climate action, environment, resource efficiency and raw materials) and Horizon Europe (Resilience) programmes all attest to this increase, as do related product-specific initiatives (e.g., for battery technologies).

The set of general CRM policies discussed by now is complemented with bilateral agreements and product/raw-material specific policies at the EU level. Like the general CRM policies, they do not only target supply security, but seek to regulate, among others, sustainability aspects. Examples of bilateral agreements are the 'Strategic Partnerships on sustainable raw materials value chains'[18] between the European Union and Chile, DRC, Zambia, Kazakhstan, Namibia, Canada and Ukraine, respectively, which were established in the period 2021-2023. These are discussed further in Section 3.4.3 "Strategic partnerships outside the EU" starting on page 43.

An example of product-specific policy actions are the battery-related policies (targeting CRMs used in batteries), in particular, the establishment of the 'European Battery Alliance'[19] in 2017 and the 2023 'EU Sustainable Batteries Regulation'[20], which targets, e.g., recycling rates and, thus, secondary CRM supply. A further example (of raw-material specific policy framework elements) is the 2021 EU Regulation 'Supply chain due diligence for minerals from conflict-affected and high-risk areas'[21], which relates to tin, tantalum, tungsten and gold originating from conflict-affected and high-risk areas.

Overall, the EU policy framework described in this section should be understood as embedded within or interacting with

- other multilateral (supranational) policy frameworks, in particular, the World Trade Organisation framework (General Agreement on Tariffs and Trade) and multilateral agreements across non-EU countries (e.g., the Regional Comprehensive Economic Partnership in Asia and Oceania)
- non-EU bilateral agreements related to critical raw materials (whether trade agreements or industrial policy frameworks, e.g., the China-Indonesia cooperation on nickel production)
- national policies relevant for international trade with CRMs, e.g., quotas, duties, taxes and general industrial policy (e.g., the Inflation Reduction Act in the USA targeting CRMs among others).

Moreover, beyond the EU level policy initiatives, there are national level CRM-relevant policies, which are, in part, representing the implementation of EU directives. The discussion of these efforts is beyond the scope of this chapter. However, we point out that the nature of those policies depends heavily on the degree of industrialization and the domestic raw material production of each country: Highly industrialized countries without a strong domestic CRM supply tend to focus on substitution research, resource efficiency and investment abroad whereas countries with a strong domestic supply but a weaker industrial base tend to focus on policies for sustainable mining (Eckartz et al. 2015, Tercero Espinoza et al. 2015).

[18] https://single-market-economy.ec.europa.eu/sectors/raw-materials/policy-and-strategy-raw-materials_en

[19] https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-battery-alliance_en

[20] https://eur-lex.europa.eu/eli/reg/2023/1542/oj

[21] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2017:130:FULL&from=EN

3.2.1. Sustainability issues of CRMs

CRMs provide a paradox of sustainability; they are essential for the green transition but have important negative impacts on the environment and social groups.

How CRMs contribute to increased sustainability

CRMs can be used for a number of application areas, including military, space exploration and a large number of consumer products (like TVs and jewellery), but are also key for the green transition. CRMs are used in solar panels, wind turbines and electric vehicles batteries and motors. Such technologies are important to replace fossil-based energy and fuels, which is necessary to combat climate change and fulfil EU climate goals. CRMs are also used for storing energy in batteries and for improving energy efficiency in light bulbs. They are used in computers and other digital technologies that are necessary for the digital transition that also contributes to increased efficiency in the use of resources.

CRM extraction, processing and manufacturing also amount to a significant income and livelihood in low-income countries. Also, in Europe there may be job scarcity in rural areas with mining and processing opportunities. Thus, mining and processing may contribute to social sustainability.

Sustainability challenges of CRMs

The most notable sustainability challenges are related to the extraction and processing of CRMs.

For all mining, the use of energy and water is significant, leaving a large climate and water footprint. A significant amount of waste, some of which may be toxic, is generated and must be dealt with responsibly[22]. Labour safety can be difficult to maintain, especially in countries with more lax regulation and governance, and accidents can be of grave damage to workers, the local society and the environment. Mines may be located in areas of conflict or poorly regulated crime and corruption, potentially supporting criminal groups that exploit the local societies. For all industrial mining operations, infrastructure is needed, such as power and roads, which affects the environment (and those making a living from it) and requires energy and other raw materials. Small, artisanal mining (ASM) may have less need for infrastructure, but suffer from less professional follow-up of environmental, health and safety issues for the workers and local societies, as well as of impacts on the natural environment (Hentschel et al. 2003)[23].

CRMs may be found in areas inhabited by indigenous societies and conflict with their use of the land, for instance reindeer herding.

Open-pit mining is relatively cost-effective, but has significant effects on the local environment, in terms of changes to the bedrock, soil, vegetation, animal life and ground water (Chen et al. 2015). There is direct pollution from the mining operation, in some cases also of radioactive materials. This can affect the environment, biota, local society and workers. Air pollution may result from the operations. Aesthetic degradation is inherent to both the mining installations and the infrastructure. After the closure of the mine, restoration is necessary, but it might still take hundreds of years before the area is restored without pollutants. Developing new (greenfield) sites will have more detrimental effects than making use of previously developed sites (brownfield)

There is an anticipated significant potential for extracting CRMs from hitherto non-exploited resources, most notably from the deep seabed. A particular challenge with this is the lack of knowledge concerning the ecosystems affected, the way these systems may be affected and the indirect effects of this on the broader ecosystems and human activities that depend on these

[22] https://environment.ec.europa.eu/topics/waste-and-recycling/mining-waste_en

[23] https://www.iied.org/sites/default/files/pdfs/migrate/9268IIED.pdf

(fisheries, aquaculture, etc.). The ability to monitor impacts will also be more challenging at the deep seabed.

Sustainability challenges are also connected to the fact that extraction and processing may not be conducted in the same area (or even continent), and will after processing again be transported for manufacturing and consumption around the world, leaving a large transportation footprint.

Transparency can be regarded as a separate issue, but with implications for the sustainability of CRM value chain assessments and decisions. (Environmental) sustainability assessments of CRMs to date are reasonably clear and consistent regarding the major sustainability challenges (including human toxicity, occupational health and safety and impacts on indigenous communities which are already mentioned) but many of the existing data emerge from inconsistent / non-transparent sources. This is unsurprising since CRM production largely occurs in locations with transparency challenges and implies that there are uncertainties regarding assessments of such operations.

A problem of this lack of transparency is that it prevents us from making choices on the basis of the provenance of the material and conditions/consequences of their production. Moreover, the transparency problem with existing CRM production is a double issue, because assessment of prospective solutions (*e.g.*, urban mining, substitution) is related to avoiding the burdens of existing value chains – so if the assessment of the latter is clouded by non-transparency, then this is also a problem for the comparative assessment of the alternative solutions.

Public controversies surrounding CRMs

The sustainability challenges described above have led to public controversies and conflicts.

The Global Atlas of Environmental Justice provides a map of social conflicts around environmental issues in the world, of which several are in the EU[24]. Examples are e.g. conflicts around rare earths in Spain and rare earths and other minerals in Finland. Taking into account that exploration, mining and processing will be ramped up in the EU, it can be expected that the number of social conflict cases in Europe will increase, though new mines can also lead to new jobs in areas that otherwise have few livelihood opportunities. Though one can argue that the burdens of a mine would be there even if the mine is located outside Europe (and the negative impacts might indeed be much worse when the mining and processing is conducted in countries with a more lenient regulation and follow-up of sustainability-related issues), increasing the level of social conflict in Europe is still a concern.

Social conflicts can be due to differences in values or interests. Some conflicts can also relate to different understanding of the relevant impacts and risks, and the adequacy of the knowledge base used for decision making (for instance concerning the potential application of the precautionary principle).

In addition to local conflicts and controversies related to specific projects, there is significant diversity related to what values should guide the further development of European CRM strategy. Regarding deep sea mining, the European Parliament has taken a precautionary approach[25] and thus takes a more cautious approach than other European countries. But the EU has itself been criticised by both environmental NGOs and indigenous people. Following the EU adoption of the European Critical Raw Materials Act, the Sami Parliament criticised the EU alleging violations of EU agreements and obligations towards the Sami people[26]. Moreover, the Raw Materials Coalition published in

[24] https://ejatlas.org/

[25] In January 2024, the European Parliament referred to the precautionary principle when critizing the Norwegian government for allowing deep sea exploration: https://www.europarl.europa.eu/doceo/document/TA-9-2024-0068_EN.html

[26] https://www.sametinget.se/crma

February 2024 *Civil society guidelines for the implementation of the EU Critical Raw Materials Regulation* that criticises the Act for what they perceive as insufficient focus on reducing demand and emphasises operationalising moderation of demand through sufficiency measures as a key strategy[27].

Responding to concerns for social conflict, the concept of a 'social licence to operate' has been introduced in the mining sector. Prno and Slocombe, 2012[28] describes that a social license can be considered to exist when a mining project is seen as having the ongoing approval and broad acceptance of society to conduct its activities.

Deep sea-mining is less visible and even if the uncertainties are higher than with land-based mining, social conflicts may be at a higher organisational level rather than with local communities, as it is not equally clear whose 'backyard' is directly affected (ref. Not-In-My-Backyard-sentiments). However, as the European Parliament has taken a clear stance on deep-sea mining, this is not relevant for European CRM R&I unless European research or innovation communities are involved in projects taking place in countries that do allow such exploration.

3.3. Role of R&I and cooperation in securing CRM supply

This section discusses the vital role that R&I plays along CRM supply chains. R&I play pivotal roles in the sustainable management of CRMs and require inputs by various disciplines and stakeholders. Within the European Union, there is a growing interest in fostering long-term cooperation among relevant stakeholders under the umbrella-term knowledge triangle, which integrates research, higher education, and business. This collaboration aims to co-create solutions that tackle the complexities and challenges associated with CRMs (Smol and Kulczycka 2019).

This section starts with a general description of CRM supply chains followed by a mapping of R&I issues along these chains. Furthermore, sustainability issues along CRM supply chains are briefly introduced and discussed. Finally, a survey of projects, funding and other initiatives as they pertain to the safe and sustainable supply of CRM is presented.

3.3.1. CRM supply and value chains

Figure 6 shows a simplified and generic supply chain for (critical) raw materials. Raw materials supply chains begin long before production with the search for new deposits for greenfield development or the expansion of current operations (brownfield development). This is followed by processing and manufacturing, leading to useful products for consumers and industry, which become the basis for post-consumer recycling. Note that there is a potentially considerable time delay (ranging from months to decades) between the use of a raw material in products and them becoming available for recycling. These steps and their generic challenges are described briefly here, with more detail provided on the R&I aspects of each step in the following section.

The end result of **exploration** activities are well-characterized ore deposits that can be developed into active mining operations. Exploration is an inherently risky undertaking, with a low starting probability of success and uncertain timelines. Gaining access to exploration permits is commonly mentioned as a bureaucratic challenge as well as securing local support for the exploration itself and potentially following mining activities. From a technical standpoint, exploration is limited by the knowledge of geological landscape of the explored area and by the speed, depth and costs that characterize current technologies. An obvious but often forgotten point in the assessment of the EU's raw materials endowment is that, without sufficient exploration, we cannot know what raw

[27] https://eurmc.org/publication/limiting-environmental-damage-human-rights-abuses-and-indigenous-peoples-rights-violations-civil-society-guidelines-for-the-implementation-of-the-eu-critical-raw-materials-regulation/

[28] https://www.sciencedirect.com/science/article/abs/pii/S0301420712000311

materials are potentially available domestically. This often leads to the claim of the EU being poor in raw materials deposits. Finding and developing significant deposits of critical raw materials in the EU would change the assessment for supply risk for those materials, potentially changing the CRM list.

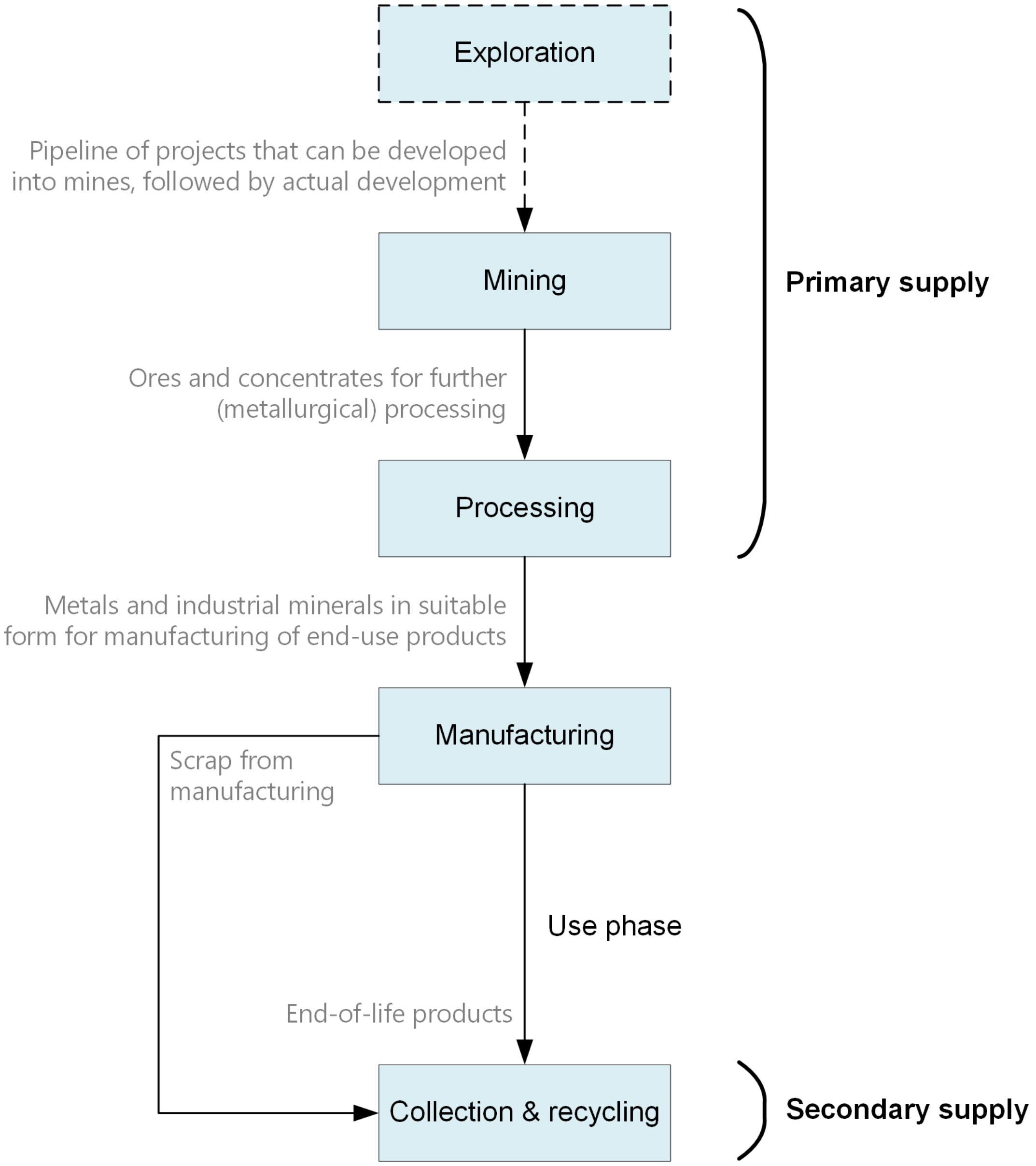
The development and operation of **mines** delivers ores and concentrates to the following processing steps. This requires substantial amounts of capital, which remain bound for decades. As in the case of exploration, the length and unpredictability of permitting procedures is often mentioned as a challenge, especially in case of local opposition to mining development ("not in my back yard", NIMBY syndrome). From a more technical angle, technologies often have to be adapted or established to process the ores available at each site, the optimization of operations in terms of energy, water and chemicals use remains important throughout the lifetime of a mine, and the establishment of adequate mine closure and renaturation plans (including their financing) is a crucial aspect of responsible mining. The current trend in electrification and digitalization of mining operations not only contributes towards increased efficiency but also increased safety and helps counteract a scarcity of skilled labour.

The **processing** of ores and concentrates delivers refined minerals or metals for further use in manufacturing. This involves high temperatures in the case of pyrometallurgical processes or extensive use of water and chemicals in the case of hydrometallurgical processes. Therefore, general challenges in processing are reducing energy use, waste generation, and limiting pollution to water, air and soil.

Manufacturing of end-use products is what delivers useful products to EU citizens and businesses. Manufacturing processes are often long and rely on delivery of components and assemblies along complex chains. Furthermore, product design belongs at this stage of the CRM value chain and is a key definer of the use characteristics of products, including their longevity, repairability and ease of recycling. Therefore, the manufacturing phase is key to the transition towards a more Circular Economy. Finally, a key element of design is the choice of materials to use, considering technical, commercial, environmental and social aspects favouring the use of one material over another (substitution).

The **use phase** is where industrial and policy actors have the least control. This follows from the multitude of products being used by every citizen and business in the EU. Consumer (both individuals and businesses) behaviour, preferences and real options collectively play a key role in the transition to a more Circular Economy. Not only do circularity measures such as reuse and repair fall within the use phase, but also strategies such as refurbishment/remanufacturing – which also involve manufacturing industries – depend on consumers delivering used/broken products into the appropriate channels as well as acceptance to purchase and use products that are not new.

Figure 6 – Simplified conceptual supply chain for critical raw materials.



Source: Fraunhofer ISI

Functional **recycling** of manufacturing and post-consumer scrap can contribute to the supply of raw materials for EU industry. As discussed in Section "Mitigation measures" on page 11, only post-consumer recycling is largely independent from primary supply. Recycling of post-consumer scrap is the result of a long chain, starting with citizens and businesses discarding products at the end of their useful lifetimes. These products are then collected and channelled to appropriate sorting and pre-processing facilities, and the relevant fractions are collected and transported to further specialized facilities for material recovery. Therefore, challenges in recycling are behavioural, logistical as well as technological in nature.

3.3.2. How is R&I essential for CRM supply?

The following section provides an overview of current research questions and topics arising in the various CRM stages. The research topics are categorised according to the different stages of the CRM supply chain.

R&I along the CRM supply and value chain

R&I in exploration

A central demand for R&I stems from the need to improve systems for gathering and predicting orebody and rock mass data, such as seam and grade definition, rock mechanical properties, and seismicity (Elvnert et al. 2018), which are essential for the safety and efficiency of mining activities.

Another central topic lies in utilising big data to improve access to mineral resources (Elvnert et al. 2018). Here, the term "big data" encompasses more than just large datasets; it also contains various data characteristics, including different formats and data sources (Hu et al. 2014, Xiong et al. 2018). In this context, the purpose of big data analytics lies in prediction, making it a suitable approach for the predictive mapping of mineral-rich areas (Xiong et al. 2018). Developing a comprehensive database of mineral and metal resources within the EU should facilitate the assessment of the economic value of the identified resources (Elvnert et al. 2018).

Collaborative approaches are becoming increasingly essential for successful mineral exploration. Given the diverse nature of mineral exploration challenges, there is no singular methodological solution. Therefore, a diverse range of disciplines, such as geosciences, engineering, and social sciences, are increasingly required to collaborate to ensure the success of exploration efforts (Malehmir et al. 2019). Researchers, high-tech industries, and mining companies require collaboration to complement each other. Collaboration with societal stakeholders such as environmental and/or social NGOs already at the exploration phase may ensure that the development of mining projects that carry greater societal or environmental risks are avoided, and that projects are developed that duly consider societal and environmental concerns.

Developing new technologies is crucial for efficiently locating and exploring deep mineral deposits and technologies that can withstand high pressure and extreme conditions at such depths (Elvnert et al. 2018, ETP SMR 2023). Moreover, various methodological improvements are needed, including geological, geochemical, geophysical, drilling, and mineral-chemical methods (ETP SMR 2023). In addition, to enhance cost-efficient, environmentally friendly exploration and to increase resource diversity, improvements are required in microanalytical techniques and genetic models for major ore types and prospecting techniques, including integrated multi-disciplinary 3D/4D modelling (Elvnert et al. 2018). Ecological studies of the potentially involved ecosystems is necessary for documenting the environmental sustainability effects of potential development projects.

R&I in mining

Mining is confronted with a multitude of challenges that go beyond technological considerations. In particular, environmental considerations demand advancing sustainable mining practices. Ensuring the shift towards sustainable and responsible mining requires training experts capable of interdisciplinary collaboration. Facilitating communication and knowledge sharing among scientists with diverse interests is essential for improving scientific research standards, methods, and techniques to promote sustainable mining (Dino et al.2022).

One area of focus is studying and improving the blasting process to optimise the use of explosives and to minimise environmental impact (Elvnert et al. 2018). Strategies that aim to achieve cleaner and more efficient mining are linked to using advanced technologies to monitor mining activities and their impacts. These technologies include using various sensors for real-time data collection, advanced mining equipment, and employing remote sensing techniques through different platforms such as satellites and drones (Kasmaeeyazdi et al. 2021).

Moreover, developing new technologies and adapting existing technologies and operations are required to boost automation in quarries and mines. This will reduce the energy consumption of rock mass transportation and haulage while pushing forward the goal of fossil-free production (Elvnert et al. 2018). Also, new methods and technologies must be developed to improve ore recovery and fragmentation (Elvnert et al. 2018, Zhang et al. 2023).

In addition, utilising mine tailings as a secondary source for extracting valuable elements is a relatively new avenue that needs to be developed at an industrial scale. Therefore, many opportunities for improvement exist, which could ultimately result in the effective valorisation of mining waste. However, adopting a multidisciplinary approach is essential to ensure the successful reprocessing of mine tailings for obtaining CRMs (Araya et al. 2021).

Health and safety are other aspects of sustainable mining practices. Developing new methods and tools for improved ground control and rock support in deep mines is essential. Additionally, creating systems, technologies, and processes for integrated real-time process control, digitisation and automation in mines can improve workers' health and safety conditions. Furthermore, new methods and technologies are required to utilise thermal heat and improve mine ventilation (Elvnert et al. 2018). Furthermore, additional research is necessary to assess the potential risk of mining to the ecosystem and human health (da Silva-Rêgo et al. 2022).

Moreover, there are gaps in understanding the interplay between social and environmental elements, particularly the effects of mining on local and indigenous communities (Haddaway et al. 2022). Studies investigating the environmental and socioeconomic impacts of mining on indigenous people's well-being throughout the mine lifecycle are also limited (Leyton-Flor et al. 2024).

Since deep-sea floors and regions of Antarctica have not seen extensive commercial extraction of minerals, there has been growing interest in exploring these areas for potential mineral resources. However, it presents a sustainability dilemma (Levin et al. 2020). Transitioning from discussions of terrestrial mining to the exploration of deep-seabed mining, it becomes evident that social acceptance remains a challenge, which underlies its continued relevance and complexity in the discourse on CRM extraction (Carver et al. 2020, van Putten et al. 2023). There are significant knowledge gaps related to deep-seabed mining that could hinder effective regulatory measures. Moreover, due to the remote and unfamiliar nature of the technology, ensuring inclusive stakeholder engagement to inform decisions at the international and state levels is crucial (Levin et al. 2020). Also, it is essential to establish a global research agenda and timeline aimed at gathering and synthesising high-quality scientific data. This effort is crucial for addressing identified knowledge gaps necessary for informed decision-making and effective environmental management. Further interdisciplinary research is needed to facilitate identifying, declaring, and enforcing spatial protections (Levin et al. 2020).

R&I in processing

The major challenges for innovation in the mineral and ore processing domain include economic factors like costs and energy consumption. In addition, there is a need to enhance traditional metallurgical methods to extract these valuable elements from low-grade and non-conventional ore deposits, such as complex polymetallic ores and secondary material streams. Developing innovative and smart metallurgical processes is also essential to optimize resource utilization while reducing environmental impacts (Elvnert et al. 2018).

Moreover, developing advanced information and communication technology (ICT), including augmented and virtual reality solutions, are promising fields of R&I. By leveraging these tools, higher process efficiency can be achieved, improving material flow and increasing resource efficiency, process stability, and machine productivity, allowing for customer-driven, on-demand customisation (Elvnert et al. 2018).

Crushing, selective grinding, and sorting technologies represent some of the most energy-intensive stages in mineral processing. Reducing energy usage through new technologies will help make these processes more sustainable. Moreover, fine particle processing requires developing highly efficient dry separation technologies (Elvnert et al. 2018), which offer advantages due to reduced water requirements (Pukkella et al. 2023).

In addition, other areas of focus are developing more efficient and environmentally friendly flotation technologies and commercially viable refining methods for critical raw materials (Elvnert et al. 2018).

R&I in manufacturing

Improved material efficiency is a crucial factor in enhancing the circular economy and maximizing value in the industry. Enhancing material efficiency involves reducing industrial waste generation, decreasing the extraction and utilization of resources, and lowering energy demands along with carbon emissions. However, the understanding of material efficiency within the manufacturing sector as a strategy for recyclability, reusability, and mitigating industrial waste is still developing. More research is needed to clarify the practical implementation of material efficiency strategies within manufacturing processes (Shahbazi et al. 2016).

Effective product design can enable the efficient use of critical raw materials. Within the circular economy framework, it is evident that products are not optimally designed to integrate easily into their intended recycling processes. There is a lack of synergy between the product design stage and its end-of-life management due to the weak communication between product designers and stakeholders in the recycling chain (Maudet et al. 2007, Martínez et al. 2020). As such, it is essential to communicate recyclability assessments through design guidelines as early as the product development phase. In addition to design *for* recycling, design *from* recycling evaluates the feasibility of incorporating secondary raw materials into new products already in the design phase (Martínez et al. 2020). There is still ample room to include minimizing both the environmental impact and the supply risk for CRMs into the process (Ferro et al. 2021).

Cultivating substitution options (including material substitution and alternative technologies) is crucial at this stage of CRM value chains (Carrara et al. 2023). Substitution relies heavily both on fundamental and applied research. To be usable in case of a supply disruption (cf. Section "Mitigation measures" on page 11), substitution options must be already available to industry, and this often relies on medium to long term engagement to explore and validate these options.

Other product design gaps are related to promoting reuse and repair through careful design, which can contribute to reducing the demand for critical raw materials (Carrara et al. 2023). In this regard, the digital product passport (DPP) is another research avenue gaining attention for its role in providing detailed information regarding the product's origin, composition, repair options, and guidance on recycling or disposal at the end of its lifecycle. It is seen as a tool for establishing a circular economy by disclosing essential information about the sustainability of products, serving various stakeholder's interest, including consumers (University of Cambridge and Wuppertal Institute 2022). Such comprehensive information on product composition is essential to promote sustainable product design, manufacturing and use. However, there is a need for additional research on various matters, such as streamlining bureaucratic procedures and enhancing incentives for manufacturers to disseminate specific information. Additionally, there is a call to explore the methods and tools, like databases, through which relevant data can be gathered and distributed to respective stakeholder groups (Adisorn et al. 2021).

R&I in recycling

Recycling is crucial in enabling Europe to meet the demand for critical raw materials. However, several factors currently limit its contribution, which are explained in the following. One major obstacle is the lack of economic feasibility in recycling many materials from end-of-life products and waste streams. Additionally, there is a shortage of suitable technologies for effective recycling. Some materials, like those used in buildings or long-lasting products such as wind turbines, pose difficulties in extraction for recycling purposes. Moreover, the increasing demand for these materials further strains the recycling system (Peiró et al. 2020, Vidal-Legaz et al. 2016).

Moreover, recycling is an essential aspect of achieving a circular economy, but the recycling efficiency for many CRMs is currently very low, falling short of what is necessary to realize the vision of a circular economy. This deficiency arises from shortcomings in collection, treatment, and recycling technologies (Di Girolamo et al. 2018, Graedel et al. 2011). There is a gap regarding the quantity of collected waste (Tansel et al. 2020). The availability of waste materials for recycling is restricted due to the delayed generation of scraps and the decentralized nature of scrap collection (Guo et al. 2023). To improve the recycling rates of CRMs, technology advancements, standardisation of treatment and certification, and possible incentives need to be implemented (Di Girolamo et al. 2018).

Also, further research and innovation are required to enhance the efficiency and cost-effectiveness of recycling technologies. This will serve as a significant economic catalyst for expanding recycling efforts (Carrara et al. 2023). Establishing recycling infrastructures is crucial for gathering, disassembling, and processing relevant products, components, and materials. Additionally, there is a need for further research to develop innovative recycling techniques that not only result in high recycling rates but also generate high-quality secondary materials (Carrara et al. 2023).

The high value of components found in end-of-life products, particularly those from electronics or products containing electronic parts, has brought them to the forefront of attention (Elvnert et al. 2018). Urban mining, which is the concept of using the materials that exist within the anthroposphere as a source for the raw material supply (Lanau et al. 2019, Müller et al. 2017, Tercero Espinoza et al. 2020), offers new potential for the recovery of resources, especially for limited raw materials and minerals. Urban mining is one of the strategies for transformation to a circular economy (Cossu et al. 2015, Schiller et al. 2017, Simoni et al. 2015), while promoting sustainable mineral resource utilization and enhancing supply chain circularity. However, implementing urban mining faces challenges, like gaining permits to access and treat landfilled material and the economic challenge of competing with comparatively cheap primary materials, lacking expertise and developing/adapting technologies for different sites (Tercero Espinoza et al. 2020). Further data on different aspects of urban mining are essential to identify the most effective policy measures (Kazançoglu et al. 2020). Since post-consumer recycling currently (and in the foreseeable future) delivers the largest Urban Mining contribution to CRM supply, effective regulation for recycling is key to enhancing the recovery of raw materials from the urban mine (Tercero Espinoza et al. 2020).

Policy scenarios and cross-cutting issues

The subsequent section provides a concise overview of current policy scenario studies that are relevant for formulating R&I policy aimed at securing a sustainable supply of raw materials in Europe. Additionally, it addresses several overarching R&I issues that transcend individual elements of the CRM value chain, highlighting their broader relevance.

Policy scenarios

In the formulation of policy options, it is crucial to take into account the current global landscape, existing policies, and the various scenarios that shape its evolution. Although this report does not create its own policy scenarios, incorporating the significant research conducted by others in this field is essential. This inclusion is vital for the subsequent discussion and placement of policy options within the trajectories that are commonly anticipated. Accordingly, the upcoming section will provide a concise summary of two pivotal reports that encompass scenario analysis: one from the Joint Research Centre (JRC) and the other from the International Energy Agency (IEA).

There is significant consensus in the literature that CRM use remains a salient issue on the background of unstable political and economic global developments and volatile pricing for minerals and commodities in the global markets (Domaracka et al. 2022). While the EU has a long history of extracting and processing raw materials, domestic mining and processing has declined and consequently the EU's CRM import dependency has significantly increased in the last decades (European Commission 2011, Guzik et al. 2021, Lewicka et al. 2021). This is recognized by the European Commission, as shown in the published policy documents since the Raw Materials Initiative (cf. Section "EU policy framework for CRMs" on page 12) and the latest forecast- and policy scenarios included in relevant EU publications, including the European Commission 2023.

In terms of CRM-related R&I policies, relevant studies usually include two different (quantitative) analyses, namely supply chain analyses and demand forecast analysis. The latter assesses the "future demand for the raw materials" (usually within a selected spectrum of various technologies), based on policy-relevant scenarios and market trends.

The JRC-study

Recently, the JRC published a demand forecast analysis including scenarios for material demand contrasted with supply-chain dependencies (Carrara et al. 2023). The report is based on policy-relevant scenarios, and its forecasting (scenario) model includes three main parameters: technology deployment (or otherwise future evolution of technology availability), sub-technology market shares (or estimates of the future technology mix), and material intensity and efficiency (i.e., the amount of material needed per unit of technology deployed). Thus, the study considers a number of central technologies (but not all) and the materials necessary to deploy them widely. To capture possible trajectories, the JRC modelling framework includes two main scenarios: the High Demand Scenario (HDS) and the Low Demand Scenario (LDS). Both are representing extremes but combinations of the two are also highly likely.

The HDS envisions an accelerated deployment of technology alongside significant increases in material intensities, leading to a sharp rise in materials demand. This is especially true for the energy and mobility sectors, where political objectives play a critical role, highlighting the politically motivated nature of the transition. Accordingly, the HDS operates under the assumption that stringent energy and climate mitigation goals, such as those outlined in the REPowerEU targets for 2030 and the aim for complete decarbonisation by 2050, are achieved. However, for other sectors under consideration, such as Information and Communication Technology (ICT), there are no comparable political mandates in place.

In contrast, the LDS projects a more gradual rollout of technologies and a slower increase in material intensities, leading to a moderate reduction, and in certain instances, an actual decline in materials demand. Consequently, the pace of future technological expansion under this scenario is slower. Established technologies, like wind power and solar photovoltaic (PV), are expected to continue expanding along their historical growth paths. Meanwhile, technologies that have not yet been widely adopted are anticipated to experience substantial growth, although not as extensive as that projected under the HDS.

The demand scenarios have been constructed not just for the European Union but also for the United States, China, and the global market. The modelling of future demand covers the years 2030 and 2050, apart from ICT sectors, for which projections extend only to the year 2030.

Overall, the JRC scenario analyses show an "unprecedented increase in demand" for CRMs, projected to increase multiple times if current targets of the twin transition (green and digital) are achieved. Compounded by the increased demand, the report also shows the EU is heavily dependent on third countries (particularly China) at multiple stages in the CRM supply chain (Carrara et al. 2023).

The IEA study

Another important benchmark in terms of policy scenario analysis is the International Energy Agency (IEA). Since its landmark special report in 2021 (IEA 2021), the IEA has been updating its projections for future mineral demand based on the latest policy and technology developments. Critical minerals are fully integrated into the IEA's Global Energy and Climate Model, meaning the "projections for critical minerals demand and supply are regularly updated in line with latest policy and technology trends in the IEA energy scenarios" (IEA 2021).

In many ways, it is similar to the JRC scenario for which it provides foundational inside. Again, in each scenario, demand differs depending on how fast and how substantial ambitious energy transition goals are met, which require a substantial deployment of clean energy technologies. Technologies explored are solar PV, wind turbines, electricity networks, EV, and battery storage. The IEA differentiates between two main policy scenarios: the stated policy scenario (STEPS) and the sustainable development scenario (SDS). The pace of mineral intensity improvements differs in both scenarios with only minimal improvements in STEPS and modest improvements of 10 % in SDS. Moreover, they evaluate different assumed technology pathways, due to the high uncertainty in determining future technology deployment.

Key findings from the IEA study highlight that the necessary growth in supply for the majority of materials significantly exceeds observed historical levels over the past decades. This indicates a considerable demand for investment in new sources of supply, which is not currently met by existing or planned mining projects.

Further and cross-cutting R&I issues

In addition to the selected R&I issues we identify along the CRM supply chain, certain aspects stand orthogonal to or cross-cutting through them. They address issues that are often not technology-related but highly relevant for the successful application and diffusion of technological innovations. These issues are often addressed by social science and humanities scholars (SSH), which is important because the moment most technological inventions become innovations, they become socio-technical in nature, which implies that they depend heavily on public and/or social acceptance. Thus, additional research perspectives are necessary to address the predominately social or regulatory barriers to innovation.

Social acceptance is a concept relevant for understanding the NIMBY phenomenon (NIMBY – Not In My Back Yard), which applies to numerous societal sectors. For instance, it can refer to the apparent contradiction of citizens expressing broad support for renewable energies but resisting wind power next to their houses. Moreover, this phenomenon is also highly relevant for mining and processing sites, which can lead to various societal conflicts among actors and interests in the proximity. The concept of social acceptance was developed to grasp and tackle NIMBY phenomena. Social acceptance encompasses more than public acceptance, which concerns itself with, for example, general approval (or lack thereof) of a proposal in a particular issue. As different societal actors are differently affected by certain issues, such as a new mining site, and have different roles in driving change by, *e.g.*, promoting, blocking, or tolerating such a mining site, a more nuanced understanding is required to comprehend society's reactions. Social acceptance can be understood along three dimensions:

1. Community (local stakeholders, residents, local authorities), measurable, *e.g.*, by the amount and type of public protests against a new mining site or the embeddedness

a particular company has in a community (*e.g.*, as a crucial employer in a particular region);

2 Markets (customer, investors, inter-firms), including factors influencing market creation or customer bases

3 Socio-political (public at large, key stakeholders) (Wolsink, 2018).

Investigating all these dimensions is equally essential to capture the essence of social acceptance (Fournis and Fortin 2017). A political operationalisation of this concept is the 'social licence to operate' (cf. Section 3.2.1).

There are numerous factors essential for the social acceptance of activities related to raw materials. These include resource accessibility, landscape changes, economic effects such as job creation, local support initiatives, infrastructure development, and instances of public unrest. The success of extraction will not depend solely on further technological advances or suitable locations, but rather on the need for public support and acceptance (Goldberg et al. 2022). Moreover, similar issues are relevant for processing, manufacturing, and recycling sites, where social acceptance and its influencing factors are equally important. However, the possible and actual impacts of raw materials-related activities, such as mining, processing, or recycling, can affect different groups variably (e.g., local communities in particular areas, demographics). This unevenness of impact is particularly challenging when developing commonly understood impact methodologies. However, such impact methodologies are needed and require further research to better understand the complex dynamics of conflicts and the motivations behind local protest actions (Dunlap and Riquito 2023; Noever Castelos 2023).

To better analyse those, it is essential to further develop impact assessment methodologies that focus on the impacts along the CRM supply chain (e.g., on mining, Hansen et al 2023). Moreover, establishing an open and regularly updated information database by competent authorities regarding ongoing or proposed industrial activities can build trust, facilitate constructive dialogue and mitigate polarization of public opinion arising from biased interpretations or speculations (Mateus and Martins 2021). Such activities could be further complemented through education and science popularization campaigns.

A promising way forward for R&I activities to constructively engage with potential criticisms is by strengthening trans-disciplinary approaches that encourage stakeholder and citizen participation. Methods like constructive technology assessment can help provide a forum for affected citizens to articulate hopes and grievances with a particular practice, which allows researchers and innovators to address those in their technology development.

3.3.3. R&I and sustainability of CRM supply

R&I is highly relevant to the sustainability of the CRM supply chain, including substitution, reduction of demand and circularity, specifically with regards to the fostering of relevant and sustainable technological and methodological advancements, providing opportunities for truly holistic and comprehensive interdisciplinary and cross-sector research collaboration and forward-thinking solutions-based project development that can function in a dynamic market. It has become clear that there is a need for research well beyond the natural sciences and engineering. The role of R&I for sustainability regarding CRM can be further specified thus:

- Exploration: R&I will give more precise scouting, through earth observation and artificial intelligence, facilitating selecting areas with the least negative environmental and social impacts. While scouting for new mining opportunities, R&I must at the same time assess the vulnerability of the considered sites' ecosystems and the potential for adequate monitoring/governance of the sites. Research must determine the availability of knowledge and the potential access to relevant data in order to make knowledge-based mining decisions. This includes consideration of societal risks, interests and values affected by development decisions.

- Mining: R&I is necessary for developing more efficient mining technologies, with improved characteristics such as reduced carbon emissions, better worker safety and less pollution of the immediate environment. R&I can also allow for better knowledge of staff and societal concerns, to further develop the practices with more care. Progress in mining technologies help extend the lifetime of active mines and may render abandoned mining sites attractive again. R&I can provide insight into more circular mining practices, both regarding circularity of input materials (such as water) and output materials (such as waste masses).
- Processing: R&I can facilitate reduced production losses, increased exploitation of the ores and less generation of waste. It can also make the process more energy and water efficient and reduce the use of environmentally harmful process materials.
- Manufacturing: At an overall level, R&I is necessary for developing effective digital passport systems for the CRMs. R&I is also required for designing end products with longer lifetimes, better repairability and easier recycling/recovery. At this phase, R&I for reducing the amount of CRMs in products or eliminating them entirely (substitution) is paramount.
- Use phase: Here, R&I is important for understanding consumer behaviour related to prolonging use of devices that contain CRMs and developing regulations and infrastructure for increasing the optimal use. Moreover, social science R&I (such as environmental psychology) will be needed to understand how the society can take a sufficiency approach and actually reduce the consumption of goods and services that require CRMs, reducing demand and thereby increasing self-sufficiency rates without increasing supply.
- Recycling: R&I is needed for improving recycling and recovery characteristics of goods and services containing CRMs. It is also needed for developing knowledge-based regulations, solutions and incentives for increased recycling.

Some additional general points:

Providing better research-based insights, conducted by research actors perceived as neutral, related to local development plans, can potentially be important for facilitating informed dialogue between stakeholders. Though facts may be only part of the disagreements (values and interests in themselves may be more central), establishing what is known, unknown and disputed may help sorting arguments and positions in a way that indicates what further knowledge should be generated, what monitoring programs should be planned and what countermeasures would be relevant.

Research collaboration with third countries in all the supply chain phases can help improve the sustainability of the supply of CRMs by increasing competence in countries that mine, produce or manufacture and in some cases receive waste containing CRMs.

Increased data sharing will provide a better basis for conducting valid research and will allow for more realistic comparisons between mining and production practices allowing for better sourcing and purchasing decisions. Data sharing about waste treatment and recycling solutions will enable the sharing of best practices globally.

Life Cycle Assessments (LCA) must be expected for all products and services containing CRMs as it will lead to better purchasing decisions allowing for a premium on products with value chains that take sustainability-guided decisions. Such assessments can include both environmental and social aspects, and may be prospective when conducting R&I or planning investments.

3.3.4. Possible impact of R&I initiatives

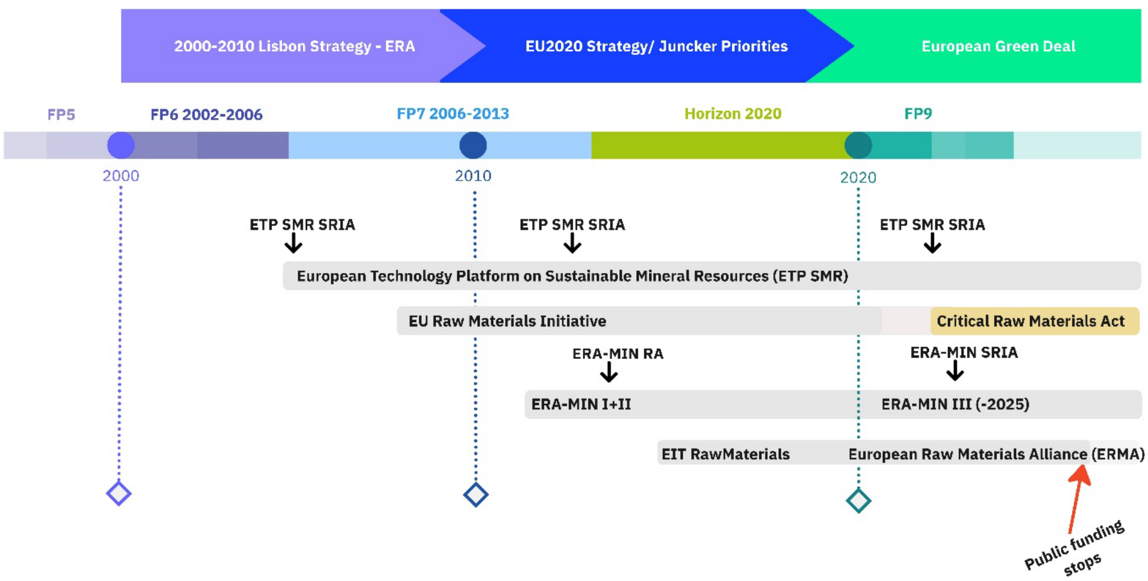
The following section takes a closer look at the impact of R&I initiatives. To this end, we first briefly present the current R&I initiatives in the area of CRM, in particular, ERA-MIN, EIT Raw Materials and CRM in the framework programmes. We then offer an analysis of the projects currently funded in Horizon Europe with CRM links regarding their foci, scope and gaps.

Overview of R&I CRM initiatives

Overall, there are a multitude of R&I policy initiatives within the EU that extensively address the topic of CRM. From the EU's perspective, this is important not only due to the intrinsic value of scientific work but also for diversifying suppliers and addressing demand management by ensuring, e.g., better extraction, more efficient use, or substitution.

Consequently, it is unsurprising that various R&I CRM policy measures within the EU are implemented at different stages of the innovation cycle. Some policies focus more on fundamental research (i.e., low TRL), others focus on the development phases that are more applied (medium to high TRL), and there is also an increasing call for support specifically for innovations moving towards market readiness. The following graphic (Figure 7) provides an overview of the historical development of some of these R&I programs, highlighting the strategic research and innovation agendas (SRIA) of European Technology Platform on Sustainable Minerals Resources (ETP-SMR), the political landscape and the European framework programs.

Figure 7 – Evolution of EU research and innovation initiatives.



Source: Adapted from Nilsson 2023

ERA-MIN

ERA-MIN is a European network of research funding organisations that has existed since 2011 and is currently beginning its third iteration, ERA-MIN3. Its main aim is to support the European Innovation Partnership on Raw Materials (EIP RM) and the EU Raw Materials Initiative. It is a transnational funding scheme for research and Innovation, fostering the development of the RM sector in the European landscape. The types of projects funded are from all across the RM theme, resource efficiency, recovery, recycling, reuse of end-of-life products, substitution and cross-cutting topics like environmental assessments, policy, and public perception.

The relevancy of ERA-MIN for the European CRM R&I landscape stems from its configuration to support smaller-size collaboration projects than those funded by Horizon Europe. Thus, ERA-Min complements it. On average, it funds projects between TRL 2-6, meaning low TRL projects are also supported. The flexibility in this regard allows for the inclusion of even more fundamental research, which is very relevant in the context of CRM. Furthermore, the funding coordination is based on the project receiver's country's law, increasing the attractiveness to non-European project partners that could be discouraged by complicated foreign regulation, thus, facilitating international cooperation (more in Section "R&I in International Raw Materials Policy Instruments" on page 44).

EIT RawMaterials

EIT RawMaterials functions as an innovation platform and an accelerator. It is the thematic Knowledge Innovation Community (KIC) in the European Institute of Technology Framework and, in addition to implementing applied innovation projects and promoting start-ups, is also active in university education through training courses on the postgraduate level as well as courses addressed to working professionals. The focus is on RM and the supply chain.

In the sense of the "knowledge triangle", the aim is not to initiate individual projects but ultimately to drive an entire ecosystem for the RM industry. The central vehicle here is the public-private partnerships (PPPs), as which EIT RawMaterials itself functions, as well as the support of other such PPPs. A unique feature of the KICs is that they are designed to be self-financed after a certain period.

The emphasis for EIT RawMaterials is on bringing solutions to the market as products and services that are economically self-sustaining. In this logic, the projects are generally considered suitable from TRL 6 upwards. However, approaches with a lower TRL can also be funded in the area of start-ups, for example, those that emerge from university research as spin-offs.

EU R&I framework programmes

R&I (including the focus on CRMs) has been central to the EU's policy landscape since its founding. EU's R&I policy has been significantly expanded from the 1980s onward, establishing the First European Framework Programme for Research (FP) in 1984 (Polluveer 2023). Since then, there have been a series of multiannual FPs. In 2014, the FP was expanded, and most EU research funding came under the umbrella of Horizon 2020, covering the period 2014-2020 and focused on contributing to the EU's global competitiveness (Andrijauskiene et al. 2021). Its successor Horizon Europe, the current EU research and innovation programme, was launched in 2021 for the period 2021-2027.

Horizon Europe represents an evolution from Horizon 2020, characterised by three main developments: the integrated approach to societal challenges and competitiveness, adopting a mission-oriented strategy in research and innovation (R&I) policymaking, and a focus on fostering new market opportunities. These shifts reinforce a commitment to societal transformation. While Horizon 2020 initiated efforts in this direction, it was noted that there existed a significant disparity between the program's ambitious goals and the practical achievements of its projects (Dinges et al. 2020, Weber et al. 2019). The impact of the Framework Programs is generally viewed as positive; however, there are notable concerns that require attention, including uneven and inconsistent progress across different countries (Andrijauskiene et al. 2021). Consequently, it is reasonable to infer that similar issues may also be present in the context of CRM topics.

Horizon Europe review

In the following section, the projects currently funded through Horizon Europe in relation to CRMs are reviewed and presented. As they are currently running and have not concluded yet, this section focuses on a qualitative analysis of the projects. Their focus, scope, expected impacts and approach to the CRM theme is discussed to conclude with some key insights, limitations or gaps.

Thus, this section delves into the Horizon Europe funding program, where we examined ongoing projects related to Critical Raw Materials (CRMs) by using the Cordis Database (https://cordis.europa.eu/). A corpus of 90 relevant projects was established. The following subsections present the results of this review, clustering the main takeaways about these projects and what they target by stages of the supply chain.

Most of the projects address more than one aspect of the CRM supply chain, as each stage is related to the others in some way. However, it was attempted to regroup them according to the stage they relate to the most or where they have the most impact. The projects mentioned in this section are not an exhaustive list of the currently running projects relevant to the CRMs topic, but rather some representative examples.

Projects on mineral exploration in Europe

11 current projects from the Horizon Europe Program have their main focus on the exploration stage of the CRM supply chain, all characterised by their exploration practically solely on European land. Some combine exploration in Europe and non-European countries, like the project AGEMERA (Agile Exploration and Geo-modelling for European Critical Raw materials), aiming at mapping CRM resources in six EU member states as well as in Zambia. In certain cases, exploration is integrated as part of a project with a larger scope, like VECTOR (Vectors to Accessible Critical Raw Material Resources in Sedimentary Basins), studying means for a sustainable and responsible CRM exploration and mining in Europe through combining geosciences and social sciences.

An important element of the exploration stage are Earth Observation (EO) technologies, as they are the focus of multiple projects in this section. TERRAVISION (Integrated Earth Observation based platform for novel services to enhance raw materials mining life cycle) and S34I (Secure and Sustainable Supply of Raw Materials for EU Industry) are both projects using EO and innovative data analysis techniques for improving exploration and mining practices. For the same purpose, the project GOLDENRAM (EO-Platform supporting critical raw material industry in Europe) wants to use EO in combination with AI (machine learning).

SEMACRET (Sustainable exploration for orthomagmatic (critical) raw material: charting the road to the green energy transition) applies the mineral system approach, creating more predictive models for exploration, for the first time in the EU. Two projects are exploring historical mines, DECADMEA in the Harz Mountains and LAURICON in the Laurion mines, using, among others, archaeological data.

Projects on mining and extraction of CRM

Around 20 projects are currently doing research on the extraction stage of the CRM supply chain. Also, mining is being improved thanks to EO models, as explained in the previous section.

Other projects are innovating on the extraction methods, such as AVANTIS (Sustainable, decarbonised vanadium, titanium and iron extraction from Europe's low-grade vanadium-bearing titanomagnetite deposits), which is developing a novel selective blasting approach for mines with complex mineral assemblage. Likewise, the project BioRevolution (Bio Solution for Global Mineral Crisis and Increased Food Production without Chemicals) introduces an ecological bioleaching method to release specific elements.

Furthermore, the process is being increasingly digitised and automated for carbon footprint reduction purposes, as in MASTERMINE (European Mining in the Green and Digital Era) and MAASIVETWIN (Manufacturing as a Service and Supply chain predictive Twin for critical raw materials). In the latter, one goal is to introduce a digital twin to track and optimise the mining process. Similarly, new tools and methods are being developed, as in NETHELIX (Intelligent digital toolbox towards more sustainable and safer extraction of mineral resources).

Finally, the CIRAN (Critical Raw materials extraction in environmentally protected areas) project takes a larger view by studying the framework around permits, policies and social aspects of mining in Europe.

Processing and refining CRMs

A total of 17 projects are currently contributing to the processing stage of the CRM supply chain. The processing stage can take different shapes. In some cases, it is combined with the mining and extraction stage. For example, EXCEED (Cost-effective, sustainable and responsible extraction routes for recovering distinct critical metals and industrial minerals as by-products from key European hard-rock lithium projects) studies a novel extraction process with additional processing to recover additional CRMs from lithium mines.

Other ways in which the processing stage is targeted in these projects is by exploring new technologies for processing specific CRMs, either to reach the domestic benchmark or target specific technologies (e.g. batteries). The majority of projects under the processing umbrella are in this pool. Some examples are LITHOS focusing on lithium (Cost-effective processing and refining of lithium into lithium hydroxide from strategic European multi-mineral lithium hard-rock projects), SUPREEMO on REEs (Sustainable European Rare Earth Elements production value chain from primary Ores) and CICERO on nickel, cobalt and manganese (MSA-based circular hydrometallurgy for sustainable, cost-effective production of NMC cathode materials).

Similarly to the work on exploration and mining, some projects are also developing more sustainable practices for processing or refining ores, for example, using methanesulfonic acid (MSA) instead of H_2SO_4, as in CICERO. Also here, digitalisation plays a certain role, as in RESOURCES (Refractory Sorting Using Revolutionising Classification Equipment), in which they introduce automated sorting solutions of particles or MAASIVETWIN, where they use a digital twin to optimise and track the processing stage. Additional projects targeting the processing stage will be presented in the following sections about recycling and recovery, as these latter stages often overlap with the first one.

Manufacturing of technologies with CRMs

No projects focus solely on the manufacturing stage, it is rather embedded in many others that have a focus on processing, recycling and recovery or substitution. However, there seems to be a trend for projects introducing circular economy (reuse of scraps, closed loops, etc.) in manufacturing, like PLOOTO (Product Passport through Twinning of Circular Value Chains) using digital information systems for waste reduction and traceability of the raw materials. Both DaCapo (Digital assets and tools for Circular value chains and manufacturing products) and MAASIVETWIN use the concept of Digital Twin for this purpose, for an overview along the whole value chain and to create predictions of supply for the manufacturer.

Substitution and usage optimisation

Closely related to the Manufacturing section, this section presents projects focusing on both substitution and on usage optimization, as these two dimensions overlap in most of them. Issues that can be characterised as substitution can often also be understood as usage or design optimization. However, not all projects exploring usage optimization are substituting CRMs, some are simply lowering or avoiding the CRM content in the manufacturing of new technologies.

Most projects addressing CRM substitution can be clustered into three main groups according to the specific applications: catalysts, capacitors and batteries. Six projects are developing catalytic technologies with no or low CRM content for the purpose of hydrogen production. Some examples are 2D4H2 (Anion Exchange Membrane Water stack based on Earth Abundant 2D Materials for Green Hydrogen Production) or REDHY (Redox-Mediated Economic, Critical Raw Material Free, Low Capex and Highly Efficient Green Hydrogen Production Technology). Five projects are working on capacitors or supercapacitors for various purposes without CRM, like GREENCAP (Graphene, MXene and ionic liquid-based sustainable supercapacitor), and at least three projects are developing innovative batteries without CRMs, like VanillaFlow (Artificial Intelligence Guided Development of Vanillin-based Flow Batteries), a project replacing CRMs with renewable resources in flow-batteries. Here, AI is used as a means to assist in the process of CRM replacement. Even if these projects aim at the CRM replacement or lowering of demand, they particularly affect the manufacturing process, if the projects are successful.

Around ten projects focus on the design or usage optimization of specific technologies. In these cases, the CRMs' usage cannot be avoided, and the projects focus on lowering its content or rendering the manufacturing more sustainable, some examples of these technologies are solar panel production (RESILEX), energy storage systems (SMHYLES) or the metallurgy industry in general (CESAREF).

Recycling and recovery of CRMs

Around 35 projects target the recycling or recovery stage of the CRM supply chain. They each have their own specific focus and way of approaching the issue, which makes it difficult to group them, but some tendencies can be defined. One of them is the recovery of CRM from e-waste. EECONE (European ECOsystem for Green Electronics) and FUTURAM (Future Availability of Secondary Raw Materials) focus on the larger framework and explore recovery methods from e-waste in general.

Others focus on specific EoL technologies, like solar panels in SOLMATE (Reuse of Solar PV Panels and EV Batteries for low cost decentralized energy solutions and effective Recycling of critical raw Materials from their EoL products), vehicles in CRUSADE (Recycling technologies for ELV components to create a sustainable source of market grade materials for EU applications), all types of batteries in BATRAW (Recycling of end of life battery packs for domestic raw material supply chains and enhanced circular economy) and cathodes in LiCORNE (Lithium recovery and battery-grade materials production from European resources).

Another trend is the recovery from CRM through bioremediation and bio-based technologies like in SYMBIOREM (Symbiotic, circular bioremediation systems and biotechnology solutions for improved environmental, economic and social sustainability in pollution control), extracting them from soil and groundwater. Similarly, EcoMetalophosphore (Economic and ecological recovery of indium, gallium and germanium from industrial waste) uses novel types of bio-solvents to extract certain CRM in mines in a more efficient, non-toxic way.

Here again, digitalization is very present and helping to tackle complex dismantling and recycling challenges, like in the project FPD Recycling (CircularPro-Robust AI and robotics for the WEEE recycling sector). Projects like PLOOTO or CE-RISE (Circular Economy Resource Information

System) are developing information systems or digital passports for tracking the CRMs through the whole supply chain and facilitating the recycling or recovery process.

Key insights, limitations and gaps

The currently running Horizon projects addressing CRMs are diverse in their scope, focus and impacts. The recycling and recovery of CRM, combined with process optimization, are the areas that get most of the spotlight at the moment. On the other hand, the exploration stage is the focus of the smallest share of the projects. More research on EU mining could be profitable if the goal is to ensure a safe and sustainable supply in the EU. Research on reduced consumption in general are not funded in the selected programmes examined here but may be funded elsewhere.

Mining and especially sustainable (social and environmental) practices for extracting CRMs could benefit from more attention. Currently, the sustainability of mining projects is mainly addressed through the digitalization and automation of the sites. However, considering additional studies on their impact on the environment or the social acceptance of the local populations could be constructive and add to the debate.

Considering the technologies targeted by all the reviewed projects, batteries (especially lithium-ion batteries), catalysts (especially for hydrogen production), and capacitors are the most researched. Others that are little researched but highly relevant are magnets for wind turbines (only three projects) and solar panels (four projects). Thus, these last two could also benefit from more representation.

Concerning the RMs or CRMs at target, the five most represented CRMs in the pool of 90 Horizon Europe projects are cobalt (Co), lithium (Li), platinum group metals (PGM), nickel (Ni) and manganese (Mn), all respectively mentioned 14, 12, 9, 8 and 7 times. Also present in the projects with 4 or more mentions were copper (Cu), REEs, aluminium (Al) and silicon (Si). Referring to Figure 2, it appears that elements such as niobium, phosphorus, strontium, gallium, boron, scandium, vanadium, bismuth, etc. which are at high supply risk and of high economic importance, are underrepresented in these reviewed projects and would benefit from more research. Many projects, however, do not explicitly mention what CRMs or elements they target.

Few non-European countries are being targeted in the projects discussing exploration or mining, only Zambia (AGEMERA) and South Africa (MASTERMINE). Only one project, AfricaMaVal, focuses specifically on fostering strategic partnerships. Concerning European countries, Finland, Greece, and Portugal are the most targeted for demo sites or pilot technologies.

3.4. Positioning of the EU in R&I for a sustainable CRM supply and use

3.4.1. EU global competitiveness

In the following, we will outline the relative positioning and collaboration patterns of the EU-27 and selected EU-27 Member States in the domain of technologies relevant for Raw Materials. It was developed based on more general patent search strategies for mining developed by the World Intellectual Property Organisation (WIPO) as well as internally developed strategies for Recycling.

The fundamental challenges in the process of developing such strategies is the intrinsic multi-purpose nature of many mining and recycling technologies. This is relevant as the oil and gas industry as well as the coal industry remain the primary drivers of innovation in the area of mining, and technologies for recycling cover various other domains unrelated to the recuperation of the critical raw materials here discussed. Hence, it is a challenge to focus any analysis on technologies relevant for critical raw materials exclusively. First, because it is technically rather difficult. Second, because it might, when overdone, exclude relevant inventions that have a primary application in other industries, but a rather central one for the critical raw materials domain as well.

Technically, utmost care has been taken to refine all available search strategies in such a way as to remove patent classes relevant for techniques known to pertain to other sector only. In particular, this applies to technologies visibly specific to the oil and gas industry or known to not be applied when extracting the largely solid-state materials within the critical raw materials domain (e.g. certain types of piping, wells and methods for lateral drilling). In our analysis, we now focus on technologies specifically relevant to either opencast or underground mining. To further refine the analysis, patents with a number of keywords in either their title or their technical abstract were explicitly omitted from counting, including, despite its potential ambiguity the term 'oil' as such.[29]

However, there is no avoiding the fact that many innovations in the mining industry are driven by the oil and gas industry. In the following illustrations, some of the observed patterns, in particular in the domain of exploration, may therefore reflect certain trends that are driven by dynamics external to the mining sectors in the focus of this study. Based on several in-depth investigations of the concrete inventions behind these trends, however, we maintain that they nonetheless reflect innovative activities relevant to the critical raw materials sector.

Patents are reported at the "transnational level", i.e. as patents filed at the WIPO or for the European market at the European Patent Office (EPO). Due to the 18 months period until an application is published and further delays incurred through the PCT procedure, newest reliable patent figures are available for 2021.

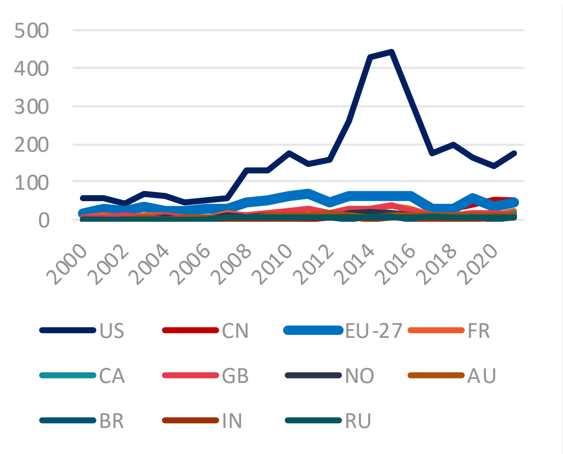
Overall trends

Based on our thus adapted WIPO-based definition for mining techniques, five primary areas of activity (plus recycling) can be distinguished.

Exploration

Exploration includes different techniques of both remote sensing and on-site exploration, such as radar- and sound-based techniques. The primary driver in the development of these techniques remain large North American corporates in the oil and gas industry. While their overall level of patenting is stable at around 150 p.a., it saw a peak in the mid-2000s as the result of the preceding increase in oil and gas prices which triggered a new round of exploration, prompting demand for novel techniques at about the same time. As mentioned above, this peak in inventions was very obviously not directed towards the mining of critical raw materials. But it is, just as in the past, rather likely that other parts of the mining sector may profit from inventive activities in the domain of oil and gas as well. Europe's level of patent applications reaches about 26% of that of the United States in 2021 with a more or less stable trend. In recent years, there has been an

Figure 8 – Number of transnational patent applications in the field of exploration



Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

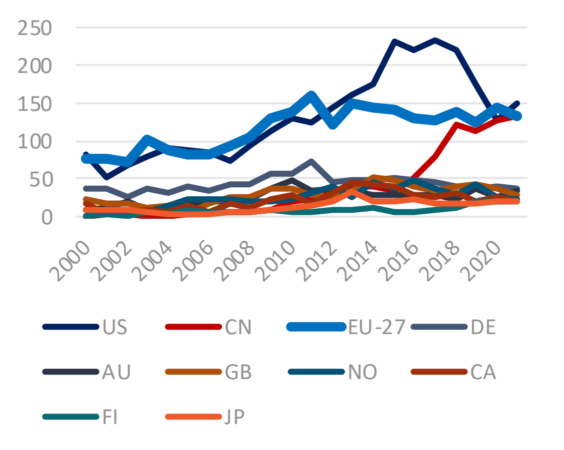
[29] ("coal" OR "oil" OR "naphta" OR "petroleum" OR "gasoline" OR "diesel" OR "natural gas" OR "domestic gas" OR "petroleum gas")

uptake in Chinese patent activity that now reaches about one third of the American level. In France and the United Kingdom, the level of inventive activity has decreased since about the mid-2010s.

Mining (extraction)

In the domain of mining proper, i.e. techniques with a focus on full-scale extraction, the dominance of the United States used to be just as pronounced as in the domain of exploration. Since the mid-2010s, however, China has caught up rapidly and is now reaching a level similar to that of the United States. More generally, innovation in the domain of mining has seen a stable upward trend since the end of the 2000s only to then decrease substantially at the end of the 2010. By 2021, the American level of patent was merely around 60% of its 2018 level. In most smaller countries, in contrast, the trend has been comparatively stable during the last decade, although, in 2021, none of them reached more than quarter of the US or Chinese level. Europe's level of patent applications reaches about 88% of that of the United States in 2021 with a more or less stable trend. Again, some of the innovation trends here observed were prompted by mining activities related to increases in demand for other, non-critical raw materials. Nonetheless, they have helped build a pool of technical expertise on which European mining industries in critical areas will have to draw in the future.

Figure 9 – Number of transnational patent applications in the field of mining (extraction)

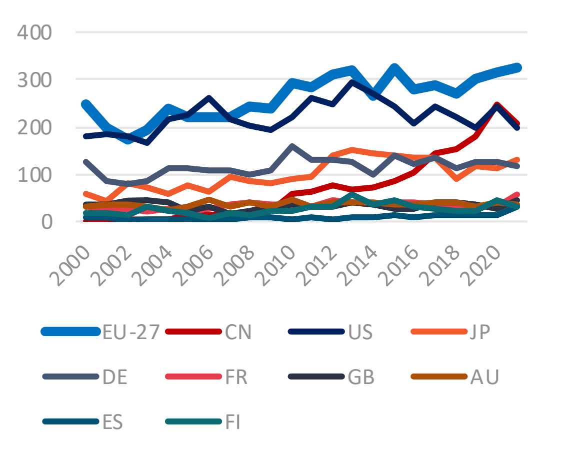


Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

Processing

With a view to processing, i.e. technologies related to the treatment and exploitation of extracted materials, China and the United States dominate the technological domain with around 200 annual patent applications each. China has caught up in this domain earliest, before mining as such or even exploration. As early as 2015, when its catch-up with a view to extraction technologies only began, China already reached about one half of the American level. Since about 2019, there is no significant difference. Different from exploration and extraction, Germany and Japan play strong, secondary roles in the domain of processing reaching about 60% of the US or the Chinese activity each. Overall, all trends but that of China are comparatively stable. Europe's level of patent applications exceeds that of the United States by 64% in 2021, with a further increasing trend. Other than in the exploration or extraction domain, there are no pronounced peaks which could be attributed to specific market trends or fluctuations.

Figure 10 – Number of transnational patent applications in the field of processing



Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

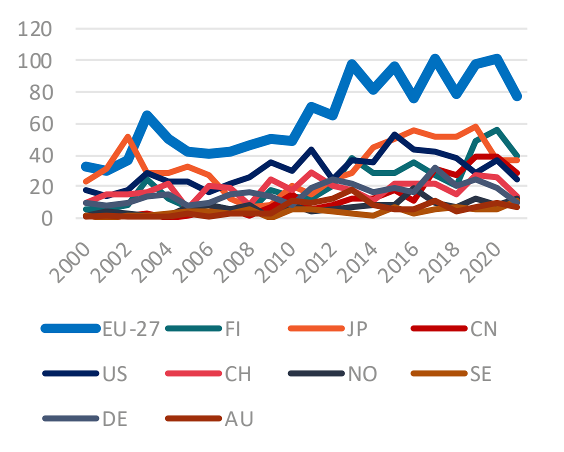
Mining-specific transport technologies

Overall, the domain of mining specific transport technologies is smaller than that analysed above, by about factor three. At the same time, the level of invention in all countries but the United States are not remarkably different from those in exploration. Overall, there is a more mixed field of lead countries, including Finland and Japan alongside China and the United States, with Switzerland and Sweden haven reached notable levels in the past as well. In many countries, the number of applications is very small. As a function of different Member States' contributions, Europe is the leading provider of technological inventions in this field, reaching about three times the US value with a stable trend. Other than in the exploration or extraction domain, there are no pronounced peaks which could be attributed to specific market trends or fluctuations.

Environmental

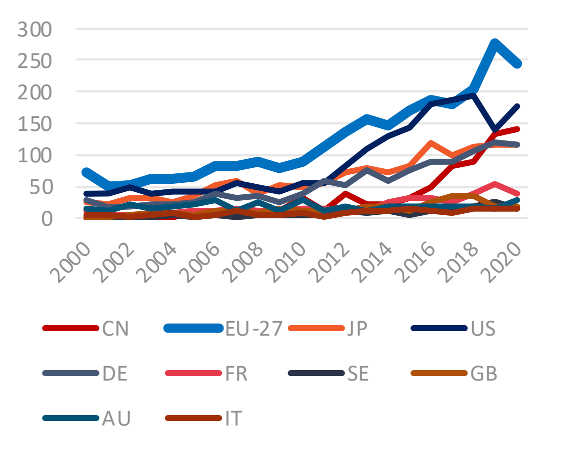
The trend for environmental technologies in the mining sector is relevant in particular as, in this case, the overall uptake in activities only starts in the early 2010s, putting nearly every relevant country on a positive trajectory otherwise only known from China. Since the early 2010s, the extent of patenting activities in this field has easily doubled. Current lead nations include China, Japan, Germany and the United States. As a function of primarily Germany's strong role, at par with Japan, Europe's level of patent applications continued to exceed that of the United States and China by more than 50% in 2020. Very recently, there is some volatility in the trends in both the EU27 and the US that suggest that future developments in this core areas of European strengths should be monitored closely. In particular as monitoring them is only possible with a one year delay compared to the other fields, due to particularities assigning relevant classifications in the patent system.

Figure 11 – Number of transnational patent applications for mining-related transport technologies



Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

Figure 12 – Number of transnational patent applications in mining-related environmental technologies

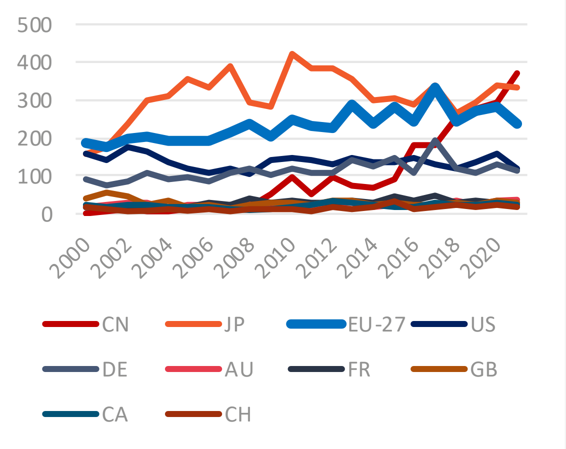


Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT). Note that due to the delayed assignement of patents to environmental classes, no data is available for 2021.

Recycling

The field of recycling displays relevant patterns of its own. Here Japan has been the long-term lead nations whose activities have, since about 2018, been become matched by Chinas. Germany and the United States hold strong, secondary positions at about 40% of the Chinese or Japanese level. Apart from Japan's rise during the 2000s and China's since the mid-2010s, most of the trends in the field are more or less stable. Europe's level of patent applications reached about 70% of that of Japan or China in 2021 with a more or less stable trend. Other than in some of the mining domains, there are no pronounced peaks which could be attributed to specific market trends or fluctuations.

Figure 13 – Number of transnational patent applications in recycling



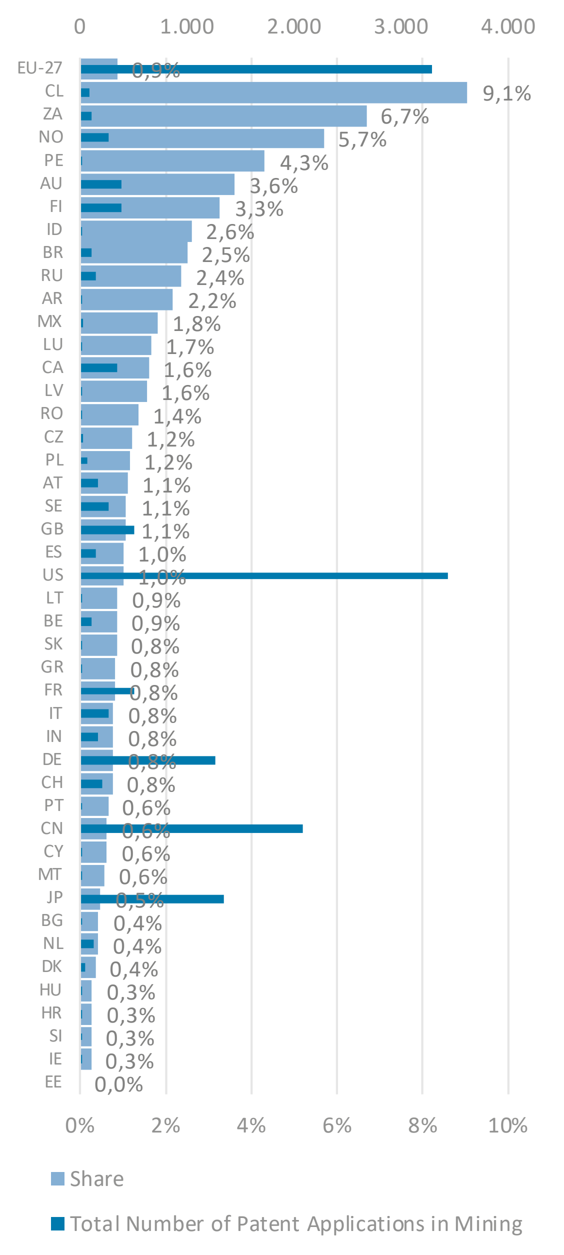
Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

Relative importance of mining patents in overall national patenting

As Figure 14 clearly indicates, few European Member states' innovation systems are to a similar degree characterised by mining innovation as those of nations to whose economies mining is central: Chile, South Africa, Norway, Peru, Australia, Indonesia, Brazil, Russia, Argentina, Mexico or Canada. The exceptions are Finland (at par with Australia) and Luxemburg (with a very small absolute, but high relative contribution). Other Member States with comparatively high shares of mining patents (above the EU 27 average of 0.87%) include Latvia, Romania, Czech Republic, Poland, Austria, Sweden and Spain – of which only Austria, Sweden and Spain make a relevant absolute contribution, at par e.g. with Canada and, in relative terms, the United States.

For recycling the picture is similar in that mining nations like Chile, Peru, South Africa and Australia display the highest relative share of such patents in their overall portfolio of inventions. Among those, however, only Australia contributes in substantive numbers. In all other countries, the share of recycling patents in the total is below 1%. Among the larger Member States with significant absolute levels of activities, Germany reaches 0.4%, France 0.3%, the Netherlands 0.3%, Spain 0.3% and Italy 0.2%.

Figure 14 – Number of transnational patent applications in mining (top axis) and share of these in total patents of the respective countries (bottom axis)



Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

3.4.2. Global cooperation

With regard to collaboration, the picture below illustrates the degree of collaboration, i.e. the share of a nation's 2017-21 patents in the mining industry which are co-patents. Typically, co-patents are a sign of corporate relations, indicating a branch-headquarter collaboration, or a collaboration between two branches. Genuine, cross-organisational co patenting is a lot less common.

In light of this, our analysis shows that, in smaller countries, the share of co-patents tends to be higher, as these are controlled by foreign subsidiaries. Some exceptions may be given by Luxemburg, and, to a more limited extent, Austria and Spain, where a small country is the seat of relevant headquarters as well. In mid-sized nations like Germany but also in the United States in their globally leading position, about 15-20% of all patents tend to be co-patents. That is high in intersectoral comparison, as the figure for the overall share of co-patenting at world level tends to be below 10%. Probably, it is indicative of the strong corporate structures that characterise the mining domain.

Despite general, size related trends, our analysis confirms earlier that China and Japan are not part of the global corporate system in the domain of critical raw materials but stand largely separate. Their corporates perform close to all research and development domestically. India, to the contrary, displays a much more integrated position both due to extensive foreign operations within the country and through Indian corporates own international operations.

Most larger EU Member states fall into the middle category, with co-patent shares between 10-25%: France's comparatively high integration stands out alongside that of smaller Member States like Belgium, Austria or Spain - as well as the United Kingdom. Smaller Member States, in part with significant mining traditions (Czech Republic, Slovakia), seem to be conducting less independent R&, Ireland's position may be explained through its attraction of formal corporate headquarters. An exception from the overall picture seems Finland whose firms so not seem to collaborate much at a strategic level, despite the countries' limited size. Overall, Europe's Member states seem to be solidly embedded into international innovation chains.

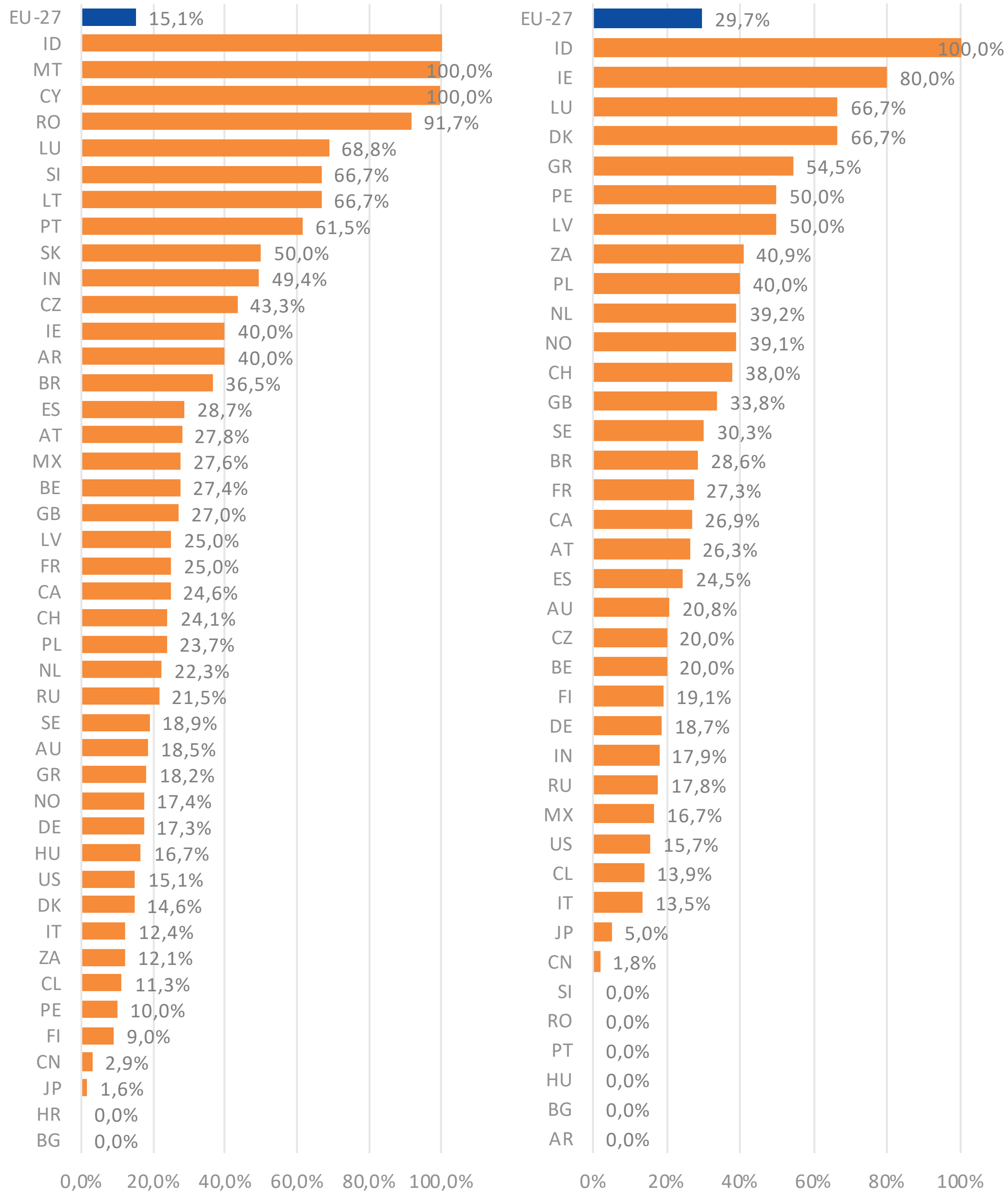
Whether or not the below inclination to collaborate implies exposure to non-European players can be deduced from the European aggregate value which includes only those patents that are not among Member States. Consequently, Figure 15 underlines that about 15% of Europe's inventive activities in the domain of critical raw materials (exploration, mining and processing) happen in collaboration with other, non-European countries.

In the recycling domain, a comparatively elevated level of collaboration is found in the EU-27 when compared to the US 15,7%, Japan 5,0% or China 1,8%. Within the Union, smaller countries like Latvia or in innovative terms less active like Poland, display higher collaboration intensities (of about 40%) which, except possibly in the cases of Luxemburg and the Netherlands, can likely be attributed a strong local role of foreign multinationals. Switzerland, too displays high levels of collaboration, in this case likely based on domestic strengths spurring international engagement

Likewise, France displays relatively high rates of foreign engagement (27%) close to at par with that of smaller nations like Sweden (30%) and Austria (26%), or, outside the Union the United Kingdom (34%) and Canada (27%). Germany displays a somewhat lower propensity to collaborate (19%) in line with that of Finland (19%), India (18%) or, at the time, Russia (18%). Italy displays the lowest level of collaboration in the European Union with a mere 13,5%.

That said, the EU-27's overall level of collaboration with non-European partners remains higher than in the mining domain.

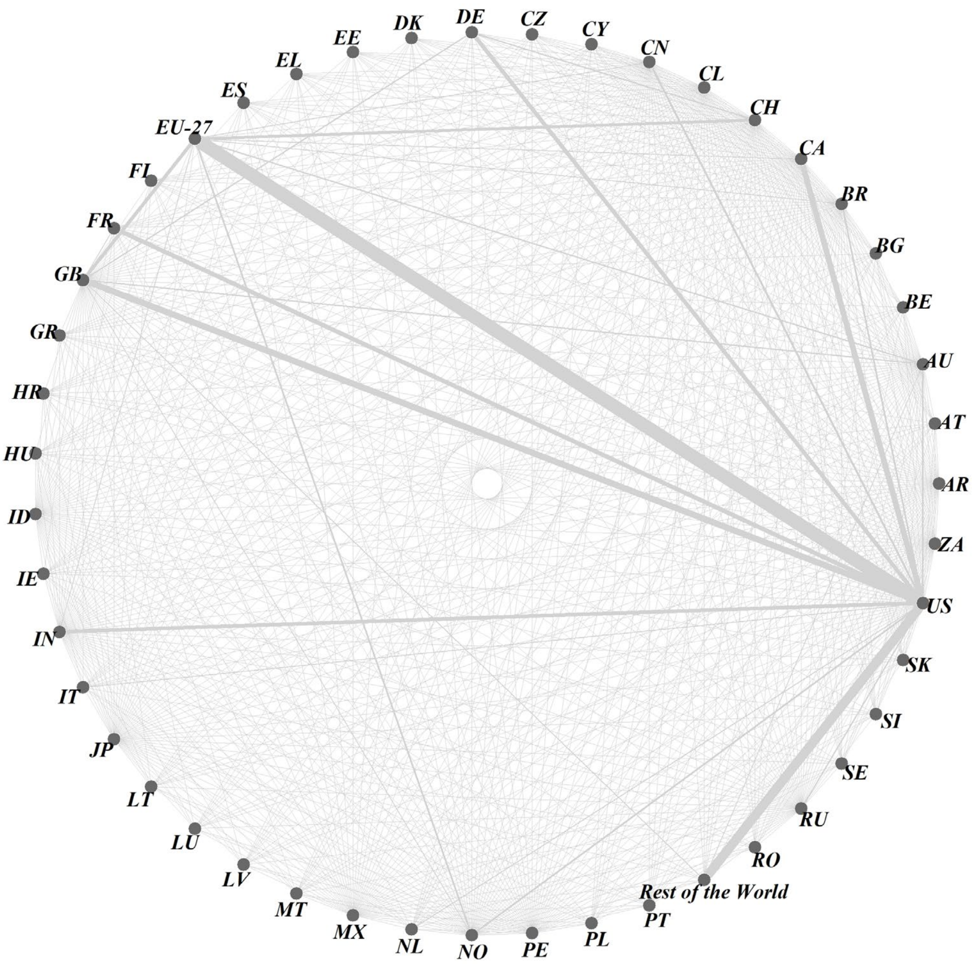
Figure 15 – Share of transnational patent applications in exploration to processing (left) and recycling (right) for the EU and its Member States as well as selected third countries.



Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

Figure 16 documents that US-European collaboration is one of the primary axis cooperative R&D in the global innovation system for mining technology. In addition, European firms collaborate closely with partners from the United Kingdom and Switzerland, as could be expected. The map underlines the U.S. position as the primary hub in the innovation chain, with links also to India and Canada, whereas China hardly engages hardly at all. India's strong focus on the US seems to suggest that its strong integration indicates dependency rather than self-standing sovereignty – which would require more than one major link. Hence, Europe is the only other player on the global scene that – in aggregate – forms a hub and spoke network akin – if not fully alike – to the of the United States. The main EU Member states, which contribute to forming that network in absolute terms are Germany and France, with relevant individual networks in the same order of magnitude than those of the United Kingdom.

Figure 16 – Co-patenting between the EU and its Member States and third countries (only includes global links for EU Member States, neither links among each other nor with EU-27 aggregate).



Source: Fraunhofer ISI based on the EPO worldwide Patent Statistical Database (PATSTAT)

For recycling, the EU27 and the US have an equally central position. Both are connected by a strong mutual link, as well as specific links to other countries respectively. Other than in the mining domain, the US does not occupy a more dominant position than the EU-27. While the EU-27 displays particularly strong linkages to Switzerland and Japan (yet not the UK) the US entertains somewhat stronger collaborations with Canada, China and India. Among the Member States, Germany is an important player. The UK entertains strong linkages with Australia.

3.4.3. Strategic partnerships outside the EU

The following section will briefly shed light on Research and Innovation (R&I) cooperation with partners outside of the European Union, detailing their structure and identifying potential areas for development. Similar to R&I policy initiatives that predominantly focus their activities within Europe, there are numerous initiatives and policies of a more international nature involving both European and non-European participants, more than could be exhaustively discussed in this report. However, several recent activities merit specific attention. Overall, the role of R&I in international RM cooperation is equally affected by increase in geopolitical tensions and the intent to reduce dependence on single countries – particularly Russia and China. This reduction of dependence (sometimes termed as de-risking) and the European twin transition made a renewed focus on raw materials necessary in the first place (Gstöhl et al. 2024).

The following section briefly discusses, first, the current nature of science and science diplomacy, second, established forums for international cooperation, R&I cooperation in RM policy instruments, and R&I in European raw materials diplomacy.

Science and science diplomacy

Despite the inherent competitive elements in the discussions around security of supply, in the field of raw materials and related topics, e.g., processing, manufacturing, and recycling, science is as global in nature as in other research fields. Thus, an international exchange of knowledge and skills occurs through academic conferences, labour mobility, globally active companies, etc.

In principle, there is already a series of scientific partnership agreements, which, for example, either enable cooperation (for industrialised countries) or participation (for selected developing countries) in framework programmes such as Horizon Europe. Additionally, other Science and Technology Agreements exist with third countries (European Commission n.d.).

A critical perspective in this regard is summarised under the term "science diplomacy", which is recently getting more discussed in policy and academia (Adamson et al. 2021, Turchetti et al. 2020). Science diplomacy holds significance for the European Union as it offers a strategic approach to fostering international relations within the realms of R&I. This approach facilitates the EU's engagement in constructive global collaborations, enabling shared scientific endeavours and access to essential resources. The concept is vital in navigating the complex dynamics surrounding CRMs, where securing stable and ethical supply chains is paramount. By adopting a science diplomacy perspective, the EU can contribute to and benefit from a collective global effort to address resource scarcity and promote sustainable practices. Therefore, viewing international R&I cooperation through the lens of science diplomacy allows for a more integrated and strategic approach, combining scientific inquiry with diplomatic engagement to tackle shared challenges and foster mutual understanding. Moreover, R&I collaboration can be a crucial contribution of the EU to resource-rich countries and is one dimension of making a club approach – where resources are shared among states – mutually beneficial (Findeisen 2023). However, it should be noted that critics from civil society regard the current setup as not yet beneficial to all included parties (Fern et al. 2023).

Established forums for international cooperation

In addition to academic exchanges, there are several international forums for policymakers with EU participation that, despite being concerned with other issues of raw materials policy, have a particular emphasis on matters of research, development, and innovation. Noteworthy examplesare the "Conference on Critical Materials", launched as a trilateral conference in 2011 and now being held as the EU-US-JP-AU-CA Conference on Critical Materials and Minerals. This forum has a strong focus on research and development topics.

Recently, two multi-lateral forums of RM-related R&I policy became important. Both are global forums with a similar composition of members – Western and industrialised countries. First, the cooperation in the context of the Minerals Security Partnership (MSP) that also claims a strong R&I focus (US State Department 2022). Second, there are IEA- and OECD-related activities (IEA 2023). Moreover, there are various activities of EU Member States.

From a European perspective, all of these activities are similar in that they are concerned with reducing the risks regarding materials supply by ensuring diversification of sources on the one hand and by managing the dependence on single resources by reducing their demand in the first place.

R&I in international raw materials policy instruments

A noteworthy framework facilitating international collaboration is offered by ERA-MIN, which, at the time of this writing, is advancing into its third phase. Like other ERA-NET programs, Horizon Europe supports the organisational aspects. However, the calls for proposals are managed by the research funding organisations of the participating member states, which coordinate the calls in collaboration with a select few others. Regarding international cooperation, it is noteworthy that ERA-MIN includes some non-European member states, exemplified by Turkey (as a candidate member) and neighbouring countries like Morocco. Moreover, countries such as Canada, Chile, and Argentina are also participating. This mechanism provides benefits for international collaborations, as researchers or innovators can submit their applications to their respective national funding organisations, thereby circumventing the complexities of European law and similar issues.

Another critical approach is the EU Global Gateway initiative (JOIN/2021/30 final). Established in 2021, it aspires to support the development of sustainable and high-quality infrastructure projects that align with the priorities of partner nations, aiming for enduring advantages for local populations. This strategy is particularly relevant in the context of CRMs, which are vital for the twin transition. The initiative seeks to engage the private sector, intending to stimulate public-private partnerships (PPPs). These partnerships aim to leverage public funding with private investment. By fostering these partnerships, the Global Gateway aims to enhance the resilience of supply chains for critical raw materials. A key actor in this context is EIT RawMaterials, which can also serve internationally as an accelerator for PPPs and set ethical requirements. Although the importance of financing options for innovation projects is undisputed, there is always the risk of free-riding effects (Liese et al. 2011). Additionally, adopted in 2022 as part of the REpowerEU package, the EU External Energy Engagement Strategy underlines the advantages of cooperation on the energy transition. One aim is the development of green industry value chains in partner countries.

R&I in EU raw materials diplomacy

Since 2021, the European Commission has been committed to building so-called strategic partnerships with non-European countries to address the central strategic importance of CRMs for the twin transition and minimise risks in this regard. These activities are subsumed under the title of Raw Materials Diplomacy. This term refers to a wide range of agreements aimed at creating mutually beneficial sustainable value chains for raw materials. These initiatives are structured to consolidate raw material value chains, foster collaborative projects, and enhance research and development efforts, all while maintaining adherence to environmental, social, and governance (ESG) standards. So far, such agreements have been concluded with 11 countries, with more to come in the near future. Most of them are still at the declaration of interest stage (e.g., Memorandum of Understanding – MoU), which will be followed by more detailed roadmaps and then closer cooperation in many areas (European Commission 2024c). All agreements are included as part of the mentioned global gateway strategy that aims to leverage private capital through public-private partnerships.

Most agreements are similarly structured (Table 1), but some agreements with specific countries stand out. Particularly noteworthy are the sub-chapters on critical raw materials in the EU–Canada Comprehensive Economic and Trade Agreement (CETA), which had a long genesis. Another key agreement is the one with Ukraine, which should be viewed differently due to its unique political relationship. Ukraine is a significant global titanium supplier and is a potential source of over twenty critical raw materials for the EU (EIT RawMaterials 2021). In addition, there is not yet a strategic partnership but a letter of intent agreement with Serbia to strengthen cooperation in critical raw materials and electric vehicle value chains. While the scope of the majority of the agreements is exclusively in the area of critical raw materials, the one with Namibia also includes hydrogen value chains.

All of the agreements considered here (Table 1) have a stated R&I component that usually includes, in some form, cooperation on research and innovation along the raw materials value chain. Some are much more concrete due to the long-standing relationship in these areas with the EU, as in the example of Greenland, which is already eligible to participate in European Framework Programs such as Horizon Europe, Earth Observation Data, and Copernicus. The MoU already provides for particular R&I topics in geological surveys and mining and waste management monitoring, including environmental impacts, etc.

Table 1 – Overview of international CRM agreements with an R&I component

Country	Status	Date	Notes
Strategic partnership on raw materials			
Canada	adopted	June 15, 2021	Part of CETA agreement
Ukraine	signed	July 13, 2021	
Kazakhstan	signed	November 07, 2021	
Namibia	signed	November 08, 2021	Includes Hydrogen
Argentina	signed	June 13, 2023	
Chile	signed	July 28, 2023	
Zambia	signed	October 26, 2023	
DRC	signed	October 26, 2023	
Rwanda	signed	February 19, 2024	
Greenland	signed	November 30, 2023	
Serbia	LoI	September 22, 2023	Includes EV value chain
Norway	signed	March 21, 2024	sustainable land-based RM & battery value chain
Uzbekistan	signed	April 04, 2024	
Selected multilateral initiatives			
EC, UK, US, Australia, Canada, Finland, France, Germany, Japan, Republic of Korea, Sweden		June 14, 2022	Minerals Security Partnership
Member Countries		-	IEA-OECD
EU, US, Japan, Australia, Canada		Since 2011	Conference on Critical Materials and Minerals

Similar topics are already delineated in the Memorandums of Understanding (MoUs) with Kazakhstan and Ukraine and in the critical raw materials (CRM) section of the CETA agreement. These agreements emphasise a broad array of R&I areas, explicitly targeting crucial issues such as the harmonisation of standards, technology and information exchange, and participation in Horizon Europe. Although other MoUs may appear less comprehensive and detailed at first glance, they, too, offer the potential to cover these significant topics in the future.

4. Conclusions

Critical raw materials are essential for the EU economy and diverse in their nature and challenges. High-level methodologies are in place to assess and monitor risks and possible impacts of supply disruptions. Despite remaining challenges regarding access to timely, high-quality data, these methodologies address both the status quo (critical raw materials, CRM) and future developments (strategic raw materials, SRM) regarding supply and demand for raw materials. The outcome of the CRM assessments has changed over time due to changing supply and demand realities. This will continue to be the case, and also applies to the assessment of SRM. These assessments and the accompanying background work provide a view of the entire supply chain for critical raw materials, which is necessary for the development of actions to minimise risks and increase resilience.

The EU has tackled the issue of raw material criticality with a variety of actions, including strong engagement in research and innovation (R&I) for critical raw materials. The role of R&I is stressed in policy documents, from the raw materials initiative (2008) to the recent Critical Raw Materials Act. In parallel with this political attention, funding has increased significantly in EU programmes, including Framework Programmes, Horizon 2020, Horizon Europe, and EIT RawMaterials (which is reaching the end of the extended funding period). The EU as a whole is an important actor in patenting in mining/processing and recycling, with strong international ties, especially to the US. Continued funding and policy support will be key to maintaining and profiting from this position.

Overarching themes in R&I and sustainability challenges for critical raw materials are:

- Reducing costs and impacts of mining, processing and recycling;
- Managing complexity (from mining and processing complex ores to recycling complex products);
- Understanding and engaging with stakeholders, securing public acceptance;
- Covering the entire chain, from exploration to recycling, including circularity strategies;
- Ensuring access to data and creating transparency along supply chains.

5. Policy options and their assessment

In the coming years, the European Union will face a number of policy challenges related to research and innovation in the domain of critical raw materials. Overall, these follow logically from three central concerns that have moved to the centre of European policy makers' attention in recent years: (1) Open strategic autonomy, (2) international competitiveness, and (3) sustainability and values.

First, open strategic autonomy. Geopolitically, the world has become a less safe and more uncertain place. Against this background, the EU aspires to sustain a strategically independent position and, in areas of own weakness, avoid becoming unilaterally dependent on other nations. Other than in the domain of raw materials extraction with its geological constraints, there is no fundamental reason for the EU to suffer from such a dependency in research and innovation, in which it possesses great strength. All capacities could, at least in theory, be locally built – although our analyses have shown that they are not yet universally present. At the same time, global strength in research and innovation also derives from productive partnerships. To remain at the forefront of development, any country needs to engage (i.e., both collaborate and compete) with the most capable partners in the field. Given the new geopolitical framework conditions, however, such relations will be built in priority with nations sharing similar values, often called value partners.

In summary, research and innovation related to critical raw materials is one area in which the EU can inject new momentum, (re-)building domestic capacities and consciously reviewing its web of existing partnerships in parallel. When it is no longer possible to rely on established global innovation chains, renewed effort to invest in autonomous problem-solving capacity is an obvious option.

Second, international competitiveness. Regardless of geopolitical developments, Europe's competitiveness has suffered in several important fields, most prominently in exploration, where the US holds sway with some distance to every other nation. Moreover, China has become a strong contender in all other fields where it is projected to surpass European investment and strengths in the near future. As a result, the EU's position as a central provider of technologies and solutions to global raw materials operations is increasingly in jeopardy. If the EU wants to uphold the ambition to remain an important provider of advanced technological solutions to mining and processing operations with worldwide distribution (including urban mining and substitution) , it will have to invest in improving its firms' position in value chains, by upgrading their technological capacity and supporting their global operations, responsibly, by political means. In addition, the EU is still capable of developing a leading position in some fields, e.g., with regard to capacities required for the environmentally sustainable and socially acceptable extraction and processing of raw materials, as well as in recycling and substitution. In these fields, additional investment will be required.

In summary, a minimum option is to direct Europe's investment towards covering and amending weaknesses, as outlined under 'open strategic autonomy'. A more ambitious option would be to follow the evidence-based identification of strengths and weaknesses in this report and seek to expand activities in those areas where true technological sovereignty and leadership at a global scale remains within reach.

In addition to these first two aspects, which are primarily aimed at retaining the basis for societal wellbeing – i.e., value creation – in the EU, the EU also promotes a **third** and broader normative agenda. The EU has committed to developing European CRM value chains with **sustainability and moral values** as guiding principles. For example, Europe wishes to establish clear standards for the environmentally sustainable and socially acceptable extraction and processing of critical raw materials and will, for this purpose, launch pilot cases for such activities on the continent as well as within global partnerships. How this can be successfully achieved also remains a matter of research, as few fully convincing solutions have been found so far. Reopening of domestic extraction sites appears no longer an option but an imperative, with the implication that European global businesses must be simultaneously economically enabled and morally disciplined. The development of clear, fit-for-purpose and at the same time commercially viable, regulation and guidelines are only some of the challenges yet to be resolved in this area. In the coming years, much remains to be done to better interface and reconcile social sciences and technological research in the critical raw materials domain, if sovereignty is to be paired with sustainability and public acceptance. In parallel, the EU can explore and develop the market's readiness for recycled products and material substitution.

In summary, research and innovation in the domain of critical raw materials does not relate to engineering and technological development alone. It can be claimed that, to sustainably strengthen Europe's autonomy and global sovereignty, large-scale projects on home soil must remain feasible and large-scale overseas operations must be ethically defendable. To achieve this, an indispensable contribution has to come from the social sciences and humanities.

A first step to achieve such a high aim is to further improve European **intelligence, analysis and monitoring capacity**. In this respect, this study can be the beginning of building a clearer understanding of the EU's own capacities in an area of such profound strategic importance to EU wellbeing.

Second, Europe must **invest in improving research and innovation capacity**, both in areas of current weakness (to ensure autonomy) and in areas of current strength (to reinforce sovereignty). To achieve this, diverse means can be leveraged, and the EU should consider strategic, large-scale investments at par with those in other key enabling technologies.

A third important area for public policy decision making, is activities in the areas of **public outreach and citizen engagement.** In the EU, experience shows that larger efforts with regard to the (re-)opening of additional extraction and processing sites will create societal controversy if not carried out appropriately. An option to be considered is to incentivise development projects to include consultation processes beyond what is legally mandated, helping to make these projects collaborative and locally owned, thereby better contributing to sustaining Europe's autonomy and reinforcing its technological sovereignty in CRM.

In these times of transition, stakeholders hold that Europe's public has justified concerns that must be taken seriously, to the extent that they should even impact the course of governmental intervention, naturally within democratically legitimate bounds. At the same time, both the European Union and its Member States are challenged by the fact that they see Europe losing ground globally and – in the interest of the very same constituencies that remain wary of change – cannot stand by idly and avoid taking decisions, even if they are uncomfortable for some people.

This section proposes a list of concrete action points that, in the view of the authors, are relevant policy options to boost Europe's global competitiveness and reassert its autonomy while at the same time remaining conscious of the societal cost that any expansion of mining and processing activity (including recycling) necessarily entails – in the EU and elsewhere.

The areas sketched out below can be topics for further action at the European level:

- Own institutional and R&I capacities
    - **Retain and reinforce own capacities, develop modern and more effective solutions for technologically mature fields.** EU institutions tasked with the implementation of the CRMA will require additional resources for establishing

effective assessment and monitoring methodologies and for maintaining an up-to-date overview of CRM supply chains in the EU. Furthermore, EU mining and processing firms as well as equipment and technology providers require support in their effort to provide competitive solutions to the world market. Under existing State aid rules, this will primarily relate to reinforced investments into research and development efforts, alone and in collaboration with research institutions.

- **Build capacities and lead in dynamic fields; secure a key position in evolving future areas along the entire cycle (from mining to recycling).** The EU needs to be conscious that to defend and extend its leading position in fields where it retains a cutting-edge, granular support for single projects will not be enough. The domain of critical raw materials research deserves attention as a key area of 'common European interest'.
- **Encourage smaller, innovative change agents (SMEs and citizen initiatives) outside established structures throughout the entire cycle.** If all support and attention were focused on established, large businesses, the EU would risk consolidating the status quo and achieve merely incremental innovation. Hence particular attention should be paid to young, dynamic firms with disruptive ideas.

- International collaboration
  - **Collaborate with the best to learn faster – regardless of whether Europe leads or needs to catch-up.** In research and innovation, collaborations with leading players are needed to maintain or regain a cutting edge. In the CRM domain, intensified collaboration with the US, Japan, and increasingly also China, appear therefore advisable – in addition to joint intra-European efforts.
  - **Develop bridgeheads in raw materials-supplying nations by collaborating with the best local research partners.** While many nations with a focus on extraction may not count among the scientific leaders, they have specific knowledge on site conditions and practical experience that are essential to making European solutions technologically and commercially viable at home and abroad.
  - **Combine strategic materials diplomacy with existing science diplomacy efforts.** The embedding of CRM-related activity, also related to R&I, into a robust political fabric is essential. Science diplomacy should be extended to key nations in the CRM supply and waste chains.
- Legitimacy and regulation
  - **Identify and assess social and environmental conflicts arising from the development of new or the re-activation of old mines.** Potential investors in mining operations are not necessarily dismissive but may lack contextualised knowledge of the problems that the (re-)opening of processing or extraction sites causes to the local population. These problems need to be duly acknowledged and precisely analysed, ideally by neutral third parties.
  - **Develop procedures to facilitate new mining operations while taking into account justified grievances.** Societal conflicts will arise if the resulting impacts are real and substantive. Hence, the political task should be neither to avoid them entirely nor to seek to talk stakeholders into compliance. Instead, means must be found – and agreed – that allow for actions that secure Europe's CRM sovereignty.
  - **Develop a sound, evidence-based foundation for standards in future international partnership agreements (methods and data).** While within the EU, political processes can be implemented to ascertain that local interest groups are duly consulted, this is not always possible in the case of operations outside

Europe. Hence, there is a need to define exactly what European businesses are expected to do in concert with local governments.

Following this outline of general rationales for intervention and areas in which additional effort is required, the following paragraphs identify concrete leverage points for action in light of the existing portfolio of European policy tools:

- Own capacities: EU institutions
  Achieving the goals of the CRMA will require extensive data gathering, analysis and monitoring capacities beyond what is available to-date. This pertains both to methods and data, e.g., for assessing criticality or conducting stress tests. This implies:
  - Strengthening and bundling of expertise in European institutions;
  - Better use of existing capacities in the EU research ecosystem;
- Own capacities: EU research and innovation landscape
  The specific benchmarks on EU sourcing will require significant research and development efforts along the entire CRM supply chains, from exploration and mining to processing, use and recycling.
  - Increase funding allocated to raw materials topics in Horizon programmes; encourage work on 'less popular' CRM;
  - Continued funding for bringing research results to the market (EIT, EIC, ERA-MIN). This action also supports build-up of SME capacity across EU countries;
  - Strengthen R&I on demand reduction (reduced consumption, substitution and longevity).
- International collaboration
  The EU has strong R&I along the CRM supply chains. The opportunities and incentives for international collaboration, especially with raw materials supplying nations, could be improved and contribute to securing access to sustainably sourced raw materials.
  - Strengthen incentives for research collaboration with non-EU partners;
  - Use international projects to generate data on opaque supply chains;
  - Ensure funding for R&I aspects of strategic partnerships on raw materials.
- Legitimacy and regulation
  Developing new raw materials projects – both primary and secondary – will likely lead to controversy. R&I can help to identifying and addressing the issues, thus contributing to achieving the goals of the CRMA regarding self-sufficiency.
  - Support demo-cases and living labs for citizen engagement and responsible innovation around new or reactivated exploration, mining and processing sites;
  - Encourage integration of social sciences and humanities aspects into technical R&I projects along the CRM supply chains, when relevant;
  - Research solutions to regulatory barriers and strengthening drivers to achieve the goals of the CRMA, also addressing the retention and mobility of scrap within the EU.

A list of more specific actions along the CRM supply chain (e.g., addressing specific technological challenges) has been developed and is provided in Annex B.

Table 2 –Assessment of R&I policy options

Option	Assessment dimension	Assessment
Strengthening and bundling of expertise in European institutions	Costs	Depending on the extent of implementation, from few full-time equivalents (FTEs) for coordination of existing and emerging activities across EU institutions and Members States to a full-blown office with own analytical capabilities (akin to the AI office)
	Benefits	Ability to focus on the implementation of the CRM Act. Independence and continuity in the build-up of expertise on CRM at EU level
	Feasibility	Expertise on CRM is present at EU institutions, notably at DG GROW and JRC and can serve as a starting point for strengthened capacities.
	Effectiveness	Building and strengthening own capacities will help in the implementation of the CRM Act
	Sustainability	No adverse sustainability effects are anticipated. Moreover, this will help promote EU sustainability goals in the sector
	Risks and uncertainties	Determining a reasonable relation between capacities and duties is key. Risks of creating coordination effort with little positive effect or wasting resources by duplicating capacities already existing and available through third parties
	Coherence with EU objectives	Coherence with EU objectives are strengthened with such a bundling
	Regulatory impacts	None expected
	Social and ethical impacts	None expected
Better utilise existing capacities in the EU research ecosystem	Costs	Depending on form and extent of implementation, from ad-hoc projects to framework contracts with individual institutions or consortia
	Benefits	Fully flexible in costs and access to expertise
	Feasibility	The EU research ecosystem offers varied and extensive expertise at different institutions, partly already known through EU-funded projects
	Effectiveness	The EU research ecosystem can effectively complement EU institutional capacities, flexibly providing needed expertise
	Sustainability	Sustainability can be enhanced by utilising the substantial expertise in the EU research ecosystem, built up through years of targeted research and sustainability policy

Option	Assessment dimension	Assessment
	Risks and uncertainties	Actual capacity development and personnel fluctuation outside the direct influence of EU institutions
	Coherence with EU objectives	Coherent especially with the Regulation on Horizon Europe and the Green Deal
	Regulatory impacts	None expected
	Social and ethical impacts	None expected
Increase funding allocated to raw materials topics in EU framework programmes; encourage work on 'less popular' CRM	Costs	Depending on the extent of sustained funding increase
	Benefits	Broader capacity development; availability of expertise along CRM value chains and across disciplines. Better ability to support competence and capacity building on CRMs currently less researched
	Feasibility	Feasible using existing framework
	Effectiveness	In line with the CRM Act, research and innovation actions are seen as an effective contribution to reach policy goals
	Sustainability	Assuming that sustainability is included as a requirement in R&I funding, the increase in funding will amount to increased knowledge-building on sustainability challenges and solutions in CRMs
	Risks and uncertainties	As with all research, uncertain extent of transfer of funding to research success to innovations on the market
	Coherence with EU objectives	Coherent especially with the CRM Act and the Green Deal
	Regulatory impacts	None anticipated
	Social and ethical impacts	None anticipated
Continued funding for bringing research results to the market (EIT, EIC, ERA-MIN)	Costs	Depending on the extent of sustained funding increase
	Benefits	This will enable European SMEs and larger corporations to exploit the investments in research, facilitating innovative market solutions, ultimately increasing EU CRM sovereignty
	Feasibility	Feasible using existing framework
	Effectiveness	This is anticipated to lead to increased commercial activity in the European CRM supply chains

Option	Assessment dimension	Assessment
	Sustainability	Assuming that sustainability is included as a requirement in R&I commercialisation funding, the increase in funding will amount to increased commercial capacity that tackles sustainability challenges and promotes commercially viable solutions
	Risks and uncertainties	A certain number of commercialisation projects will never succeed; however, this is not a particular challenge related to CRMs
	Coherence with EU objectives	Coherent with the political goals of the Green Deal, A Europe Fit for the Digital Age and A Stronger Europe in the World
	Regulatory impacts	None anticipated
	Social and ethical impacts	Job creation along the CRM supply chains
Strengthen R&I on demand reduction (reduced consumption, substitution and longevity)	Costs	Depending on the extent of sustained funding increase. Demand reduction is intended to lead to reduced consumption which will change the need for products globally, including European ones, affecting commercial actors and jobs.
	Benefits	Substitution of CRMs with non-critical raw materials will increase European sovereignty regarding technologies for the green transition. Keeping existing CRMs longer in the life cycle by increased circularity will reduce the need for new sites, with their accompanying societal and environmental effects. Demand reduction contributes directly to reducing CO_2 emissions, avoiding further decrease in biodiversity and helping keep society within planetary boundaries.
	Feasibility	Feasible using existing framework
	Effectiveness	This measure is anticipated to be effective on reducing the demand for new extraction of CRMs
	Sustainability	See benefits above
	Risks and uncertainties	There is a certain political and economic risk. Demand reduction will require societal change to focus on preserving and increasing functionality instead of possessions – a possibly unpopular proposition, at least initially. At the same time, reduced demand for new products implies a shift in jobs away from manufacturing and towards repair and other (technical) services.

Option	Assessment dimension	Assessment
	Coherence with EU objectives	Coherent with the Green Deal
	Regulatory impacts	No impacts foreseen
	Social and ethical impacts	Increased societal awareness of consumption patterns and sustainability effects
Strengthen incentives for research collaboration with non-EU partners	Costs	This can be handled within existing funding regimes, so need not imply additional costs
	Benefits	Will facilitate learning both among European and non-European actors. It is anticipated to give better access to data and help build up capacity in third countries to supply data required by the Transparency Act and the Corporate Sustainability Reporting Directive. This may improve the actual documentation of the assumed higher sustainability of European CRM supply.
	Feasibility	From EU's side, this is feasible
	Effectiveness	Increased capacity to achieve CRM Act aims
	Sustainability	As European actors will follow EU sustainability policy/regulation, this can lead to sustainability competence and capacity building in non-EU countries.
	Risks and uncertainties	The follow-up of third countries cannot be guaranteed. Some European research funding may be subject to corruption or manipulation.
	Coherence with EU objectives	This is coherent with political goals such as the Green Deal and A Stronger Europe in the World.
	Regulatory impacts	New bilateral R&I agreements might be needed.
	Social and ethical impacts	Increased global understanding of CRM issues and adoption of common ethics governance processes internationally.
Use international projects to generate data on opaque supply chains	Costs	This can be handled within existing funding regimes, so need not imply additional costs.
	Benefits	This will help companies' implementation of the Transparency Act and the Corporate Sustainability Reporting Directive. It may also improve the actual documentation of the assumed higher sustainability of European CRM supply.
	Feasibility	Such a policy is feasible from Europe's side, but the feasibility at the receiving end is uncertain.
	Effectiveness	New data and knowledge on international supply chains.

Option	Assessment dimension	Assessment
	Sustainability	Increased data from CRM supply chain will facilitate the assessment of sustainability impacts, which may allow for more informed purchasing decisions taking sustainability into account.
	Risks and uncertainties	It may still be difficult for European researchers (or other actors) to access the desired data and ascertain its quality.
	Coherence with EU objectives	This is coherent with the Green Deal and supports the aims of the Corporate Sustainability Reporting Directive and the Corporate Sustainability Due Diligence Directive.
	Regulatory impacts	New bilateral R&I agreements might be needed.
	Social and ethical impacts	No negative impacts are foreseen. Positive impacts are intended by having increased access to social and environmental sustainability data.
Ensure funding for R&I aspects of strategic partnerships on raw materials	Costs	Will involve some costs for the partners to the partnerships, including the EU. As the other partners may also bear costs, there will be added value for the EU.
	Benefits	Increased collaboration on the level of research with strategically important third countries. Synergies are expected when international partners share research. Learning processes can be assumed at several levels of collaboration, from research to business to public institutions.
	Feasibility	This is a further development of existing partnerships and should be feasible.
	Effectiveness	Effective for further developing EU research competence and capacity
	Sustainability	EU policy goals on sustainability can be communicated and strengthened through such partnerships.
	Risks and uncertainties	No additional risks are anticipated from further developing the R&I dimension in these partnerships.
	Coherence with EU objectives	This is coherent with already existing practice.
	Regulatory impacts	No impacts foreseen
	Social and ethical impacts	European values can be transmitted in such partnerships.

Option	Assessment dimension	Assessment
Support demo-cases and living labs for citizen engagement and responsible innovation around new or reactivated exploration, mining and processing sites	Costs	Depending on the complexity of the undertaking, but little elaborate infrastructure is required.
	Benefits	Early identification of citizens' concerns and engagement of different stakeholder groups in dialogues facilitating the exchange of knowledge and values, to establish platforms for further responsible development of CRM mining and processing.
	Feasibility	Easily organised based on existing experience.
	Effectiveness	Increase democratic legitimacy of decisions and decrease social conflicts.
	Sustainability	Social sustainability will be strengthened through such undertakings. Environmental sustainability may also be strengthened when environmental NGOs are included, and through embedding citizens' concerns.
	Risks and uncertainties	Harmonious dialogue processes cannot be guaranteed, and neither can conflict resolution.
	Coherence with EU objectives	Compatible with the EU Open Science policy, where citizen engagement is highlighted.
	Regulatory impacts	No such impacts anticipated
	Social and ethical impacts	This option is motivated by democratic concerns and respect for human rights.
Integrate social sciences and humanities (SSH) aspects into technical R&I projects along the CRM supply chains, when relevant	Costs	Generally, this does not increase the costs of R&I programmes significantly, but it does require a certain reallocation of funding across disciplines.
	Benefits	A transdisciplinary approach can contribute to the success of projects along the CRM supply chain, which is a socio-technical system.
	Feasibility	Easily applicable. Such integration is already done in some funding programmes, such as the Materials era.net.
	Effectiveness	The effectiveness on reducing conflict cannot be assured, but this allows for a better understanding of the social and environmental values, so that R&I can be developed that maximises potential positive impacts and minimises negative impacts.
	Sustainability	More publicly acceptable decision making in the area is expected.

Option	Assessment dimension	Assessment
	Risks and uncertainties	Integration of SSH perspectives and transdisciplinarity can sometimes be hard to achieve in practice. Building experience and culture for such integration can reduce this risk.
	Coherence with EU objectives	This is coherent with the Open Science policy.
	Regulatory impacts	No such impacts foreseen
	Social and ethical impacts	This option is intended to increase the social sustainability of CRM supply chain innovations and developments.
Research into overcoming regulatory barriers and strengthening drivers to achieve the goals of the CRM Act, also addressing the retention and mobility of scrap within the EU	Costs	Costs depend on the funding level.
	Benefits	CRM Act goals will be more effectively reached, including the sovereignty and sustainability of European CRM supply.
	Feasibility	This is a highly feasible option as there is sufficient expertise available.
	Effectiveness	This option is assumed to be effective as a good knowledge base is necessary for driving change.
	Sustainability	As sustainability is a goal for the CRM Act, and circularity is an important aspect, this option contributes to sustainability.
	Risks and uncertainties	Knowledge building may not be sufficient for driving change, but it is still an important instrument for this ambition.
	Coherence with EU objectives	This is in particular coherent with the CRM Act.
	Regulatory impacts	This research is meant to have regulatory impacts, promoting the achievement of the goals of the CRM Act.
	Social and ethical impacts	There are no particular social and ethical impacts of this R&I, but the potential impact of the research is intended to strengthen societal interests.

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Annex A – List of CRM relevant EU policies

With a focus on general (i.e., not country specific or product specific) policies, the following list contains, in chronological order, the names of the CRM-relevant EU-policy acts (excluding research funding initiatives) and the years they went in force or are announced (based on International Energy Agency 2024):

- EU Generalised Scheme of Preferences, 2023, In force
- European Critical Raw Materials Act, 2023, Announced
- Directive on Corporate Sustainability Due Diligence, 2022, Announced
- Joint Communication to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the regions. EU External energy engagement in a changing world, 2022, Announced
- RePowerEU Plan, 2022, In force
- EU Corporate Sustainability Reporting Directive, 2021, In force
- EU Regulation 2017/821 Supply chain due diligence for minerals from conflict-affected and high-risk areas, 2021, In force
- European Commission Recommendation on the use of Environmental Footprint methods, 2021, In force
- European Raw Materials Alliance, 2021, In force
- Global Gateway, 2021, In force
- European Action Plan on Critical Raw Materials, 2020, In force
- Green Deal: Circular Economy Action Plan, 2020, In force
- The 2020 EU Critical Raw Materials List, 2020, In force
- European partnership for responsible minerals (EPRM), 2016, In force
- Horizon 2020: Climate action, environment, resource efficiency and raw materials, 2013, Ended
- European Innovation Partnership on Raw Materials, 2010, In force
- Industrial Emissions Directive (2010/75/EU), 2010, In force
- European Raw Materials Initiative, 2008, In force.

Annex B – Specific actions along the CRM value chain

Important policy initiatives such as the twin transition depend on a safe and sustainable supply of critical raw materials (cf. Section 3.3). In order to be sustainable, R&I will be required along the entire chain, not only at the initial stages of exploration and mining (cf. Figure 6). For the concretization of R&I policy options along the CRM value chain, we assume they should contribute to:

- maintaining and improving the resilience of the EU towards supply chain disruptions and enhancing strategic autonomy in a geopolitically contested world,
- maintaining and improving EU competitiveness as a provider of CRM mining and processing related technologies,
- making EU CRM-based value chains more circular and sustainable, ideally reaping economic benefits.

Therefore, we focus on:

- activities to expand capacities in existing areas of strength, to strengthen the position of the EU in CRM value chains
- activities to build capacities to close gaps in areas of weakness which constitute current vulnerabilities in EU CRM value chains
- activities to strengthen collaborations with reliable partners.

Policy options are listed below, roughly following the CRM value chain depicted in Figure 6.

Enabling exploration

- Expand funding to improve technical capacities in exploration.
- Fund SSH projects (including citizen involvement) to identify the wider societal effects of exploration and ways to improve acceptability by affected stakeholders.
- Fund empirical R&I on commercial and regulatory barriers that currently prevent the exploration, initiation and extension of mining operations in Europe and that helps develop potential, regulatory compliant solutions to existing bottlenecks.
- Fund interdisciplinary research efforts to assess the viability of intra-European alternatives to current CRM supply chains originating in unreliable non-EU countries.

Improving efficiency in extractive industries

- Provide R&I funding for existing mines and activities based on European natural deposits already available for commercial use.
- Fund empirical research on socio-economic barriers to further investments in existing European deposits.
- Fund start-up and scaling activities to aid in the development of relevant new businesses in the field of extraction technology.

Improving capacities for value creation in processing and refining

- Fund pilots for more sustainable and efficient processing and support their scale-up.
- Fund R&I focusing on increasing economic efficiency in mining residual products.
- Fund R&I initiatives focused on closing gaps in European manufacturing and production capacities relevant for CRM based products.
- Fund start-up and scaling activities to help related new businesses in the field of processing and refining technology develop along the CRM value chain.

Improving efficiency and resilience in manufacturing

- Fund R&I efforts to accelerate research on alternatives to currently used CRMs (material research)

- Include requirements for sustainability-by-design (SSdB) in all research and innovation funded by the EU
- Continue to fund research on Digital Product Passport for CRMs

Improving capacities for recycling and enabling circularity

- Prioritise R&I on extending the lifetime of consumer electronics, focus on CRMs products critical for the twin transitions
- Fund R&I to better understand the behaviour of all actors dealing with end-of-life products (households, enterprises, government) and on that basis improve European's inclination to recycle (including citizen engagement)
- Fund R&I to technically, organizationally, and procedurally improve existing recycling processes and generate commercially viable innovations for end-of-life stages
- Fund start-up and scaling activities to help related new businesses in the field of recycling technology develop along the CRM value chain
- Fund projects on end-of-life infrastructure development in third countries to increase the share of secondary versus primary mining content in imports

Internationalisation

- Enhance alignment of funding initiatives including Framework Programmes, ERA-MIN, and EIT RawMaterials with national research and innovation programs as they relate to the cooperation with non-EU countries.
- Further specify the R&I dimension of Strategic Partnerships, formed under the auspices of Raw Materials Diplomacy, through specific roadmaps and activities.
- Further integrate the Critical Raw Materials (CRM) theme into existing R&I programs and recognising it as a pivotal element of the EU's Science Diplomacy.
- Fund interdisciplinary R&I efforts to assess the viability of extra-European alternatives to current CRM supply chains originating in unreliable non-EU countries
- Improve funding for R&I collaborations with reliable non-European partners and make those eligible for funding

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This study aims to illuminate the role of research and innovation (R&I) in ensuring a safe and sustainable supply of critical raw materials (CRM). It provides background information on CRMs, related EU policies, sustainability issues, and public controversy, tying all these in with their respective R&I needs. The study reviews the role of R&I and cooperation in securing the EU's raw material supply, highlighting the significance of R&I along the value chain and analysing patenting activities and international cooperation. It concludes by presenting 11 policy options on EU institutional and R&I capacities, international collaboration and legitimacy and regulation, assessing each against a list of dimensions (e.g. costs, benefits and feasibility).

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